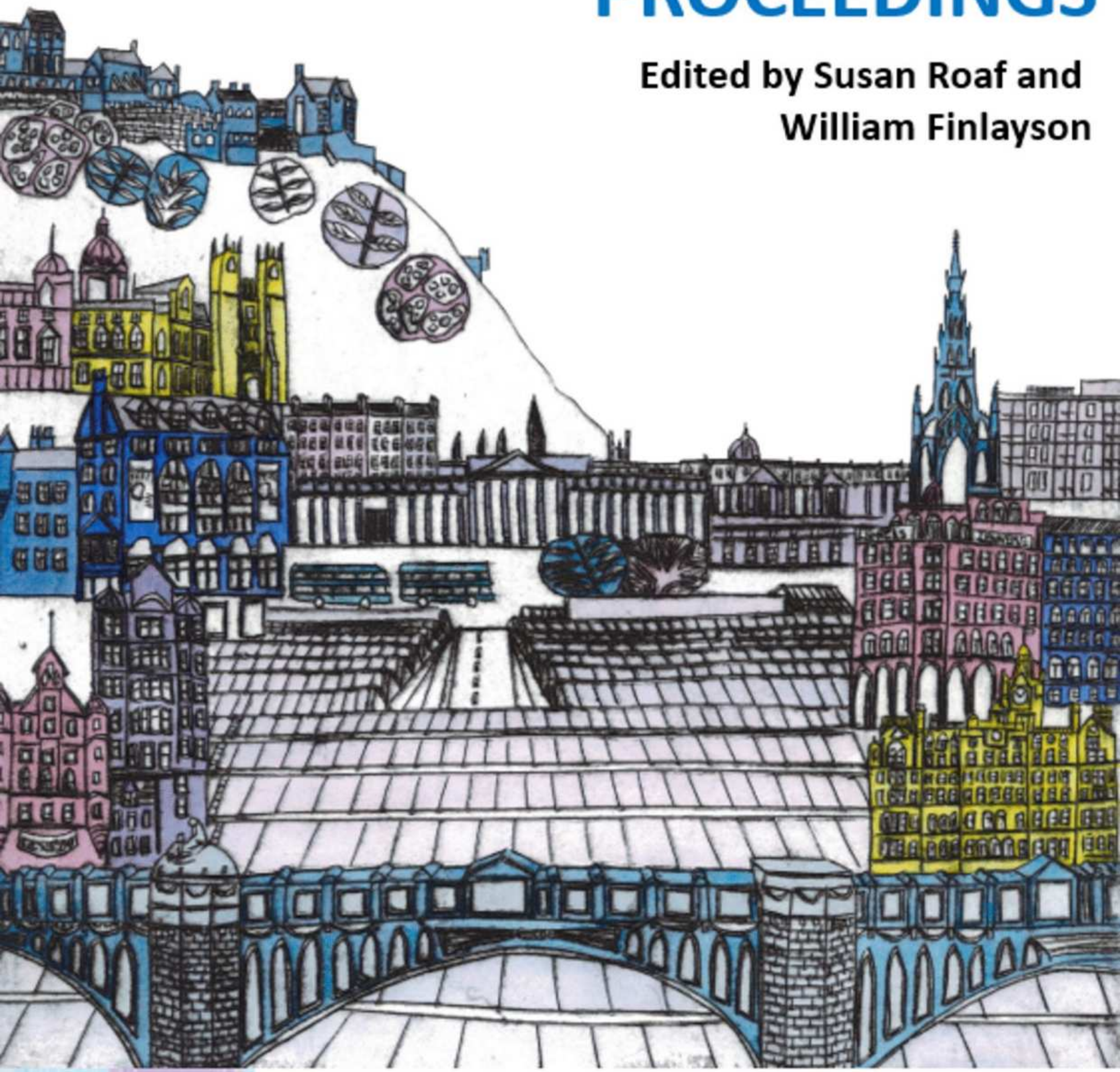
Measuring Net Zero:

CARBON ACCOUNTING FOR BUILDINGS AND COMMUNITIES

PROCEEDINGS

Edited by Susan Roaf and William Finlayson



ICARB

8th International ICARB Conference 2023:
25th - 26th September 2023 Edinburgh

PROCEEDINGS

Of the 8th International ICARB Conference on Carbon Accounting

MEASURING NET ZERO:

CARBON ACCOUNTING FOR BUILDINGS AND COMMUNITIES

Held at The Edinburgh City Chambers

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INTRODUCTION

Measuring Net Zero:
Carbon Accounting for Buildings and Communities:

ICARB 2023 was convened because humanity has a terrible problem.

The ambitious GHG emission reduction targets and budgets that we are told will reduce carbon emissions from the built environment are simply not working in practice. Globally emissions keep rising at alarming rates. Around 47% of emissions come from buildings and communities and their related industries. Five key questions were framed at the start of the Conference to concentrate minds:

1. *Who decides what the Net Zero Targets are, and are their priorities right?*
2. *What issues Matter Most for buildings and communities in unpredictable futures? Net Zero or Resilience?*
3. *How far can we rely on Grid Decarbonisation to meet built environment carbon reduction targets in reality?*
4. *What Net Zero Policies work in practice in Real Buildings and Communities?*
5. *How are Carbon Targets and Standards best planned, costed and validated?*
6. *Is it even possible to Account for the Benefits of Energy Sufficient and Resilient features in designs like shading, thermal mass, and natural ventilation within existing carbon accounting metrics, methods, standards and rating systems? If Not - Why Not?*

Over a hundred delegates from twenty-four countries attended including politicians, academics, the professions, community groups and the construction industry to clarify, inform, share, link and explore the related challenges, opportunities, options, viewpoints and possibilities as we urgently search for the strategies that will actually work well enough for buildings and communities to follow a safe and successful path to a low carbon future.

Two full days of Plenary and Panel sessions and six Specialist Workshops were held on the 25th and 26th of September, linked by a networking event in Edinburgh Castle on the evening of the 25th. There is the halls of a thousand year old building complex concerns and experiences were shared and future directions explored. Having many experts from different sides of the Net Zero debate helped to open minds to different aspects of the same challenge. Real progress was made at ICARB 2023. Read about some of it here and in the pages of the Legacy Document that accompanies it, capturing some of the discussions on the days.

Susan Roaf
Will Finlayson   1st October 2023
Julio Bros-Williamson

CONTENTS

Monday 25th September 2023

Tuesday 26th September 2023

Non-attending Authors

Reliably Accounting for Negative Emissions of Waste-to-Energy with Carbon Capture and Storage

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Abstract:
When equipped with Carbon Capture and Storage (CCS), the Waste to Energy (WtE) sector can play a significant role in creating an overall system that removes excess greenhouse gases from the atmosphere while sustainably managing waste. Ultra-high CO2 capture rates can be achieved to eliminate all CO2 emissions from the combustion of the waste feedstock. As the biogenic carbon in most waste feedstocks originates in the atmosphere, the implementation of CCS on WtE plants can create a 'negative emissions' system; i.e., the removal and permanent storage of atmospheric carbon dioxide. Existing studies exploring the negative emissions potential of this technology are of limited scope, however, and do not account for the system-wide change in impacts or identify relevant cause-effect pathways. By not accounting for the impact of removing recyclable materials from the supply chain, for example, the comparative benefit of sending biogenic materials for recycling or to WtE with CCS is poorly understood. It is important to understand these benefits in the context of the whole economy. This paper reviews existing analyses of the carbon reduction of WtE with CCS and discusses the challenges of understanding its role in the transition to Net Zero in the context of the circular economy.

Keywords: Waste to energy; carbon capture and storage; negative emissions; biogenic carbon

1. Introduction

Waste-to-energy (WtE) is rapidly becoming one of the primary methods of treating residual waste in Europe, due to legislation diverting waste from landfills, and mandating the implementation of energy recovery on waste incineration plants (European Union, 2018, Brown et al., 2023). This process, however, still has significant carbon emissions, estimated to be 700 to 1200 kg CO_2eq/t_{MSW} (IPCC, 2003). The addition of post-combustion carbon capture and storage (CCS) can completely eliminate all CO_2 emissions from the waste incineration process, significantly reducing the climate change impacts, and potentially creating a negative emissions pathway due to the biogenic carbon in the waste feedstock (Su et al., 2023).

A significant proportion (50-70%) of the carbon in residual waste (waste that remains after separation for re-use and recycling) is of biogenic origin (Herraiz et al., 2023). Traditional waste treatment processes, including landfill and WtE, release this biogenic carbon back into the atmosphere in the form of methane or carbon dioxide. WtE-CCS, like other types of bioenergy with carbon capture and storage (BECCS), will capture and permanently store it. Existing studies suggest that significant carbon dioxide removal can be achieved, with an estimated potential removal of 30 to 100 Mt CO_2eq/yr in the European waste sector (Muslemani et al., 2023).

Waste-to-energy is, however, considered only one step above landfill as a waste treatment option (), with circular economy principles aiming to minimise the amount of material reaching this stage. If the addition of CCS to WtE plants results in a greater reduction in atmospheric CO_2 concentrations than material reuse and recycling, should this still be the case?

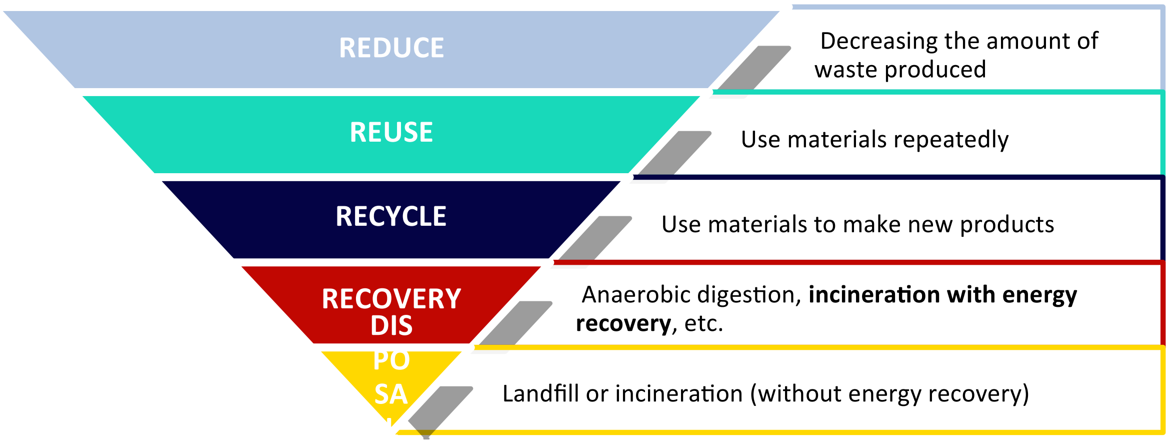

Figure 1 - Waste hierarchy

While the principles of the circular economy are intended to minimise material consumption and waste production, a key driver for this is environmental sustainability. Initial results from analyses considering a range of different waste compositions suggest that the diversion of dry biogenic waste away from WtE-CCS plants to recycling may actually have a higher carbon impact (Herraiz et al., 2023). If these results are correct, there is a potential conflict between circular economy policies, which aim to minimize waste and promote recycling, and climate policies, which seek to maximize negative emissions to achieve Net Zero.

A comprehensive analysis comparing the relative environmental merits of WtE-CCS and recycling for dry biogenic waste has not yet been carried out to test this conclusion. Furthermore, the existing analyses are limited in scope, considering only the direct emissions and assumed avoided impacts of the waste treatment process within the boundaries of attributional life cycle assessment (Bisinella et al., 2021, Bisinella et al., 2022, Pour et al., 2018, Struthers et al., 2022, Herraiz et al., 2023). The conventional methodologies applied in these studies are unable to account for the system-wide change in impacts caused by waste management interventions, and related cause-effect pathways, such as the displacement of existing uses through diversion of constrained resources.

Furthermore, there is an ongoing debate whether WtE-CCS is a true carbon removal technology or not; it may not qualify as a NET (Negative Emission Technology) due to an assumption that the removals would have occurred anyway, as the production of the biogenic material is independent of the waste treatment process. This debate over the language used to describe atmospheric emissions reductions could divert attention away from the potential benefits of this technology, and merits clarification. The conversion of waste to energy with geological CO_2 storage is the only known waste treatment method that can prevent the majority of biogenic carbon from returning to the atmosphere over geological timescales. It typically includes conversion of waste to electricity and/or heat in Waste to Energy plants, but could be extended to the production of zero-carbon fuels from waste.

There is an urgent need to identify the most cost-effective and rapid routes to reducing carbon emissions and atmospheric carbon concentrations. In order to improve confidence in negative emissions processes like WtE-CCS, the uncertainty about the analytical methods and the clarity of the language applied to describe them must be addressed. More comprehensive and integrated approaches are required to understand the implication of WtE-CCS for carbon emissions and removals, and to allow analysts, investors and policy makers to have confidence in the conclusions about the position of this technology in the pathways to Net Zero.

The overall aim of this paper is, therefore, to review how well the carbon benefits of waste-to-energy with carbon capture and storage are understood in the context of the whole circular economy, and discuss what methodological developments are needed to reliably evaluate any trade-offs between Net Zero and Circular Economy targets.

2. Defining negative emissions

Negative emissions technologies (NET) are defined as those that remove and permanently store greenhouse gases (GHGs) from the atmosphere, through intentional human efforts (Minx et al., 2018, Terlouw et al., 2021). In order to mitigate the impacts of climate change through atmospheric carbon removals, "an overarching necessity is to ensure that the total effect of all components within the complex system of a NET is the permanent removal of atmospheric greenhouse gases, and thereby a net decrease in the greenhouse gas concentration in the atmosphere" (Tanzer and Ramírez, 2019).

A number of studies have examined the GHG emissions of WtE-CCS technologies and have found them to be net-negative, resulting in the assertion that WtE-CCS is a NET (Bisinella et al., 2021, Bisinella et al., 2022, Pour et al., 2018, Struthers et al., 2022). When calculating the net GHG emissions of a technology through LCA, however, both the 'avoided emissions' from substituting alternative processes (such as displacing energy production through combustion of fossil fuels) and the true 'negative emissions' are often aggregated, which can easily cause misinterpretation (Allen et al., 2020, Forster et al., 2021). Although calculations for avoided emissions result in negative numbers, they are distinct from the measurable physical removal of greenhouse gases from the atmosphere (Tanzer and Ramírez, 2019).

In order to evaluate the negative emissions attributable to WtE-CCS, it is therefore important to understand the positive, negative, and neutral flows of GHGs within the WtE-CCS system. These can be classed as follows:

- **Net direct emissions from MSW incineration** (positive flow): This includes all GHGs released in the flue gases after air pollution control and the carbon capture process, characterised according to radiative forcing in units of kg CO_2eq. Note that biogenic CO_2 emitted to the atmosphere is typically given a characterisation factor of 0 kg CO_2eq/kg, so is a neutral flow (ReCiPe, 2016). The direct emissions-reduction due to capture and long-life/permanent storage in geological formations of CO_2 of fossil origin is directly accounted for within this metric, in reducing the GHG content of the flue gases.
- **Net direct emissions from CCS** (positive flow): This includes all GHGs released in the CCS process (typically amine and degradation products like ammonia), and leakage of CO_2 during transportation and storage.
- **Net indirect emissions from WtE-CCS** (positive flow): All GHG emissions associated with the life cycle of the WtE and CCS infrastructure, and the materials consumed during operation.
- **Avoided emissions from co-products/processes** (negative flow): This is the estimated reduction in emissions due to the displacement or substitution of

other processes by conventional means, such as energy generation, primary metal production or waste treatment. This is highly subjective and difficult to test; for example, it is unclear which type of electricity generation reduces its output as a result of electricity exported from a WtE plant, and thus the corresponding emissions intensity of this displaced generation. It is not typically calculated as part of an attributional LCA, but is often considered in the analysis of the results in evaluating the significance of the findings. This has been included in several published LCA studies of WtE-CCS (Struthers et al., 2022, Bisinella et al., 2021, Bisinella et al., 2022, Pour et al., 2018).

- **Negative emissions from biogenic CCS** (negative flow): The capture and permanent storage of CO_2 from incineration of biogenic materials in the MSW feedstock.

The assertion that this final activity is a true negative emission is an open question for debate, particularly with regards to WtE-CCS. This is because the biogenic feedstock is a waste material; the removal of carbon from the atmosphere happens as the plants are grown to make bio-based products (food, paper, card etc.), which are then disposed of as waste. This happens independently of the existence of the WtE-CCS plant, and therefore the removals can be considered outside the system boundary and would happen anyway. This assumption is in line with the existing guidance for evaluating BECCS as a NET, where the production of the biogenic feedstock *is* included in the system boundary, so it includes a removal from the atmosphere (Tanzer and Ramírez, 2019).

The IPCC defines a “removal” as the transfer of GHGs from the atmosphere to non-atmospheric reservoirs, which is separate from “storage” (IPCC, 2006). In WtE-CCS, the removal of the GHG from the atmosphere into the biospheric reservoir occurs outside of the system boundary (note that the growth of the crop also doesn’t meet the definition of a NET, as it is not permanent). It may be appropriate to expand the system boundary to include this upstream removal, but this is contentious as the upstream impacts of product manufacture are not included. If the carbon removals of making a cardboard box are attributed to the waste treatment process, then there is a case for attributing all of the manufacturing impacts to the waste treatment, rather than to the product. The problem arises because this analysis is only considering a partial life cycle of the cardboard box (disposal, from gate to grave).

The intervention of the carbon capture process in the biogenic carbon cycle with subsequent long-term storage, however, does occur within the system boundary, and should be accounted for. This process prevents the transfer of the biogenic CO_2 back into the atmosphere by transferring it into long-term storage in the geosphere. The impact on climate change of impermanent removals into the biosphere is different from the impact of permanent removals into the geosphere. The current taxonomy does not have appropriate terminology for this; the best approximation is that this is an “avoided emission”. These avoided emissions are, however, distinct from the “avoided emissions” due to displacement of processes like landfilling and energy generation, so the term “negative emissions” is retained in this paper.

The attribution of biogenic CO_2 capture and storage as a negative emission aligns with the current convention in attributional LCA of giving biogenic CO_2 a characterisation factor of 0 kg CO_2eq/kg at the point of absorption from/emission to the atmosphere. This is either due to the assumption that it is in balance as part of the natural carbon cycle, or that the biomass is continually replaced by an equivalent amount of new planting, thus balancing out the CO_2 absorption and emissions (Tanzer and Ramírez, 2019). (Note that emissions of other GHGs of biogenic origin, such as methane, are given the same characterisation factors as those of fossil origin.) Although the assumption of the carbon neutrality of biogenic CO_2 is contested (Liu et al., 2017) in all the analyses discussed in this article, the permanent removal of biogenic CO_2 to geological storage is, therefore, given a characterisation factor of -1 kg CO_2eq/kg at the point of human intervention in the carbon cycle, as this is the point where the balance has been disrupted.

3. Negative emissions of WtE with CCS

Although the application of carbon capture to waste-to-energy is currently only operational at pilot scale in a handful of locations (Aker Solutions, 2019, Fortum Oslo Varme AS, 2020), or at commercial scale to sell CO_2 as a commodity (i.e. without geological storage) (Wright, 2021, Ros et al., 2022) a number of studies have been published that assess the potential environmental impacts and burdens of this technology (Bisinella et al., 2021, Bisinella et al., 2022, Pour et al., 2018, Struthers et al., 2022). In accordance with legislation on environmental sustainability evaluation of waste treatment (European Union, 2009), these assessments are based on the internationally-standardised LCA methodology (ISO, 2006a, ISO, 2006b). The results from these studies have been used to draw conclusions on the relative benefits of WtE with CCS over other waste treatment and energy generation options.

3.1. Carbon impacts per tonne of waste treated

Figure 2 summarises the current estimates of the carbon impacts and benefits of WtE with CCS (Struthers et al., 2022, Bisinella et al., 2021, Bisinella et al., 2022, Pour et al., 2018). These are all process-based attributional LCA studies examining a single WtE plant, with the results reported per unit of waste treated, ranging from -532 to -773 kg CO_2eq/t_{MSW}. This includes direct emissions from the combustion of waste and supplementary fuels and the environmental burdens from the production of required ancillary materials and energy. Defining the system boundary at the level of the WtE-CCS plant implicitly excludes the consequential impacts on the wider economy; however, these studies have all reported the captured and stored CO_2 of biogenic origin as a negative emission at the point of removal from the flue gases.

All of these studies also account for the avoided emissions due to energy export and metal recovery. Assumptions of the carbon intensity of the avoided processes may significantly over- or under-estimate the emissions reductions – particularly with the rapid decarbonisation of the energy sector – so these estimates should be treated with caution. This is illustrated well by the high emissions reduction attributed to electricity export in Pour et al. (Pour et al., 2018), which is due to the case study plant being in Australia where there is a higher-carbon energy generation mix than for the European countries considered by Struthers et al. (2022) and Bisinella et al. (2021, 2022). Without the avoided emissions impacts, the net emissions are -350 to -533 kg CO_2eq/t_{MSW}.

Avoided waste treatment is not considered in any of these studies, because the results are reported per unit of waste treated to enable comparison with other waste treatment options, so inclusion of the emissions reduction of avoided waste treatment could lead to double-counting.

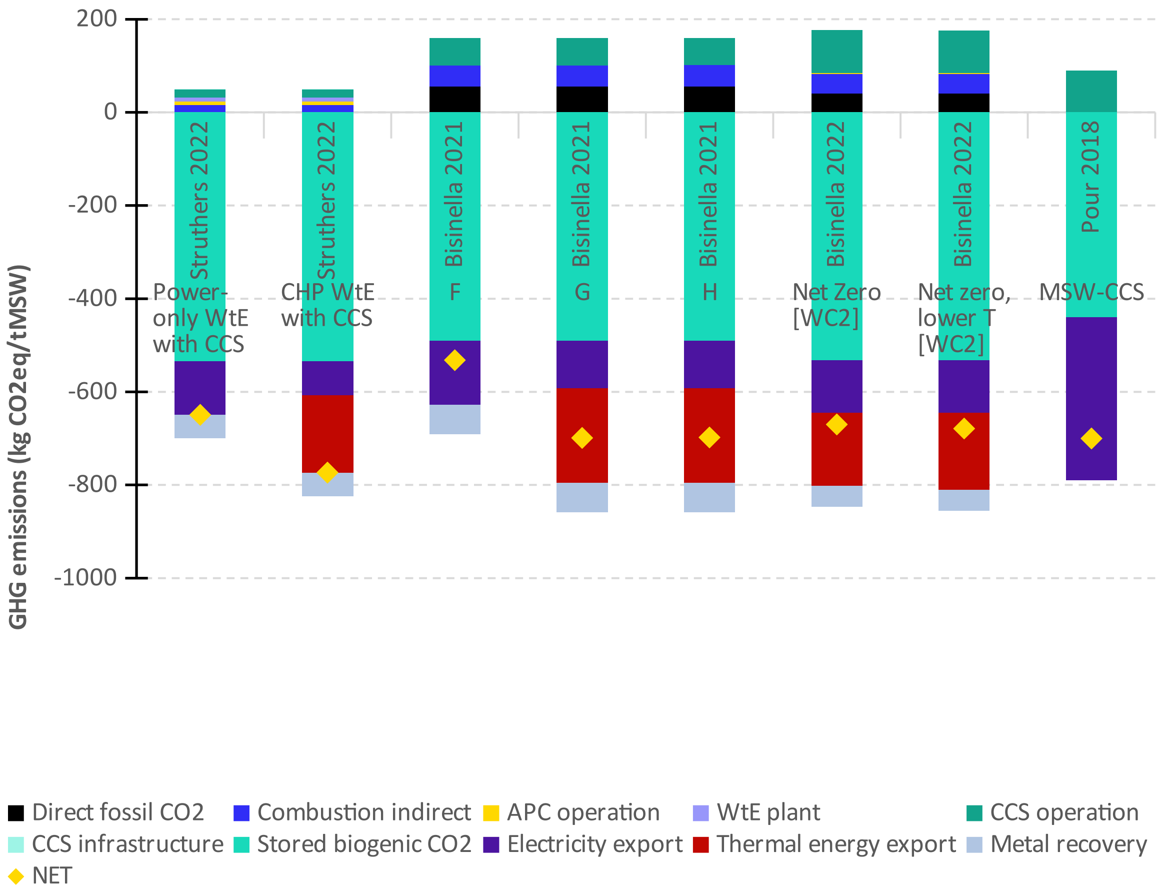

Figure 2 – Published estimates of the climate impacts of WtE with CCS, with detailed breakdown of impacts (Struthers et al., 2022, Bisinella et al., 2021, Bisinella et al., 2022, Pour et al., 2018)

If the avoided or negative emissions are excluded from the analysis, the GHG emissions of the WtE-CCS process are found to range from 50 to 177 kg CO_2eq/t_{MSW}, significantly lower than waste-to-energy without CCS (388 to 448 kg CO_2eq/t_{MSW} from the same studies) or landfill (estimated to be 744 kg CO_2eq/t_{MSW} calculated by applying characterisation factors from the ReCiPe method to data on treatment of municipal solid waste in sanitary landfill) (Struthers et al., 2022, Bisinella et al., 2021, Bisinella et al., 2022, ReCiPe, 2016, ecoinvent, 2021). The lowest of these estimates is from Struthers et al. (2022), which has very low direct CO_2 emissions due to the ultra-high capture rate that has been shown to be possible with current technology (Su et al., 2023). While the impacts of plant infrastructure and operation are also very low in Struthers et al. (2022), Pour et al. (2018) does not account for these at all. This is due to the cut-off criteria applied, where all processes contributing less than 5% to the total impacts were excluded (Pour et al., 2018). It is worth noting that if the captured and stored biogenic CO_2 were not given a negative emissions value in this analysis, this cut-off criteria would no longer exclude the plant infrastructure and operations.

3.2. Carbon impacts per unit of energy output

While these studies have all reported the carbon impacts of WtE-CCS per unit of waste treated, under the Carbon Reporting Framework applied to UK national and regional greenhouse gas inventories all emissions from waste-to-energy are reported in the energy category (Brown et al., 2023). This has the effect of burden-shifting waste incineration emissions from waste treatment to energy production, which could be misleading if applied inappropriately in decision-making.

The impacts of WtE-CCS per unit of energy produced are shown in Figure 3, with the avoided impacts of energy production replaced by the avoided impacts of landfill (estimated to be 744 kg CO_2eq/t_{MSW} as described in Section 3.1.). It can be seen that the power only configurations (which include case F in Bisinella et al. (2021)) have the higher greenhouse gas emissions and reductions per unit energy than the CHP configurations, due to the higher total energy production of the CHP plant. Note that this is an artefact of the denominator being larger due to the greater total energy production in the CHP configuration.

It is also interesting to note that when the avoided or negative emissions are excluded from the calculation, the GHG emissions of the WtE-CCS process are found to range from 42 to 330 g CO_2eq/kWh, the upper range of which is very high for a renewable energy technology, even with ultra-high CO_2 capture rates to minimise direct fossil emissions at the plant. This is because all of the environmental burden has been allocated to the energy production processes, without accounting for the co-product of waste treatment.

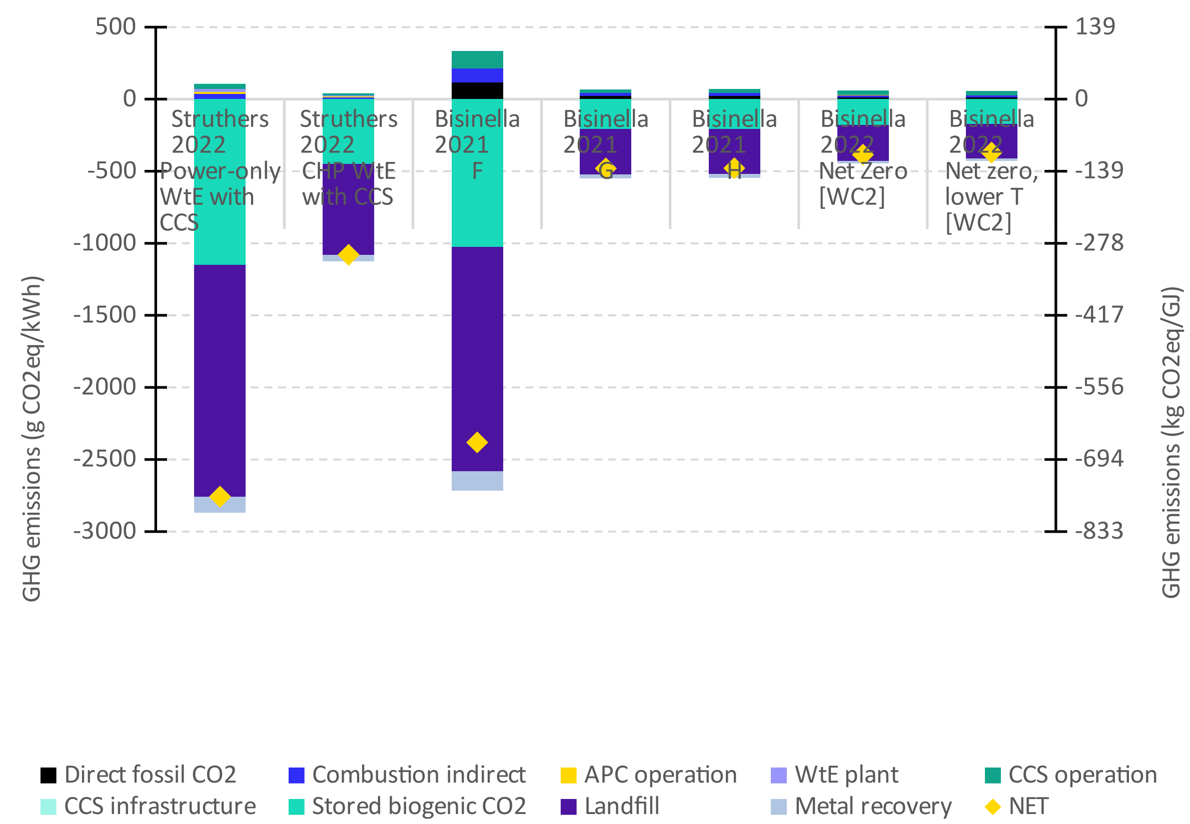

Figure 3 – Published estimates of the climate impacts of WtE with CCS per unit of energy (thermal and electrical energy output combined) (Struthers et al., 2022, Bisinella et al., 2021, Bisinella et al., 2022). The avoided impacts of landfill are also included.

3.3. Economic allocation of carbon impacts between co-products

It may be more appropriate to allocate the carbon impacts and benefits of WtE-CCS between the multiple co-products. Allocation is commonly applied in LCA, and could be of value for informing decision-making about WtE-CCS. Correct allocation will ensure that the total emissions impact will remain constant, but in national reporting allocation could allow for a more realistic division of carbon impacts between the waste and energy sectors.

A number of allocation methods exist and are discussed in detail in the LCA literature (Baumann and Tillman, 2004). For the purposes of this preliminary analysis, a simple economic allocation has been applied to allocate the impacts between the three co-products of waste treatment, thermal energy and electrical energy. Note that carbon reduction could be considered a fourth product (by means of selling carbon credits), but this has not been considered here.

Table 1 – Revenue estimates for use in the economic allocation

Gate fee at EfW plants	£110/tMSW	(Wrap, 2022)
Average selling value electricity	£0.23/kWh	(Statista Research Department, 2023)
Estimated selling value heat	£64/GJ	(Statista Research Department, 2023, ecoinvent, 2021)

The estimated revenue for each of the three co-products is based on 2021 data and shown in Table 1. The resulting allocated impacts for each of the co-products are given in Table 2. This shows that CHP WtE-CCS compares favourably with established renewable generation technologies (e.g. wind has a carbon footprint of ~11 g CO_2eq/kWh (Dolan and Heath, 2012)) , even when negative emissions from biogenic CO_2 capture are not considered. In order to avoid double-counting, the avoided impacts from displacing alternative waste treatment and energy production are not considered, but the avoided impacts of metal recycling have been included. In future work it would be more accurate to include waste metal as a fourth co-product rather than an avoided impact, but this requires reliable estimates of the value of the output material.

Table 2 – Carbon impacts for each co-product after applying economic allocation. Energy production values are as reported in the original analyses (Struthers et al., 2022, Bisinella et al., 2021, Bisinella et al., 2022).

	Struthers 2022	Struthers 2022	Bisinella 2021	Bisinella 2021	Bisinella 2021	Bisinella 2022	Bisinella 2022
	Power-only WtE with CCS	CHP WtE with CCS	F	G	H	Net Zero [WC2]	Net zero, lower T [WC2]
Excluding avoided emissions from metal recycling and capture of biogenic CO2							
Waste treatment ($kg\ CO_2eq/t_{MSW}$)	25	14	79	27	27	24	24
Electricity produced ($g\ CO_2eq/kWh_e$)	54	8	167	7	8	5	5
Heat produced ($kg\ CO_2eq/GJ_{th}$)	0	6	0	13	13	13	12
Including avoided emissions from metal recycling and capture of biogenic CO2							
Waste treatment ($kg\ CO_2eq/t_{MSW}$)	-269	-153	-196	-66	-66	-55	-54
Electricity produced ($g\ CO_2eq/kWh_e$)	-570	-81	-415	-18	-19	-12	-12
Heat produced ($kg\ CO_2eq/GJ_{th}$)	0	-67	0	-33	-33	-29	-28

4. Negative Emissions v the Circular Economy

As mentioned in Section 1., the principles of the circular economy promote the recycling and reuse of materials before incineration with energy recovery (Figure 1). This, however, is based on an implicit assumption that the former is more environmentally sustainable, which may no longer be the case in the context of WtE-CCS being a net negative emissions technology.

Herraiz et al. (2023) investigated the sensitivity of the negative emissions found in Struthers et al. (2022) to MSW composition. This found that a 60% decrease in the amount of plastic or wet biogenic (kitchen and garden) waste in the MSW mix would result in slightly higher negative emissions of CHP WtE-CCS (Herraiz et al., 2023). This suggests that it might be preferable to divert these waste streams to reuse or recycling, if possible..

The results for the sensitivity analysis of dry biogenic waste (paper & card), however, are particularly interesting. It was found that diverting 109 kg of paper and card out of the fuel-waste stream (the “enhanced paper and card recycling” case) reduces biogenic CO_2 removal of the CHP WtE-CCS plant by 112 kg CO_2/t_{MSW} (Herraiz et al., 2023). This implies that, from an emissions reduction perspective, it might be preferable to send dry biogenic waste to a WtE-CCS plant than to recycle it, in direct conflict with the waste hierarchy.

In order to test this, it is necessary to compare these findings with the avoided emissions of paper and card recycling. There is ongoing debate, however, about the true benefits of paper and card recycling with regards to climate change and it is challenging to identify consensus on the avoided emissions associated with these processes (van Ewijk et al., 2021). For the purposes of this article, the values collated by the Swiss Centre for Life Cycle Inventories are used: the application of the ReCiPe 2016 midpoint, hierarchist method (v1.07) to the ecoinvent v3.8 data on recycling of paper estimates the avoided emissions due to recycling to be due to avoiding softwood pulp production (ReCiPe, 2016, ecoinvent, 2021). Recycling 109 kg of paper and card results in carbon emissions of only -15 kg CO_2eq/t_{MSW}, which is significantly less beneficial for mitigating climate change than the 112 kg CO_2/t_{MSW} that would have been captured and stored if the same paper and card had passed to the WtE-CCS plant.

This is, however, only a very preliminary assessment, that is limited in its inclusion of the system-wide effects of the relevant cause-effect pathways. These could include aspects such as an induced demand for waste, diversion of constrained resources displacing other existing uses, reliable assessment of the substitution effects from the supply of co-products, and other market-mediated effects. Furthermore, other non-CO_2 environmental benefits, such as biodiversity and land use change, are not accounted for.

Alongside a clarification of the definition of negative emissions technologies, there is clearly also a need to clarify the carbon accounting and LCA methodologies to properly account for the impacts and benefits of carbon capture and storage in the waste treatment sector. This could include an expansion of system boundaries to include the removals that occur at the beginning of the product system, the product waste streams, consequential system-wide analysis and more sophisticated analysis of the time-series of emissions and removals.

5. Conclusions

The application of carbon capture and storage to waste-to-energy plants creates a form of BECCS that is a promising technology for reducing concentrations of atmospheric carbon dioxide, with significant negative emissions. There is, however, some debate as to whether it fits the strict definition of a Negative Emissions Technology, as the removal of greenhouse gases from the atmosphere occurs outside the system boundary. Instead, the CCS process moves the biogenic carbon dioxide in the waste stream from short-term storage in the biosphere to long-term storage in the geosphere. While this has a clear benefit for climate change, there is a need to clarify the language around such processes to ensure that their benefits are properly realised.

A review of existing life cycle analyses of WtE-CCS plants has found that they are expected to achieve net emissions of -350 to -773 kg CO_2eq/t_{MSW} due to avoided emissions from energy and metal recovery and negative emissions from the captured biogenic CO_2. This makes assumptions about the displaced impacts of energy production, and applies all of the GHG emissions to the waste treatment process. Economic allocation was used to divide the impacts between the three co-products of CHP WtE-CCS plants and found these to average -79 kg CO_2eq/t_{MSW}, -28 g CO_2eq/kWh_e and -38 kg CO_2eq/MJ_{th} for the waste treatment, electricity and heat respectively.

It has also been identified that the negative emissions of WtE-CCS are highly sensitive to the content of dry biogenic waste (paper and card) in the fuel-waste stream. The findings of the existing attributional LCA studies suggest that diverting such waste towards recycling instead of WtE-CCS would actually increase atmospheric GHG concentrations. There is a need to develop more nuanced approaches to properly account for carbon emissions and removals in scenarios involving waste-to-energy processes and carbon capture, assess the true system-wide carbon impacts.

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A new local area energy mapping approach for capability assessment of households to adopt low carbon technologies

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Abstract: The recent UK Government funded £102 million smart local energy system research and innovation programme has concluded that local area energy planning (LAEP) is vital for achieving net zero carbon emissions. In response, this paper presents the application of a novel local area energy mapping approach (LEMAP) to assess the technical and social capabilities of how likely households are to adopt low carbon technologies (LCT)s, and those who may be left behind in Eynsham, Oxfordshire (UK). LEMAP is an online and interactive spatial-temporal tool that has been developed for conducting analysis and visualisation of baseline energy use, targeting suitable areas and dwellings, and forecasting the take-up of LCT at property, postcode, and neighbourhood level. While technical capability was found to be moderate, digital capability was low, raising concerns about the roll out of smart energy technologies without adequate awareness raising, education and training. A significant proportion of households were considered 'deprived' with annual income of <£20,000, indicating the need for grants and subsidies. Social capability was relatively high with around 54% of households 'fully convinced' or 'motivated' to adopt LCTs. This new approach to local area energy planning can help community energy project developers, local authorities, and community groups plan for local energy initiatives that are smart and fair.

Keywords: Local area energy planning, Low carbon technologies, GIS mapping, Capability assessment, Retrofit

1. Introduction

As the UK Government has legislated net zero by 2050 and recognized the need to shift to electrification, decarbonisation will place more demand on the electricity network. The need for technology and the ability to balance demand on the network at different periods provides opportunities for new markets to be created, and new demand to be accommodated through a smarter, secure, and more flexible network. Local area energy planning (LAEP) is a data driven and whole energy system, evidence-based approach. It sets out to identify the most effective route for the local area to contribute towards meeting the national and local net zero targets. The scope addresses electricity, heat, and gas networks, future potential for hydrogen, fabric and systems of the built environment, flexibility, energy generation and storage, and providing energy to decarbonised transport. LAEP provides the level of detail for an area that is equivalent to an outline design or master plan but is expected to be updated at least every five years (ESC, 2021). As a part of LAEP, the challenge to rapidly and efficiently supply the residential sector with LCTs, e.g., PV and heat pumps, and evaluate the changing grid dynamic will require compiled and accessible socio-economic and technical data of local areas throughout the UK. That is, an area-based approach that has the capability to target homes at scale will be necessary for rapid deployment of LCTs.

As such, cities, districts and communities need ways to geographically identify suitable and appropriate locations for LCTs, categorise and track their current (baseline) energy use and carbon emissions, energy systems and network geographies (LEO, 2021), & ways to estimate (calculate) their future use based on new buildings and retrofit impact. Geographic information system (GIS) driven geospatial energy mapping tools are emerging as essential tools to provide rapid and accurate spatial intelligence by providing holistic critical insights in a digital and visual manner to fill the capacity gap between creating plans and implementing them (Camporeale and Mercader-Moyano, 2021). As a solution local area energy mapping LAEM tools aid in addressing carbon emission goals by providing spatial intelligence and critical insights in a digital and especially in a geographical visualisation manner for the implementation of local energy initiatives.

With the intent to make LAEP inclusive, the Centre for Sustainable Energy's (CSE) developed the "capability lens" to holistically assess capability of areas so that no one is left behind in the energy transition. This capability assessment identifies individual householders who can or cannot take advantage of the new opportunities in the transitioning energy system. The main purpose is to identify the potential for energy inequity (Banks, 2022, Roberts et al., 2020). Against this context this paper describes the application of a new online and interactive local area energy mapping tool called LEMAP to a local area (Eynsham) in Oxfordshire (UK). The study brings together versatile spatial datasets on energy, buildings, socio-demographics, tenure, fuel poverty and electricity networks to investigate the technical suitability as well as digital, social and financial capabilities of households to take-up low carbon technologies for achieving local net zero.

2. Literature review

The growth in smart local energy initiatives has enabled the rise of spatially based energy mapping tools and approaches to help with decision-making at a local scale. Though not limited to only the past decade, this period has seen several studies that have explored how online spatial energy visualisation can contribute to decision-making, design, planning, and implementation processes in local energy initiatives (D'Oca et al., 2014, Wate and Coors, 2015, Flacke and De Boer, 2017, Camporeale and Mercader-Moyano, 2021). Most recently GIS has been used to enhance the analytical power of energy planning and modelling techniques at different geographical scales, as well as to provide rapid and accurate spatial intelligence for planning and implementing LAEP and enhancing the digitalisation of the energy systems (Ali et al., 2020, Camporeale and Mercader-Moyano, 2021). Other researchers and grey literature further confirm the key role that the LAEM tools have in providing deep insight to decision-makers in a visual and, more importantly, easy-to-understand manner (Yamamura et al., 2017, Morstyn et al., 2018). The role of the tools during the implementation of LAEP varies depending on the context.

In general, the benefit of using LAEM tools for LAEP relies on the offering of intelligence about the local area, such as having interactive rapid analysis and clear visualisation of energy flows and related contextual data about the locality. The benefits of LAEM tools include the aggregation and visualisation of performance data, high level understanding of requirements, constraints, and investment needs of a local area (Balest et al., 2018), to help DNO's improve system management (Deconinck, 2021), and aid in the engagement of diverse actors in the implementation of low carbon energy technology (Acosta et al., 2018, Savelli and Morstyn, 2021, Vigurs et al., 2021). The main challenge for LAEM tools is to produce useful knowledge in relation to the target audience. A common problem that arises in lab-based research is that tools are designed to frame energy system problems before encountering societal and political contexts of the target locality. This with further complexity brought by a multiplicity of scenarios that tools can bring often does not make the outputs more useful locally. Instead, results can be perceived as confusing, making it hard to build local confidence as a guide to decision making (Cowell and Webb, 2021). Depending on their nature, LAEM tools may not be accessible to everyone everywhere. As the subject is community scale, often tools are designed for a specific region and will not cover the needs of other localities. Challenges also include data alignment, e.g., the combination of 2018 Energy Performance Certificate (EPC) data with 2011 UK census data. In this example, the tool makers are limited to the timed release of the data leading to a year discrepancy that influences the accuracy of the output of the tool. The outcome may reduce the audience use due to lack of confidence in the data. Furthermore, validation processes are not yet addressed in the grey literature.

Ford et al. (2019) and Francis et al. (2020) found that a full assessment of smart local energy system projects must examine the socio-technical environment alongside an integrated assessment of the multiple factors that drive the low carbon transition, including economic, social environmental and political dimensions. Though Bale et al. (2014) considered social factors within the district heating development process and Gupta and Gregg (2020) integrated socio-economic classifications for England into considerations for targeting dwellings for whole house retrofit to pinpoint and mitigate fuel poverty, altogether very few models were found to integrate socio-economic factors into local/urban energy modelling.

The CSE capability lens offers a comprehensive method for considering the intersection of the socioeconomic and technical aspects for householders. It considers the householder's ability, suitability, and willingness to participate in smart energy offers and developments based on the nature of the offers and developments and a wide range of characteristics and capabilities of the household. The capability lens has the potential to provide new insights into how the development of a smarter energy system alters what is required of domestic consumers to participate fully in the new benefits it can offer, which consumer characteristics and capabilities are – or become – key to such participation, and what might be effective to increase inclusion (Roberts et al., 2020). Within this context, this paper seeks to combine assessment of technical suitability of dwellings with social, economic, and digital capabilities of households using LAEM of potential LCT uptake.

3. Local case study: Eynsham, Oxfordshire, UK

The Eynsham smart and fair 'neighbourhood' (SFN) is a 102km^2 area (figure 1) located in the West Oxfordshire District. The SFN covers five wards, 10 Lower layer super output areas (LSOA), 325 postcodes, and approximately 3,600 dwellings.

Figure 1. Eynsham location in context

The Eynsham SFN contains a predominance (77%) of owner-occupied homes indicating an established area. In addition to this 10% of the households are socially rented. A total of 408 (6%) households in the SFN are fuel poor. The proportion of households experiencing fuel poverty ranges between 5-8% among the LSOA divisions (boundaries containing up to 1200 households). In contrast, in Oxford, fuel poverty can be over 20% in several LSOAs. The average age of the population in the SFN is in the range of 35-64 years (43%) commonly referred to as the working-age group. The second-highest age group are 65+ or retired (22%). The unemployment percentage of the area (2%) is half of the UK's national average, which has averaged about 4% since 2018[1]. Education and social grade play an essential role in the adoption of innovative / new technologies. The predominant social grade (36%) is classified as high or intermediate managerial, administrative, or professional occupations[2]. This clustering is relatively high, as only 27% of the population of the UK is in this social grade. Overall, the Eynsham SFN would be classified as socially and economically stable, with small-medium pockets of deprivation.

Based on EPC data most dwellings were of semi-detached built form (37%). The remaining were detached at 32%, terraced at 30% and 1% were undefined. Houses (including bungalows) were dominant at 90%, flats and maisonettes made up 9% and 1% of the remaining respectively. Considering construction:

- 74% of domestic properties had double glazing; 24% were not identified, and the remaining 2% were split among those with single, secondary, and triple glazing.
- 56% were insulated with internal or external insulation; the remaining 44% had partial or no insulation.
- The most common wall type was cavity (filled or not) (58%), the remaining were solid wall at 10%, sandstone at 10%, timber at 1%, and the remaining system built, cob or granite at <1%. Wall type for 20% of dwellings were not identified.
- 70% of dwellings had a pitched roof; 19% were not defined. The remaining 11% had roof rooms (5%), had a dwelling above (5%), flat or thatched.
- 73% of dwellings were estimated to have less than the minimum suggested roof insulation (220mm).

4. Methods

LEMAP was developed to provide spatial analysis and communication of baseline energy use, energy resources and potential for take-up of low carbon technologies (LCT) at property and postcode level. The intent was to help stakeholders such as community energy project developers, local authorities, and local community groups to plan for localised smart and fair energy initiatives in the focal areas. The LEMAP tool brings together public, private, and crowdsourced data on energy demand, energy resources, building attributes, socio-demographics, fuel poverty and electricity networks within the ESRI (Environmental Systems Research Institute) ArcGIS platform. It is a district to building scale, blend of top-down and bottom-up modelling. The LEMAP tool has four technical and four engagement elements that include 'Baselining' local area energy flows in relation to socio-economic characteristics; 'Targeting' suitable properties for LCT; 'Forecasting' energy demand profiles at postcode level for different LCT scenarios which uses the CREST energy demand model (McKenna et al., 2020); and 'Capability profile' to show the social, digital and financial propensity of the household to take up LCTs. The engagement elements include: 'Participatory mapping' to allow residents to visualise their energy demand profiles, compare against the neighbourhood, and see how the profile changes with LCTs; 'Storymap' for creating blogs on local energy flows; 'Dashboard' for summarising the results by postcode; and 'Forum' to

[1] https://www.ons.gov.uk/employmentandlabourmarket/peoplenotinwork/unemployment

[2] https://www.nrs.co.uk/nrs-print/lifestyle-and-classification-data/social-grade/

enable chats amongst users of LEMAP and project stakeholders. This paper focuses specifically on the targeting and capability profiles.

Building the LEMAP tool involved the assessment of 69 datasets in total. Datasets include sub-national energy and fuel poverty, EPC, Geomni UK buildings characteristics, Experian's Mosaic socio-economic dataset, Historic England's listed buildings, and Scottish & Southern Electricity Networks (SSEN) secondary substation locations and capacity. All datasets could be roughly categorised into GIS boundary definitions, land use, building use, socioeconomic / lifestyle, energy consumption / network, and transport.

4.1. Targeting: suitability assessment

The targeting or suitability assessment used various datasets to evaluate potential for smart energy technologies. Table 1 lists the assumptions and criteria for each technology evaluated and the data layer(s) used to evaluate suitability.

Table 1. Suitability criteria, assumptions and data layers

No.	Criteria / assumptions	Data layer used
	General	
1	Private or social rented properties, listed buildings, flats will not install PV, heat pumps or EV charger.	OS Mastermap / Geomni / Mosaic / EPC / Historic England
	Photovoltaics	
2	All houses will have at least one roof slope orientation that is suitable for PV.	OS Mastermap / Geomni
3	Properties with thatch roofs are not suitable for PV.	Geomni
4	EPC rating A – D are only suitable for PV (to claim the full Feed - In Tariff, properties must be rated EPC D or above).	EPC
5	Properties capable of improvement to EPC rating 'D' are marked as suitable after improvement.	EPC
	Air source heat pump (ASHP) / Ground source heat pump (GSHP)	
6	Heat pumps are cost effective in insulated homes: (EPC above average insulation levels and double glazing).	Geomni / EPC
7	Properties using electric heating as main fuel type are prioritized for heat pumps.	EPC
8	Dwellings with gardens are suitable for GSHP as the equipment needs to be installed underground. Mid terraced dwellings are omitted as gardens are usually small and access to them is obstructed.	Geomni
9	GSHP are suitable for large dwellings, only properties with three bedrooms or more were considered suitable.	Geomni
	Battery Storage	
10	IF suitable for PV, then suitable for battery	Ref. PV suitability
11	It is assumed that council (social) dwellings are not suitable for batteries	EPC / Mosaic
	EV charger	

12	Off-street parking is required	OS Mastermap / Energeo

4.2. Capability assessment

The capability assessment was based on the capability lens approach developed by the Centre for Sustainable Energy (CSE) (Roberts et al., 2020). The assessment helped identify how likely households are to adopt different LCTs and those who may be left behind based on their socioeconomic characteristics. The capability assessment for Eynsham was analysed and displayed (mapped) in four categories. Each category was divided into four levels to evaluate and grade each household related to their capability profile. The capability categories are described in more detail below; however, in summary:

Table 2. Capability weights

No.	Technical	Digital	Financial	Social
1	Full potential	High tech user	Happy investor	Fully convinced
2	Partial potential	Tech. savvy	Venturers	Motivated
3	Need improvement	Training required	Penny savers	Sceptical
4	Unsuitable	Other priorities	Deprived	Not interested

The technical capability grade was calculated based on LCT suitability for each dwelling. The more LCTs that were technically suitable for installation in the dwelling, the higher the grade. The grades for technical capability are:

- **Full potential** – Fully capable of adopting multiple LCTs
- **Partial potential** - capable of adopting some LCTs.
- **Need improvement** – capable of adopting LCTs if relevant improvements are made to the dwellings.
- **Unsuitable** - dwellings unsuitable for LCTs, such as listed buildings.

The digital capability grade was calculated based on the Experian's Mosaic digital group classification of households. The Mosaic digital group has 11 types ranging from 'Capital connections' to 'Tentative elders'. Table 3 indicates the alignment of Experian's types to LEMAP's digital capability grades. The grades for digital capability are:

- **Hi-tech users** – households with cutting-edge hardware immersed in digital technology.
- **Tech Savvy** – households composed of avid users of social media and smartphones that aspire to obtain cutting-edge hardware.
- **Training required** - households that only use digital technology for entertainment, shopping or practical purposes.
- **Other priorities** - households with limited, little or no interest in digital technology, preference given to non-digital approaches.

Table 3. Alignment of Mosaic's digital groups and LEMAP

No.	Mosaic Digital Groups	LEMAP Digital capability grades
1	Capital Connections, Digital Frontier, Mobile City	High tech user
2	First-gen Parents, Aspirant Frontier, Online Escapists	Tech. savvy

3	Upmarket Browsers, Savvy Switchers, Cyber Commuters	Training required
4	Beyond broadband, Tentative elders	Other priorities

The financial capability grade is an average of Mosaic's affluence rating and equivalised household income band grouping. Mosaic's affluence uses several variables such as income, property value, council tax, outstanding mortgage, etc., to arrive at 20 bands. In addition, there are nine equivalised household income bands ranging from >£65,000 to <£10,000. Table 4 indicates the alignment of Experian's financial groups to LEMAP's financial capability grades. The grades for financial capability are:

- **Happy investors** - households with ability to invest in LCTs without looking for a financial return.
- **Venturers** - households with access capital or funding to acquire LCTs and expect some economic payback or delay of payments.
- **Penny savers** - households that depend on loans, grants, or programmes to implement LCTs or change life patterns towards energy flexibility.
- **Deprived** - socially or economically deprived households with priorities beyond LCTs.

Table 4. Alignment of Mosaic's financial groups and LEMAP

No.	Mosaic Affluence Groups	Mosaic Equivalised household income groups	LEMAP Financial capability grades
1	Bands 17-20	>£50,000	Happy investor
2	Band 16	£30,000 – 49,999	Venturers
3	Bands 5-15	£20,000 – 29,999	Penny savers
4	Bands 1-4	<£20,000	Deprived

The social capability scale brought together EPC and Mosaic data combining consideration for existing LCTs as indicated by EPC assessments and Mosaic's consumer behaviour types labelled Financial Strategy Segments (table 5). The grades for social capability are:

- **Fully convinced** – households that prioritise activities towards the environment.
- **Motivated** - households with some interest and knowledge on the effect of flexible and LCTs on the environment.
- **Sceptical** - Households that need to be trained or guided to understand the benefits of implementing LCTs or making changes in their lifestyle to flexible energy patterns.
- **Not interested** - households with lifestyles that do not align with using low carbon technologies.

Table 5. Alignment of Mosaic's social groups and LEMAP

No.	EPC LCTs	Mosaic Financial strategy segment groups	LEMAP Financial capability grades
1	At least one preexisting LCT (wind turbine, PV, solar hot water)	Money makers, Established investors	Fully convinced

2	No preexisting LCT	Earning potential, Growth phase, Deal seekers, Career experience, Mutual resources, Respectable reserves, Golden age	Motivated
3	No preexisting LCT	Family pressures, Small-scale savers, Single earners, Home-equity elders, Declining years	Sceptical
4	No preexisting LCT	Cash economy	Not interested

4.3. Data limitations

Although the methodological approach of LEMAP is applicable widely, the study relies on data from a specific region in the UK, which may restrict the generalizability of the results due to geographic and environmental differences. Despite utilizing multiple data sources and techniques, accuracy and precision of the results may be affected by data limitations.

5. Results

5.1. Potential for smart energy technologies

The following section breaks down the suitability assessment for the smart energy technologies. Note that though the statistical data covers the entire SFN, the following figures will focus on Eynsham Village as it has the highest density in the SFN and allows for better visualisation of the data being presented. Figure 2 shows Eynsham Village in relation to the SFN boundary.

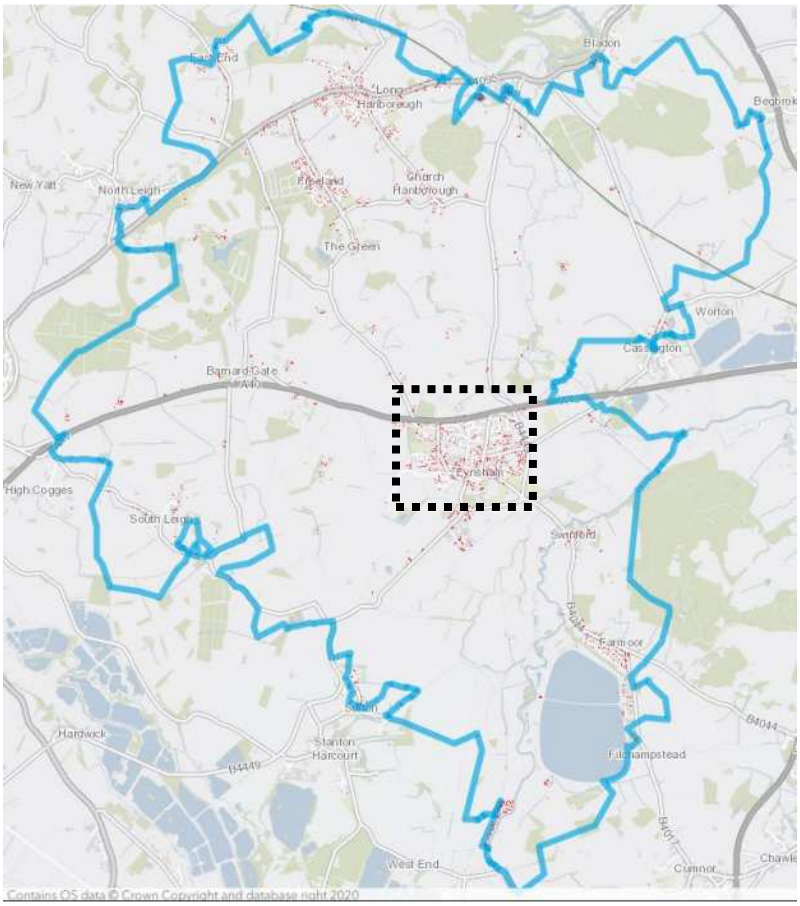

Figure 2. Eynsham SFN boundary with Eynsham Village identified

In the Eynsham SFN area, 580 dwellings were considered suitable for PV systems, which corresponds to 16% of the dwellings analysed. It was also estimated that 3,100 additional dwellings could be suitable for PV systems if their EPC rating were improved (86% of dwellings in the area). Figure 3 shows the dwellings suitable for PV and the dwellings that could be targeted for an improved EPC energy rating so that PV could be installed.

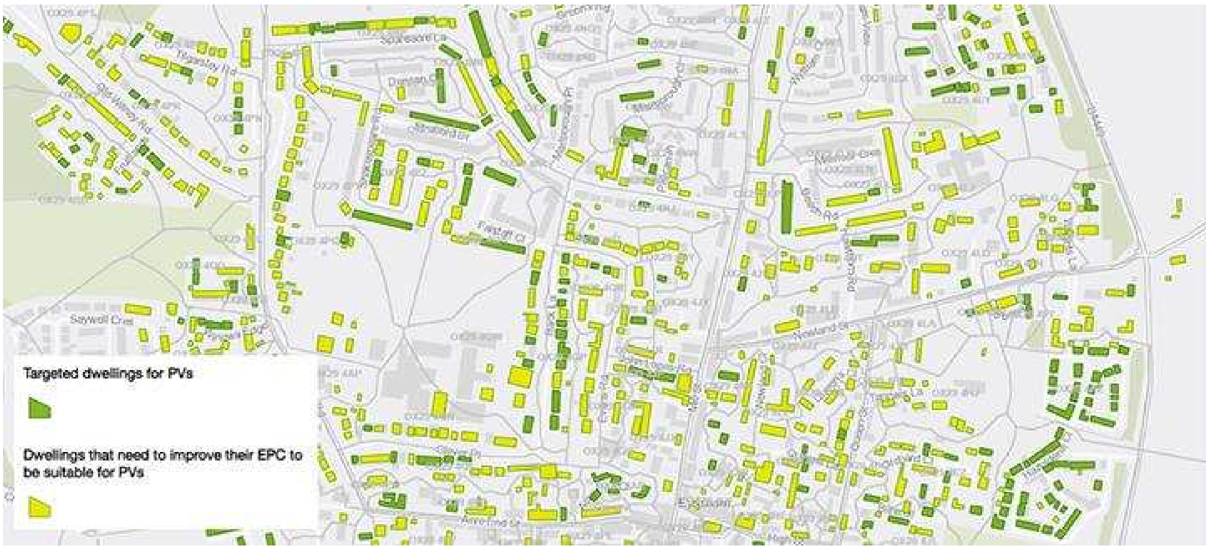

Figure 3. Eynsham Village PV suitability

The Eynsham SFN has high electricity and gas consumption, ASHP and GSHP can aid in the energy reduction and thermal comfort of the properties. Priority can be given to GSHP in relation to their efficiency; however, fewer properties are suitable for this technology as it requires appropriate garden space area and is best for airtight properties with good thermal insulation. A total 2,100 dwellings were identified as suitable for GSHP, which corresponds to 58% of the dwellings analysed. A total 2,165 dwellings were identified as suitable for ASHP, which corresponds to 60% of the dwellings analysed. Figure 4 shows the dwellings suitable for ASHP or GSHP. Note: all dwellings suitable for GSHP are suitable ASHP.

Figure 4. Eynsham Village heat pump suitability

A total 1,847 dwellings were identified as suitable for EV chargers, which corresponds to 51% of the dwellings analysed. Figure 5 shows the dwellings suitable for EV chargers in Eynsham Village.

Figure 5. Eynsham Village EV charger suitability

A total 1,355 dwellings were identified as suitable for battery storage, which corresponds to 37% of the dwellings analysed. All 580 dwellings suitable for PV systems were identified as suitable for having batteries as well. In total for the SFN, only 153 (5%) dwellings were identified as suitable for an all-inclusive LCT package of PV, HP, EV charging and home battery storage. Figure 6 shows how the dwellings suitable for the LCT package are the dwellings with EPC A and B ratings indicating the need for fabric improvement to coincide with widespread smart energy technology solutions.

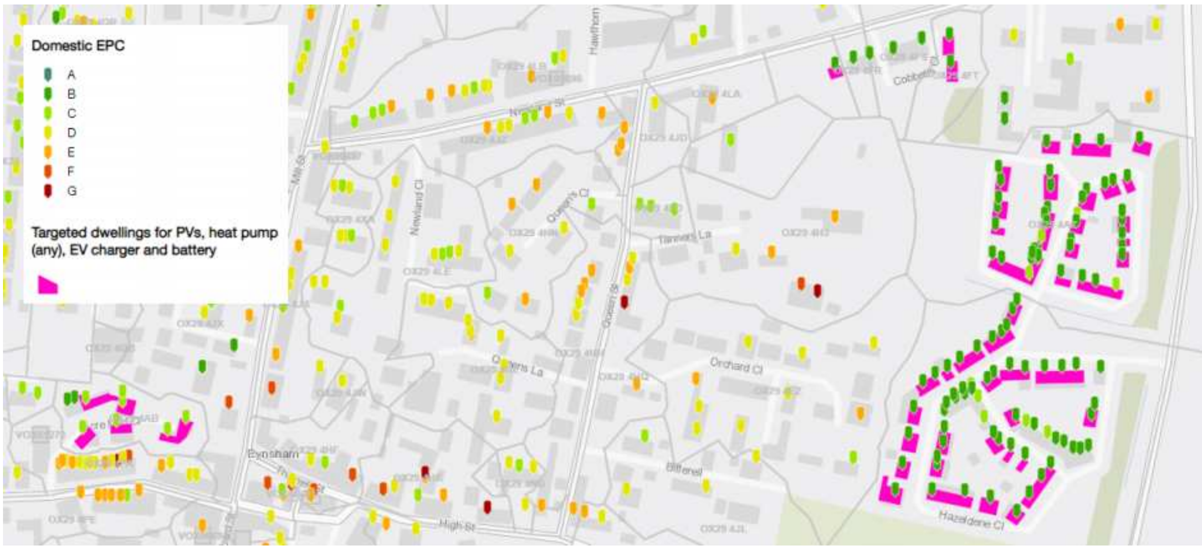

Figure 6. Eynsham Village full LCT package suitability with EPC rating tags

5.2. Capability assessment

The results of the capability assessment are described below for each type of capability. Maps are provided below showing the capability grade at the postcode scale. Figure 7 shows the overall SFN for technical capability with Eynsham Village identified.

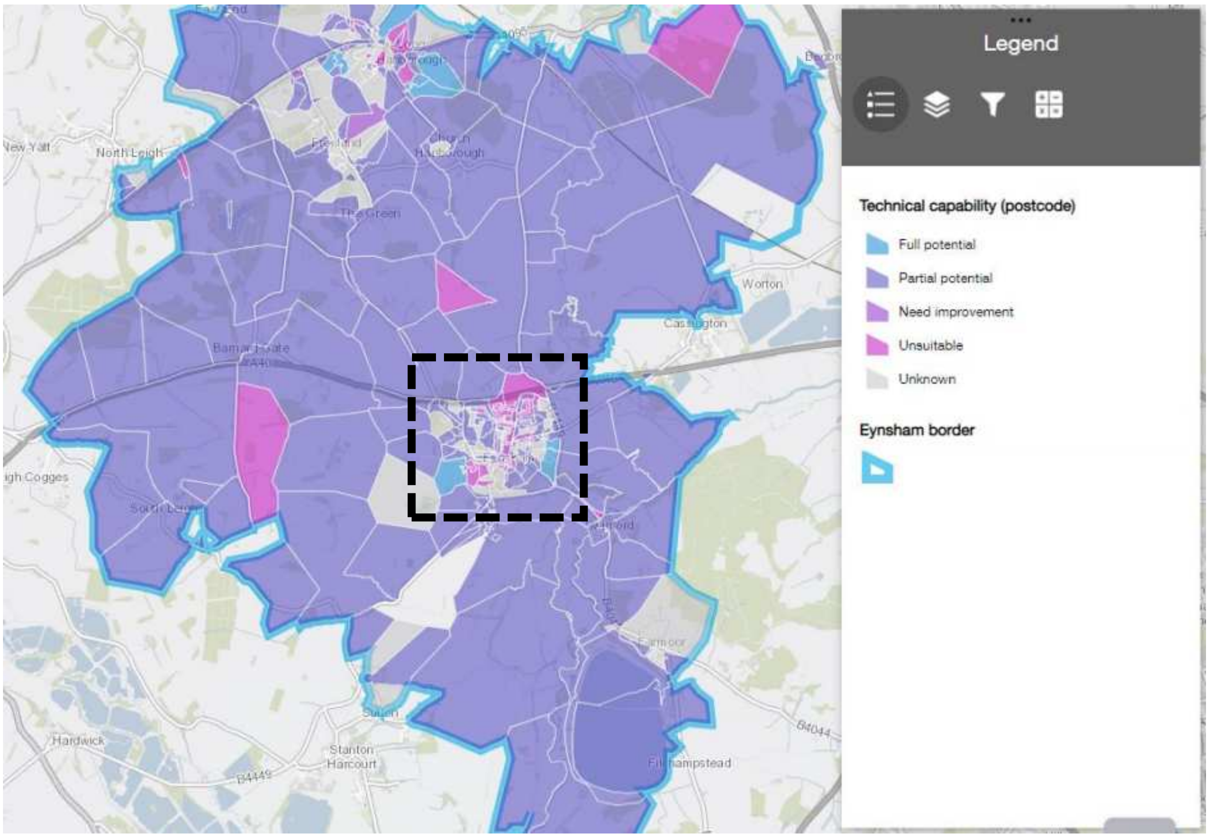

Figure 7. Eynsham SFN technical capability map with Eynsham Village identified

Over the past couple of decades there has been much effort in upgrading the building stock through government programmes like the Energy Efficiency Commitment (EEC) and the Energy Company Obligation (ECO) (Rosenow, 2012). These resulted in improved insulation and glazing in many dwellings through the years, though there is still much to do. This effort can be seen here as a little over 50% of the dwellings are considered to have full or partial technical capability. Figure 8 provides the mapped results and table 7 shows the per cent of dwellings attributed to LCT suitability and technical capability (Note that the percentages apply to the entire SFN though the figures only show a portion, focusing on Eynsham Village). The 'need improvement' and 'unsuitable' areas are key areas on which to focus greater fabric improvement.

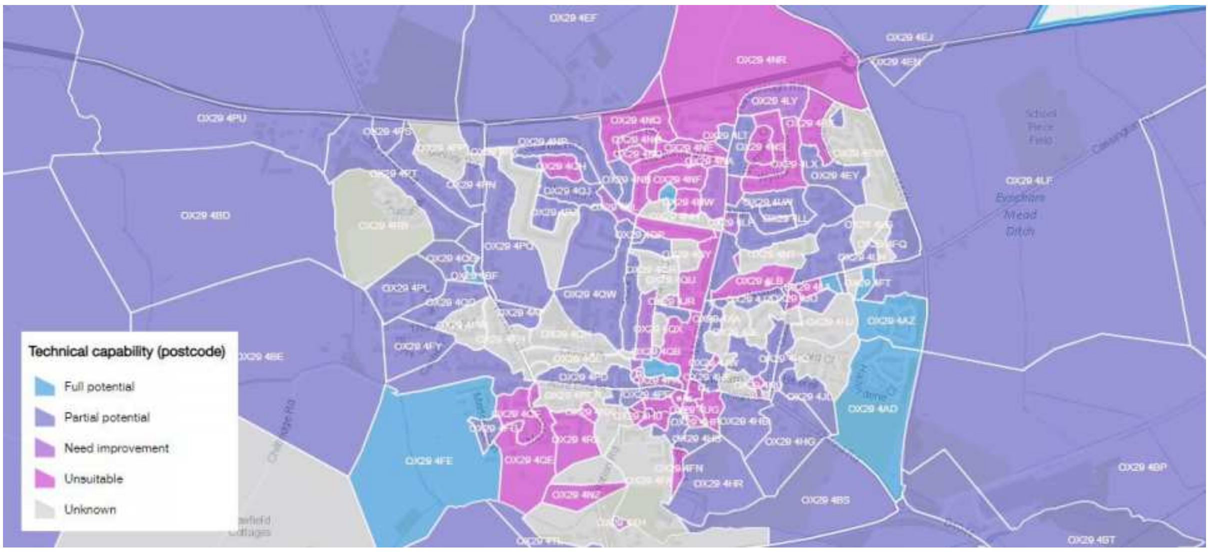

Figure 8. Technical capability map – Eynsham Village

Table 6: LCT suitability and technical capability percentages

LCT Suitability				
PV	**ASHP**	**GSHP**	**EV charger**	**Battery**
16%	60%	58%	51%	37%

Technical capability			
Full potential	**Partial potential**	**Needs improvement**	**Unsuitable**
4%	48%	7%	13%

There is currently a low level of digital capability in the Eynsham SFN; it is the category with the lowest values. These classifications would suggest that householders will require a higher level of help, education, and training to accept technological solutions to energy and climate challenges, including the interconnectedness of solutions and their management. Figure 9 provides the mapped results and table 8 shows the per cent of dwellings for each level of digital capability. Note: for digital capability a significant amount of dwellings' data was missing to calculate capability. These were mostly in the rural areas surrounding the villages (37% dwellings' data unknown).

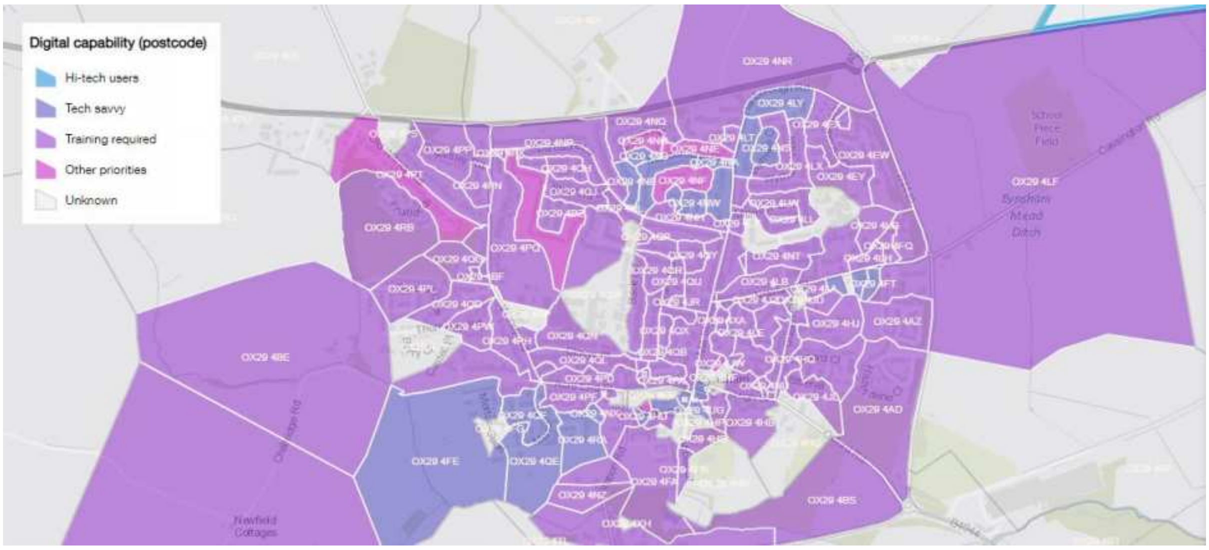

Figure 9. Digital capability map – Eynsham Village

Table 7: Digital capability percentages

Digital capability			
High tech user	**Tech. savvy**	**Training required**	**Other priorities**
<1%	6%	46%	10%

A borderline minority of households in the SFN are financially capable, i.e., happy investors or venturers; and a significant number of households are considered 'deprived (with equivalised annual income <£20,000). Figure 10 provides the mapped results and table 9 shows the per cent of dwellings in the SFN attributed to financial capability. The map is notably quite segmented on a postcode scale. The villages have a higher concentration of Happy investors and Venturers, whereas the Deprived households are mostly concentrated outside of the village centres. Financial capability is particularly helpful whether seeking able to pay households or households qualified for income-based grants. Furthermore, fuel poverty can also be addressed using financial capability data.

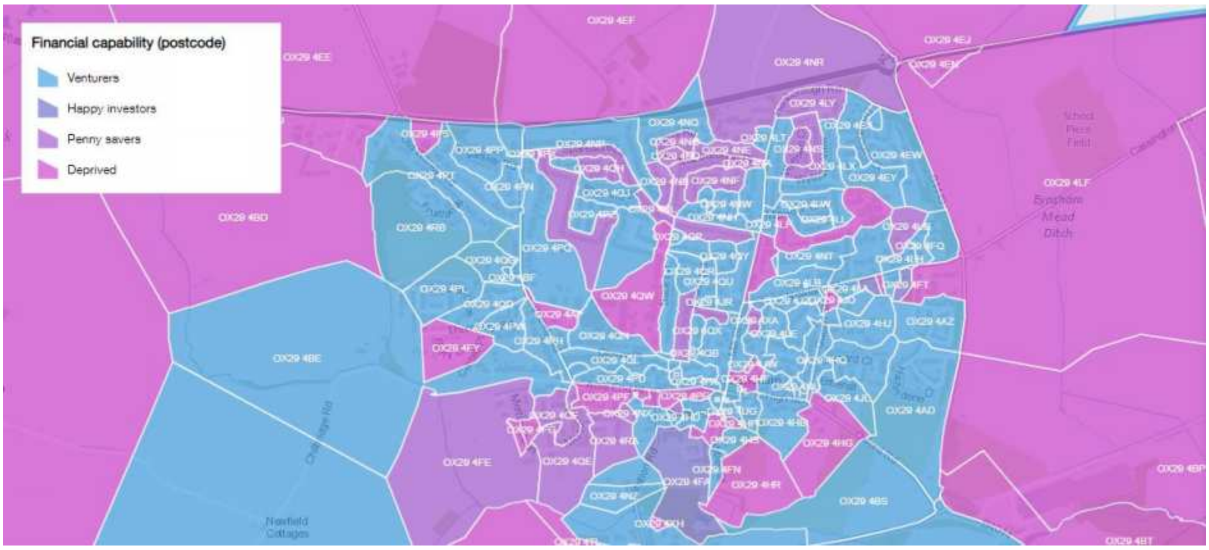

Figure 10. Financial capability map – Eynsham Village

Table 8: Financial capability percentages

Financial capability			
Happy investor	**Venturers**	**Penny savers**	**Deprived**
7%	42%	12%	39%

Social capability in the Eynsham SFN is relatively high. Both fully convinced and motivated make up 54% of the households; a small percentage are considered sceptical or not interested. Social capability, however, is likely the most speculative assessment as it does not include a direct survey to the householders regarding LCTs or energy and climate issues but uses broad categories based on national financial strategy segment groups - a view of UK consumer financial behaviour. Figure 11 provides the mapped results for direct targeting and table 10 shows the per cent of dwellings attributed to social capability. Note: for social capability a significant amount of dwellings' data was missing to calculate capability. These were mostly in the rural areas surrounding the villages (37% dwellings' data unknown).

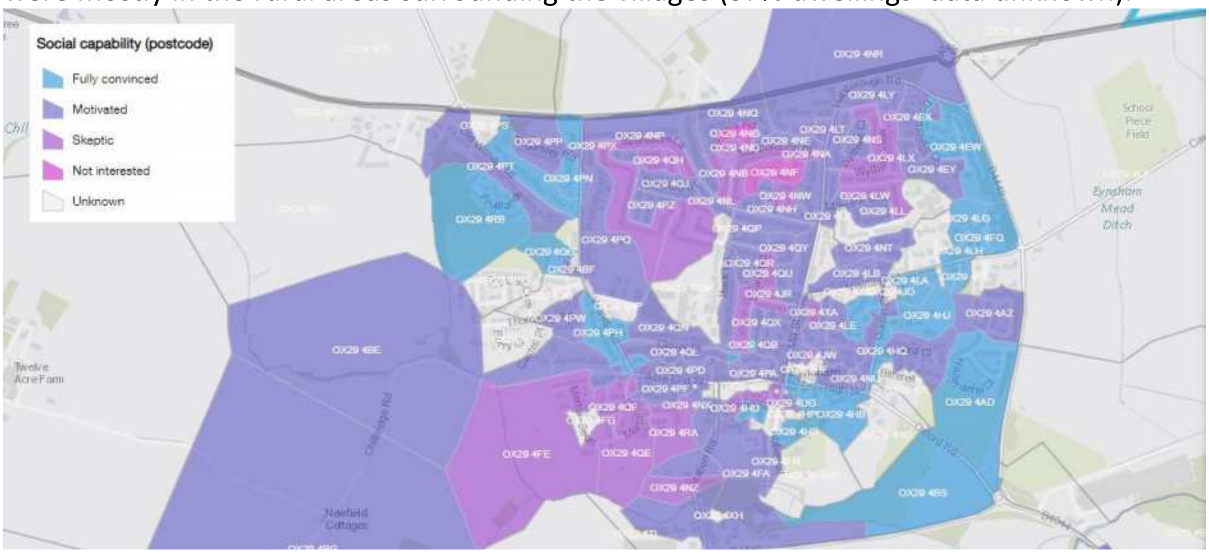

Figure 11. Social capability map – Eynsham Village

Table 9: Social capability percentages

Social capability			
Fully convinced	**Motivated**	**Sceptical**	**Not interested**
23%	31%	8%	<1%

6. Discussion

Local area energy planning is vital for achieving area-based net zero emissions. Furthermore, addressing the climate crisis and meeting national targets cannot be done successfully without addressing local social and economic problems. The capability assessment approach of LEMAP combines socio-economic and technical data to support a fair and equitable approach to upscaling a local area for a low carbon future. Though inequity is often inevitable due to uneven distribution of capabilities (Banks, 2022), the mapping of capabilities provide a powerful tool to identify the vulnerable spots and focus on these to deliver a smart and fair energy transition.

Meeting decarbonisation challenges requires local leadership and engagement to bring together the large number of people and organisations who will need to be involved in the design and delivery of LAEP. Local Authorities, for example, are critical actors in managing the transition and the vital connection between micro-scale small group action and macro-scale states and markets (Tingey and Webb, 2020). Local authorities across the UK will need to be equitably and technically supported in their effort to contribute locally to the national goal. LAEP tools like LEMAP can provide local authorities, community groups and LCT suppliers with the integration of socio-economic and technical data needed to identify households fit for LCT installation that also meet policy or support goals. Depending on policy support, the goal may be to target those that can afford and are willing to pay or to provide equitable opportunities to others that may be digitally and social capable but not financially capable. Where it does not exist, local authorities will also need to be supported with expertise to work with stakeholders to ensure effective uptake and installation of LCTs and supportive follow-through / training. Further support will need to be provided in areas of research, development, innovation and experimentation, e.g., trialling new products, services and business models with less restrictions (Morris et al., 2022).

Where a householder or community do not have the capabilities considered necessary to participate in a large-scale approach to upgrade the housing stock, the appropriate approach would first necessitate increasing capability. Interventions include either adjusting the capability to enable participation or change the expectation of the smart energy solution to meet and work with the communities' capabilities (Banks and Darby, 2021). Ideally, the solution would include both meeting current capabilities and improving capabilities in the process. Examples of improving capabilities include reducing costs (e.g., support, grants, etc.), ensuring households are maximizing financial benefits, providing the appropriate training and support for technological solutions, socially - providing examples of neighbours' benefits, successes from installed technologies. As noted in the assessment, several dwellings needed fabric upgrades to be technically capable for ASHP (for example). There will need to be continued effort in both LCT solutions and energy efficiency through fabric upgrades to maximise the benefits of each.

7. Conclusion

For creating local area energy plans, spatially based data-driven approaches are required that can target appropriate areas for LCTs and also engage with local community, planners and networks. This paper has demonstrated the application of a new local area energy planning tool (LEMAP) with the capability to combine disparate datasets for identifying rapidly and accurately areas and dwellings for LCT deployment. The LEMAP approach enabled the assessment of every postcode and dwelling in the Eynsham SFN on the basis of technical suitability and the likelihood of householders to be capable of accepting, understanding the need for, and financially supporting individual LCTs. LEMAP was designed to engage with community groups, community interest companies, local electricity network operators, local authorities, and residents. In doing so it has the potential to provide the structural framework around which coordination between different stakeholders can be enhanced, and sustainable business models can emerge for mass deployment of LCTs for achieving Net Zero.

A little over 50% of the dwellings were deemed to have full or partial technical capability. However digital capability was the category with the lowest capability in Eynsham. These classifications would suggest that householders will require a higher level of help, education, and training to accept technological solutions to energy and climate challenges, including the interconnectedness of solutions and their management. A borderline minority of households in the SFN were financially capable, i.e., 'happy investors' or 'venturers'; and a significant number of households are considered 'deprived' (with equivalised annual income of <£20,000). Social capability in the Eynsham SFN is relatively high. Both 'fully convinced' and 'motivated' classified households make up 54% of all Eynsham households; a small percentage were considered sceptical or not interested.

In future application, LEMAP can be deployed in a variety of local areas that aim to install low carbon heating with time-of-use tariffs, EV chargers, and rooftop solar with batteries. Further future work can involve a comparison of socio-economic data gathered through actual uptake or refusal of LCTs in the area with modelled assumptions. The LEMAP tool can also aid in the tracking of energy consumption in dwellings where LCTs are installed. Additional future research could also investigate the implications of climate change on the modelled predicted savings and generation of the proposed LCTs.

8. Acknowledgement

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Carbon accounting in the context of multi-criteria assessment for SLES: challenges and opportunities

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Abstract: In the UK, national carbon emission reduction targets aim to reach Net Zero by 2050, with a fully decarbonised electricity system by 2035. Smart Local Energy Systems (SLES) are being deployed to combine and intelligently control complementary low and zero carbon technologies within micro-grids to amplify their impacts and accelerate this ambitious transition towards a decarbonized energy system and low-carbon society.

Today, national and local governments monitor the potential carbon reduction of energy system retrofitting and policy implementation through simplified carbon accounting methods, which allow for calculation of the accumulated carbon emissions. This focus on carbon may, however, neglect broader socioeconomic impacts and benefits of these actions.

This paper describes the how the application of a multi-criteria assessment tool focusing on SLES can be used to evaluate (i) the carbon emissions from an energy system and (ii) the carbon reduction potential of renewable and smart energy technology implementation. Alongside the carbon accounting this MCA-SLES tool provides assessment and insights into the local socioeconomic and environmental benefits and impacts of the SLES development. The application of such a complex assessment tool has challenges in application, such as data collection, the intensity of the stakeholder approach, and the large volume of information for user dissemination. This paper illustrates how the developed assessment tool mitigates for these challenges and highlights the opportunity for small-scale energy development projects to employ it to assess project feasibility and progress towards economic, social, and environmental co-benefits.

Keywords: Carbon Accounting, Life Cycle Assessment, Multi-Criteria, Energy System Assessment

1. Introduction

Transitioning the global energy systems away from burning of fossil fuel for energy generation towards greener and low-carbon energy systems is a critical element in global efforts to combat the climate crisis and mitigating the overall negative future impact caused by climate change (Blanco et al. 2020; Morrissey et al. 2020; Ford et al. 2021). Carbon reduction is thus one of the core objectives of the energy transition strategy centred around the phase-out of fossil-fuel-driven energy technologies with renewable and low-carbon energy technologies (Clarke et al. 2017; Bottero et al. 2021; Ahmed et al. 2023).

This energy system transition on a national scale can be achieved through various approaches and strategies. In the United Kingdom, the energy system decarbonization strategy includes full-scale development and deployment of new energy system solutions, i.e., the development and deployment of Smart Local Energy System (SLES) projects like Reflex in the Orkney Islands (Reflex Orkney 2020; Couraud et al. 2023). Alongside this, the UK strategy includes more focused investment and development of offshore wind farm projects, greener buildings, and technology for energy generation from emerging low-carbon energy sources, such as hydrogen (Foxon 2013; Nerini, Keppo & Strachan 2017; BEIS 2020; HM Government 2020, Lovell & Foxon 2021).

Modelling and energy system analysis are critical to assess the dynamic interaction between all dimensions associated with an energy system (energy, technology, social, economic, and environment) (de Blas et al., 2020; Gudlaugsson et al., 2022). Models are widely used to understand the potential impacts of energy system changes, and implementation of energy policy and strategy (Antenucci et al., 2019; Bottero et al., 2021; de Blas et al., 2020; Blanco et al. 2020).The ability to monitor the potential of energy projects alongside overall emission reduction capabilities is, therefore, important for project developers and policymakers to ensure that the project contributes to the overall objectives of the energy transition (Antenucci et al., 2019; Bottero et al., 2021; de Blas et al., 2020; Blanco et al. 2020**).**

The framework for such models is based on a number of standardised methods. In recent years LCA methodology has been widely recognised as a powerful modelling tool to assess the environmental impacts of energy systems (such as GHG emissions, impact of human health, ecosystem and biodiversity) throughout the whole life cycle of components and processes (Blanco et al., 2020; Ahmed et al. 2023). Ahmed et al. (2023) also points out that various economic analysis tools like Cost-Benefit Analysis (CBA) have been developed and applied to understand the impacts and benefits of energy system retrofitting. Integrated Assessment Models (IAMs) are often used to connect together core elements of society and the economy dimensions with environmental and climate dimensions when assessing energy system transition (De Blas et al., 2020). Carbon accounting assessment and modelling is another approach that has been used in relation to sustainability management (Schaltegger & Csutore 2012, de Souza Leao et al. 2019).

The application of a broad multi-criteria assessment (MCA) to complex SLESs is, however, a challenge. This paper provides insights into the development of such an MCA-SLES tool, describing how it embraces and integrates carbon accounting and LCA fundamentals to track climate change impacts alongside multiple other criteria in a simplified and user-friendly modelling framework. The rest of the paper is organised as follows: **Section 2** provides a brief background on the carbon accounting and LCA methods, and the MCA-SLES Tool. **Section 3** addresses the discussion on how the MCA-SLES tool delivers a simple assessment framework for a wide range of users, adapting for the complex nature of LCA and carbon accounting, and the limitations and challenges. **Section 4** provides the concluding remarks.

2. Background

2.1. Carbon Accounting

According to Stechemesser and Guenther, (2012) carbon accounting comprises the recognition, evaluation and monitoring of greenhouse gas (GHG) emissions on all levels of the value chain and the corresponding effects of these emissions on the carbon cycle of ecosystems. Therefore, carbon accounting has become the favoured tool to assess GHG emissions for, for example, national emission numbers (Department for Energy Security and Net-Zero, 2023), corporation emissions numbers (Schaltegger & Csutore 2012) and urban emissions (de Souza Leao et al. 2020). Nevertheless, de Souza Leao et al. (2020) points that the carbon accounting method has its limitation when assessing GHG emissions at different levels, which can result in some GHG emissions sources being underestimated or neglected. This limitation is associated with the scope and carbon accounting approaches selected, data availability, and higher degrees of uncertainty.

2.2. Life-Cycle Analysis

LCA has become one of more prominent assessment methods used to assess and understand the environmental impacts of the energy system transition (Blanco et al. 2020) and national emissions (Clarke et al. 2017). There are several LCA methods including: input-output (IO) analysis (a top-down technique); process-based (PB) LCA, which is a bottom-up approach; hybrid LCA that combines both IO and PB systems (Kennelly *et al.*, 2019). IO analysis is a form of consumption-based accounting. For all methods the system boundary should identify how allocation is managed when there are multiple co-products: whether it is based on physical or economic allocation or system expansion.

The LCA method, however, has limitations when it comes to assessment of the environmental impacts of an energy system (Blanco et al., 2020; Clarke et al., 2017). These include: (i) double-counting of related values when expending the LCA assessment model, leading to double counting of emissions or factors attached to inputs and outputs in the system; (ii) uncertainties introduced by assumptions on the performance of future technologies with regards to factors such as fuel consumption, energy production, and efficiencies, which can vary between models and studies; (iii) spatial differences in source data depending on data variability (i.e. geographically local or global information), which can impact the overall results when looking at the local level impacts (Blanco et al., 2020; Clarke et al., 2017).

2.3. MCA-SLES Tool

The MCA-SLES tool that was developed by the Energy Revolutions Research Consortium (EnergyREV) focusses on delivering a simplified energy system assessment framework for local policymakers, project teams and planners for smart local energy systems developed and deployed in local communities (Francis et al. 2020; Francis et al. 2022; Gudlaugsson et al. 2023a; 2023b). The MCA-SLES tool enables identification of the benefits, potential risks and underlying consequences associated with the energy project. The MCA-SLES tool assesses two main sections (see Figure 1).

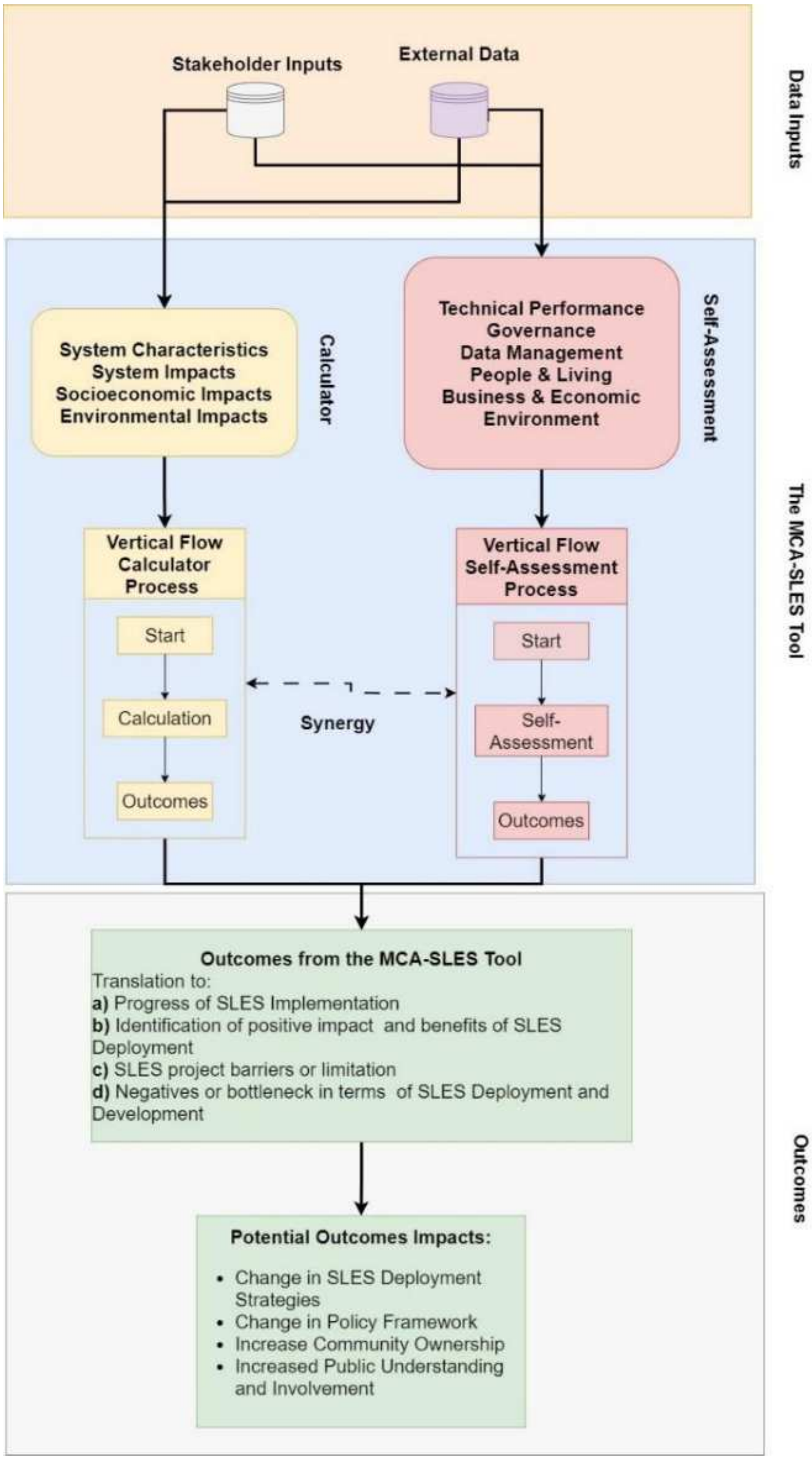

Figure 1: MCA-SLES Tool – Flowchart illustration of the tool processes and outcomes

The first section is a general calculation of a range of variables to be measured (system characteristics and impacts; socioeconomic and environmental impacts). The second section is a qualitative self-assessment (across six high-level themes: technical performance, governance, data management, people and living, business economic and environment) by the project team focused on setting targets of their goals for each of the variables, which allows for progress analysis to carried out in the second sections, and results present as shown in figure 2 below. Consequently, the input-data provided to assess the multiple criteria for the SLES monitors the progress made towards the objectives set by the project team and primary stakeholders.

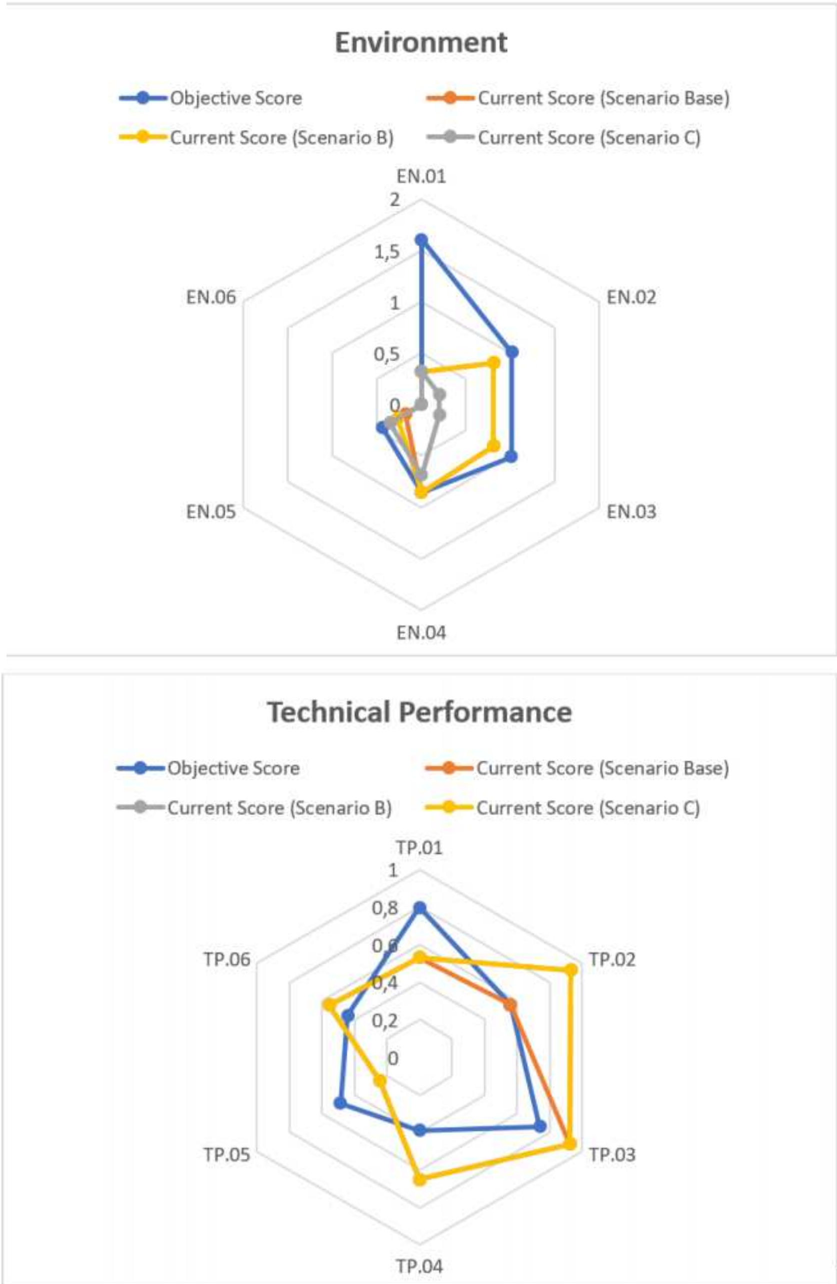

Figure 2: Visual illustration of the outcomes from Self-Assessment Section

The Calculator includes 93 parameters across four sections, some of which require inputs from the practitioners of the MCA-SLES tool to carry out the assessment calculations (Gudlaugsson et al. 2023b). The Self-Assessment includes 37 parameters that all need to be input by the practitioners in relation to project aspirations and objectives when setting up the MCA-SLES tool (Gudlaugsson et al. 2023b). These parameters and the relationships between the MCA-SLES tool sections are presented in Figure 3 below. This also gives some examples of required inputs; for example, Technology Readiness Level of the technologies in the current and proposed system, job creation in relation to system changes, and land requirements for each energy technology in the current and proposed systems.

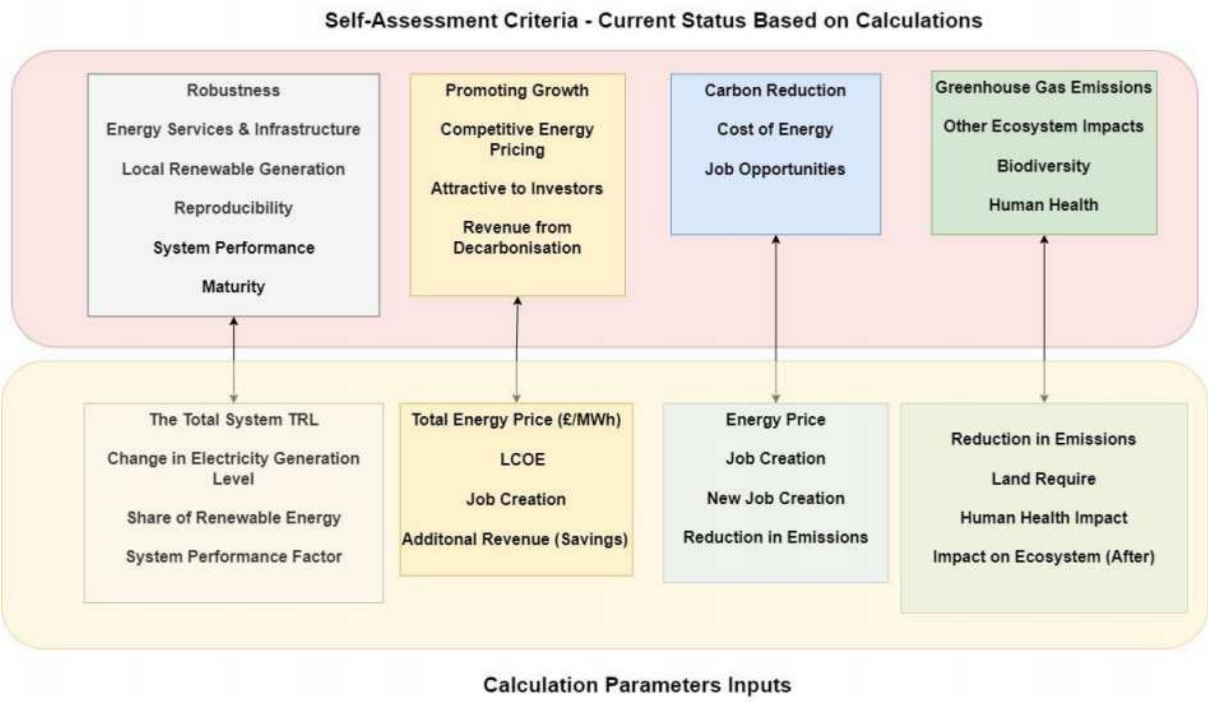

Figure 3: MCA-SLES tool parameters, and relationship between the Calculator and Self-Assessment Sections

The MCA-SLES tool estimates the carbon footprint of the whole SLES from climate change impacts per kWh for each type of energy generation. One of the limitations of this method is that the environmental impacts of renewable energy are assumed to be constant per unit of energy produced, as with fossil generation. For the latter, however, most of the environmental impacts are associated with fuel combustion for energy production, while for renewables they largely arise during manufacture and installation, and are thus independent of energy production. This can lead to an overestimate of environmental impact in areas with a higher availability of renewable resource. Future development of the MCA-SLES tool should estimate the impacts of non-thermal renewable generation based on installed capacity, rather than energy production. This will properly allow for the benefits or penalties of higher/lower availability of the renewable resource.

In order to test this, we estimated the LCA of different renewable energy technologies and fossil fuel-based technologies from a leading Life Cycle inventory dataset and the ReCiPe impact assessment method (Goedkoop et al., 2009).

Table 1. Case Study Information – Energy Technology and Generation Capacities (AquaTerra Ltd & Community Energy Scotland, 2022)

	Energy Technologies (Local)	Generation Values	Unit
	Large Scale Offshore wind power	44.7	MW
	Hydropower	30	MW
	Photovoltaic	1.3	MW
Case A	**Total Energy Generation**	**76**	**MW**
	Large scale Offshore wind power (accepted/planning)	47.3	MW
Case B	**Total Energy Generation**	**123.3**	**MW**
	Large Scale Offshore Wind power (in development)	183.5	MW
Case C	**Total Energy Generation**	**306.8**	**MW**

Then we mapped out the energy system and energy technology portfolio of a small local energy system (in this case the Orkney Islands), and generated three development scenarios based on published reports (Matthews & Scheer, 2020; Orkney Islands Council, 2022; AquaTerra Ltd & Community Energy Scotland, 2022). The LCA data was used to calculate the carbon emission and footprint of the current technologies in the system and added installed capacities. Figure 4 illustrate the system boundaries of the energy system that used as case study in the analysis, and table 1 provide information on generation capacity of the different energy technologies.

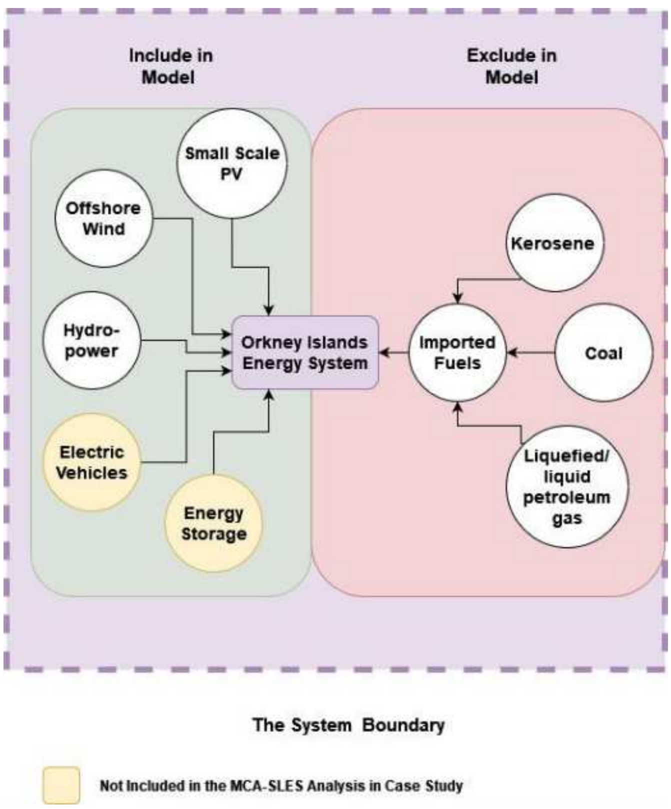

Figure 4: System Boundaries for the Testing Case for MCA-SLES Tool

The results obtained from the application of the MCA-SLES tool when looking at the carbon footprint in relation to the three scenarios, presents that the carbon footprint for the three scenarios were found to increase between the scenarios; being 0,012 kgCO2eq/kWh in scenario A, 0,013 kgCO2eq/kWh in scenario B, and 0,015 kgCO2eq/kWh in scenario C. Therefore, highlighting the overall impact of change in generation mix of the Orkney Islands, this increase is due to the higher share of the offshore wind added to the system, which has a higher carbon footprint then existing hydropower. The MCA-SLES tool is capable of evaluating the impacts of some demand and infrastructure technologies, such as electric vehicles and energy storage, but does not strictly consider the whole system as the impacts of the network infrastructure and any imported fuels are excluded, as illustrated in Figure 4.

This shows that the MCA-SLES Tool is has the ability to carry out environmental impact (carbon footprint), however the application is a result of the highly simplified nature of the analysis. This compromise was made to facilitate rapid use of the MCA-SLES tool for a holistic multi-criteria assessment. Furthermore, the results have a significant uncertainty due to the uncertainty of the source data. Further work is required to refine the carbon accounting process to improve the reliability and robustness of the results without creating an unacceptable burden for the end-user.

3. Discussion integration of Carbon Accounting and LCA Methods to MCA-SLES Tool

3.1. System Boundaries and Framing of Analysis

The first activities of an LCA or carbon accounting are to define the system boundaries and frame the analysis (Grafakos et al., 2017, Blanco et al. 2020). These provide the scope of the analysis and highlight what input data are required, identifying what components or factors of the system are included and excluded (Blanco et al. 2020).

The MCA-SLES tool integrates the LCA, carbon accounting and system thinking fundamentals into the tool's analytical process (Gudlaugsson et al. 2023a, 2023b). The MCA-SLES tool provides the practitioners with predefined system boundaries and framing of the analysis. The MCA-SLES tool's analytical framing is structured around energy system modelling and assessment, and the system boundary is structured around the energy system and key energy vectors (energy resources, generation technologies, energy demand and generation).

The MCA-SLES Tool users are given analytical framing and boundaries with creative freedom to adjust the energy system that being analysed i.e., a practitioner is asked in the System Characteristics section of the Calculator (see Figure 1) to define what energy technologies are in the system currently as well as those which are planned to be added to the system. In addition, the user is also asked to provide technical information on each technology, and current and planned generation capacity (following new technology integration), which allows the MCA-SLES tool to calculate any change in impacts associated with the change in generation capacity and energy technologies portfolio mix due to the SLES development.

Within the MCA-SLES tool the application of this process was intended to minimise the time required for extensive data collection and fully defining and framing an LCA modelling analysis. It also allows for consistency and comparison across assessments. The emphasis is to provide the users with an Excel-based tool that is ready to use, similar to the BEIS Whole Life Cost of Energy Calculator developed by the Department of Business, Energy, and Industrial Strategy (BEIS, 2020b).

The testing of the MCA-SLES tool by local government policy makers, academics, and industry stakeholders that attended an EnergyREV event in March 2023 provided insights into its usability. The policy makers found the tool extremely interesting for application in assessing energy system transition policies, with straightforward application, and easy understanding of the system framing and data input requirements, partially due to the MCA-SLES tool being implemented in Excel.

3.2. Accounting for System-Wide Impacts

Carbon accounting and LCA are commonly-used methods to assess overall system GHG emissions, alongside wider environmental impacts such as ecosystem degradation, biodiversity loss, and impact on human health (Blanco et al. 2020**)**. Moreover, in recent years both methods have been more commonly used in integration with others, such as Life-Cycle Costs (LCC), IO analysis, Multi-Criteria Decision Analysis (MCDA) and IMAs to enable the assessment and analysis of wider-system impacts of the system being analysed (Clarke et al 2017). This mitigates some limitations, such as neglecting or underestimating specific sources of GHG emissions within the system, or being too focused on the environmental impacts and not capturing the wider social and economic system impacts.

The MCA-SLES tool integrates carbon accounting and LCA fundamentals into a whole-system multi-criteria analysis, as illustrated in Figures 1 and 2. The MCA-SLES tool is designed to account for multi-dimensional aspects of an energy system in 4 separate sections. The calculation parameters (Figure 2) are divided as follows: *Section 1* – System Characteristics – focuses on the technical aspects of the energy system and gives insight into share of renewables, Technology Readiness Level, etc.; *Section 2* – System Impact – focuses on the economic impact such as cost of energy, level of renewable and fossil fuels in the system, and potential revenue; *Section 3* – Socioeconomic – focuses on the social impact such job creation and energy price; *Section 4* – Environmental Impact – focuses on understanding the environmental impact of the system change. The Tool incorporates data from LCA databases and analyses for values on land usage, emissions, human health impact and ecosystem impact for different energy generation technologies to enable the whole-system analysis to capture the holistic environmental impacts of the energy system transition and development.

The application process of the MCA-SLES tool allows for whole-system analysis of the current local energy system and comparison with the planned or intended local energy system. The MCA-SLES tool provides results and information on the wider system impact, enabling users to better understand the holistic impacts and benefits expected or attained from projects and strategies undertaken as part of the energy transition.

4. Conclusion and Further Work

The ability for local communities, policymakers, and energy strategy designers to carry out energy system analysis may be increasingly important to the success of local energy system transitioning towards greener and low carbon energy system. The described SLES MCA-SLES tool empowers local community policy making and design by providing visual illustrations and easily digestible information on the potential impacts, co-benefits and barriers concerning a specific energy policy strategy at a specific local level. The MCA-SLES tool incorporates LCA and carbon accounting methodological frameworks to conduct emissions and environmental impacts assessment while also incorporating multi-criteria and system thinking approaches to accounting for the dynamic and interconnective nature of an energy system to being able to carry out the wider system analysis of an SLES project. The MCA-SLES tool accounts for, and mitigates the potential limitations and challenges resulting from issues pertaining to the system boundary and double counting challenges of input and output values by providing practitioners with a structured analytical framework focused on the energy system with some predefined input parameters.

Regarding the collection of geographical location and local data availability the MCA-MCA-SLES tool requires local practitioners using the MCA-SLES tool to engage with the local stakeholders to acquire local data is possible. Where that is not possible the MCA-SLES tool provides a generic data input sheet providing information attained from literature, LCA databases and simulations. Overall, the MCA-SLES tool developed by the team at IES at the University of Edinburgh can provide practitioners with an excel based analytical tool that can be used carry out whole system assessment on current local energy systems while also providing a comparative scenario analysis tool to compare current local energy system performance before and after the proposed energy system changes in policy or strategy are implemented. Lastly, further work is required to test the MCA-SLES tool in real communities, real data and work with a range of possible practitioners to explore how the MCA-SLES tool might best be employed in future to cost-effectively accelerate the transition to a lower carbon future.

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Variations of input parameters in Energy Performance Certificate calculation methodologies across European countries

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Abstract: The Energy Performance of Buildings Directive (EPBD) establishes a broad framework for determining the calculation methodology for energy performance certificates (EPCs). However, it delegates the responsibility of specifying the calculation details to individual member states. This has led to significant differences in methodologies, making cross-country comparisons challenging. As harmonization efforts continue to gain traction across Europe due to the new EPBD recast, it's crucial to delve into the details of calculation methodologies and pinpoint potential sources of diversion. This will help ensure that the harmonization process is as effective as possible. A crucial task is considering the potential discrepancies in calculation input parameters. An EPC assessment requires numerous inputs and collecting all the necessary information from the actual building is not always practical. While some methodologies only allow actual values to be used in the calculation process, others provide estimations and standard values linked to certain building characteristics, or rely on the expertise of the assessor. This paper aims to review such key differences among selected European countries, intending to facilitate efforts of cross-EU convergence of EPCs.

Keywords: Energy Performance Certificate, Next generation EPCs, EPC methodology, U-values, Occupant behaviour

1. Introduction

Buildings account for 36% of direct and indirect greenhouse gas emissions in the EU (European council, 2023). Energy Performance Certificates (EPCs), as important sources of information regarding the energy performance of the building stock, can be utilized in driving buildings' decarbonisation and reaching the goal of a decarbonised building stock by 2050 set by European countries (Li et al., 2019). The Energy Performance of Buildings Directive (EPBD) is the main legislative tool in EU member states setting the general outlines of regulations concerning EPCs (EPBD, 2018). While the EPBD provides the general requirements of the EPC calculation methodology, it leaves the calculation details to the relevant authorities in each country. This has led to a high level of diversity in EPC methodologies across European Union (EU) member states, making it difficult to understand performance ratings of other countries and using EPCs for EU wide policy making decisions.

In 2021, the European Commission published a round of proposals for new legislative measures called the "Fit for 55" package. The goal of this package is to reach at least 55% net greenhouse gas emissions reduction by 2030 and to achieve climate neutrality by 2050 (European council, 2023). As a part of the package, an overhaul of the EPBD is proposed, which includes introducing EU-level minimum energy performance standards based on harmonised energy performance classes. This has sparked a lot of interest towards harmonization of EPCs across the EU. As a result, several H2020 projects have been launched addressing concepts related to the next-generation of EPCs such as building renovation roadmaps, European voluntary scheme certificates, new indicators and scales, datasets, market recognition of energy building renovation or engagement of end-users through people-centred platforms (Hernandez, 2019, EUBsuperhub, Carnero Melero et al., 2022). These efforts aim at facilitating the monitoring and mapping of energy efficiency conditions in the building stock across Europe, which will pave the way for implementing more informed policies towards EU's climate change goals. A few example projects include UCERT (UCERT, 2023), D2EPC (D2EPC, 2023), and QualDEPC (QualDeEPC, 2023). However, there is still a need for extensive, detailed comparison between different EPC calculation methodologies to clarify the main similarities and differences in country specific approaches. The Horizon2020-funded project "crossCert" (crossCert, 2023) is aiming to achieve this goal by cross assessing EPCs across ten European countries. One of the initial steps of the project is studying the EPC methodology of each country and comparing certain aspects to highlight the main differences, the results of which will be used in later phases of the project for devising recommendations towards next generation harmonized EPCs. This paper reports part of these comparisons, reviewing the methodologies of the project partner countries Austria (OIB, 2019), Bulgaria (Ministry of Regional Development and Public Work, 2017), Denmark (The Danish Transport, 2018), Greece (Technical chamber of Greece, 2012), Malta (BRE, 2012b), Poland (Rozporządzenie Ministra Infrastruktury I Rozwoju, 2015), Slovenia (PIS, 2014), Spain (IETcc-CSIC, 2019), and UK (BRE, 2020, BRE, 2012a).

Firstly, the general approach of calculation methodology and the software used for assessment in each country are reviewed, highlighting the differences in the provision of official software in some countries and reliance of commercial tools in others. The next step is comparing the categories of energy consumption included in the calculation. The foundation of all EPC calculation methodologies is based on calculating the energy consumption for building services, however, it's important to consider which categories of energy consumption are included in calculations for each country. While it is suggested by the EPBD to include heating, cooling, hot water, and lighting (EPBD, 2018) in calculations, variations can be seen in including some of these categories across different methodologies.

The main focus of comparison will be on parameters affecting the heating and cooling loads. Heating and cooling load calculation is a fundamental task in an EPC methodology regardless of the approach type. Thermal characteristics of the building envelope, including U-values of walls, floors, roofs and U-values and G-values of windows as well as the infiltration rates are amongst important inputs that determine cooling and heating loads of the building. The way these parameters are represented in EPC calculations are similar across all methodologies, but there are still variations in how these values can be obtained. Some countries strictly allow actual values to be used, while others provide estimates based on certain building characteristics. Furthermore, how the building is used by the occupants can also change the energy consumption of building services. Heating and cooling temperature setpoints, the hours of operation of lighting, electrical equipment, and HVAC systems all can significantly change the energy consumption results of calculations. Some countries choose providing standardized values for these inputs to make comparisons between different buildings more feasible, while others allow the assessor to use their judgement and some countries only allow using actual data to create more accurate results. HVAC performance parameters representation differences across different methodologies are also discussed.

The main body of information used in this study has been collected using questionnaires answered by each partner country involved in the crossCert project, and complemented by the results of desk research. It is worth noting that there are numerous other inputs involved in EPC calculations which can vary between methodologies and can greatly impact the results, however, the mentioned categories have been selected as examples to highlight different approaches in EU countries in this study.

2. EPC methodologies across Europe

2.1. Software and general assessment methodology

EPBD allows countries to issue EPCs based on calculations (asset rating) or actual energy consumption (operational rating) (EPBD, 2018). While all countries have an EPC calculation methodology, some allow specific groups of buildings to be certified merely based on actual energy consumption data. In Denmark, if monthly energy consumption for at least one year is available for a building, the EPC can be issued based on the actual data. In Poland, the minimum required data for issuing an operational EPC is 36 continuous months of utility bills. Slovenia only allows the use of energy consumption data for EPC certification for existing non-residential buildings. All of the other studied countries only allow EPC certification based on calculations. In Bulgaria, even though the EPC is based on calculation, real energy consumption is used for calibrating the EPC model.

The EPC calculation methodology can be either steady state or dynamic (EPBD, 2018). Most of the studied countries use the steady state approach, with the exception of UK and Spain. In the UK, complex buildings with certain HVAC systems or architectural characteristics (e.g., atrium, demand-controlled ventilation, automatic blind control) should be modelled using government approved dynamic simulation tools such as IES-VE, EnergyPlus, etc. (EEABS, 2022). In Spain, some official software tools including HULC, SG SAVE, CYPE THERM HE PLUS and TEXTON3D TK-CEEP use DOE-2 or EnergyPlus calculation engines which perform dynamic simulation.

For easier application, some countries allow using a simplified version of the steady-state methodology for certain building types, where all the necessary input data for calculation is not available. Among crossCert countries, Spain, UK and Austria provide simplified versions of their methodology for certain categories of buildings. In the simplified Spanish methodology, which can only be used for existing buildings, some of the input data can be taken from default values or they can be inferred from certain building characteristics. In the UK, a reduced data version of The Standard Assessment Procedure (SAP) (BRE, 2012a), named RdSAP (Reduced Data SAP) is used for existing residential buildings where the complete dataset for SAP calculations is not available. In addition, the Austrian calculation software has a simple/default input mode for buildings with lower data availability, and an advanced input mode for more complex buildings with better data availability.

In all of the studied countries, the national calculation methodology has been implemented either in an official software or several commercial ones. Malta, Denmark, and Greece have specific official software which should be used by all assessors for the certificate to be valid. For Greece and Denmark, there is one official calculation program in each country, but it has been implemented in several commercial tools as well, which are also certified for EPC assessments. UK only offers an official software for non-residential building assessments, while the official calculation methodology for residential buildings has been implemented in several approved commercial software. Bulgaria and Spain offer several different official tools, while there is no official software in Austria, Poland and Slovenia and only commercial tools are used in these countries. Table 1 provides a list of the software used in the studied countries for EPC calculations.

Table 1- Software used in each country for EPC calculations.

Country	Official/Commercial	Software
Poland	Official	-
	Commercial	Audytor OZC, ArCADia-TEROMCAD PRO 2020, BuildDesk
Malta	Official	Residential buildings: 'Energy Performance Rating of Dwellings in Malta' (EPRDM). Non-residential buildings: iSBEM software
	Commercial	-
Austria	Official	-
	Commercial	ArchiPHYSIK, AX3000, ecoline, Ecotech Gebäuderechner, GEQ, Grüner GmbH, Gebäudeprofi.
Bulgaria	Official	EAB, EECalc and Shtrakov
	Commercial	-
Denamrk	Official	Be18
	Commercial	Energy10 and others
Greece	Official	TEE KENAK
	Commercial	4MKENAK, Buildingsoft GoEnergy CAD-PRO, Civiltech Energy Certificate CAD
Slovenia	Official	-
	Commercial	KI Energy or URSA
Spain	Official	New and existing buildings: HULC, SG SAVE, CYPE THERM HE PLUS, TEXTON3D TK-CEEP for more detailed inputs. Existing buildings: Ce3X, CE3, CERMA
	Commercial	-
UK	Official	Non-residential buildings: Official: iSBEM.
	Commercial	Residential buildings: commercial: Stroma, Elmhurst Energy, etc. Non-residential buildings: Dynamic simulation tools such as IES-VE, EnergyPlus, etc.

2.2. Energy categories

The first step in comparing EPC calculation inputs is considering which energy consumption categories are included in each methodology. The Annex I of the revised EPBD published in 2018 (EPBD, 2018) states that the energy performance of a building "shall reflect typical energy use for space heating, space cooling, domestic hot water, ventilation, built-in lighting and other technical building systems", where "technical building systems" refers to any technical equipment used for the purposes of space heating, space cooling, ventilation, domestic hot water, built-in lighting, building automation and control, or on-site electricity generation (EPBD, 2018). However, comparison between the studied methodologies show differences in countries' approaches. While all the studied countries include heating, domestic hot water (DHW) and ventilation in their EPC calculation, inclusion of cooling, lighting and electrical appliances energy consumption tends to vary.

Lighting is included in EPC calculation of non-residential buildings in all countries. But for residential building assessments it is not included in Polish and Spanish methodologies, and for Danish buildings only the lighting in communal spaces in multi-family residential buildings is included in calculations. For cooling energy consumption, the approach is similar to lighting where it is included in non-residential buildings' calculations in all of the studied methodologies. However, for residential buildings cooling is not included in calculations in UK and Austrian methodologies. Table 2 provides a summary of the energy categories included in each methodology.

Table 2- Energy categories in each country methodology

		Heating	Cooling	ventilation	DHW	Lighting	Electrical Appliances
Austria	Residential	✓	-	✓	✓	✓	-
	Non-residential	✓	✓	✓	✓	✓	-
Bulgaria	Residential	✓	✓	✓	✓	✓	-
	Non-residential	✓	✓	✓	✓	✓	✓
Denmark	Residential	✓	✓	✓	✓	only in communal parts of multi-family houses	-
	Non-residential	✓	✓	✓	✓	✓	-
Greece	Residential	✓	✓	✓	✓	✓	-
	Non-residential	✓	✓	✓	✓	✓	-
Malta	Residential	✓	✓	✓	✓	✓	-
	Non-residential	✓	✓	✓	✓	✓	-
Poland	Residential	✓	✓	✓	✓	-	-
	Non-residential	✓	✓	✓	✓	✓	-
Slovenia	Residential	✓	✓	✓	✓	✓	-
	Non-residential	✓	✓	✓	✓	✓	-
Spain	Residential	✓	✓	✓	✓	-	-
	Non-residential	✓	✓	✓	✓	✓	-
UK	Residential	✓	-	✓	✓	✓	-
	Non-residential	✓	✓	✓	✓	✓	-

2.3. Energy and carbon indicators

Comparing the EPC certificates of different counties (Table 3) shows different metrics are used for reporting calculation results. While all the studied countries provide carbon emissions values on their EPCs, the energy consumption metrics vary across countries. Some countries only provide primary energy consumption, while others provide more detailed information including total final energy consumption as well as values for energy consumption of various building services such as heating, cooling, domestic hot water and lighting.

As can be seen from Table 3, the EPC certificates in Scotland only include primary energy consumption and carbon emissions values, non-residential EPCs in England and Wales only include CO_2 emissions values, and EPCs in Malta only include primary energy consumption and CO_2 emissions values.

Table 3- Metrics provided in each country's EPC.

Austria, residential buildings	Final energy consumption for heating and hot water - total final energy consumption- total primary energy consumption- CO_2 emissions
Austria, non-residential buildings	Final energy consumption for heating, cooling, hot water, lighting, and humidification- total final energy consumption- total primary energy consumption- CO_2 emissions
Bulgaria	Final energy consumption for heating, ventilation, cooling, hot water, lighting, and electrical appliances- total final energy consumption- primary energy consumption- CO_2 emissions
Denmark	Final energy consumption for heating, and electricity for building operation- CO_2 emissions- Annual cost disaggregated by fuel type
Greece	Final energy consumption for heating, cooling, hot water, and lighting- total final and primary energy consumption disaggregated by fuel type- CO_2 emissions
Malta	Primary energy consumption- CO_2 emissions
Poland	Final energy consumption for heating, cooling, hot water, and lighting- total final and primary energy consumption- CO_2 emissions
Slovenia	Final energy consumption for heating, ventilation, cooling, hot water, lighting, and auxiliary power- total final and primary energy consumption- CO_2 emissions
Spain	Primary energy consumption and CO_2 emissions for heating, cooling, hot water, and lighting- Final energy consumption for heating and cooling, total primary energy and CO_2 emissions
UK (Scotland), non-residential buildings	Primary and final energy consumption- CO_2 emissions
UK (Scotland), residential buildings	Primary energy consumption- annual cost rating- Environmental Impact Rating (calculated based on CO_2 emissions)
Rest of the UK, non-residential buildings	CO_2 emissions
Rest of the UK, residential buildings	Annual cost rating- Final energy consumption for heating and hot water- CO_2 emissions

2.4. Building zones

The ability to use zoning in the EPC software is an indicator of the level of details required during the assessment and provides insight into the overall approach of a methodology. Dividing a building into multiple zones allows for a more detailed and accurate analysis. On the other hand, it increases the number of inputs which can make the EPC issuing process more time consuming and increase the potential of human errors.

Criteria used by different methodologies for dividing the building into various zones include temperature set points, HVAC systems, type of activity, and significant differences in heat loss or heat gains (e.g., south facing rooms). Comparing the methodologies in different countries shows that all countries allow zoning for non-residential buildings, whilst treating residential buildings as single zone spaces. However, EPC methodologies of Greece, Spain, Poland and Bulgaria allow the assessor to divide residential buildings into multiple zones as well, which is an option rarely used by the assessors.

2.5. Building envelope parameters:

Thermal transmittance of materials (i.e., U-values) and other similar characteristics of building fabric are usually either calculated by the EPC software using a library of commonly used material or taken from databases of default values for common structure types in a country. It is worth noting that these libraries and databases are specific to each country, therefore identical material might have different values in each country. In all of the studied countries, if enough data is available, the assessor uses the software to calculate these values based on the information they collected during a site visit, using building drawings, or other documents such as wall construction certificates (in the case of Denmark).

For most countries, a database of commonly used wall, roof and floor constructions as well as U-values and G-values for windows is implemented in the calculation software. Exceptions are the Bulgarian methodology and the Maltese methodology for residential buildings, for which there is no database implemented in the national software and assessors must calculate U-values separately using information from other official resources and enter the results into the software.

Some countries also allow estimating the thermal transmittance of the building envelope using general information about the building, such as building age or use-type. Spain and UK use such feature for existing buildings, which infers values based on the building sector, climate zone and the building regulations that were in use at the time of construction.

Infiltration rate is also an important input which is linked to the building fabric and opening types and affects the building energy consumption results. The EPC methodologies of most countries require the assessors to perform a pressure test at 50 Pa to measure the infiltration rate (Austrian Standards, 2019, Dansk Standardiseringsrad (DS), 2020, PIS, 2014, Official Gazette of the Republic of Slovenia, 2019, Ministry of Regional Development and Public Work (Bulgaria), 2021, BRE, 2020, BRE, 2012a, BRE, 2012b). Similar to U-values, in the absence of a measured value, some methodologies provide default values based on building characteristics. For example, the default infiltration rates in the Austrian methodology depend on the building type, whereas in the Danish methodology they depend on the level of weatherproofing of the building (The Danish Energy Agency, 2021). The Polish methodology determines the default infiltration value depending on whether a building was built before or after 1995. In some countries it is also possible to infer infiltration rates from building characteristics. This is the case for all buildings in Greece and Spain and the existing residential buildings in Malta and UK. However, in the UK, it is mandatory for the assessor to measure the infiltration rate on-site for new residential and non-residential buildings. In the Bulgarian methodology, assessors use infiltration rate values based on their experience, and adjust the values by calibrating the model against actual energy consumption data.

2.6. Temperature setpoints

Temperature setpoints have a direct impact on the calculation results for heating and cooling energy demand. All of the studied countries apart from Bulgaria (for certain building types) use default temperature setpoints for EPC calculations. However, unsurprisingly, these setpoints are different across different countries, mostly due to the country specific norms of temperature settings in buildings. Default temperature setpoints are generally defined in a static way; and for some countries don’t change between cooling or heating seasons.

For non-residential buildings, it is common to link the setpoints to activity types, which is the case for Greece, Malta, Poland, Slovenia and UK. Greece sets the default values based on the building use-type. Slovenia, Malta, and the UK define different setpoints for each zone activity type such as offices, circulation areas, etc. Poland uses a similar approach, but instead of specific activity type, the default values are based on the level of physical activity (seated, standing, walking) and clothing type. Denmark uses a different approach where temperature setpoints are linked to building controls instead of activity type, and Austria and Spain use fixed heating and cooling setpoints regardless of activity type.

For residential buildings, some countries use a fixed value for all seasons (Austria and Denmark) whereas others use different setpoints for cooling and heating seasons (Greece, Malta, Poland, Slovenia, Spain, UK). Figure 1 shows a comparison of temperature setpoints used in residential buildings assessments for some of the countries included in this study.

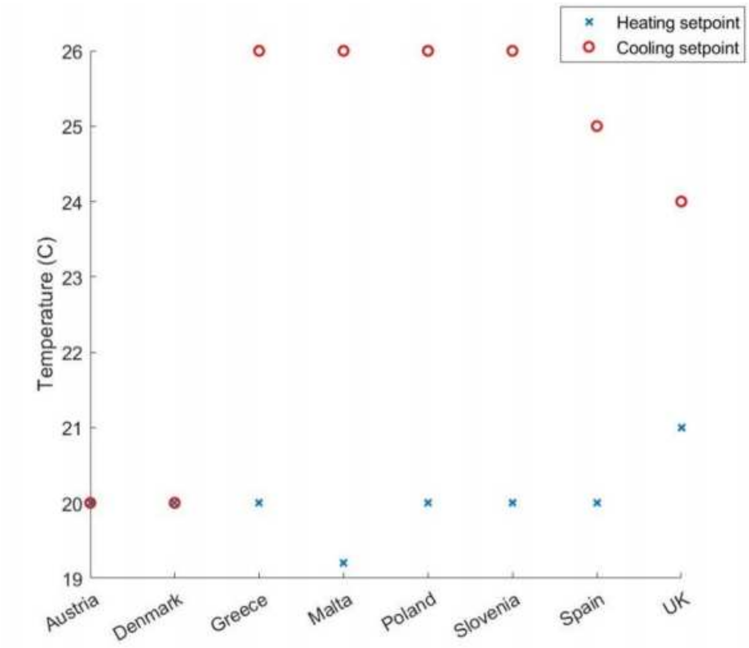

Figure 1- Temperature setpoints for residential buildings

2.7. Occupant behaviour schedules

Internal heat gains are an important factor in calculating heating and cooling demands which can affect the EPC rating of a building. Therefore, comparing how internal heat gains (i.e., occupancy, lighting, and electrical appliances) are defined in each methodology can provide valuable insights for any future harmonization effort. In addition to affecting the internal heat gains, HVAC and lighting operation times can directly change the energy consumption results of the model and should be considered in any comparison of EPC methodologies.

Most of the studied countries use pre-defined profiles in their EPC calculation methodologies in order to standardize and facilitate better comparison between buildings. Assessors must use these profiles in order for the EPC to be valid. Exceptions to this approach are Bulgaria, Poland and Slovenia. Bulgaria and Poland don't provide standard profiles and leave it up to the assessor to collect the necessary information during site-visits or use their own professional judgement, whereas Slovenia provides default schedules for various activities but allows the assessor to override these and use customized profiles based on the actual building activity. Spain also allows the assessor to use actual schedules for HVAC operation, but only in the case of non-residential buildings. Even though such approaches could lead to results closer to the actual building operation, they might also lead to variations in assessment results even for the same building when assessed by different assessors or during different times, rendering EPCs less useful.

Since the calculation methodologies of most of the studied countries are steady state, the exact timing of occupancy or system operation does not affect the results. Therefore, in most methodologies, occupancy and system operation profiles are defined in terms of a fixed number of hours in a typical day (sometimes different between weekdays and weekends, and heating and cooling season). These numbers vary across different countries as well. For example, public buildings are assumed to be occupied for 8 hours per day in Poland, whereas in Denmark this value is 9 hours. Another example is the variations of the HVAC operation profiles for residential buildings across different countries. In the Spanish methodology, the HVAC system operates from 7 AM to 11 PM from October to May and from 3 PM to 11 PM from June to September. Whereas Malta assumes the HVAC system to run from 6 to 8 AM and 5 to 11 PM. The UK methodology assumes the heating schedule to be between 7 to 9 AM and 4 to 11 PM on weekdays and 7AM to 11PM for weekends and a uses a standard cooling schedule of 6 hours/day. Slovenia and Denmark both assume 24-hour HVAC operation all year round.

Some countries provide more detailed profiles for non-residential buildings which are also suitable for using in dynamic simulation. This is the case for the UK and Spanish methodologies which have dynamic simulation options in their methodologies. The UK's National Calculation Methodology (NCM) (BRE,2020) provides different hourly profiles for occupancy, lighting, HVAC operation and electrical equipment operation based on zone activity type for non-residential buildings. The Spanish methodology divides all building types into 8hr, 12hr, 16hr and 24hr operation times and provides the default profiles for each type. It is worth mentioning that in the Spanish methodology, it is not possible to define different profiles for each zone separately, and the operation profiles apply to all zones in the building.

2.8. HVAC systems

For defining HVAC equipment, most countries take a similar approach by requiring the assessor to collect information regarding system efficiency parameters such as the Coefficients of Performance (COP), EER (Energy Efficiency Ratio), and SEER (Seasonal Energy Efficiency Ratio) using manufacturer documents or equipment nameplates. Some countries require more detailed inputs, for example for defining boilers, in addition to the system efficiency Slovenia requires the heating power at 30% operation, the efficiency at 30% operation, and the heat loss in standby mode.

In the absence of the required information, different countries provide assessors with different options. Austria, Denmark, Greece (Technical chamber of Greece, 2012), Malta (only for non-residential buildings), Poland (Rozporządzenie Ministra Infrastruktury I Rozwoju, 2015), Slovenia, and the UK provide default values in the software or in a separate database which can be used in the calculations instead of the actual values. These values are selected based on system type, range of system power, or device manufacturing date. However, this is not the case in all countries. For Bulgaria, if manufacturer data isn't available, the assessor should use instruments to measure device performance on-site. Also, Spain only allows using default parameters in cases where the installed HVAC system doesn't meet the necessary setpoint temperatures, for example in older buildings with no installed heating systems.

2.9. Ventilation rates

Comparing countries' approaches to ventilation rates shows that most countries provide databases in their software with default minimum values for different activity types. Bulgaria, however, doesn't provide default values for ventilation rates and requires the assessor to use system design values or measure the ventilation rates on-site using a thermo-anemometer.

Although, this is usually not the case in practice, mostly due to the low cost of EPC assessments, and most assessors use values based on their experience and make the necessary adjustments during the calibration step.

3. Conclusion

The EPC methodologies in EU vary across different countries. With increased attention towards EU-level convergence of these methods, it is vital to understand the main similarities and differences between methodologies in order to create harmonized methodologies for next generation EPCs.

This study compares some technical aspects of EPC methodologies of the countries involved in the crossCert project. The general approaches as well as some detailed inputs to the EPC calculation methodologies of these countries are compared against each other. The comparison reveals while the general outlines of calculations are similar, there are differences in types of approaches to EPC calculation, all of which vary on a spectrum between a highly standardized approach and a largely tailored one. Table 4 provides a summary of the review conducted in this report, highlighting the similarities between country methodologies in each comparison criteria.

Table 4- Summary of comparisons across crossCert countries

	HVAC schedules	HVAC specification	Lighting and equipment schedules	Occupancy	Construction thermal parameters	Ventilation rates	Infiltration rate	Setpoints	Asset/operational rating
Austria	Default based on building type	Default values available	Default values	Default values	Database available	Database available	Default values available	Fixed	Asset rating
Bulgaria	Assessor	Actual values	Assessor	Assessor	Database available	Measurement/assessor's knowledge	Measurement/assessor's knowledge	Assessor	Asset rating
Denmark	Assessor	Default values available	Default values	Default values	Database available	Database available	Default values available	Depends on use type/activity level/control	Both
Greece	Default based on zone activity type	Default values	Default values	Default values	Database available	Database available	Default values available	Depends on use type/activity level/control	Asset rating
Malta	Default based on zone activity type	Default values available for some building categories	Default values	Default values	Database available/ Inference based	Database available	Default values available	Depends on use type/activity level/control	Asset rating
Poland	Assessor	Default values available	Default values or assessor	Assessor	Database available but outdated	Database available	Default values available	Depends on use type/activity level/control	Both
Slovenia	Default based on zone activity type	Actual values	Default values	Default values or assessor	Database available	Database available	Measurement/assessor's knowledge	Depends on use type/activity level/control	Both
Spain	Default based on building type	Actual values	Default values	Default values	Database available/ Inference based	Database available	Default values available	Fixed	Asset rating
UK	Default based on zone activity type	Default values available for some building categories	Default values	Default values	Database available/ Inference based	Database available	Default values available for some buildings	Depends on use type/activity level/control	Asset rating

Given the comparative purpose of an EPC, most partner countries' approaches are closer to the standardized end of the spectrum with the exception of Bulgaria, which uses a highly tailored approach. In the Bulgarian methodology, default values for the inputs are not provided by the methodology, and the assessor uses their experience or actual data collected on site to fill in such inputs. While the gap between actual building and calculation results might be lower due to this approach, such an approach makes EPC rating comparison between buildings a fundamentally different exercise, where assessors could provide different inputs to the calculation software resulting in different ratings for a given building. Poland and Slovenia also use approaches with some inputs tailored to each building and provide the assessor with a higher degree of freedom in terms of the inputs of EPC calculation. Other countries seem to follow a more standardised approach, with single values or ranges of values provided for each parameter. It should be noted, however that the degree of standardisation should be considered within specific categories, not just across the whole assessment approach. It is not necessarily the case that a country using a high degree of standardisation for one parameter will adopt the same approach for other parameters.

It is worth noting that while this study has tried to overview some important aspects of the EPC methodologies, more research is required in the future stages of this project and other similar ones to clarify the differences in EPC calculations.

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Solar Cooling Integrated Façades: Towards investigating product applicability

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Abstract: The application of façade products integrating solar cooling technologies tends to be one of the promising options to be considered for challenges related to the increase in global demand for cooling in the built environment. Accordingly, the technological innovation of such products represent an essential task to be taken into account for meeting the future cooling demand in buildings. However, selecting the right technology and tackling technical and product-related aspects in the context of solar cooling can be challenging, since each technology is different from one another in terms of their working principles. Furthermore, developing such building products can be a complex endeavour, due to the involvement of various components. This paper aims to propose a conceptual approach for designing and developing façade products integrating solar cooling technologies. Proposing this approach required establishing a matrix of key attributes and criteria affecting technological selection through referring to identified key perceived enabling factors by expert interviews in an earlier stage of the study. The outcomes of this study outlined various attributes, such as product performance and efficiency as well as compactness and space usability, that can be used in product development of solar thermally and electrically driven systems, in order to ensure to support the widespread application.

Keywords: renewable, building envelope, component, design, attribute

1. Introduction

The global demand for cooling in the built environment has been estimated to dramatically increase in the coming years due to climate change as well as global population growth (Enteria and Sawachi, 2020; Sahin and Ayyildiz, 2020; Santamouris, 2016). These factors have a vital role in the widespread application of air-conditioning (AC) units in order to meet thermal comfort requirements. Accordingly, the increase of such AC units represents a critical environmental challenge since most of these cooling systems depend on the electricity generated in power plans (Santamouris, 2016). Therefore, it is essential to consider the application of cooling systems that rely on renewable sources of energy to minimize greenhouse gas (GHSs) emissions resulted from the energy consumed by AC units. The application of façade products integrating solar active cooling technologies tends to be one of the potential options to be considered for reducing the use of conventional air-conditioning systems. This is due to the fact that building façade surfaces are exposed to high solar radiation, providing an opportunity to harvest solar energy for driving cooling equipment (Prieto et al., 2017). Accordingly, the technological innovation of such products represent an essential task to be taken into account for meeting the future cooling demand in buildings. Taking into account that there are different types of solar active technologies, solar active façades (SAFs) were defined by the International Energy Agency-Solar Heating and Cooling Program IEA SCH Task 56 as follows (Ochs et al., 2020):

“the envelope systems entailing elements that use and/or control incident solar energy, having one or more of the following uses:

- *To deliver renewable thermal or/and electric energy to the systems providing heating, cooling, and ventilation to buildings.*
- *To reduce heating and cooling demands of buildings, while controlling daylight.”*

When considering the façade integration of solar cooling technologies, solar cooling integrated façades (SCIFs) were previously defined as “*façade systems which comprise all necessary equipment to self-sufficiently provide solar driven cooling to a particular indoor environment*”, which indicated that the necessary equipment needed at least for cooling generation and distribution should be integrated by façade systems (Prieto et al., 2017). While the definition stands from an academic standpoint, the nuances of reality dictate that the development of building products based on solar cooling should consider a certain flexibility, such as that not all components could or should be integrated into the façade. Accordingly, in order to provide more flexibility while considering the two aforementioned definitions of SAFs and SCIFs by (Ochs et al., 2020) and (Prieto et al., 2017), respectively, a more practical definition that can be considered is as follows:

“*Building envelop systems that include elements using and/or controlling solar radiation to deliver self-sufficient solar renewable electric and/or thermal energy needed to generate cooling effect in a particular indoor environment*”

The design and development of façade products integrating solar cooling technologies involve including additional functions into the façade. The inclusion of such functions represents a secondary step when the indoor requirements cannot be met by other measures, such as shading systems and/or thermal insulations (Figure 1) (Prieto et al., 2017). Current approaches that have been used to evaluate the product applicability are based on the theoretical calculation of the Solar Fraction (SF) (Noaman et al., 2022; Prieto et al., 2018). The calculation involves dividing two main parameters. The cooling effect delivered by a solar cooling system to a particular indoor environment is divided by the cooling demand of that particular indoor environment. Hence, the system is considered to be able handle the cooling demand when SF value is 100% and more. It should be noted that the development of building products with the required technical attributes is essential to support the application of SCIFs in the construction industry (Hamida et al., 2022). However, since solar active cooling technologies have different forms related to the energy conversion and working principles through producing hot water through Solar Thermal Collectors (STC) (thermally-driven technologies) or producing electricity through Photovoltaic (PV) panels (electrically-driven technologies) (Alahmer and Ajib, 2020; Alsagri et al., 2020; He et al., 2019; Karellas et al., 2019; Neyer et al., 2018; Sarbu and Sebarchievici, 2016), selecting the right technology and tackling technical and product-related aspects in the context of SCIFs can be a challenging task. This is due to the fact that each technology, electrically-driven or thermally-driven, is different from one another in terms of different aspects, including their sizes and working principles. Also developing such products can be a complex endeavour, due to the involvement of various components. Accordingly, proposing an approach to investigate product applicability through involving matrix of key attributes to be considered for designing and developing SCIFs concepts can play a vital role in enabling the widespread application.

This paper aims to propose a conceptual approach for designing and developing façade products integrating solar cooling technologies, including both of solar thermally and electrically systems. Proposing this approach required having a matrix of key attributes and criteria affecting technological selection through referring to identified key perceived enabling factors by expert interviews in an earlier stage of the study (Hamida et al., 2023). The research materials and methods section (Section 2) presents the steps required to propose the aforementioned approach. Then section 3 provides a theoretical background about solar cooling technologies, whereas section 4 presents and discusses the proposed approach. Finally, the paper ends with the conclusion section (Section 5) that states future research scope.

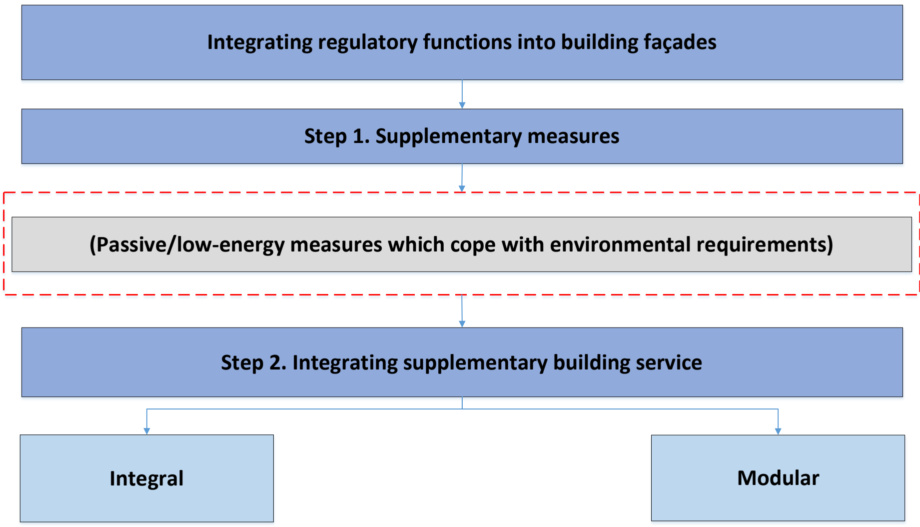

Figure 1. Decision-making process for façade integration of regulatory functions (Prieto et al., 2017)

2. Materials and Methods

To propose a conceptual approach for designing and developing façade products integrating solar cooling technologies, the research materials and methods are as follow:

1. Determining key attributes that can be considered in the process of designing and developing facade products integrating solar cooling technologies. The determination of these attributes was obtained through considering potential quantifiable key enabling factors that were identified by expert interviews in an earlier stage of the study (Hamida et al., 2023). These enabling factors were perceived to enable the widespread application of SCIFs. The scope and criteria considered for determining the attributes to be taken into account in the matrix consider that the attribute can potentially be measured during the design phase, such as dynamic energy simulations and life cycle cost analysis (LCC).
2. Determining criteria affecting the technological selection of solar cooling technologies. The determination of these criteria was obtained from aspects identified to affect the perception of the status of current technologies that were obtained from the expert interviews (Hamida et al., 2023).
3. Proposing a conceptual approach to investigate product applicability through combining the outcomes of the aforementioned steps. Proposing the approach involves a sequential steps covering a matrix of key measurable attributes to be considered for designing and developing, as well as the criteria affecting technological selection.

3. Theoretical Background

As indicated in Figure 2, there are different types of solar active thermally and electrically-driven solar cooling technologies (Alsagri et al., 2020).

3.1. Thermally-Driven Technologies

The solar thermal energy is utilized in these technologies for the purpose of achieving one of the following options (Sarbu and Sebarchievici, 2016):

- Generators of sorption cooling systems are powered by the thermal energy.
- Thermal energy is converted to mechanical energy which is therefore is used for producing cooling effects.

Table 1 summarizes technological options for the thermal solar sorption cooling that consist of mature components (Mugnier et al., 2017). The solar collectors are the fundamental components needed for all installations of solar thermal energy systems. Their main function is to capture and convert sun radiations into useful heat to be used for solar thermal applications. Such heat is transferred to heat transfer fluids. The fluids can be water, air, or oil that flow through solar collectors. Heat carried by heat transfer fluids can be utilized for the following options (Karellas et al., 2019):

- Satisfying heating or cooling loads
- Charging thermal energy storage systems. Such systems discharge the heat during night, cloudy, or foggy periods

There are different types of solar thermal collectors that are available in the market. The flat plate collector, evacuated tube collector, and parabolic through collector are the main types of collectors. The utilization of different solar collectors based on temperature variations and their applications is illustrated Figure 3 (Alahmer and Ajib, 2020).

Solar thermal cooling technologies can be categorized into closed sorption cycles, open sorption cycles, and the thermomechanical cycles. In solar sorption cooling systems, either closed or open, the cooling effect is produced using the sorbent and sorbate (He et al., 2019).

Table 1. Technological options for the thermal solar sorption cooling (Mugnier et al., 2017).

Type of Temperature Application	Type of Collector	Cooling Device
Low Temperature (<100°C)	**• Air collectors • Flat plate collectors • Evacuated tube collectors**	**• Absorption chiller (Single-effect) • Adsorption chiller • Solid desiccant cooling • Liquid desiccant cooling**
High Temperature (>100°C)	**• Compound parabolic collectors • Single axis tracking concentrating collectors**	**• Absorption chiller (Double or triple effect) • Low-temperature refrigeration**

Closed sorption cycles have two main divisions, according to the sorption material, which are the liquid sorption and solid sorption. The absorption is referred to liquid sorption whereas the adsorption is referred to solid sorption. The absorption cooling usually comprises sorbents, liquids or solids, that absorb refrigerant molecules into their inside and then change, either in a chemical and/or physical way, during the process (Alahmer and Ajib, 2020). It requires dissolving liquids or gases in the bulk of a sorbent in one process phase and then releasing them in another phase, which is carried out through a closed loop comprising four steps. The steps include evaporation, absorption, regeneration, and condensation (He et al., 2019). The adsorption cooling comprises evaporating and condensing a refrigerant in a combination with adsorption (He et al., 2019). It is a solid sorption process that involve an attraction of refrigerant molecules into the surfaces of the solid sorbent through physical or chemical forces as well as without any changes in the sorbent form during the process

(Alahmer and Ajib, 2020). The removal of adsorbed particles from surfaces can be carried out through heating adsorbents. An additional step is required for regenerating or exchanging exhausted adsorbents due to discontinuity in adsorption cooling equipment process (He et al., 2019).

Open sorption cycles are commonly known as the desiccant cooling due to the use of sorbent for humidifying air (Sarbu and Sebarchievici, 2016). The classification of open sorption cycle is either solid desiccant cooling systems or liquid desiccant cooling systems which are used for dehumidification or humidification (Alahmer and Ajib, 2020). Solid desiccant cooling systems use rotary adsorption wheels as sorption materials, such as the silica gel (He et al., 2019). The system generally consists of two slowly rotating wheels in addition to other various elements between two airstreams from as well as to the cooled space (Sarbu and Sebarchievici, 2016). The achievement of dehydration process in the liquid desiccant cooling systems is carried out by absorption (He et al., 2019). Desiccant wheels in liquid desiccant cooling systems are replaced by a dehumidifiers and a regenerators (He et al., 2019; Karellas et al., 2019). Liquid desiccant cooling systems involve a circulation of liquid desiccants between absorbers and regenerators that is similar to absorption systems (Karellas et al., 2019; Sarbu and Sebarchievici, 2016).

Finally, thermomechanical cycles have three different forms, which include the following (He et al., 2019):

- Rankine Cycle which consists of producing mechanical work from solar heat and then deriving conventional vapor compression cycles.
- Stirling cycle involves a volumetric change resulted by pistons that change both of temperature and pressure of gas. However, this technology has practical limitations related to the capacity and efficiency.
- Ejector systems are similar to the conventional vapor compression systems. However, the ejectors that consist of nozzles, mixing chambers and diffusers are used in such systems instead of the mechanical compressors.

3.2. Electrically-Driven Technologies

The solar energy associated with such technologies are considered as a Photovoltaic (PV)-based systems, which involves an initial conversion of solar energy into electrical energy that is then used to produce cooling effect that is similar to conventional systems, or through thermoelectric processes (Sarbu and Sebarchievici, 2016). The utilization of PV for cooling through coupling it with conventional vapor-compression units is considered to provide advantages related construction simplicity and high efficacy (Sarbu and Sebarchievici, 2016). An example for such electric systems is the solar electric chillers that comprises PV panels, batteries, inverters, and electrically driven refrigeration devices. It should be noted that the refrigeration systems are recognized by the vapor compression cycles (Karellas et al., 2019). The term Building-Attached Photovoltaics (BAPV) has been defined when PV modules are mounted directly on a building envelop. On the other hand, Building-Integrated Photovoltaics (BIPV) has been considered in case when conventional building materials are replaced by PV modules (Singh et al., 2021). Figure 4 summarizes the technologies and applications of BAPV and PIPV, including the façade. The consideration of vapor-compression air-conditioning equipment was identified as a relevant option due to the decrease in PV prices (Montagnino, 2017).

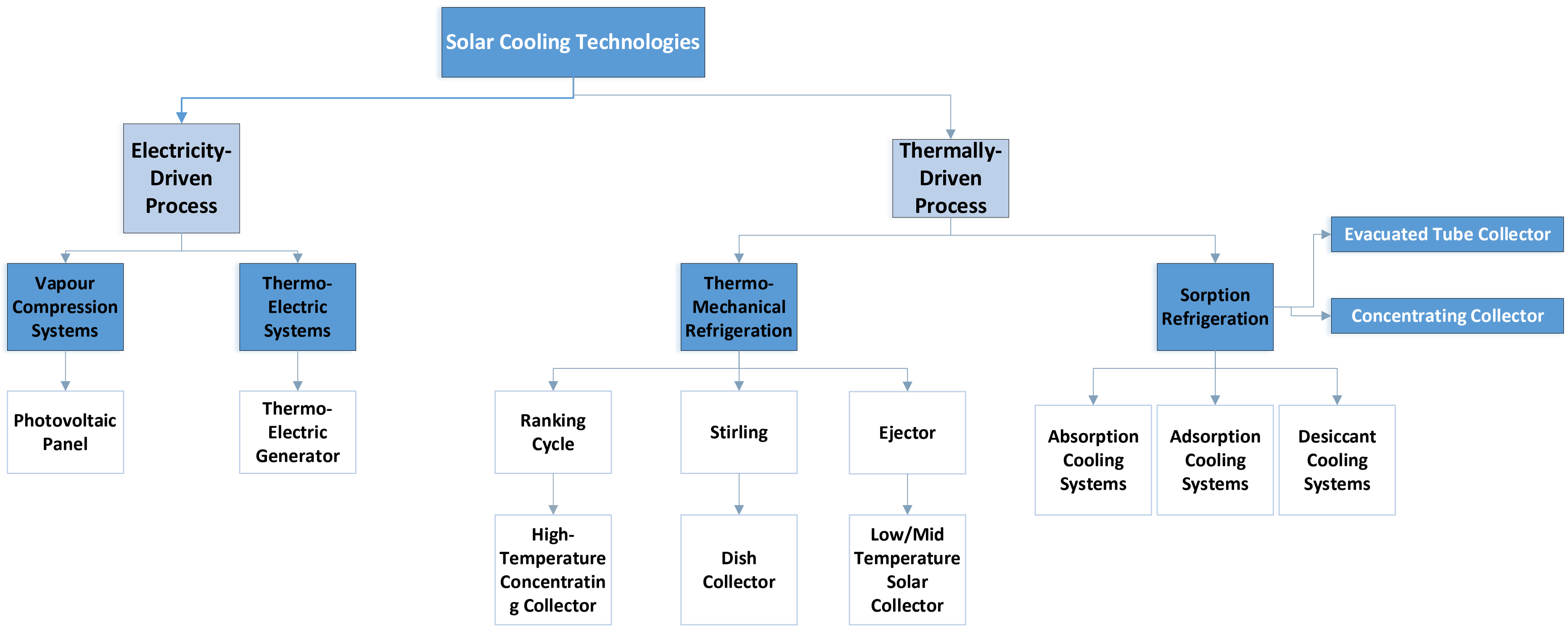

Figure 2. Solar Cooling Technologies (Alsagri et al., 2020)

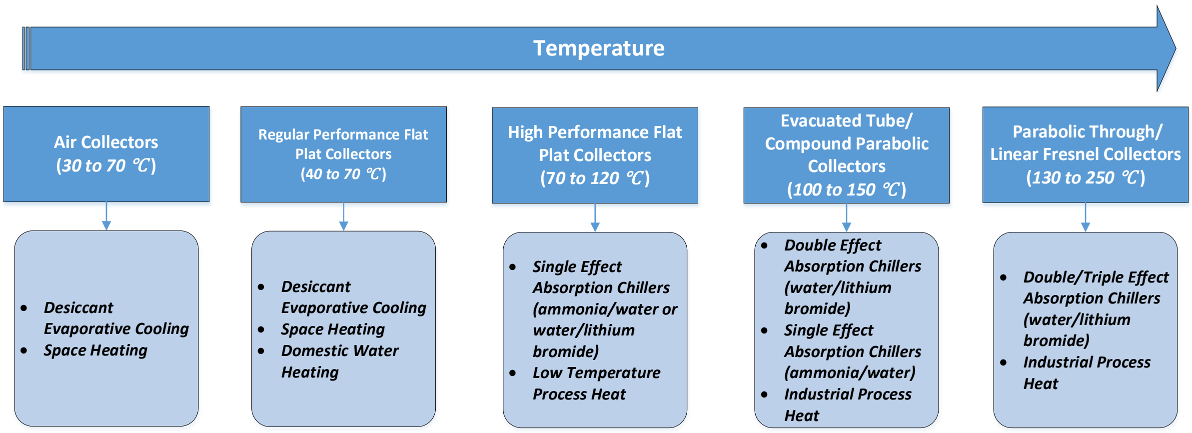

Figure 3. Use of solar collectors based on temperature variations and their applications (Alahmer and Ajib, 2020)

Solar thermoelectric systems involve a conversion of solar radiations to electrical energy through PV. Accordingly, the thermoelectric system is supplied by the produced electrical energy (He et al., 2019). A thermoelectric generator consists of thermocouples producing low thermoelectric power that however have the ability to produce high electric currents. It provides benefits related to lowering the operational level of heat source which is useful for the conversion of solar energy to electricity. The thermoelectric refrigerator also comprises thermocouples made of semiconducting thermoelements where the current produced by generator run (Sarbu and Sebarchievici, 2016).

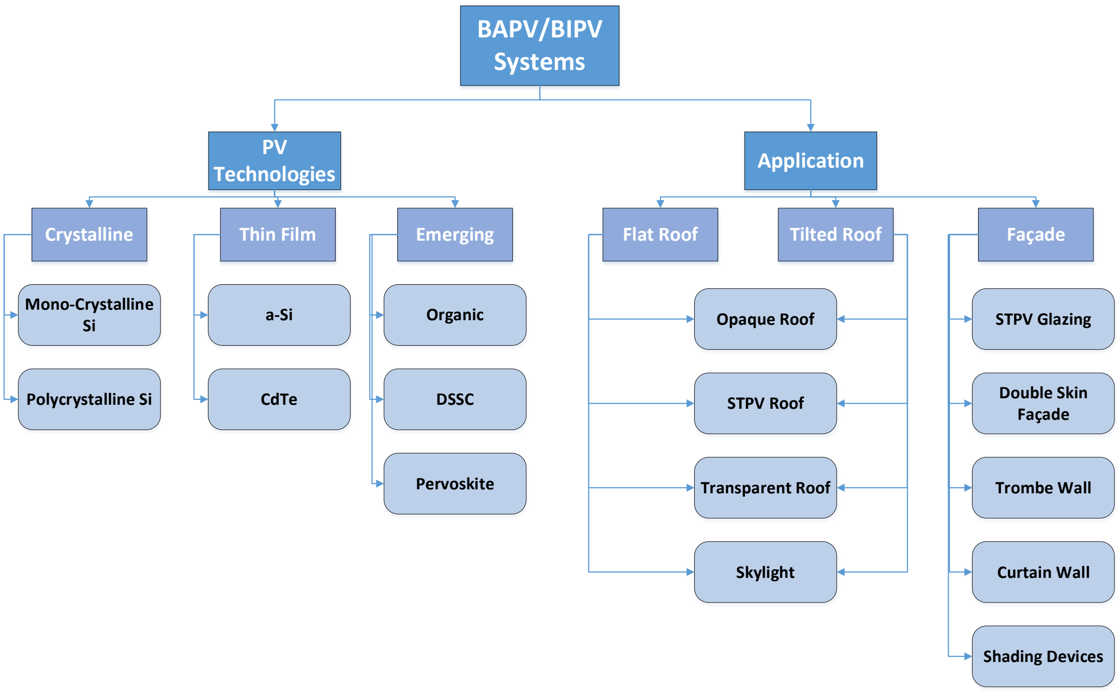

Figure 4. Technologies and applications of BAPV and BIPV (Singh et al, 2021)

4. Towards Investigating Product Applicability

In order to understand key aspects enabling the product applicability of SCIFs in the construction industry, a total of 23 interviews were conducted with various experts in the European building industry (Hamida et al., 2023). The interviews were conducted between May and September 2022, and involved experts from different fields. The fields included façade design and construction, application/façade integration of solar (or solar cooling) technologies, and research and development in multifunctional façades. The outcomes of these interviews have been adopted in this paper to propose the conceptual approach, which included determining key attributes and criteria affecting technological selection. The findings included key factors enabling the product applicability which are related to the technical & product (T&P)-related, financial (F)-related, as well as process and stakeholder (P&S) aspects. These findings were obtained from a deductive analysis focusing on the three aforementioned aspects. The results also included findings related perceptions of the status of current technologies, which were obtained from an inductive data analysis. Taken into account the scope and criteria considered for determining attributes involved in designing and developing SCIFs concept (section 2), Table 3 summarizes the attributes identified from the key enabling factors. Regarding the determination of criteria affecting the technological selection of solar cooling technologies, the interviews outcomes revealed various perceived aspects influencing the perception of the status of current technologies, for both of electrically-driven as well as thermally-driven. Some of these aspects were also related to the enabling factors identified enabling factors, as indicted in Table 3.

Table 3. Matrix of key attributes and criteria affecting technological selection.

Item	Attribute as a Key Enabling Factor			Selection Criteria as an Aspect Influencing the Perception of the Status of Technologies	
	Related Aspect			Related Technology	
	T&P	F	P&S	Electrically-Driven	Thermally-Driven
Product performance and efficiency	×	×	×	×	×
Compactness and Space Usability (Size)	×	×	×	×	×
Meeting user comfort requirements	×	-	×	-	-
Durability and long life span	×	-	×	-	×

Table 3. Matrix of key attributes and criteria affecting technological selection (cont.).

Item		Attribute as a Key Enabling Factor			Selection Criteria as an Aspect Influencing the Perception of the Status of Technologies	
		Related Aspect			Related Technology	
		T&P	F	P&S	Electrically-Driven	Thermally-Driven
Financial and life-cycle costs	Project Budget	-	×	×	-	-
	Initial Cost	-	-	-	×	-
	Government Subsidies	-	×	×	-	-
	Taxes and Fees	-	×	×	-	-
	High Energy Prices	-	×	×	-	-
	Operating/Ownership Cost	-	×	×	-	-
	Return on Investment (Payback Period)	-	×	×	-	-
	Ability to Compete Traditional Systems	-	×	×	-	-

Table 3. Matrix of key attributes and criteria affecting technological selection (cont.).

Item	Attribute as a Key Enabling Factor			Selection Criteria as an Aspect Influencing the Perception of the Status of Technologies	
	Related Aspect			Related Technology	
	T&P	F	P&S	Electrically-Driven	Thermally-Driven
Aesthetical Acceptability	×	-	×	×	-
Applicability at Different Climate Conditions (Adaptability in Multiple Cases)	×	-	×	-	-
Plug and Play (Assembly and Connections)	×	×	×	×	×
Waste and Product End of Life	-	-	×	×	×
Fire Resistance (Safety)	×	-	×	×	-
Maturity and Advancement (Proven Technology)	×	-	×	×	×
Periodic Maintenance	-	-	-	×	×
Working Principle	-	-	-	×	×

Based on the established matrix of key attributes and criteria affecting technological selection, a conceptual approach to investigate product applicability is proposed. As indicated in Figure 5, investigating the product applicability requires determining particular technologies. Selecting the technology can involve different criteria such as the availability, size, and maturity. After that, design and development of façade concepts can be carried out through considering the attributes, which are related to the three main aspects. Designing and developing façade concepts should take into account particular boundary conditions, such as the following:

- Focusing on façade products to be used in a particular building vintage, such as considering new building construction projects or existing buildings.
- Considering a particular building typology, such as office buildings, due to the considerable amount of heat gains resulted from the building occupants, lighting systems, and office equipment (Konstantinou and Prieto, 2018).
- Focusing on premises located in particular warm climate conditions (considering the Koppen–Geiger climate zones), where the use of mechanical equipment is still needed.

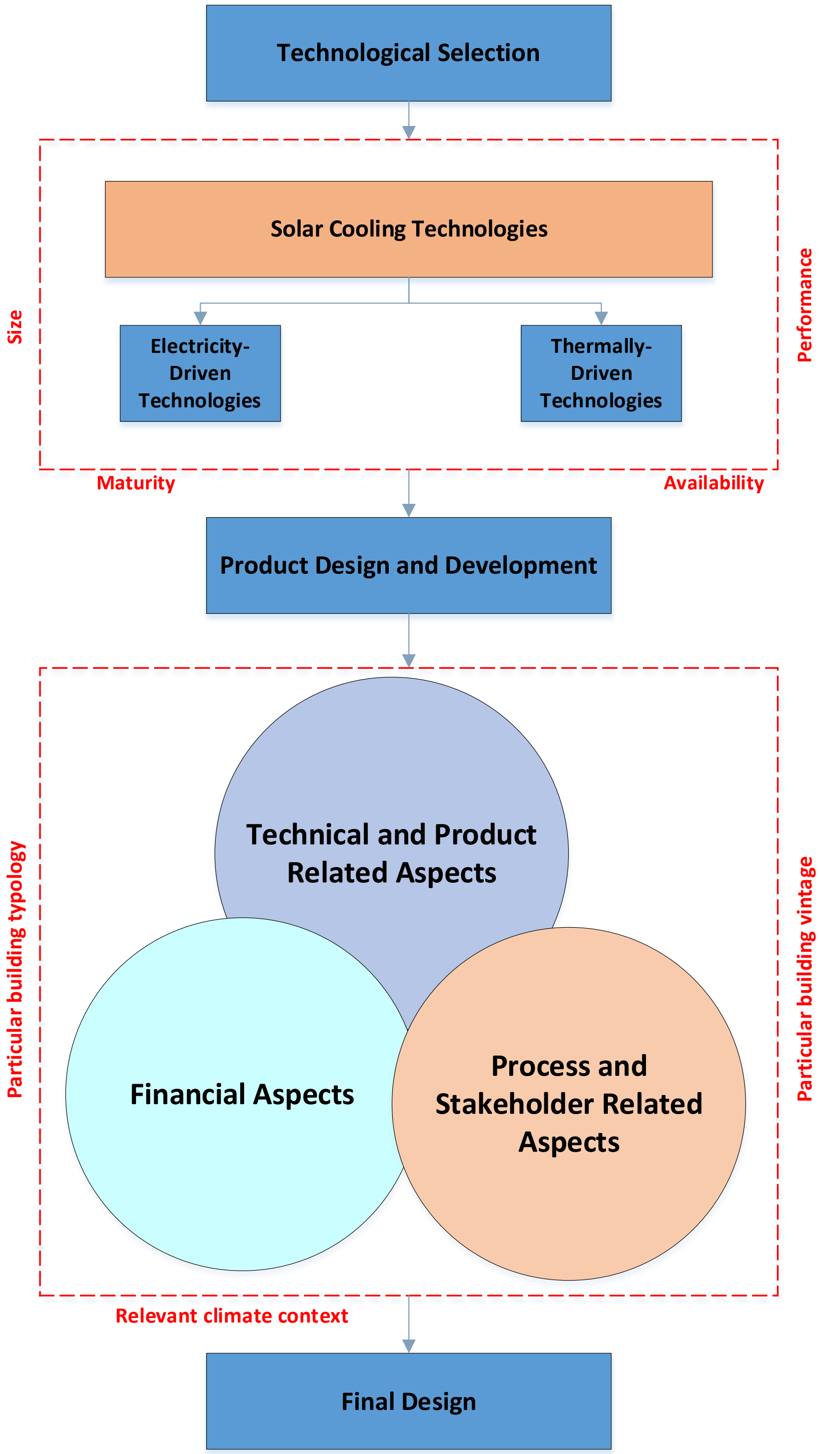

Figure 5. A conceptual approach to investigate product applicability

It should be noted that the proposed approach is considered to a secondary step after taking into account the supplementary measures needed to minimize cooling demands in buildings, as indicated in Figure 1. The approach is still also in the conceptual level and represents a basic foundation for further developments. This require a movement towards a more practical and detailed level, such as considering operational level as well as process flow charts (Rahman Abdul Rahim and Shariff Nabi Baksh, 2003).

5. Conclusion

The application of façade products integrating solar cooling technologies tends to be one of the promising options to be considered for challenges related to the increase in global demand for cooling in the built environment. Accordingly, the technological innovation of such products represent an essential task to be taken into account for meeting the future cooling demand in buildings. However, selecting the right technology and tackling technical and product-related aspects in the context of solar cooling is challenging, since each technology is different from one another in terms of their working principles. Furthermore, developing such building products can be a complex endeavour, due to the involvement of various components. This paper aimed to propose a conceptual approach for designing and developing façade products integrating solar cooling technologies, including both of solar thermally and electrically systems. Proposing this approach required establishing a matrix of key attributes and criteria affecting technological selection through referring to identified key perceived enabling factors by expert interviews in an earlier stage of the study. The outcomes of this study outlined various attributes, such as product performance and efficiency as well as compactness and space usability, that can be used in product development of solar thermally and electrically driven systems, in order to ensure to support the widespread application. Future work should take into account transforming the presented conceptual approach into a product development framework combining various technical, financial, and stakeholder related aspects while considering investigating the applicability of particular technologies in relevant contexts.

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Remote sensing-based frameworks to quantify city-level carbon fluxes in urban green infrastructures

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Abstract: The urban population is rapidly increasing, with ~90% predicted to live in cities by 2100. Since urban environments serve as hot spots for greenhouse gas and pollutant emissions, and as the urban areas are destined to become even denser, sustainable urban life requires the careful and well-informed urban planning of infrastructures that could adequately mitigate these emissions. A common means to achieve this goal is urban green infrastructures, typically considered a net sink for CO_2. However, due to the heterogeneous urban land use of these infrastructures, our ability to isolate and accurately quantify their overall impact on the carbon balance of the city is limited.
In this paper, we suggest combining remote observations with local measurements to determine the city-level carbon balance of green infrastructures and generate a high-resolution CO_2 sequestration map of these infrastructures. The offered framework developed in this study determines the contribution of green infrastructures to the carbon budget of cities to help and improve the planning of low carbon-emitting cities.

Keywords: Urban green infrastructures, urban sustainability, greenhouse gas balance, remote sensing carbon sequestration.

1. Introduction

Anthropogenic CO_2 emissions are a primary driver of the change in the global radiative budget and may significantly affect the global climate and ecological balance. Due to the constant increase in atmospheric CO_2 concentrations, many countries have pledged to achieve carbon neutrality in the upcoming decades; however, as the rise in human population continues, more and more people are designated to live in cities, which is expected to increase urban CO_2 emissions even further. Therefore, sustaining urban life requires thoughtful and well-informed urban planning and CO_2 emission-mitigation strategies. One such approach that is believed to reduce the net CO_2 emission in cities is increasing the prevalence of urban vegetation Weissert *et al.*, 2016).

Urban vegetation has many benefits, from reducing air pollution (Badach, Dymnicka and Baranowski, 2020; Fares *et al.*, 2020) and improving thermal comfort (Lai *et al.*, 2019) to serving as a center for recreational activities. The CO_2 flux balance of urban green infrastructures—defined as urban green ecosystems that include vegetation, soil, and built elements (Dover, 2015)—depends on natural sources and sinks: the respiration of the vegetation and soil, collectively termed ecosystem respiration (R_e), acts as a source, while photosynthesis, referred to as gross primary production (GPP), acts as a sink. The balance between the sources and sinks is defined as the net ecosystem productivity (NEP): $NEP = GPP - R_e$, which we generally attempt to increase to sequester more carbon and produce a more sustainable environment.

While the common conception is that vegetation serves as a net CO_2 sink for the city, the influence of the urban green infrastructure, as a whole, is not necessarily intuitive; in fact, it may even act as a net CO_2 source (Velasco *et al.*, 2016). Various factors may influence the impact of green infrastructures on the urban CO_2 flux balance, including climate(Wang *et al.*, no date), vegetation type (Zhang, Gong, Fa, *et al.*, 2019; Li and Wang, 2021), soil type (Dorendorf *et al.*, 2015), and management practices. So, while vegetation acts as a clear CO_2 sink (Zhang, Gong, Escobedo, *et al.*, 2019), the soil CO_2 fluxes cause the net CO_2 balance to be positive, thus net emission of CO_2 (Dorendorf *et al.*, 2015). Accordingly, depending on the climate and seasonality, green infrastructures could serve as either sinks or sources(Velasco *et al.*, 2016). These studies are testimony to the gap in knowledge regarding the contribution of green infrastructures to the carbon budget of the city—a gap that could be overcome by developing a platform to estimate the overall impact of green infrastructures on the urban carbon budget. Such a tool is crucial because an inaccurate estimation of the urban sources and sinks, including (but not limited to) the green infrastructures, yields erroneous conclusions regarding the role of green infrastructures and cities, preventing us from truly reaching the goal of zero carbon emission.

To date, the primary tool for characterizing the contribution of green infrastructures to the CO_2 budget of the city has been local measurements of stand-alone elements or areas, using allometric and growth-rate models for biomass estimation (Aguaron and McPherson, 2012; Oviantari *et al.*, 2018), soil carbon storage and CO_2 efflux (Raciti *et al.*, 2011; Schwendenmann and Mitchell, 2014), photosynthesis and leaf respiration (Wang, Chang and Li, 2021), and eddy covariance (EC) CO_2 flux measurements (Stagakis *et al.*, 2019; Zhang, Gong, Escobedo, *et al.*, 2019). Critically, these methods are restricted to a relatively small spatial scale; their upscaling, which is required to estimate city-scale carbon sequestration, as in the i-Tree eco-allometry-based model (Ma *et al.*, 2021), requires hundreds of measurements or more. **The presented paper proposes that the capacity of urban vegetation to sequester carbon can be quantified, at the whole-city level, by combining a small number of local measurements with remote-sensing observations and advanced machine-learning (ML) algorithms.**

Remote-sensing observations of CO_2 column concentrations, made by carbon-observing satellites (e.g., OCO-2 and OCO-3), can be readily used today to estimate urban CO_2 emissions (Fu *et al.*, 2019; Wu *et al.*, 2020; Kiel *et al.*, 2021; Park *et al.*, 2021). However, the spatial resolution of these satellites is coarse (kilometers), they only take one snapshot every few days, and quantifying fluxes from column concentrations is not possible. The city-wide vegetation carbon uptake can be estimated from satellites at a finer spatial resolution (several meters) only indirectly, namely, by sensing the reflected solar radiation from the vegetation and correlating it to the biophysical characteristics of the plants. A few pioneering studies have applied remote sensing for such purposes in the urban environment, but this methodology is still in its infancy. For example, studies in southern China and Hong Kong used satellite reflectance observations to estimate the net primary production (NPP) and the GPP of urban vegetation (Xu, Dong and Yang, 2018; Zhong *et al.*, 2019; Luo *et al.*, 2021), but the satellite-based CO_2 flux products were evaluated in mixed urban areas and with a pixel size of hundreds of meters of heterogeneous land covers, which introduced significant uncertainty to the results. Other studies employed satellite observations to estimate above-ground carbon storage (Myeong, Nowak and Duggin, 2006; Uniyal *et al.*, 2022), but they focused on extended periods and were limited in assessing daily changes, which are crucial for understanding the impact of environmental factors and the built environment on the carbon fluxes of green infrastructures. Miller et al.(Miller *et al.*, 2018) were of the few who were successful in using high-resolution satellite data to predict GPP.

Another approach (Baker, 2008; Rascher *et al.*, 2015) is to use solar-induced chlorophyll fluorescence (SIF), namely, quantify the energy that plants emit in the far-red spectral regions, which is considered a proxy for photosynthesis. Wu et al. (Wu *et al.*, 2021) recently developed a model based on SIF to estimate biogenic fluxes, employing ML and several observables to predict GPP and SIF. They used GPP fluxes from FLUXNET2015 (Pastorello *et al.*, 2017), which usually measures fluxes from large rural areas rather than specific urban vegetation. This limitation hinders its applicability to the urban environment. SIF has great potential for estimating carbon fluxes, but satellite technology is still limited, and SIF is currently measured at a coarse spatial resolution of kilometers.

Remote-sensing observations can upgrade local measurements, which, although crucial to evaluating the CO_2 balance, are insufficient for testing the contribution of green infrastructures at a whole-city level. **To date, a methodology is lacking for estimating the net carbon fluxes of green infrastructures at a high resolution throughout the different parts of the city and holistically at the city level. This lacuna hinders the ability of policymakers to reduce overall urban carbon emissions because they lack spatial and temporal knowledge of the efficiency of green infrastructures in reducing the urban carbon balance.** Accordingly, we propose a framework that (a) leverages local measurements and calibrates high-spatial-resolution remote-sensing observation-based models initially used for agriculture, (b) develops a model to map the contribution of green infrastructures to the CO_2 flux balance of cities, both throughout the city and at the whole-city level, and (c) generate generic or normalized models that could be used on other cities. This model allows us to test the impact of various relevant parameters, such as climate, shade, topography, proximity to other CO_2 sources, vegetation and soil composition, and city-level management, on the CO_2 budget of the city and, thereby, deriving the relevant conclusions to guide sustainable urban planning. Due to the high heterogeneity of urban green infrastructures, which include diverse vegetation species, our approach is first to confront each vegetation type (grass, shrubs, and trees) separately and then merge the spatial and temporal contributions of these vegetation types into a single output layer, which accounts for the contribution of all the green infrastructures throughout the city to the total carbon budget of the city.

2. Framework design and methodology

2.1. Local field measurements and local models

Local CO_2 flux measurements are needed to calibrate the remote-sensing model to generate the CO_2 sequestration maps. The measurements should include GPP and respiration of three main vegetation groups: trees, shrubs, and grasses. Soil respiration is measured to account for all the direct CO_2 fluxes, as opposed to indirect CO_2 fluxes, e.g., due to maintenance. The measurement campaign should include measurements of Net Ecosystem Production, NEP (chamber measurements), air temperature, photosynthetically active radiation, and canopy-level hyperspectral measurements (Kira, Shaviv and Dubowski, 2019, 2021; Peng *et al.*, 2019; Chang *et al.*, 2020; Kira *et al.*, 2021).

We suggest using a flux chamber to measure the CO_2 concentration near the ground. A flux chamber can measure the CO_2 concentration of the soil and low vegetation (grass and short shrubs). The measured NEP during the day and the night are computed from the rate of CO_2 drawdown and buildup in the chamber, respectively. To calculate GPP as NEP-R_e, R_e needs to be measured at least once per hour by covering the chamber with a black cloth. Care should be taken to account for light inhibition of aboveground plant respiration (Yin *et al.*, 2020). At night, NEP equals R_e (GPP = 0).

To estimate the photosynthesis of higher plants (tall shrubs and trees), we may leverage SIF measurements to estimate plant gross photosynthesis (Han *et al.*, 2022). Using SIF to estimate photosynthesis is a new and innovative aspect of this study. PAR and SIF are the observations used to model GPP in the procedure described by Gu et al. and Han et al. (Gu *et al.*, 2019; Han *et al.*, 2022).

GPP can be described according to Monteith's model, namely, as the multiplication of absorbed PAR and light-use efficiency (LUE) (Monteith, 1972; Monteith and Moss, 1977) (defined as the ratio between carbon uptake and absorbed PAR). Miller et al. (2018) (Miller *et al.*, 2018) used the LUE model together with fine-resolution satellites (Worldview-2) to estimate the GPP of urban vegetation (Miller *et al.*, 2018). Still, LUE is governed by environmental conditions that impact plant status and must be measured in real-time. Therefore, instead of using LUE and absorbed PAR, we use a simpler model based on remote observations, which was suggested for the estimation of crop GPP (Peng and Gitelson, 2012): $GPP = f(canopy\,chlorophyll) \cdot incoming\,PAR$.

Reflectance observations by multispectral satellite sensors are common in agriculture monitoring; chlorophyll and nitrogen content (Clevers and Kooistra, 2012; Kira, Linker and Gitelson, 2015; Peng *et al.*, 2017), leaf area index (Delegido *et al.*, 2011; Nguy-Robertson *et al.*, 2014; Kira *et al.*, 2016, 2017), and plant health and yield (Sakamoto, Gitelson and Arkebauer, 2013; You *et al.*, 2017; Cai *et al.*, 2019) are only a few examples of how these observations are used in agriculture. Several studies have shown the ability of reflectance-based vegetation indices (VIs) to replace LUE and the fraction of absorbed PAR to predict GPP (Wu, Niu and Gao, 2010; Peng and Gitelson, 2012; Peng *et al.*, 2019). In the proposed framework, the *f(canopy chlorophyll)* is modeled as a function of reflectance based on the field measurements of GPP and later used with remote-sensing observations to estimate the GPP of all the green infrastructures in a city.

The ecosystem respiration—the second component needed to calculate NEP—can be estimated by using an exponential regression model (Lloyd and Taylor, 1994; Reichstein *et al.*, 2005):

$$R_e = r_b \cdot \exp\left(E_0 \cdot \left(\frac{1}{T_{ref} - T_0} - \frac{1}{T - T_0}\right)\right) \quad \text{Eq. 1}$$

where r_b (µmol·m^{-2}·s^{-1}) is the reference respiration at a specific reference temperature, T_{ref} (°C); T (°C) is the observed temperature (either in the air or soil); E_0 (°C) is the temperature sensitivity; and T_0 (°C) is a temperature parameter. To retrieve E_0 and r_b, we conduct a regression based on field observations and then use these variables with remotely sensed LST observations. This Arrhenius-type model has demonstrated a good ability to derive the soil respiration of deciduous and evergreen forests by using remotely sensed LST (Huang *et al.*, 2015); it is expected to show similarly adequate results in the proposed study, which addresses similar vegetation and soil types and is conducted under similar environmental conditions. Jägermeyr et al. (Jägermeyr *et al.*, 2014) developed a different regression model based on LST and the enhanced vegetation index (EVI). The EVI was included in this model to account for the impact of vegetation growth on autotrophic respiration and, as a result, on ecosystem respiration. Ge et al.(Ge *et al.*, 2018) modified this model by adding vegetation productivity and soil moisture. However, estimating respiration through remote-sensing observations remains challenging because we can mainly sense environmental parameters and not the soil CO_2 fluxes directly. Moreover, such a model will likely be limited to the specific site it was generated on(Zou *et al.*, 2022) rather than provide a generic solution.

To model GPP, local and remote reflectance observations, and PAR measurements should be used as inputs to a regression algorithm, e.g., artificial neural networks, support vector machines regression, and random forest, to find the optimal model(Miller *et al.*, 2018; Peng *et al.*, 2019). The respiration model can be either based on separate models, the Arrhenius-type model, which uses temperature as the main observable parameter and the least squares regression method to model the connection between temperature and respiration, or a statistical regression model (Jägermeyr *et al.*, 2014; Ge *et al.*, 2018), which uses temperature and other parameters (e.g., soil moisture, relative humidity, vegetation indices, etc.) to estimate respiration. Testing these two approaches allows us to determine whether a statistical model can yield better results than the semi-empirical one.

2.2. Remote observations

The challenge in remote sensing of urban environments is the high heterogeneity of land covers in small areas. To date, multispectral satellites can sense in spatial resolutions finer than 1 meter (e.g., WorldView). These satellites are game changers in the urban environment. This is greatly demonstrated in Figures 1 and 2. Figure 1 shows an image of the same urban area in the city of Modi'in, Israel. By reducing the spatial resolution from 0.5m to 5m and 10m, we lose important information regarding the land cover. This is crucial when approaching to survey urban vegetation using remote sensing. While the 0.5m demonstrates (Fig. 1a) a good fit to the high-resolution orthophoto (Fig. 1d), the 5m (Fig. 1b) and 10m (Fig. 1c) are not allowing us to separate the different land covers clearly.

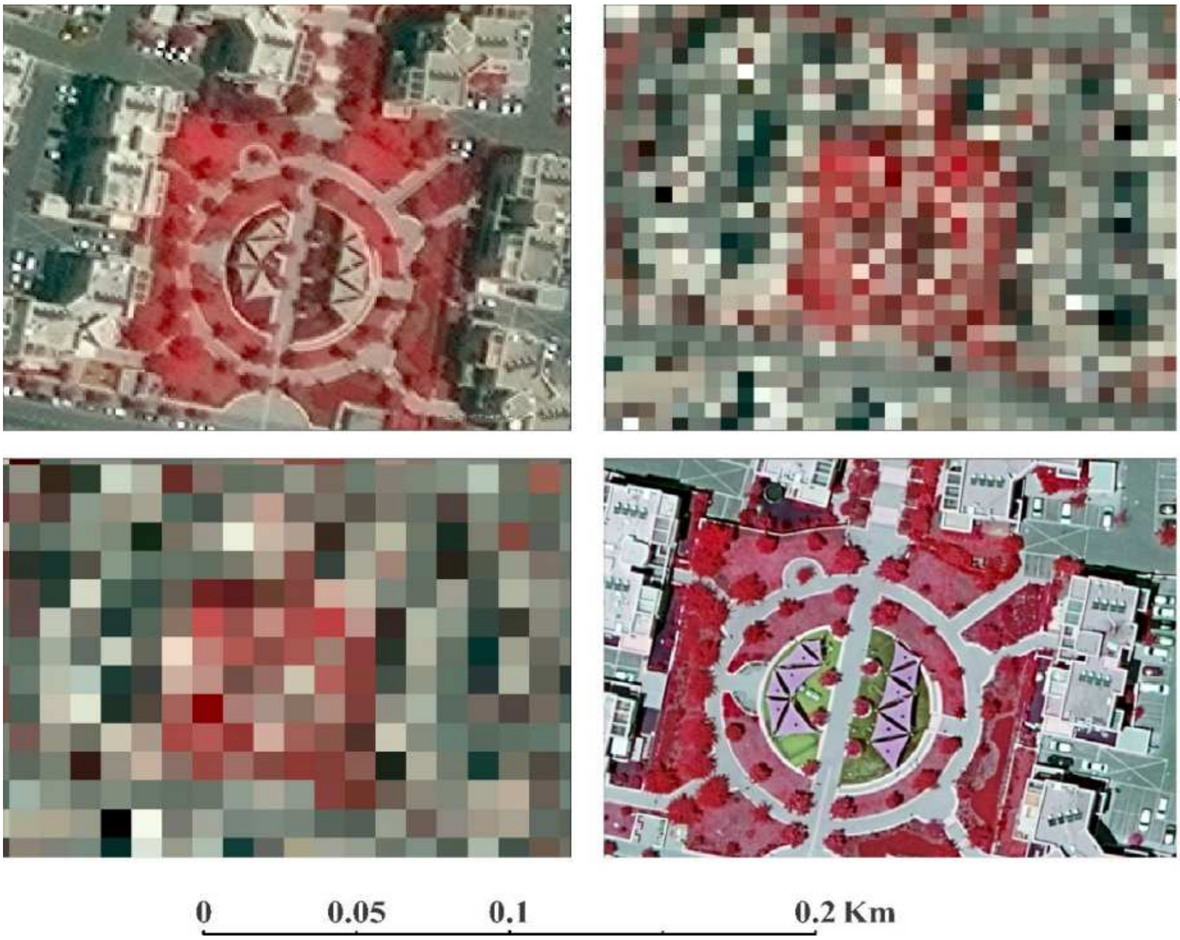

Figure 1: False color representation for WV-2 images with (A= 0.5m) resolution and resampled (B=5m, C= 10m), Orthophoto (D= 0.2m) for part of Modi'in city, Israel.

A similar pattern is seen in Figure 2. Figure 2 is a classified map of the Birds neighborhood of Modi'in. This map is a product of applying a support vector machine (SVM) algorithm on images with a spatial resolution of 0.5m (Fig 2a). It is clear that using a coarse observation (10m) causes a loss of information.

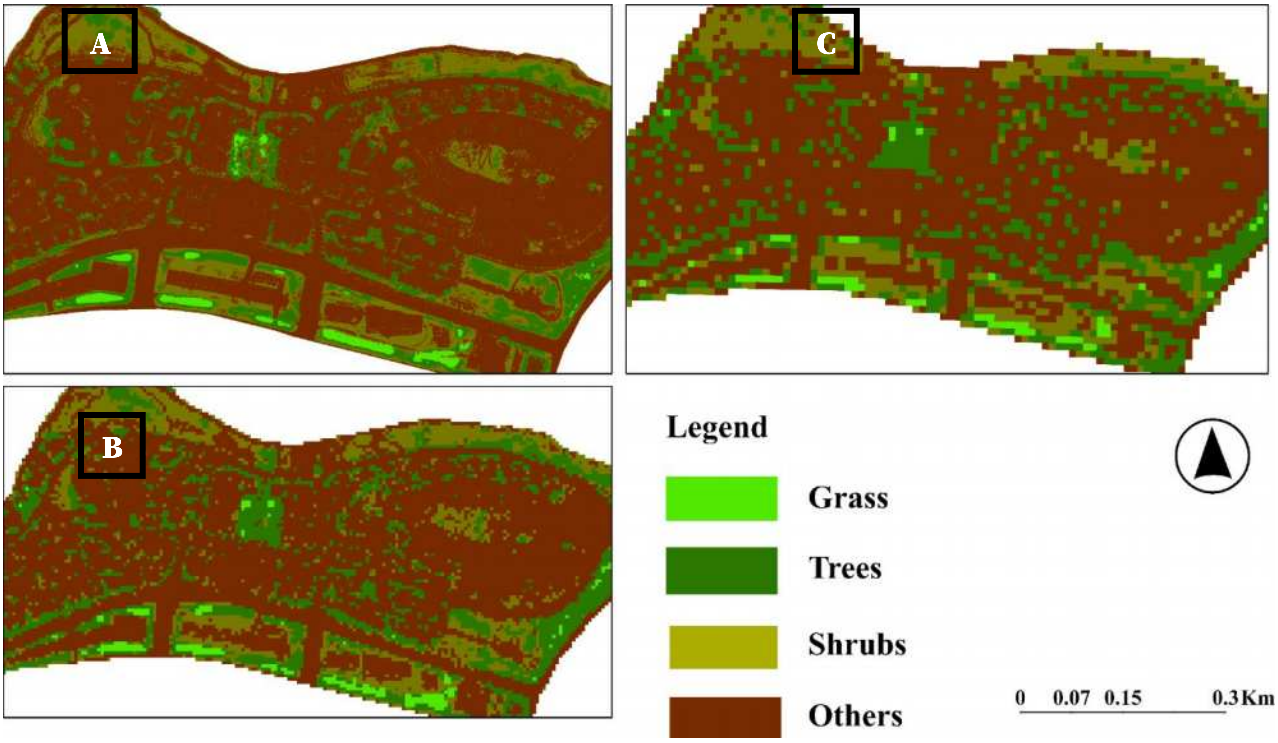

Figure 2: SVM-based classification for native (A=0.5m) and aggregated (B =5m, C= 10m) WV-2 image.

Another important issue that should be taken into consideration is the shade pattern. The diurnal shade pattern is essential to correctly estimate photosynthesis and respiration, which are directly and indirectly influenced by radiation and impact sequestration. Therefore, as city buildings cast shadows on their surroundings according to their relative position compared to the sun, and trees cast shadows usually on other vegetation (e.g., grass and shrubs), the diurnal shade pattern impacts carbon sequestration. Since vegetation's photosynthesis and respiration rates are lower in the shade, mapping the shaded areas during the day and correcting the GPP and R_e estimations are needed.

3. Preliminary results.

Local field measurements of vegetation GPP, done in May 2022, enable the generation of a high-resolution GPP map of Modi'in. The map was created using Worldview-2 observations at a spatial resolution of 0.5m. Figure 3. presents the GPP map. This map is relevant for a specific time window' as the local measurements were done only in May. To generate a yearly map, the local measurements used for it should be taken throughout the year.

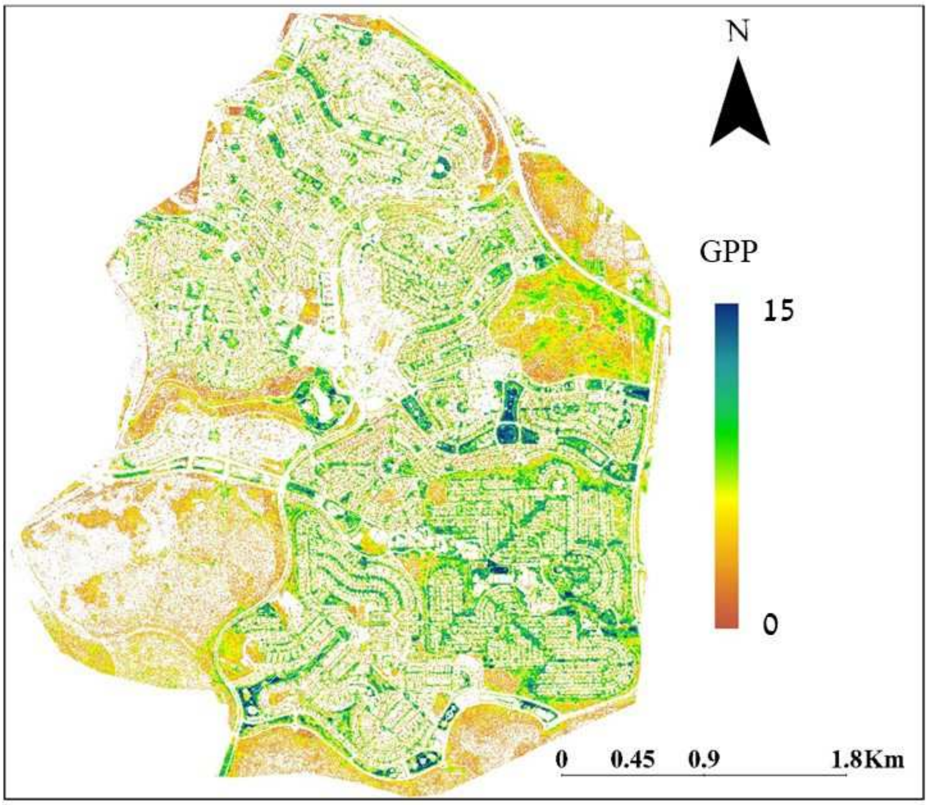

Figure 3: A GPP (µmol CO_2 m^{-2} s^{-1}) daily average map (0.5m resolution) of the vegetation in Modi'in.

4. Framework's significance and innovation.

The suggested framework is designed to quantify the city-wide carbon sequestration of green infrastructures by adapting models that were originally generated to monitor sequestration in agricultural and natural vegetation (Peng *et al.*, 2019). Significantly, the difference between agricultural/natural vegetation and urban vegetation is not merely technical; rather, land-cover heterogeneity is much greater in the urban environment. This greatly hinders our ability to use remote-sensing observations to quantify urban carbon sequestration with sufficiently high spatial and temporal resolution. Recent developments in satellite technology may solve this problem because satellites can provide a sufficiently high spatial and temporal resolution to enable direct observations and analyses without the need to unmix the pixels to isolate specific land covers—an otherwise painstaking task. The suggested framework takes advantage of these recent (and, potentially, upcoming) developments and combines remote sensing with local field measurements to gain accurate, much-needed information on the CO_2 balance of urban green infrastructures.

Developing a tool to help understand the contribution of green infrastructure to the carbon budget of the city is crucial for the future sustainable urban planning of low carbon-emitting cities and for reaching carbon neutrality. Additionally, a sufficiently high-resolution tool to measure and compare the CO_2 fluxes of different green urban areas—from private lawns to public parks and urban forests—will help improve designing principles for more sustainable cities with more carbon-efficient urban green infrastructures. Such a tool can also help to locate green areas with limited or even negative net carbon uptake and serve the green infrastructure management of the city.

Another potential outcome of elucidating how different environmental parameters (e.g., shade, precipitation, topography, etc.) affect the CO_2 sequestration potential of green infrastructures is that the gained insights could assist future studies on how the urban micro-climate impacts vegetation productivity. Specifically, by examining population-dense urban areas with tall buildings, the suggested framework may also demonstrate the impact of the future urban environment—which is expected to be denser and with higher buildings —on the carbon-sequestration function of green infrastructures, which will be highly valuable for decision-makers and city planners in developing the urban environment, and for urban ecologists in promoting their knowledge regarding urban vegetation.

5. Caveats

As with many other empirical methods, there are some limitations and concerns about uncertainties. One of the main limitations is the temporal coverage of the satellites. Most satellites pass once a day (at the most) over a specific location. This is a problem since carbon sequestration has a significant diurnal pattern. This problem is even greater considering the shade pattern of urban structures. There are several future satellite missions for geostationary multispectral satellites (which have a constant view). However, their resolution is not a good fit for urban monitoring. Using the current polar satellites (with up to a daily snapshot) is not ideal, but with the right local measurements, the suggested framework can still produce important information.

Another issue is generating a generic model fit for large areas. Based on the above suggestions, generic global models are impossible, considering the variations in climate conditions, vegetation types, soil types, and urban green management practices. However, in regions with similar vegetation and climate conditions, it should be feasible to reach a generic model.

The local measurements also have challenges that need to be addressed. The main challenge is to estimate the productivity of higher plants and trees. The SIF-based method still needs to undergo further validation. To do so, a flux chamber should be used. However, using flux chambers on trees is challenging and requires certain expertise.

6. Summary

The suggested framework is a step forward in monitoring urban green infrastructures and accounting for their carbon sequestration potential. Such a framework can significantly contribute to city planners' race for carbon-neutral cities. With technical development, methods like those suggested above will become more relevant. They will enable the scientific and civil communities to understand better the role of urban green infrastructures in the urban carbon balance.

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Potential of Natural Ventilation in Heritage Buildings: A Case Study at the 'Casa Fabiola' Museum in Seville, Spain

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Abstract: Historical heritage buildings often face challenges in maintaining suitable indoor environmental conditions, leading to high energy consumption. Insufficient control of the hygrothermal environment and indoor air quality can have adverse effects on both occupants and the valuable artworks housed within these significant structures. However, some heritage buildings also possess construction features that enable them to effectively withstand local climatic conditions.

This study focuses on the 'Casa Fabiola' Museum in Seville, which houses an art collection donated by Mariano Bellver. The main objective is to characterize the museum's hygrothermal comfort and explore the feasibility of implementing integrated passive measures to assess their impact on the indoor conditions. The study aims to reduce the ecological footprint of historical buildings while preserving their environmental legacy. It also seeks to quantify the energy consumption resulting from the implementation of stricter operational conditions.

Through energy simulations, this research aims to harmonize modern conservation efforts with the building's historical past, ensuring a sustainable and ecologically sensitive approach to the preservation of art and human habitability.

Keywords: Thermal conditions, risk assessment, preventive conservation, energy optimization, heritage buildings

1. Introduction

Historic buildings often show wide variation in indoor humidity levels and weather conditions that can be hazardous to cultural heritage materials. How much additional ventilation and thermal energy is required to ensure safe indoor conditions for cultural heritage when a historic building is exposed to extreme weather conditions or many visitors? What will happen to the hygrothermal behavior of Walls and ceilings if you change the use of a historic basement, for example? How do indoor air conditions and the envelope of buildings in temporary use react to different heating and ventilation strategies? These are some issues of the CLIMATE FOR CULTURE (*Climate for Culture*, 2014) project where it is shown that identifying the precise fluctuations of indoor humidity and humidity profiles in the building envelope is essential for an assessment of risks and noise damage, taking into account the complex hygrothermal interactions between indoor air, use, the furniture and the envelope of the building.

The hygrothermal behavior of components exposed to different climatic parameters is an important aspect of the overall performance of a building (Lucchi, 2016) (Sendra Salas and Navarro Casas, 1991) (*Climate for Culture*, 2014). One of the main innovations of this project is the use of simulation and modeling tools to predict the influence of changing outdoor climate on the microclimate in historic buildings up to 2100 and thus assess the damage of these future microclimates in art collections in various climatic zones. To do this, they use a tool that considers the main hygrothermal effects derived from the sources of humidity inside a room, the entry of moisture from the envelope by capillarity and diffusion, as well as the absorption of steam in response to outdoor climatic conditions. The result is nothing more than future energy demand and the measures needed to improve conditions.

Likewise, in the research of Jiménez Torrecillas et al (Jiménez Torrecillas *et al.*, 2007), it is ratified that lighting can damage or deteriorate the works due to a bad approach of it, so, in the spaces destined to the exhibition use, it is essential to control the factors that make up the interior atmosphere. Therefore, a system is used that adapts to the conditions of the building, without creating invasive spaces, taking into account the conservation of the exhibited goods, as well as the achievement of an appropriate level of comfort for the occupants (Jiménez Torrecillas *et al.*, 2007). This level of indoor comfort can sometimes be very complex to achieve in historic buildings due to the presence of decorated surfaces or high artistic and heritage values that do not allow any intervention on the technical elements (Boarin, 2016). However, Boarin (Boarin, 2016) is responsible for improving indoor air quality through ventilation, indoor air management, the use of low-emission materials and products and the possibility for occupants to control comfort conditions.

This last aspect is of great importance because the activity inside buildings generates microclimatic instability and indoor pollutants (Lucchi, 2016). Something that endangers the use of buildings considering the current COVID-19 crisis. Therefore, according to Manuel Duarte et al (Pinheiro and Luís, 2020), a critical exploratory evaluation is necessary, to allow measures that help reduce the transmission of this virus. Their measurements include: thermal sensors, new HVAC filters and new HVAC systems (Pinheiro and Luís, 2020) (with linear flow extractions and increased humidity control) with possible mixed modes. It also proposes contactless digital solutions and other IT solutions, such as new networks and communication systems that would not damage the building, one-way pedestrian paths and complementary wastewater monitoring and treatment measures (Pinheiro and Luís, 2020).

Therefore, it is necessary to carry out sustainable and cost-effective interventions by reducing energy and operating costs, improving building performance, without compromising human safety and comfort, aiming to ensure that cultural heritage is duly included in the response to the COVID-19 crisis (NOSTRA, 2020), as well as in long-term recovery plans (Next Generation EU) (NOSTRA, 2020).

It has been proven that the effects of thermohygrometric parameters generate mechanical, chemical and biological degradation in objects of historical value (Sahin *et al.*, 2017) since the relationship of humidity and the panels of these works change their properties, affecting their resistance, stability and permanence. It is shown that cyclical changes in humidity cause variations and generate harmful impacts on the panels, even causing an environment in favor of mold germination (Bülow, Colston and Watt, 2002).

In all these effects of the quality of the indoor environment, the fundamental role of building infiltrations comes into play. Hermeticity is the fundamental parameter that drives infiltration throughout the space as a result of air passing through cracks, leaks or other unintended openings in the building envelope (Sahin *et al.*, 2017) (Sherman and WR Chan, 2006). Therefore, it is essential to control the tightness in buildings that do not have HVAC systems, to control short fluctuations of T and HR, within the permitted limits (Sahin *et al.*, 2017) (Luciani *et al.*, 2013).

Chapter 21 of ASHRAE (ASHRAE, 2007) introduces control classes to assess the potential for mechanical, chemical, and biological degradation in library, museum, or art gallery collections. It verifies that the collections must be at the established points (T between 15 and 25 ºC, HR 50%), if the indoor climate meets the requirements indicated in any kind of control, the objects are assumed as preserved against major and minor risks of degradation.

This building is part of the historical buildings owned by the City Council of Seville

The City Council of Seville has a total of 85 heritage buildings, dating from the 13th to the 20th centuries, which are being included in a larger-scale project. From this initial sample, the most representative ones were statistically selected from generated subgroups. In this case, the study has focused on Casa Fabiola, the current museum that houses the Mariano Bellver Art Collection.

This project aims to characterize the environmental and energy conditions of a case study, the Casa Fabiola Museum, to study the conservation potential that some historical buildings represent compared to the construction of new buildings as a way to valorize historical buildings through the reduction of their ecological footprint. Envelope improvements are introduced to assess if there are significant changes in their hygrothermal conditions, as well as to evaluate the energy consumption associated with the incorporation of HVAC systems.

2. Case study: Casa Fabiola

La Casa Fabiola is a prominent historic building located in the neighborhood of San Bartolomé, in the district of Casco Antiguo in Seville, Andalusia, Spain. Built in the 15^{th} century, it exhibits a unique combination of architectural styles that reflect Gothic and Renaissance influences. The construction of Casa Fabiola has a total built area of 1,915 m^2, with over 1,600 m^2 being functional space. It is distributed across three floors and is characterized by prominent elements such as ceramic tiling, polychrome wooden coffered ceilings, decorative paintings, stuccos, and 18th-century hydraulic floors (*La Casa Fabiola y el Museo Bellver*, 2018) (IAPH, 2022).

On the ground floor, numerous offices are situated around the courtyard, while the first floor houses the most noble rooms, such as the former ballroom, which features large windows facing the street. The second floor accommodates additional multi-purpose rooms and offices.

Throughout the years, Casa Fabiola has undergone continuous renovations in the 16^{th}, 17^{th}, 18^{th}, and 20^{th} centuries. In 1970, a restoration was carried out to adapt the building into a House-Museum. The most recent intervention took place in 2019 due to its deficient state of conservation, with identified issues in the galleries and empty vaults on the ground floor, as well as damages to the ceramic coverings caused by human factors. The building also faced a wood-boring insect infestation that threatened the wooden carpentry. The museum reopened its doors in May 2023.

Casa Fabiola houses the 'Mariano Bellver Art Donation', a collection donated by art collector Mariano Bellver in 2007. The collection comprises 943 art pieces, including 364 paintings, 38 wooden sculptures, 19 marble sculptures, 156 ceramic and porcelain pieces, 87 goldsmithing pieces, and 105 furniture pieces. The collection notably features paintings from the 19th century and the first half of the 20th century, with a significant presence of Sevillian artists such as Esquivel, Barrón, Grosso, Villegas, Jiménez Aranda, García Ramos, Gonzalo Bilbao, Rico Cejudo, Cabral Bejarano, Sánchez Perrier, and García Rodríguez, among others (Ruesga, 2017)(Junta de Andalucía, 2020).

This work includes analyses of hygrothermal behavior and evaluations of HVAC systems to assess the results of the restoration carried out.

Figure 1. Central Courtyard. (Fernando Alda Photography).

Table 1. Collection of spatial and constructive characterization data of Casa Fabiola

CASA FABIOLA	
Assignment to the Department of the City Council/Assignment	Institute of Culture and Arts of Seville
Chronology	**XV-XIX**
Localization	**C/Fabiola 5**
Orientation Facade (N)	**45º**
Typology	**Residential**
BIC	**NO**
Degree of Protection	**B**
Historical Use	**Residential**
Current Use	**Cultural**
Specific use Actuality	**Exhibitions**
Morphological characteristics (number of plants/shape)	**Groud floor+2**
Height (m)	**13.45**
Volume (m^3)	**6002**
Constructed area (m^2)	**1915**
Facade area (m^2)	**246**
Constructive Characteristics	**Brick factory walls thickness of 65-90cm** Sloping roofs of wooden beams and covered by tiles

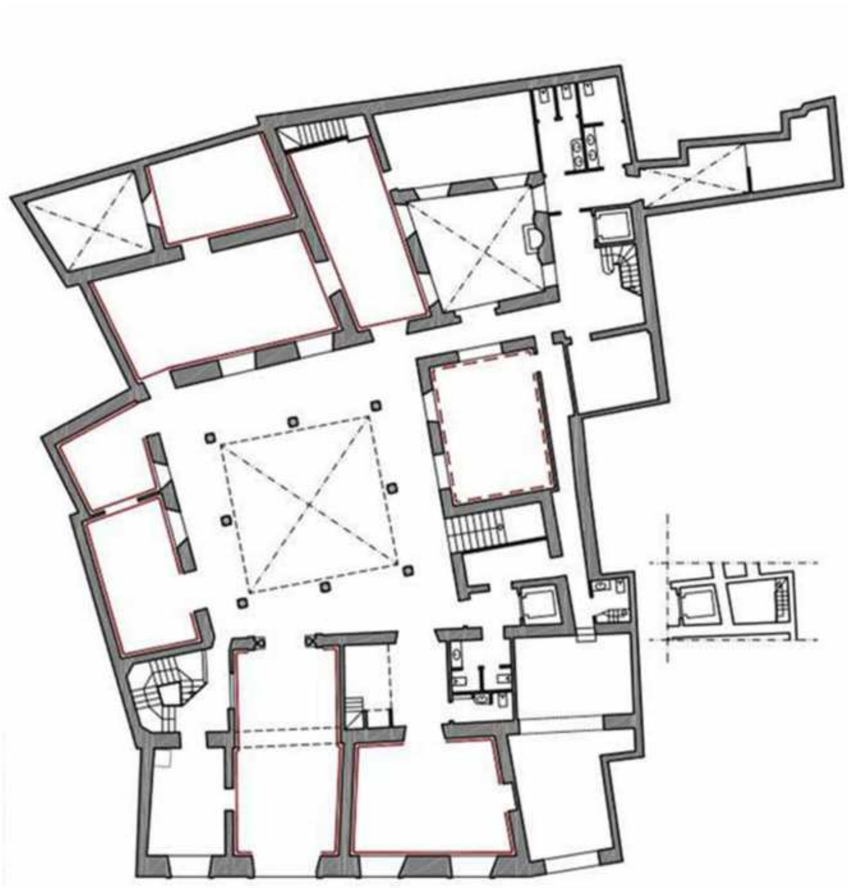


Figure 2. Type floor plan of Casa Fabiola

3. Methodology

When it comes to a museum located in a historic building, there are particular challenges in terms of conservation and environmental comfort. These buildings often have unique architectural features such as stone walls, high ceilings, old windows, and limited ventilation systems. These characteristics can create challenging environmental conditions, including temperature and humidity fluctuations, which can have a negative impact on artworks, especially paintings.

Adapting and aligning the public with the environmental comfort conditions involves educating visitors about the importance of maintaining a suitable environment for the preservation of artworks. It includes avoiding behaviors that can cause abrupt changes in temperature or humidity in the exhibition rooms.

Furthermore, it is essential to have an efficient environmental management system in the museum. This entails constant monitoring of environmental conditions such as temperature, humidity, and air quality to ensure they remain within optimal ranges for the preservation of artworks. Heating, ventilation, and air conditioning (HVAC) systems must be carefully designed and implemented to prevent extreme fluctuations and provide a stable and controlled environment.

The methodology followed includes the following phases:

- Characterization of environmental conditions
- Simulations of the model in free evolution before and after the intervention
- Inclusion of an HVAC system for studying its energy consumption.

3.1. Energy Modelling

Energy performance calculations were conducted using Design Builder software v 4.5.0.148, which is based on the EnergyPlusTM methodology developed by the United States Department of Energy and recognized by the International Energy Agency. A dynamic nodal calculus simulation of the building was performed to assess the energy demands for each housing unit. The models used in the study were calibrated and validated during the Efficacia project, which involved a monitoring campaign of energy consumption and inhabitants' behavior in control dwellings over an 18-month period (León A L et al. 2010).

Simulations were carried out for the original conditions and for each proposed intervention solution to determine the improvements in energy demand for the building retrofit. Each housing unit in the model was treated as a separate space to be climate controlled. The simulations followed the official protocol for conditions of use and operation in Spain for alternative energy simulation programs.

The hourly thermal evolution of the operative temperature was analyzed to identify peak temperature occurrences in different types of housing units. The analysis included typical days for each season. The thermal evolution of indoor and outdoor temperature was examined along with an adaptive comfort temperature band, which serves as a simplified approximation to thermal comfort, given its subjective and complex nature.
Typical climate for Seville is defined as a EPW file.

For the definition of the activity and typical schedule a standard profile for Libraries and Museums is selected.

3.1.1. Free running model

An analysis of the different parameters is carried out with the building in free running evolution, where the operation of the building in its current state can be observed.

The following parameters have been considered: relative humidity (%), indoor air temperature (ºC), radiation (ºC) and operating temperature of space (ºC).

3.1.2. Enhanced Free running model -Passive retrofit.

The study of incorporating improvements, both passive and mechanical, considering the current use of the building, is carried out.

Firstly, the incorporation of thermal insulation in the roof has been implemented, starting with solutions that would have a lesser impact on the historical image of the building, as well as its interior microclimate. This improvement has been analyzed during the free evolution of the building to compare it with the initial state and quantify the improvements in hygrothermal comfort through temperature ranges.

3.1.3. Mechanical environmental control model

A comprehensive HVAC system is incorporated to cope with the environmental control of the complex. The mechanical systems will adjust to ASHRAE and national standard to maintain indoor ambient inside visitors and workers comfort range, as well as the values set by ASHRAE for museums as previously described.

In a situation of not-strict-conservation needs, thus assuming the benefits from the inertia and the shelter capacity, indoor air temperatures could be set in an annual interval of 15 to 25 °C and air relative humidity around 50% +/-10%. The aim of such system is to avoid extreme conditions and to shave thermal peaks, assuring slow evolutions against fast changes.

However, this previous scenario presents difficulties in ensuring the comfort of poorly adapted visitors, as well as a conflict with occupational health and safety regulations. This situation draws the high energy intensity scenario considered for the assessment.

The set assume a typical compliance with HVAC figures with temperatures in ranges of 21 to 25 °C and relative humidity in ranges of 40-60%.

4. Results and Analysis

4.1. Passive control (free running scenario)

To analyze the results of the building in free running, it has been carried out, first, the study of the parameters applying the ASHRAE Standard 55 (ASHRAE, 2017) that aims to establish the acceptable thermal conditions for the occupants of the buildings, according to a set of factors associated with the interior environment (temperature, thermal radiation, humidity and air velocity), as well as the occupants themselves (activity level and clothing).

This adaptive approach assumes no mechanical control on the environment.

It defines two ranges of operating comfort temperatures for average monthly temperatures ranging from 10 to 33.5°C. For the first range, limit operating temperatures result from adding 3.5°C to comfort temperatures, assuming an acceptability percentage of 80% (proportion of people who would theoretically feel comfortable). For the second range, limit temperatures result from adding 2.5°C to comfort temperatures, resulting in a 90% acceptability percentage. This range is designed for situations where a stricter level of thermal comfort would be desirable.

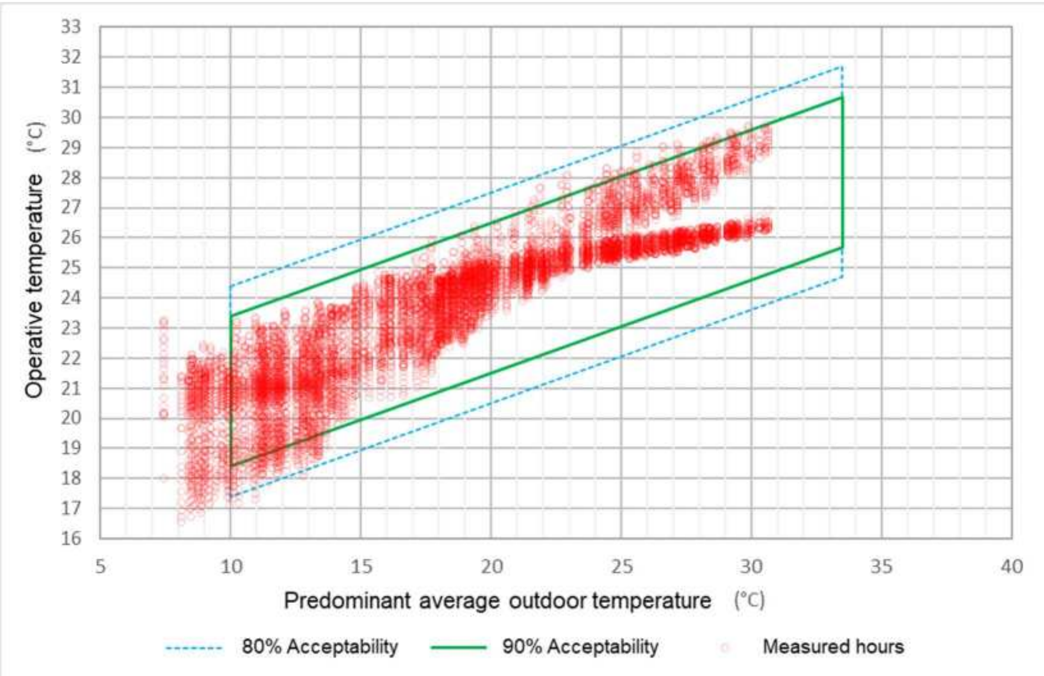


Figure 3. Adaptative Comfort Range

Table 3. Adaptative comfort results according to ASHRAE 55-207 standard

Invalid measured hours	**720 h**	
Valid measured hours	**8040 h**	
Total measured hours	**8760 h**	
Hours within 90% acceptability	**7763**	**96.55%**
Hours out of 90% acceptability	**277**	**3.45%**
Hours within 90% acceptability: HEAT	**63**	**0.78%**
Hours out of 90% acceptability: COLD	**214**	**2.66%**
Hours within 80% acceptability	**8032**	**99.90%**
Hours out of 80% acceptability	**8**	**0.10%**
Hours within 80% acceptability: HEAT	**0**	**0.00%**
Hours out of 80% acceptability: COLD	**8**	**0.10%**

The results obtained according to the criteria of ASHRAE Standard 55 are shown in Figure 3 and Table 3. Overall, favorable results were obtained regarding the passive operation of the building following the developed criteria. The building stays within the established ranges for most of the year, with only a few short periods outside of those ranges. Approximately 96.5% of the time, it falls within the "Hours within 90% acceptability" category.However, the ASHRAE 55 comfort criteria take into account very low and high temperature variations and ranges, and do not take into account relative humidity variations. If compared with the criteria followed in Chapter 21 of ASHRAE (ASHRAE, 2007), where control classes are introduced to assess the potential for degradation in museum collections, highly controlled operating temperatures and relative humidity are taken into account. The summary of these classes is shown in Table 4, which indicates that all objects should be stored at set points (T between 15-25 °C and HR50%) or at the annual historical average value when they are collections of interest. While the indoor climate is expected to differ by brief and seasonal fluctuations, if they do not exceed the values. If the indoor climate satisfies the requirements indicated in any kind of control, the objects can be assumed to be preserved against risks of degradation, otherwise damage could be observed.

Table 4. Summary of indoor climate conditions of ASHRAE Chapter 21 (ASHRAE, 2007)

Type	**Set-point or Annual average**	**Class of control**	**Short Fluctuations**	**Seasonal adjustments in system set point**
General Museums, Art Galleries, Libraries and Archives	**50% RH (or historic anual average for permanent collections) T set between 15 and 25 ºC**	**AA**	**± 5% RH, ± 2 K**	**RH no change; Up 5K, down 5K**
		A		
		A1	**± 5% RH, ± 2 K**	**Up 10% RH, down 10% RH, Up 5K, down 10K**
		A2	**± 10% RH, ± 2 K**	**No RH change, up 5k, down 10K**
		B	**± 10% RH, ± 5 K**	**Ip 10% RH, down 10% RH, Up 10K but not above 30ºC, down as low as necessary to maintain RH control**
		C	**Within 25-75% RH year-round**	
			T rarely over 30ºC, usually below 25ºC	
		D	**Realiably below 75% RH**	

On the other hand, about the health and thermal comfort of the users of the building, encompassing both the working staff of the museum and the visiting users of the same, the fact of reaching extreme temperatures both in hot periods and in the cold ones, it is not considered adequate. Well, temperatures are around 30ºC in summer periods, while in cold periods minimum temperatures of up to 16°C are reached inside. Following the RITE Technical Instruction (RITE, 2007), the interior conditions of space design should have operating temperatures in summer between 23-25°C, with relative humidity between 45-60%, and in winter temperatures between 21-23 °C, as well as humidity between 40-50%.

That is why it has been verified that despite the fact that ASHRAE 55 is more permissive in terms of adaptive comfort ranges, we find ourselves in an apparently favorable situation, based on the use of the building, which is an exhibition area and their corresponding offices, and following what is described in Chapter 21 of ASHRAE for museums as well as what is described in RITE for internal thermal conditions of workers, we would not speak of a favorable situation with regard to the functioning of the building in free evolution.

4.2. Results with improvement systems

Since we came across a building with great historical and patrimonial value, improvement systems were studied that did not imply the loss of identity of the building, nor alter its interior microclimate.

For this we consider appropriate the inclusion of a thermal insulation in the roof of the building, to control the environmental behavior and the higher temperature ranges that occur inside.

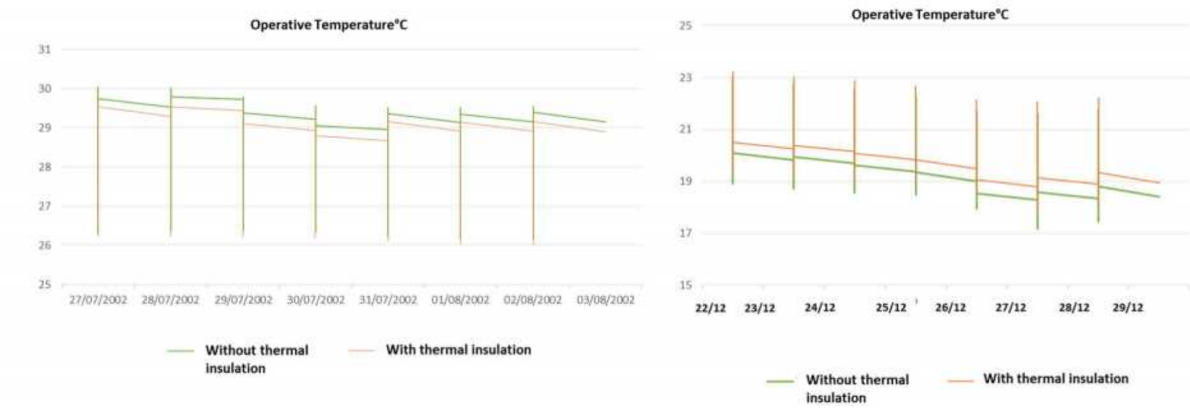
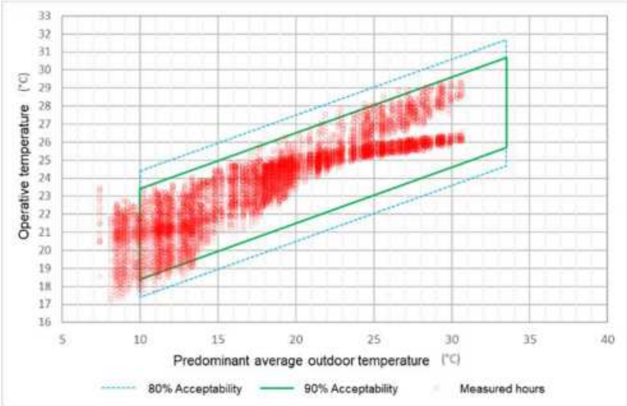


Figure 4. Comparison of temperature range in extreme weeks of summer (left) and winter (right)

In Figure 4, it can be seen how both in the extreme week of summer and in the extreme week of winter, the temperatures have improved in both cases.

More stable temperatures were obtained in winter, which above all do not become as cold as in the case of not having said insulation.



Invalid measured hours	720 h	
Valid measured hours	8040 h	
Total measured hours	8760 h	
Hours within 90% acceptability	7921	98.52%
Hours out of 90% acceptability	119	1.48%
Hours within 90% acceptability: HEAT	31	0.39%
Hours out of 90% acceptability: COLD	88	1.09%
Hours within 80% acceptability	8039	99.99%
Hours out of 80% acceptability	1	0.01%
Hours within 80% acceptability: HEAT	0	0.00%
Hours out of 80% acceptability: COLD	1	0.01%

Figure 5. Adaptative Comfort Range and Adaptative comfort results according to ASHRAE 55-207 standard with thermal insulation

That is why it is shown in Figure 5 and its adjacent table, how it has been possible to increase the number of hours that are within the range of 90% acceptability throughout the year, up to 98.52%, taking into account that this It would be for very demanding categories of spaces, and that could respond to museum spaces that store highly valuable collections, as is the case of Casa Fabiola. It was also connotative to reach 99.99% of hours that are within the range of 80% acceptability, leaving only 1 hour outside this range.

However, they continue to be temperatures that would not meet the most demanding ranges or that would not be the most suitable for exposure, especially the warmer period. Likewise, they would also be ranges that continue to be outside the effective conditions for the development of the work, as well as for the visit of the users. For this reason, the inclusion of an HVAC system was conducted, which would determine what the behavior of the building would be like, and if it could be adjusted to a more constant temperature and relative humidity throughout the year that would meet the requirements pursued.

For this, the incorporation of a VRF direct expansion system has been chosen to air-condition each of the floors of the building where the works are located. Likewise, to solve the ventilation and air treatment requirements, an independent ventilation system is incorporated, made up of an AHU that would be located on the roof of the building and that would oversee providing air at 22°C and 50% RH. An all-air system has been chosen since this would prevent the appearance of humidity, its refrigerant being a gas.

A HVAC system was included as mentioned in the methodology, and the results of the annual consumption for cooling, heating, lighting, and other appliances were obtained. In Figure 6, it can be observed that the annual consumption for cooling and heating to maintain the building at a standard and constant temperature is 58.98 MWh and 10.22 MWh, respectively, with the cooling consumption being 5 times higher than the heating consumption.

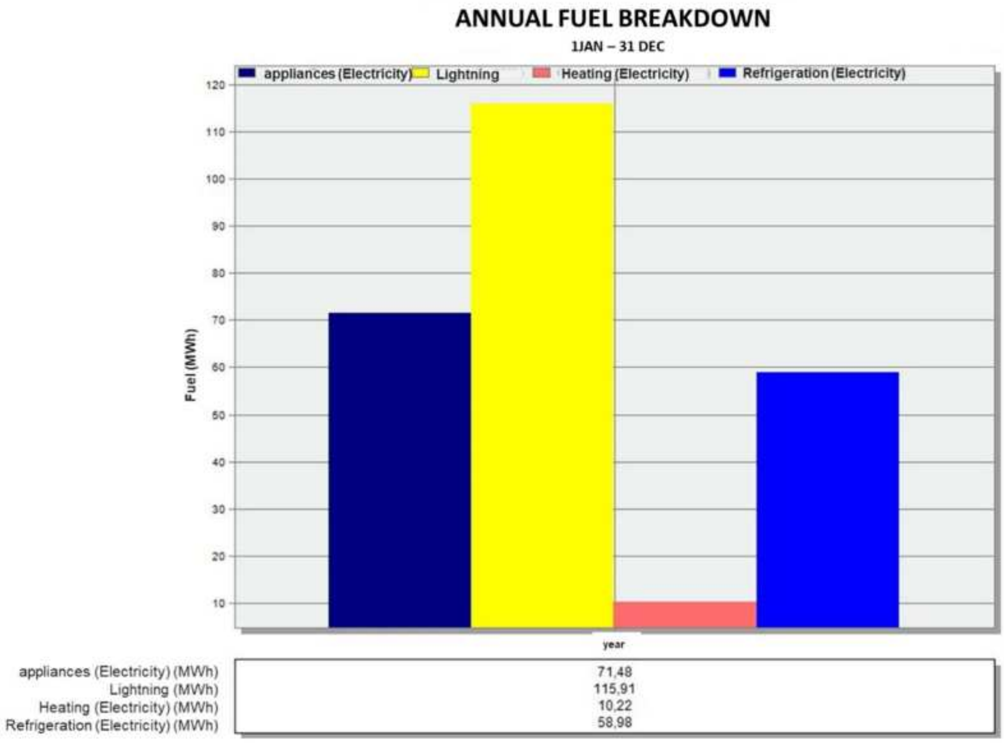


Figure 6. Annual Fuel Breakdown

5. Conclusions

This work is part of a comprehensive and in-depth study being conducted with all historical heritage buildings belonging to the Seville City Council. In this case, our focus has been on Casa Fabiola, the current museum housing the Mariano Bellver Art Collection.

The main objective was to identify the potential of this historical building for its use as a museum. Hence, it was necessary to determine if the building's hygrothermal behavior under natural conditions was sufficient for the preservation of the art collection and the comfort of its occupants. For this purpose, we considered both the parameters of ASHRAE Standard 55 and those indicated in Chapter 21 of ASHRAE and the RITE (Spanish HVAC regulation).

Under the building's current natural conditions, according to ASHRAE Standard 55 parameters, it would be on the optimum side in terms of adaptive comfort. However, certain temperatures reached during the hottest period are considered concerning, and according to ASHRAE Chapter 21, they could influence the degradation of the collection.

Additionally, these temperatures would not be considered comfortable for the building's users and visitors, following Spanish regulations that establish a fixed operating temperature range without considering adaptive comfort. The stability of the building could be explained by its high thermal mass in the building envelope, which acts as a buffer to outdoor temperatures.

Passive solutions, such as adding insulation to the roof, have been considered but have had little influence on improving the average temperature by less than 0.5°C in the building.

Another improvement measure studied was the incorporation of an HVAC system, which proved to be an optimal way to approach the most demanding operating temperature ranges. However, operating the system results in high energy consumption, so this measure may only be activated during extreme moments.

In conclusion, this study reveals the potential of Casa Fabiola as a museum, but it also highlights the need for careful consideration of its hygrothermal conditions and energy consumption to preserve the art collection and ensure the comfort of its occupants and visitors.

6. Acknowledgments

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Decision Support for the Design of a Building Form Coupling Daylight and Natural Ventilation Consideration in a Dense Urban Context

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Abstract: The urgency to address climate change, the energy crisis, CO_2 emissions reduction, and indoor air quality improvement has underscored the importance of daylight and natural ventilation for passive cooling in urban environments. This research project develops a comprehensive framework integrating passive strategies to optimize urban form and building performance in densely populated areas. The research identifies suitable approaches for incorporating daylighting and natural ventilation at two scales (building and urban), achieved by examining existing passive form-finding strategies and integrating relevant previous studies. Subsequently, a multi-step, multi-objective framework is created. The study assesses the implications of maximizing the floor area ratio on urban form and operational energy consumption through manual analyses and computer-based tools. The optimization and evaluation of urban and building forms are conducted using established rules of thumb and climate-based simulation metrics. The framework is then applied to a dense metropolitan area of Chicago, IL, US, to assess its validity and impact on operational carbon footprint. By adopting a holistic approach that considers multiple objectives and parameters, this study aims to guide designers in achieving optimal solutions for incorporating daylighting and passive cooling strategies during the initial design phases.

Keywords: Daylight, Natural ventilation, Building form, Urban configuration, Operational carbon

1. Introduction

The increased need to address climate change, energy efficiency, equity, and indoor air quality has highlighted the importance of incorporating daylight and natural ventilation for passive cooling in urban environments. Proper urban and building configurations are essential for utilizing resources effectively. Zoning regulations ensure access to daylight and fresh air in most urban areas. Historical examples and concepts such as solar zoning and the solar envelope have been explored to provide sunlight access without casting shadows on adjacent buildings. Wind energy and natural ventilation strategies, such as urban air corridors and building-scale ventilation techniques, have also gained attention. The literature review revealed a research gap regarding comprehensive examples integrating daylighting and natural ventilation strategies for shaping urban configurations and building geometries. Developing a workflow that considers both parameters simultaneously and includes the necessary metrics and targets is proposed to address this gap. The framework includes two scales with multiple objectives, using established rules of thumb, metrics, and computer tools for daylight and natural ventilation simulations. The framework is then tested in downtown Chicago, IL, US. Moreover, the study evaluates the impact of this building form on energy use and operational carbon at each step.

2. Literature review

The literature review is divided into three main topics. The first topic explores implementing these strategies at urban and building scales, aiming to identify effective integration methods and rules. The second topic concerns case studies showcasing successful daylight or natural ventilation applications. The focus is on uncovering best practices, including relevant rules and metrics, to maximize the benefits of these design elements. The third topic investigates case studies that examine the combined use of daylight and natural ventilation, which aims to identify research gaps.

2.1. Topic I: Passive design strategies for the application of daylight and natural ventilation

2.1.1. Daylight

The presence of daylight within a building is influenced by a multitude of factors: the urban context, building geometry, orientation, façade characteristics, size and location of openings, geometry, and interior space features such as colour, material, and glazing types. Achieving access to daylight requires careful consideration of these elements in the building design and site selection.

2.1.1.1. Daylight on an urban scale

A variety of daylight standards have evolved to guide the form-finding process. The notion of solar rights, initially established in 1916 for Manhattan buildings in New York City, imposes restrictions on building height and mass to guarantee access to daylight and air for the surrounding area (Boubekri, 2004). Subsequently, similar solar rights concepts have been developed in different regions. In 1978, Ralph Knowles introduced the solar envelope concept, which establishes volumetric limits to prevent the overshadowing of the surrounding environment (Knowles, 1981). However, this solar envelope concept has limitations in densely urban areas. Therefore, De Luca et al. (2021) devised the Reverse Solar

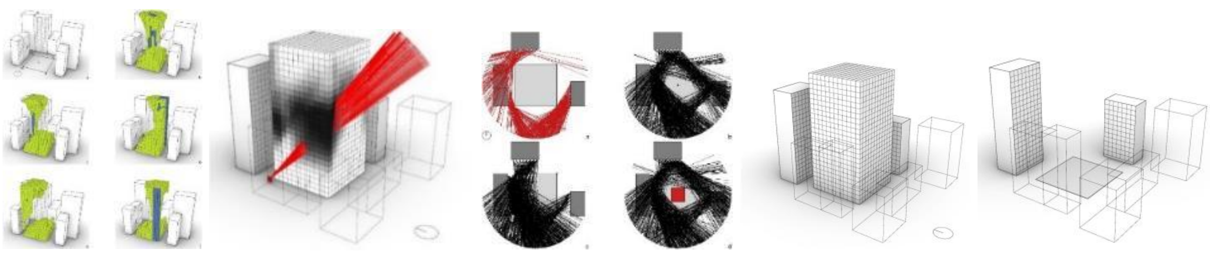


Figure 1: Reverse Solar Envelope (DeLuca et al., 2021).

Envelope (RSE) method to address these limitations, ensuring solar access to adjacent facades in dense urban areas (Figure 1). The implementation of the RSE method is facilitated by the software tools Rhino and Grasshopper, along with the plugin they developed called Solar Toolbox. The RSE process involves discretizing the building volume and facades, generating sunrays, conducting hit-or-miss analysis, and producing the reverse solar envelope.

2.1.1.2. Daylight on the building scale

Historical standards and regulations for daylight access in interior spaces only sometimes guarantee optimal daylighting due to dynamic characteristics and surrounding obstructions. (Boubekri, 2004; Reinhart et al., 2010).

This study considers several rules of thumb to guide the design process. At the building scale, the entry of sunlight depends on unobstructed openings such as windows and skylights. Shaded facades may experience reduced daylight penetration. The daylight penetration depth, which ensures sufficient light, is often determined as a multiple of the distance from the floor to window head height, ranging from 1.5 to 2.5 times. Additionally, indirect light reflected from surfaces can serve as a daylight source when direct sunlight is obstructed, provided it meets the feasibility factor calculation. The feasibility factor considers the window-to-wall ratio (WWR), glazing area visible transmittance (V_t), and obstruction from neighbouring buildings.

$$WWR > (0.88\ DF / V_t) * (90^{\circ} / \theta)$$

Reinhart (2013) refined the feasibility factor and introduced a rule of thumb called the Daylight Feasibility Test (θ * WWR > 2000), where θ represents the vertical sky angle between the building and the obstruction.

The atrium is another passive strategy to provide indirect daylight, with a rule of thumb suggesting a maximum height of fewer than 2.5 times its width. Rules of thumb do not consider the dynamics of daylight and can thus over- or underestimate illuminance on some specific days; in the early design stages, computer tools and increased computation power allows for more detailed assessment. Climate Studio, a Rhino-based platform, offers a user-friendly tool for simulating daylight availability (ClimateStudio.com, 2022) based on an annual assessment.

2.1.2. Natural ventilation for passive cooling

Optimizing natural ventilation and passive cooling strategies can also be approached at urban and building scales.

2.1.2.1. Natural Ventilation at an urban scale

On an urban scale, the spatial ratio of open spaces to built-up areas is crucial in determining wind patterns, velocity, and pressure (Passe et al., 2015). For instance, the ratio of building heights to the distance between buildings in a street canyon determines the access to natural ventilation.

2.1.2.2. Natural ventilation on a building scale

Incorporating natural ventilation at the building scale can be complex due to the influence of climate, urban configuration, orientation, and building shape on wind and airflow behaviour. Two primary strategies are commonly used: stack ventilation and cross ventilation. Stack ventilation relies on temperature differences to create a pressure difference for air movement, while cross ventilation utilizes pressure differences between inlets and outlets on opposite sides of the building based on laminar wind flow. Successful cross-ventilation requires a building form that maximizes exposure to prevailing winds and minimizes internal obstructions (Passe et al., 2015; Kwok et al., 2018). Computer software, such as Eddy 3d, a Rhino plugin, can assist in analysing wind performance through computational fluid dynamics simulations (Eddy3d.com, 2022).

2.2. Topic II: Studies that applied daylight and natural ventilation

The first study in this section is a rule-of-thumb-based design sequence for side-lit spaces focusing on diffuse daylight by Reinhart et al. (2010). The study proposes a four steps sequence to enable the designers to quickly predict the potential for daylighting in a building, considering its usage targets and any potential obstructions. The second study by Zhou et al. (2014) optimizes high-rise buildings for natural ventilation in Chongqing, China. Their optimal design procedure for natural ventilation consists of three stages: building orientation optimization at the community level, wind-path design at the floor plan, and fenestration design at the room level. The studies demonstrate the sequential approach for applying daylight and natural ventilation.

2.3. Topic III: Studies using Coupled Application of the Daylight and Natural Ventilation

The first study in this section, conducted by Loo et al. (2021), identified seven building configuration aspects that influence natural ventilation and daylighting by searching through research papers on Science Direct from 2010 to 2020. The second study by Liu et al. (2014) explores the combined application of natural ventilation and daylighting in form-finding in a specific region in China. This study uses a sequential approach, moving from macro to micro scale, to find the optimized form for the coupled application of daylight and natural ventilation. The third study, by Konis et al. (2016), develops a Passive Performance Optimization Framework that uses simulation-based parametric modeling to optimize building geometry, orientation, and fenestration configurations for improved daylighting, solar control, and natural ventilation. These studies emphasize the need for a comprehensive framework that considers all metrics and targets for the coupled application of natural ventilation and daylighting in building design.

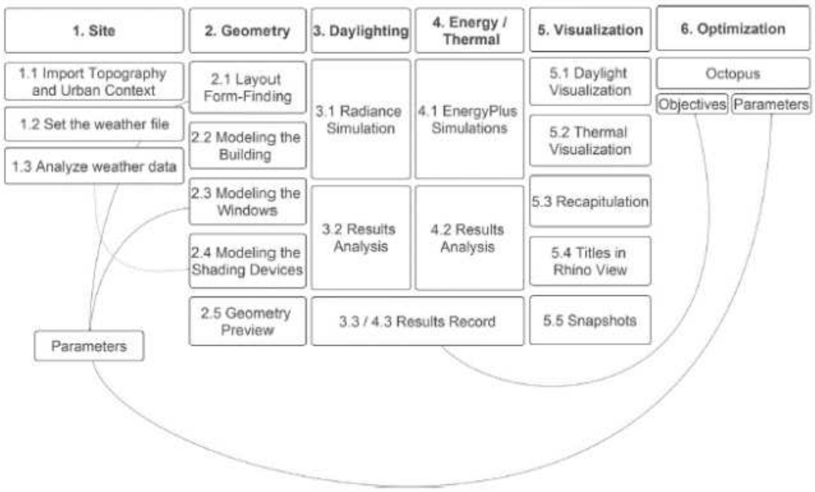


Figure1: Workflow diagram showing sequential steps to initialize passive performance optimization (Konis, et al., 2016)

3. Framework for the form-finding process of coupled application of daylight and natural ventilation for passive cooling

3.1. Summarizing daylight and natural ventilation strategies

Based on the literature review, access to daylight and natural ventilation in and around a building is influenced by several key factors. These factors can be divided into two categories:

3.1.1. Urban Context and Site:

- The proportion of open space: Unobstructed open space allows for adequate air circulation and prevents significant shadowing caused by nearby structures.
- Massing and Relation: The overall massing of the building and its relationship to surrounding structures play a crucial role. Optimized massing improves daylight and natural ventilation by considering solar exposure and wind direction.
- Building Orientation: Orienting the building to maximize exposure to diffused daylight based on the local climate conditions is important. Additionally, aligning the building with the prevailing wind direction allows for effective natural ventilation based on times of the year when cooling is desired.

3.1.2. Building Geometry, Floor Plan Layout, Fenestration, and Room Design:

- Building Floor Aspect Ratio: The floor plan of the building and its aspect ratio significantly affect the distribution of daylight and natural ventilation.
- Façade Characteristics: The arrangement of windows, shading devices, glazing types, opening area, and direction of operable window wing influences the amount and quality of daylight and airflow entering the interior spaces.
- Room Design Characteristics: Interior space arrangements, proportions, room dimensions, materiality, reflectivity of surfaces, glazing opening area, and relationships determine access to daylight and natural ventilation.

The literature review suggests that building and urban context features utilizing daylight and natural ventilation can be categorized into similar groups. Combining these features into a single step facilitates their analysis, making assessing their application easier to achieve a balanced approach.

3.2. Form-finding framework for the coupled application of daylight and natural ventilation

This paper focuses on optimizing the form-finding process for combined access to sunlight, daylight, and natural ventilation for passive cooling in both urban contexts and individual buildings and assesses the potential associated trade-offs. Due to the parameters involved in incorporating daylight and natural ventilation, a multi-phase framework with a multi-objective approach is deemed most suitable to optimize both goals. The form-finding process is conducted at the urban and building scale. Each scale consists of interconnected steps considering the building's overall shape and characteristics while comparing and evaluating optimized forms to determine the most appropriate design. The final steps aim to identify the most efficient form threshold that meets predefined performance goals for accessing sunlight, daylight, and natural ventilation within a dense urban environment (Figure 3). The framework is called CoDLNVO (Coupled Daylight Natural Ventilation Optimization) and will be described in the subsequent sections.

3.2.1. Urban scale

The first stage of the design process focuses on the urban scale and primarily involves spacing and orientation considerations. The goal is to determine the optimal orientation of the building towards the sun and prevailing wind conditions and spacing between buildings. This process begins by identifying the most suitable orientation for the sun throughout all seasons and for the prevailing wind during warm or hot seasons. ClimateStudio and Eddy3d simulation tools can assess daylight availability, wind flow direction, magnitude, velocity, and pressure. Since optimal solar and wind orientations may not always align, the aim is to find a building orientation that balances access to daylight and natural ventilation. Once the optimized orientation is determined, the next step involves justifying the spacing of the building within the context. A daylight feasibility study is conducted to assess which parts of the building may be shaded by adjacent obstructions and to identify areas that receive sufficient daylight. The key parameters for this feasibility study are the façade orientation and surrounding obstructions. The sky angle θ is manually calculated to assess the degree of obstruction, and the daylight feasibility formula is used to determine the degree and distance required to mitigate the obstruction. This information helps adjust the building's distance from its surroundings to ensure adequate daylight on desired surfaces and zones. Another aspect of this stage is to design a building form that does not block the daylight access of neighbouring buildings. Reverse Solar Envelope (RSE) can be employed to find an appropriate form, especially in dense urban areas. The Solar Toolbox includes components that generate alternative building forms based on the input data. The Grasshopper component, called RSE generator, eliminates 3D building blocks to create options for building form. For example, varying daylight access hours can significantly impact cell elimination numbers in a building.

In the urban stage's final step (1.2.3.), the distance between the building and its neighbouring structures is calculated to ensure access to natural ventilation. The Urban Aspect Ratio (UAR), a metric used to assess the potential for natural ventilation in an urban environment used for regular layouts of Central Business Districts, can be utilized in this assessment. The UAR represents the ratio of a building's height to width, providing insights

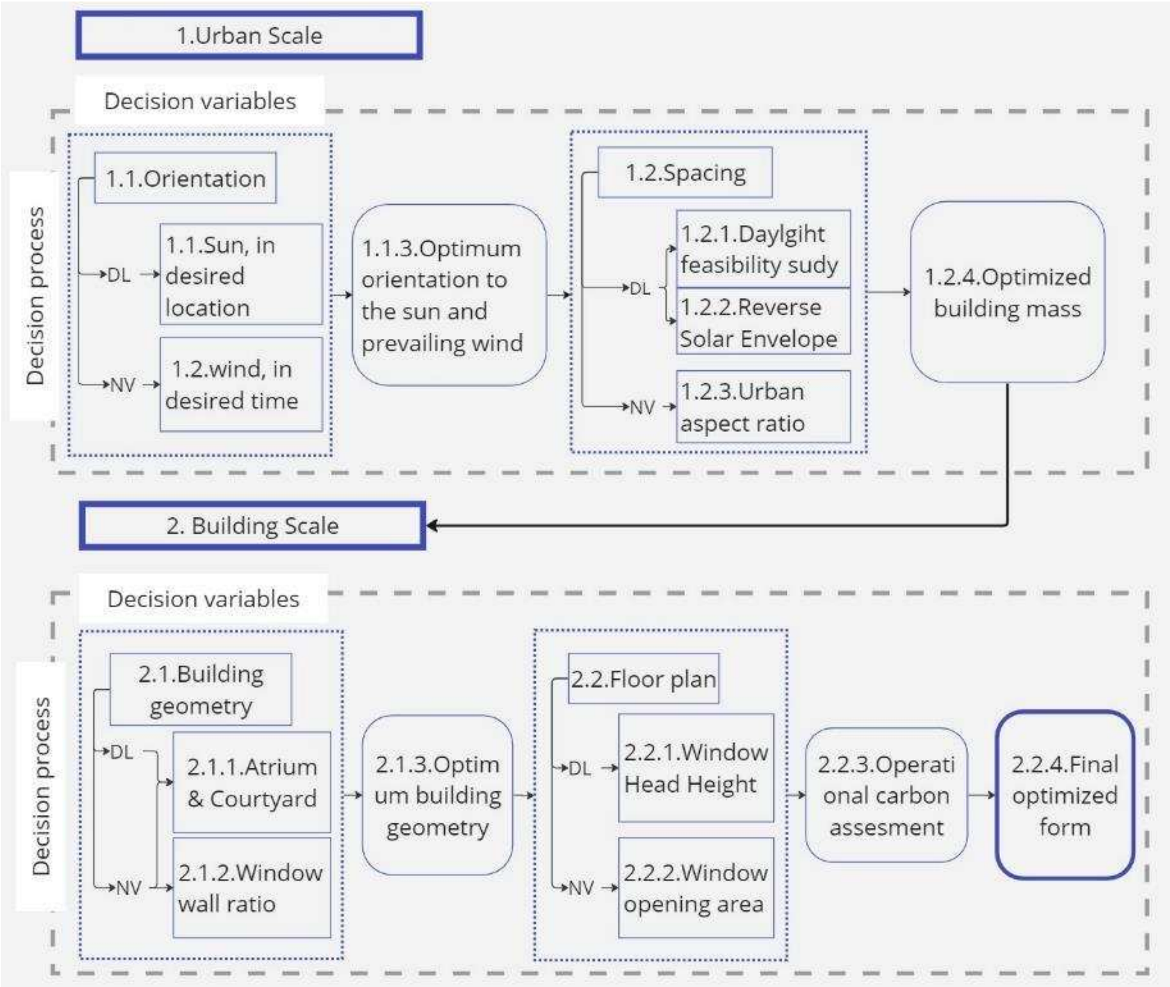


Figure 3: Workflow of design process framework (CoDLNVO).

into its verticality or compactness within the urban context. A high UAR suggests a tall and narrow building, while a low UAR indicates a broader and shorter structure. By considering the UAR in the calculation of distances between buildings, the goal is to assess the appropriate spacing between the building and its surrounding structures, considering the potential for natural ventilation (Costanzo, 2017). The outcome of step 1.2.4 determines the optimal massing for the building, which will be further studied in the subsequent building-level stage.

3.2.2. Building scale

This stage encompasses two primary objectives: building geometry (2.1) and floor plan (2.2). Building upon the preliminary mass study from the urban scale (1.2.4), the aim is to determine the optimal geometry for the building. The daylighting and natural ventilation strategies can be approached from two perspectives: perimeter strategies, which focus on side-lit windows, cross ventilation, and single-sided ventilation, or central strategies involving features such as atriums and courtyards. This leads to including a central void, such as an atrium or courtyard, or limiting access to daylight and natural ventilation through the external shell. Alternatively, a combination of these two scenarios may be chosen. The Floor Area Ratio (FAR) is a reliable decision criterion in dense urban areas. Therefore, the optimized geometry should allow access to daylight and natural ventilation while maximizing the floor area ratio compared to other alternatives. Energy use and operative carbon emission levels are other criteria to find the most appropriate solutions. The ultimate objective is to determine the floor plan's dimensions and the proportions of the rooms.

The rule of thumb recommendation of five times the floor height for cross ventilation can be utilized to determine the appropriate depth of the floor plan for effective natural ventilation (Kwok et al., 2018). The building depth can also be balanced by considering the rule of thumb suggestion for daylight penetration, which is 1.5 to 2.5 times the window head height. The final step of CoDLNVO involves calculating the window opening area (WOA) required to meet the natural ventilation requirements of each room. The WOA determines the available area for fresh air to enter and circulate indoors (Costanzo,2017).

4. Application of the developed framework to a real site

4.1. Site

This section applies the workflow to a real site. The site is in the Chicago Loop (Lat. 41,881832, Long. -87.623177), IL, USA. It is a vacant rectangular lot with a width of 97 ft. and a length of 296 ft., surrounded by mid-rise and high-rise, primarily office buildings with an average height of 100 ft. above grade (Figure 4). This site is selected because of its location in a very dense urban context. A building bulk with a height of 250 ft and a 97 by 296 ft footprint is used to start the form-finding process (Figure 5).

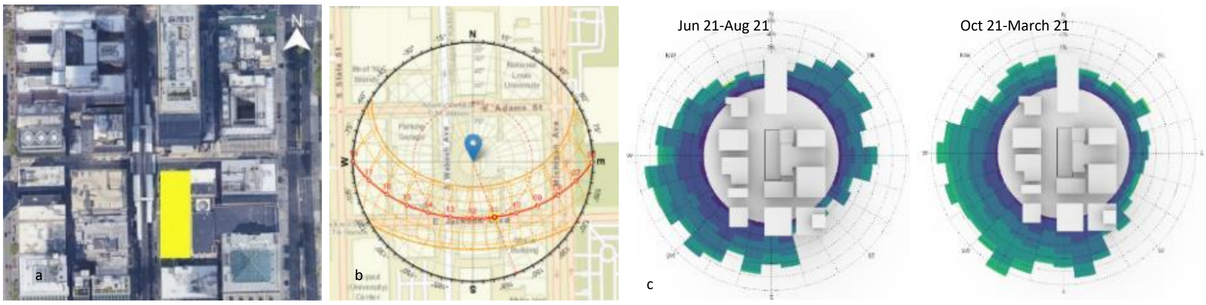


Figure 4: (a) Site, (b) Sun path diagram from drajmarsh (c) Wind rose diagrams for summer and winter months.

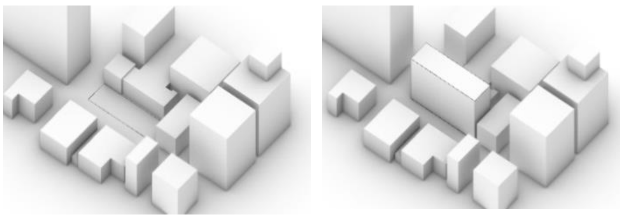


Figure 5: Plot and building mass.

5. Results of the validation experiment

5.1. Urban scale

The urban scale includes two main steps: 1.1 orientation and 1.2. spacing.

5.1.1. Orientation

5.1.1.1. Solar Orientation

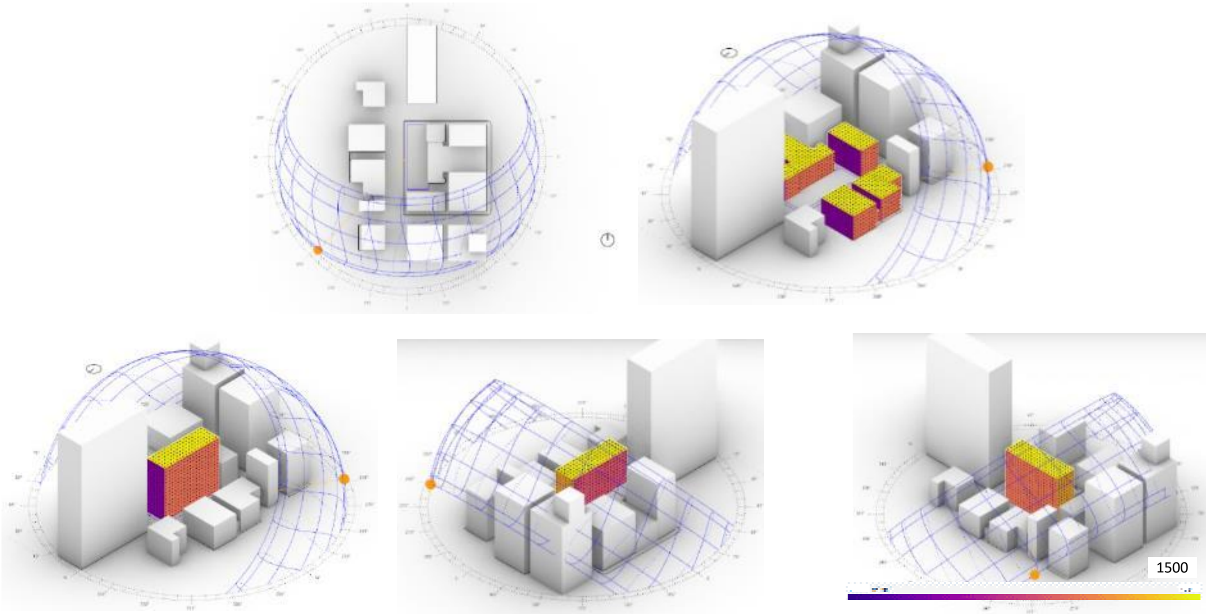


Figure 6: Radiation map of the context and building surfaces in four directions simulated by Climate Studio

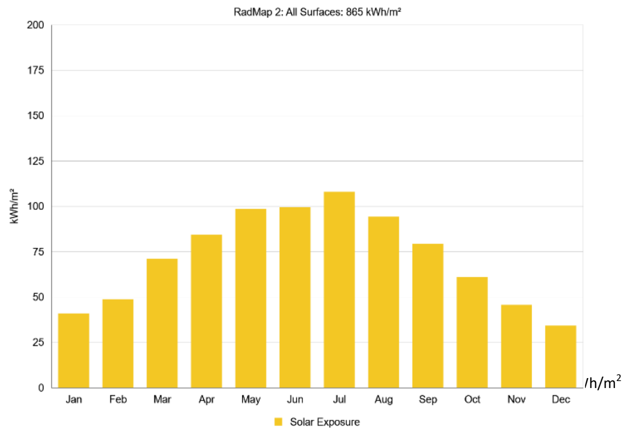


Figure 7: Diagram of monthly radiation amount on all surfaces

The initial step in building design involves determining the optimal solar orientation. Ideally, the most favourable orientation for a building is achieved by aligning its longest side towards the south, with a slight deviation of up to 15 degrees. This orientation maximizes sun access to the building in winter when the sun angle is low, while the exposure can be controlled by building features like sunshades in summer when the sun is high in the sky (Fathy, 1986). However, in cases where the site extends from north to south, such as with the current site, aligning the long side of the building with the south direction can pose challenges. In such situations, the east and west sides, the longest sides, receive more sunlight during the morning and afternoon, which is not ideal for daylight access, but it can be viable through thoughtful design features such as sunshades and blinds. The solar radiation map visualization shows the sun's intensity on the sides of the building bulk driven by the latitude of the site and the distance of buildings to each other (Figures 6 and 7).

5.1.1.2. Orientation toward the prevailing wind

To apply natural ventilation, aligning the shortest side of the building mass with the prevailing wind direction is recommended. Using a wind rose determines the location of the building mass with different wind directions. In this case, the plot's condition is perpendicular to the prevailing westerly to easterly wind direction. This alignment ensures no further changes are

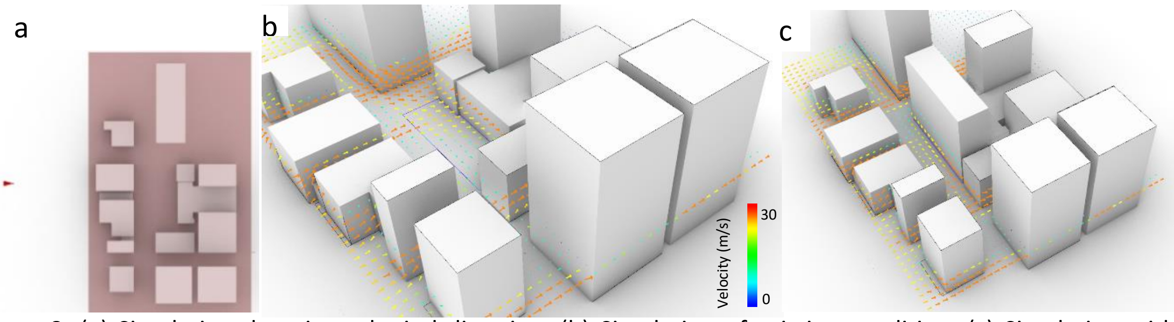


Figure 8: (a) Simulation domain and wind direction, (b) Simulation of existing condition, (c) Simulation with building mass in Eddy3D.

necessary for proper building orientation to utilize natural ventilation. To evaluate the existing conditions, a simulation was conducted using Eddy3d for an empty plot and surrounding buildings, with 100 iterations using the Chicago Energy Plus Weather file in the wind analysis template of Eddy3d, setting the wind direction to flow from the west. The simulation domain's height was twice that of the tallest building on the site. Subsequently, a simulation was performed with the basic building mass. The simulation results illustrate how the building mass impeded the wind flow, with some airflow through open spaces in the urban fabric (Figure 8). These findings provide insights into the impact of the building mass on wind flow and can inform further design considerations for optimizing natural ventilation.

5.1.1.3. Step 1.1.3. Balancing optimum orientation for daylighting and natural ventilation

The optimal orientation of a building achieves a harmonious balance between facing the sun and aligning with the prevailing wind. In this scenario, where the building mass is already oriented towards the prevailing wind, we can skip the optimization process and proceed by leveraging the results obtained from the previous steps.

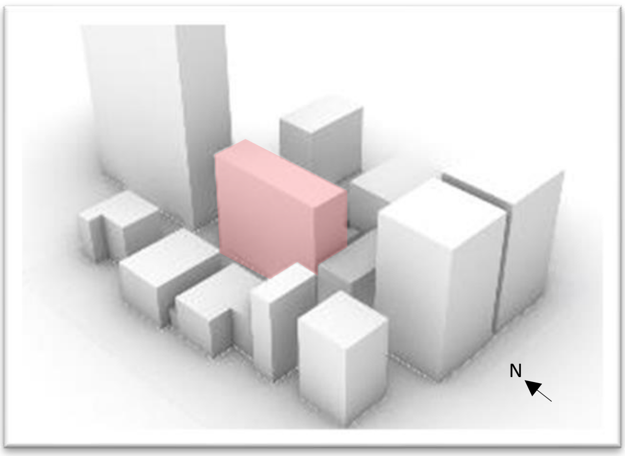


Figure 9: Optimum building orientation for daylight and natural ventilation

To prove the effectiveness of the process, this study also investigated the impact of forms at the end of each step on operational carbon emissions and energy usage. A two-zone model, consisting of offices on the west and east sides with a corridor in between, is exported from Rhino to Climate Studio (Figure 10). The width of the module is set to 97 ft and a depth of 10 ft, and windows are sized at six-by-six ft. Using the Climate Studio Office template with scheduled HVAC and natural ventilation turned off, a simulation shows 210 kWh/m^2 energy use, and the operational carbon is 80 kgCO_2/m^2.

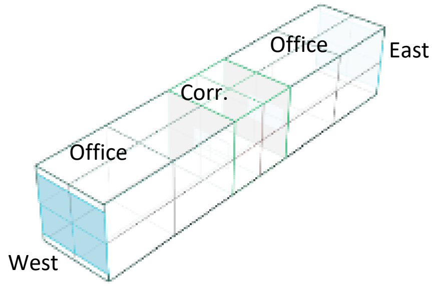


Figure 10: The module for Climate Studio simulation

5.1.2. Step 1.2. Spacing of building mass in an urban context to access daylight and natural ventilation

5.1.2.1. Spacing for daylight access

5.1.2.1.1. Step 1.2.1. Daylight feasibility study

In this step, the initial focus is placed on assessing the feasibility of daylighting. The building is in a densely urbanized area surrounded by neighbouring buildings that cast shadows and limit direct access to sunlight. Therefore, the feasibility analysis helps determine the distance between the building mass and the surrounding obstacles to ensure sufficient daylight can enter through side openings. The daylight feasibility test reveals that the building mass is obstructed on all sides, with a sky view angle of approximately ten degrees or less, except for the west side (Figure 11). Per the equation proposed by Reinhart (2013), which outlines massing studies, a minimum sky view angle of 25 degrees is required for effective daylighting. Considering that the building has its longest façade on the east and west sides, the spacing between the building and its surroundings will allow for greater sunlight penetration on these sides compared to the south and north facades. Since the west side has ample space towards the neighbouring buildings, the daylight feasibility analysis will be applied to the east side to meet the minimum requirement of a 25-degree sky view angle. Consequently, the building mass will have a reduced width to accommodate the required 25-degree sky view angle (Figure 12).

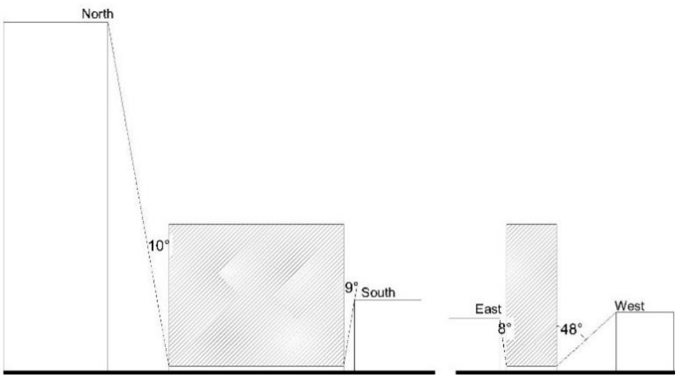


Figure 11: Sky view angle in four sides of building.

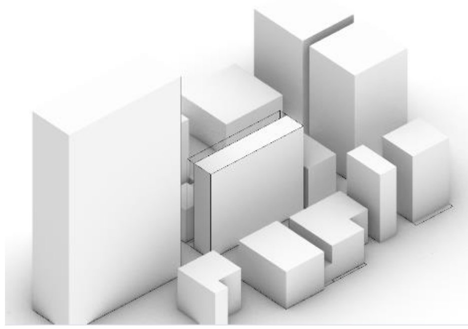


Figure 12: Building bulk to provide daylight access in the east side.

5.1.2.1.2. Step 1.2.2.: Applying Reverse Solar Envelope (RSE) concept to building mass

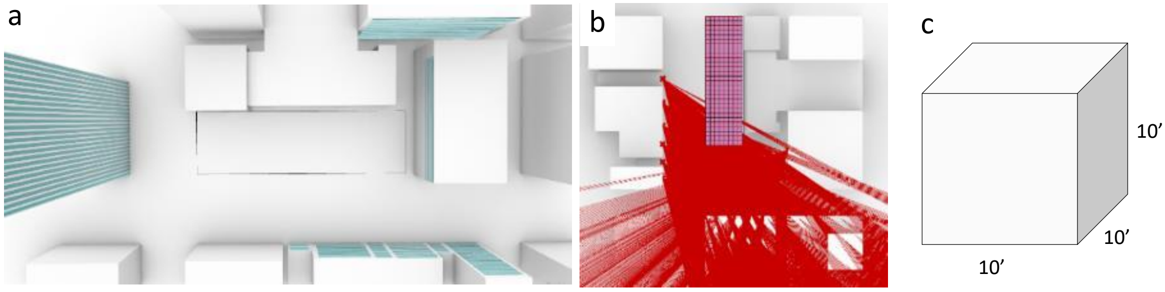


Figure 13: (a) Windows of surrounding buildings, (b) Sunrays reaching surrounding buildings windows in winter. (c) Building cell size for RSE analysis.

Step 1.2.2 utilizes the RSE concept to determine a building form allowing uninterrupted sun access to urban neighbours during a specific time frame. The RSE approach identifies the portions of the building mass that need to be eliminated to ensure sunlight reaches the windows of surrounding buildings (Figure 13, a). A script developed using the Solar Toolbox plugin within the Grasshopper environment facilitates this analysis. The geometries of surrounding building volumes, their windows, and the building plot curve are exported from Rhino to Grasshopper interface. The surrounding buildings are represented as poly surfaces, while their windows are defined as surfaces. The site is defined by a rectangular curve, with varying distances from the surrounding buildings (~12 ft. in the south, ~100 ft. in the west, and ~95 ft. in the north). The height of the building mass is set to 250 ft., and the cubic cell size to ten ft, a standard floor height and an efficient dimension for interior space divisions. The time step is set to two (representing one sun position per half an hour). The input for the vector-sum parameter is a minimum solar access of 2 hours during the summer (June to 21 September), spring (21 March to May), and winter (January to 21 March) seasons. Subsequently, the RSE component generates an optimized building volume shape allowing sun access to the surrounding buildings. During the analysis, the cells on the south side are primarily affected since the building is closer to the existing windows of neighbouring buildings that require sun access (Figure 13, a, b). The analysis considers three seasons: summer, winter, and fall/spring. Specifically, the winter analysis period spans from January to March 21. During the winter season, the angle of the sun is lower in the sky compared to other seasons. Thus, there is a minimized removal of cells to access sunlight. The oblique angle of the sun during this time leads to sunlight penetrating windows and openings at lower angles, resulting in reduced heat gain from the sun compared to other times of the year. The analysis conducted for the warmer periods (summer and spring) requires more cell subtraction (Figure 14 b, c). Winter is when access to sunlight and daylight is most favourable, and cell removal is minimal. Consequently, the massing configuration selected for further evaluation in subsequent steps is based on the winter season.

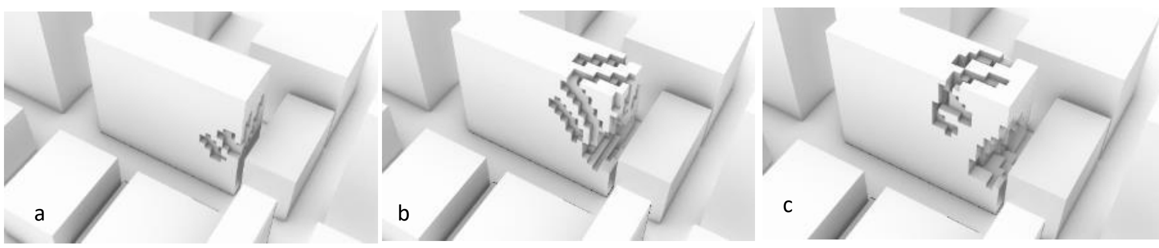


Figure 14: (a) Optimized building geometry for winter, (b) spring, and (c) summer shows the location and volume of cells that is removed to provide sunrays access to surrounding buildings.

5.1.2.2. Step 1.2.3. Establishing optimal spacing for natural ventilation

Once the appropriate spacing for sun penetration has been determined for the surrounding buildings and the building mass itself, the next crucial step is to evaluate the availability of sufficient airflow within the urban context and the building mass. An important factor in this assessment is the urban aspect ratio (UAR), which compares the average building height to the most common street width between buildings. When the UAR is close to equal, wind can flow smoothly through the urban fabric. For the selected site, the UAR values are calculated based on the definition above: in the north, the ratio is 6:2; on the west, it is 7:2; on the south, it is 123:4. Although these ratios may not provide completely unobstructed airflow, they are acceptable for the west and north sides. However, the south side presents a narrow, canyon-like condition, potentially hindering airflow. Nonetheless, due to the building's narrow southern edge and its partial exposure to the canyon-like condition, compensatory measures can be implemented through design strategies. For instance, floor layouts that promote natural ventilation, particularly through cross ventilation on the west and east sides, can help overcome this challenge. Consequently, there is no need to reduce the building mass at this stage.

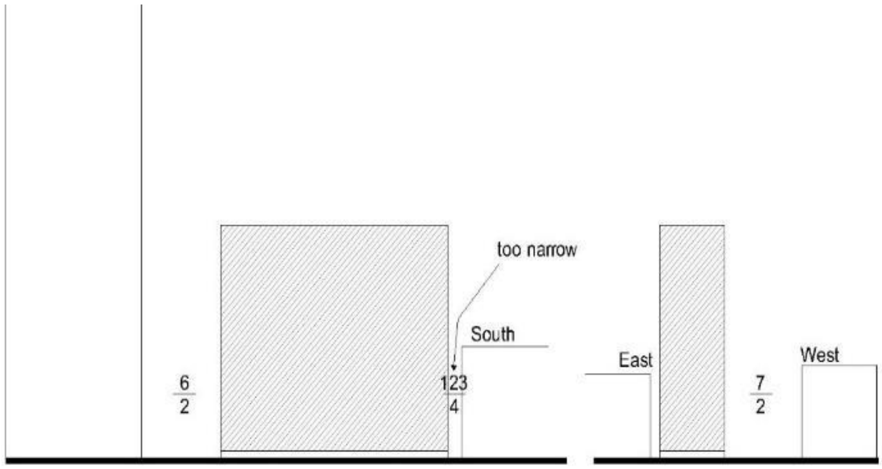


Figure 15: UAR around the building

5.1.2.3. Step 1.2.4. Developing optimum building mass on an urban scale

The results for orientation and spacing can be compared to determine the optimal building mass at the urban level, with the floor area ratio serving as the criteria for making the final decision (Figure 16).

Figure 16: The result at urban scale

Using the same setup as in step 1.1.3, except reducing the width to 63 ft., shows that the energy use of the modified module is 172 kWh/m^2, with operational carbon of 71 kgCO_2/m^2. The comparison of the energy and carbon assessment of this step with the result of step 1.1.3. shows a considerable reduction of 46% and 42%, respectively.

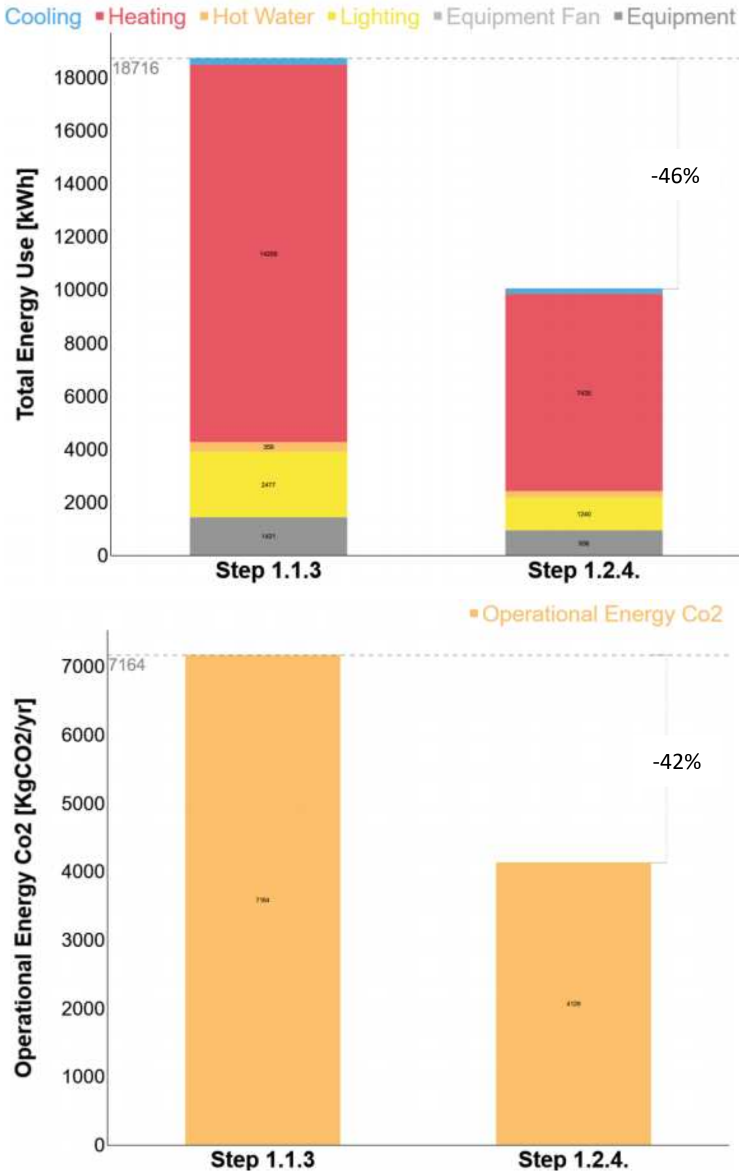


Figure 17: The comparison of energy use and operational carbon of steps 1.1.3 and 1.2.4.

5.2. Building scale

5.2.1. Step 2.1. Building geometry

This step determines the optimal geometry for maximizing daylight access and natural ventilation. Options are tested, including incorporating an atrium, courtyard, peripheral openings, or a combination. However, due to the narrow width of the mass compared to its height (250ft), including an atrium that, according to the rule of thumb, requires a maximum height of fewer than 2.5 times its width is not a suitable choice (Figure 18). Therefore, the width-to-depth ratio of the building is established to determine the final mass. In addition, WWR will be kept at 80 percent, used to calculate daylight feasibility in step 1.2.1. If needed, this ratio can be further refined in subsequent steps to finalize the floor plan layout. With 80 % WWR, two options for the window can be achieved: option A and option B (Figure 19).

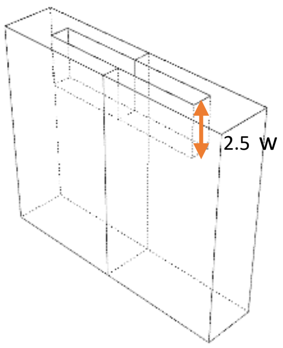


Figure 18: Atrium proportion in the building mass according to atrium rule of thumb

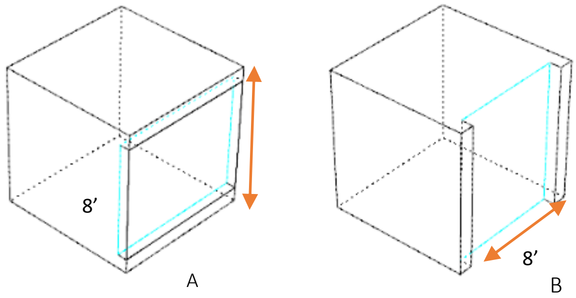


Figure 19: Two options for WWR 80%

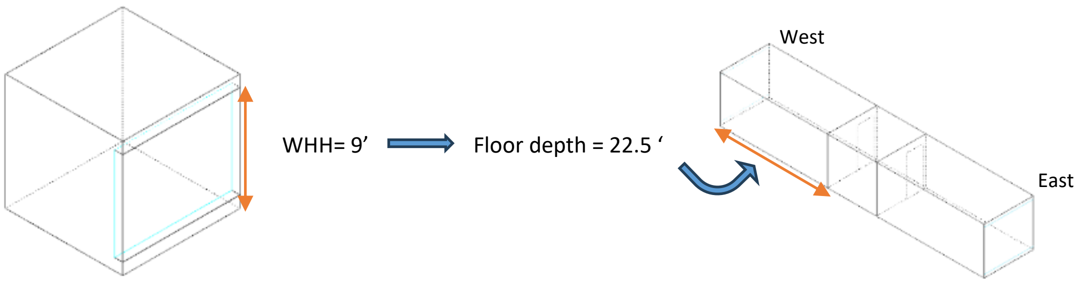


Figure 20: Room depth calculation using WHH. Rule of thumb.

5.2.2. Step 2.2. Floor plan width-to-depth ratio optimization

Based on the calculated depth of 63 ft. and a window-to-wall ratio of 80% from steps 1.2.1 to 2.1.2, this step focuses on determining the floor plan layout. The established cell dimensions (step 1.2.2.) and 80% of WWR (step 1.2.1.) will result in a glazing area with a height of 9 ft (glazing starting one foot above the floor). The recommended window head height (WHH) rules suggest that the room depth should be approximately 2 to 2.5 times the WHH. Therefore, room depths of 22.5 ft. on the east and west sides would allow adequate daylight access. Spaces with lower priority for daylighting can be distributed in the middle of the building (Figure 20).

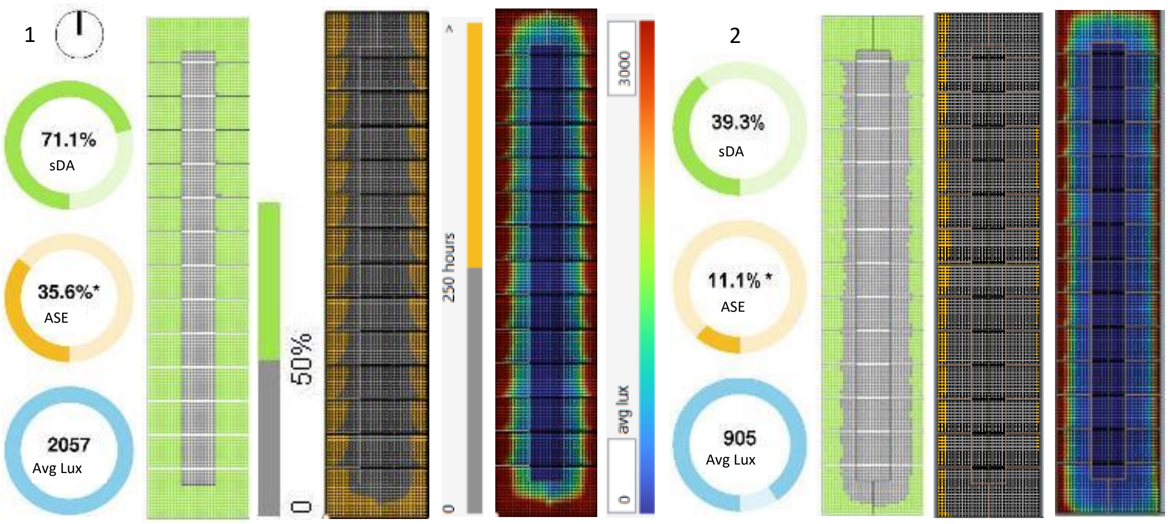


Figure 21: Daylight availability, Annual Sun Exposure. Illuminance simulation for the (1) fifth floor and (2) 20th floor

To validate the daylight availability in spaces on the fifth and twentieth floors, simulations including daylight availability, annual sun exposure, and illuminance were conducted using Climate Studio (Figure).

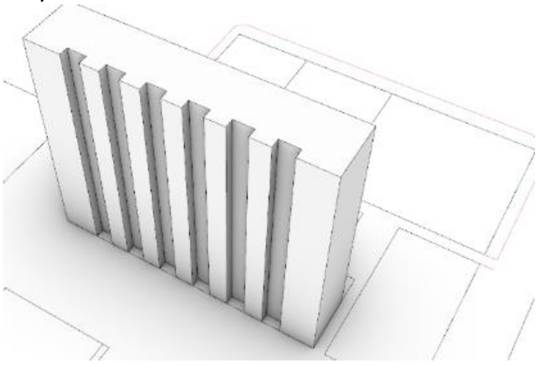
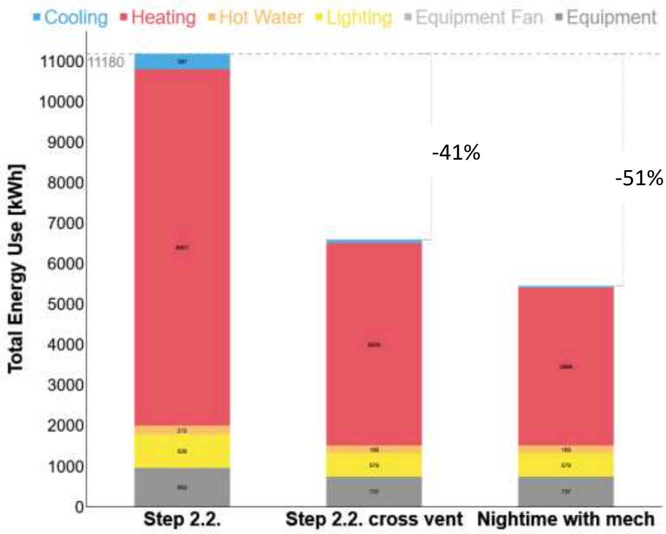


Figure 22: Reducing width to meet requirement for cross ventilation.

To assess energy use and operational carbon, the same module from step 1.2.4. is used. The width of the office is reduced to 22.5 ft, and Option A for window size is selected. The result shows an energy use amount of 191 kWh/m^2 and operational carbon of 72 kgCO_2/m^2. Natural ventilation is activated for this step from June to August (8 am to 6 pm), and the result shows reduced energy use and operational carbon.



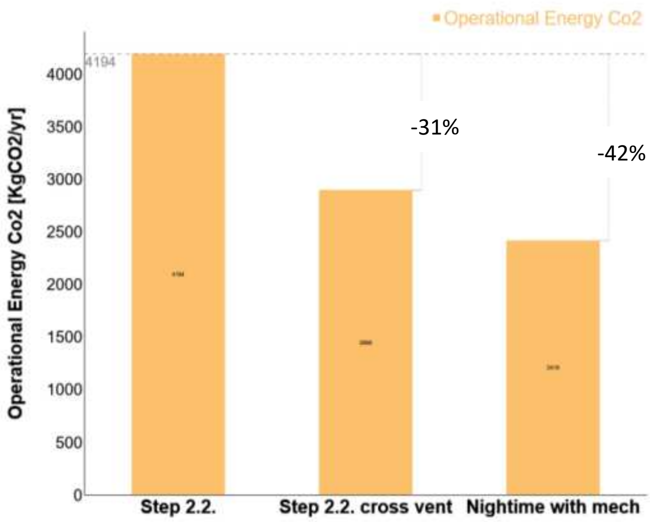


Figure 23: Comparison of simulation results of operational carbon

However, it is important to note that the current building depth exceeds the necessary depth for cross ventilation, which is five times the floor height (section 4.2.2). Therefore, adjustments to the room depth are required, aiming for a depth of 50 ft (Height = 10 ft x 5). Various alternatives for adjusting the floor depth can be explored to optimize the FAR. One option would be to reduce the depth in a toothed form instead of uniformly reducing the entire floor depth (Figure). Furthermore, the window opening area is crucial in facilitating natural ventilation, and it is typically recommended to be between 10% to 30% of the room volume (Costanzo et al.,2017). In this case, 30% of the room volume is considered, which results in approximately 60% of the glazing area being allocated as window openings.

To assess the final form with access to cross ventilation, the module width is reduced to 50 ft, and the office width is 20 ft. The energy usage is 142 kWh/$m^{2,}$ and operational carbon is 62 $kgCO_2$/m2 when daytime ventilation is assigned from 8 am to 6 pm along with scheduled HVAC.

5.2.3. Step 2.2.3. Integrating nighttime ventilation and comparison of energy use and operational carbon assessment for daylight and natural ventilation-enabled form

The final aspect of step 2.2 evaluates the feasibility of using nighttime ventilation from June to August (8 pm to 6 am) alongside mechanical ventilation. Results indicate that this strategy and scheduled heating and cooling reduce energy usage to 117 kWh/m2 and operational carbon emissions to 52 kgCO2/m2. Comparing buildings with access to natural ventilation, adjusting the form to maximize natural ventilation and daylighting significantly reduces energy consumption and operational carbon emissions. Implementing nighttime ventilation further enhances these reductions. This results in a 51% and 42% reduction, respectively (Figure 23).

In conclusion, combining nighttime ventilation, optimizing natural ventilation, and maximizing daylighting shows significant potential for reducing building energy consumption and operational carbon emissions.

5.2.4. Final form with access to daylight and natural ventilation

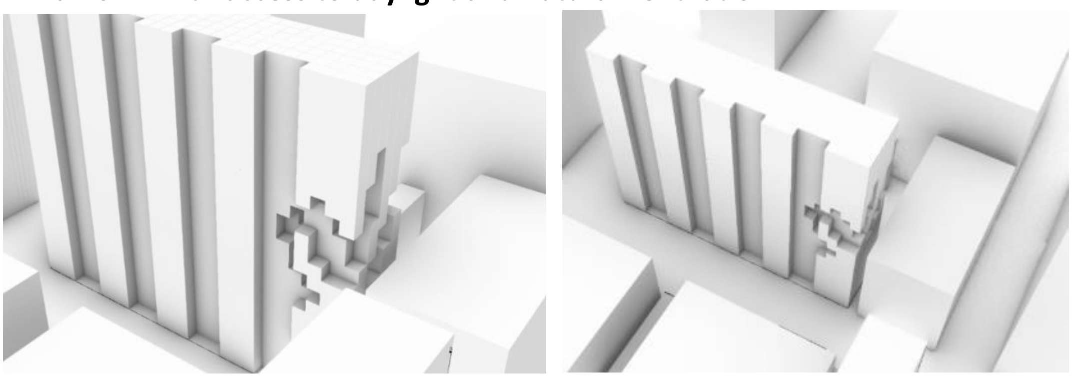


Figure 24: Final form threshold

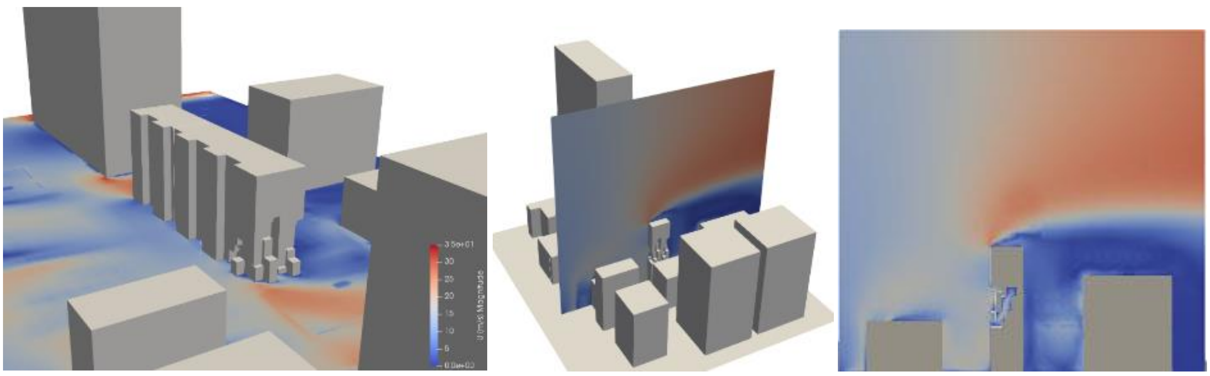


Figure 25: Wind flow pattern in the void created by RSE of the final form (120 ft height from ground)

The final building mass incorporates access to the sun on the west and east sides, allowing sunlight to penetrate the new building mass and reach the surrounding context. Additionally, the design facilitates natural ventilation through cross-ventilation during the summer months. Simulation results demonstrate that the void created by the RSE method also serves as an airflow path, facilitating natural ventilation within the building (Figure 25).

6. Conclusion

Passive design strategies, harnessing renewable energy sources like sunlight and wind, promise environmentally friendly buildings. This research study optimizes the form-finding process for combining daylighting and natural ventilation at urban and building scales. The study extensively examines daylighting and natural ventilation and reviews relevant studies in the field. It develops a sequential approach, integrating both scales and employing an objective-based method to streamline the design process. By setting specific daylighting and natural ventilation goals, designers can effectively identify appropriate metrics and strategies to achieve these objectives. A comprehensive framework of interconnected workflows guiding the decision-making process is developed to achieve the optimal building form. The framework is successfully applied to a dense urban site in Chicago, considering FAR and calculating the significant impact on carbon emissions and energy consumption. Future work will generalize the findings by incorporating automation through parametric computational tools to enable the application to other locations and scenarios.

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Exploring the influence of green roof and photovoltaic panels for public building energy savings to alleviate climate change----Case in Szombathely

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Abstract:

This paper explores the application of greening interventions in the Hungarian context. A large number of existing buildings, especially those built in the last century, have been abandoned due to the discrepancy between their materials and functional life. At the same time, this discrepancy offers new opportunities for existing buildings in social, economic, cultural and artistic terms. Under the vision of carbon neutrality, adaptive reuse of existing buildings significantly reduces material consumption in community building and development while integrating the concepts of reuse and reactivation into people's daily lives. The possibility of more green intervention methods to improve the performance of reused buildings to achieve lower energy consumption and higher comfort levels has been promoted and tested around the world. This study discusses the potential of greening interventions in the context of Szombathely, Hungary, as a carbon-neutral and inhabitant-friendly tool contributing to the adaptive regeneration of the city, as well as a turning point for the future development of the city. The paper focuses on green interventions on the existing building envelope, both as an insulation/protection of the building adjacent to the public open space, green interventions can also improve the quality of the surrounding environment, improve air and water quality, absorb noise and dust and reduce the urban heat island effect. Furthermore, the installation of photovoltaic (PV) panels have gained traction lately which can be supplementary to green interventions. Microclimate impacts of two scenarios will be studied under the scope of this paper: first, green intervention on the roof and second, the placement of PV panels on certain facades based on their solar potential and vertical vegetation on the rest. Therefore, this paper focuses on the potential of adaptive reuse of existing buildings using green intervention methods, where vertical greening interventions can contribute to the adaptive regeneration of the city as a carbon-neutral and resident-friendly tool, while also providing a turnaround for the future development of Budapest as well as studying the impact of installing PV panels on facades to enable renewable energy generation.

Keywords: Green roof; Building renovation; Energy savings; green intervention; Building Attached Photovoltaic

1.Introduction：

Carbon emissions have lately received more attention as a result of the energy crisis and the implications of global warming (Liu, et al., 2022). The architecture industry, which consumes half of the world's energy, is a major source of carbon emissions (Elghamry, et al., 2020). In the field of architecture, new constructive and design solutions have been developed. The use of new systems to reduce environmental degradation. Green façade (Lesjak, et al., 2020; Serra, et al., 2017), Water storage roof (Yang, et al., 2015),green roof system (Nektarios, et al., 2021),Building attached PV panel are the solutions. One of the main causes of climate change is the increase of greenhouse gases (GHG) in the atmosphere, due to different factors such as land use change or fossil fuel combustion. (Shapiro Ian M., 2015) . The energy requirements of Hungary's existing building stock now make up 40% of the country's total energy consumption, with heating and cooling making up the remaining 35%. The Energy Performance of structures Directive (EPBD) standards are technically not met by 4,3 million structures, or 70% of the building total. For public buildings, this rate is almost the same. This is why building restorations are prioritized, especially in the case of public buildings, which consume a lot of energy. The energy plan's purpose is to minimize heating energy consumption by 30% to 40% by 2030, in compliance with the EU Building Energy Program standards. The increase of solar energy distribution and production, on the other hand, plays a role. The European Union (EU) has set aims to address these concerns, such as the 17 Sustainable Development Goals (SDGs) ((UN), 2022). It also recommends raising energy efficiency by 32.5% by 2030 while minimizing greenhouse gas emissions by 40% (Commission, 2022).

Since the bulk of Hungary's available housing stock lacks adequate insulation in the thermal envelope of buildings, green roofs nevertheless carry significant weight. Several studies have found that adding green roofs in buildings with little or no prior insulation saves more energy than installing the identical green roofs in well-insulated constructions. The integration of functional spaces and façades is the foundation of sustainable renewal of existing buildings and places, and the façades of existing buildings are of great value as valuable existing vertical cut-off resources, both for the internal environment of the building and for the quality of the adjacent urban public space. Green roofs have been shown to decrease energy consumption and CO2 emissions due to the geometry and location of their geometry (also known as the direct solar radiation and high surface temperature) and vegetative cover. Its installation also suggests an improvement in terms regarding the environment: UHI decrease (Tiwari, et al., 2021; Liu, et al., 2012). Reduce the danger of flooding from stormwater runoff (T.L. Carte, 2006), or improve air quality (Pandit & Laband, 2010). These solutions are increasingly being researched and implemented in buildings, not only to mitigate the effects of climate change, but also to solve some of the obstacles that arise from the restoration of green and natural areas in cities.

Due to the restricted roof area, there is a need to enhance the PV area of the building through the façade. According to the study, the most photovoltaic power is recorded on the east and south elevations on the horizontal axis. Installing PV on the south, east, and west facades at appropriate tilt angles can create considerable quantities of renewable energy.

The research is dedicated explaining the results of case study simulation of a public building. It consists of three parts.The first part is designated to describe the employed methodology, using Building Energy Modeling (BEM) and the calculation of solar energy. The second part is utilized to show the results of annual energy performance of green roofs, and electricity generated by PV panels. Subsequently as one of Hungary's most important nations, Szombathely has a rising need for a pleasant, attractive, and naturally appropriate public space, whether it is the development of a new carbon-neutral community, a replicated concrete slab community developed in the previous century, or an old town with a concentration of history and culture. We investigate the renewal and revitalization of greening interventions on existing building facades from the standpoint of urban public space, and we consider how greening interventions can enhance the urban public space directly related to the buildings, in addition to their own revitalization and renewal. The study is intended to produce ideas and proposals for optimizing urban regeneration and the building of carbon-neutral cities in the context of szombathely-type cities.

2.Methodology:

The study's objectives are to offer fundamental research for the green development of existing urban structures and to evaluate the potential and capacity of vertical greening of building facades and roofs from the standpoint of green energy consumption in public buildings. A survey of the literature and BEM computations provide the study's foundation. Three topics are covered in the literature review: case studies of global prosperity, theoretical classification of green intervention applications, theoretical and practical status of green roof interventions, PV panel façade of buildings in Hungarian panel house buildings and Hungarian context, and BEM simulations that compare building energy consumption. The researchers accumulated a variety of data, including on-site observations, photographic documentation, and analysis of the building facade's percentage of green intervention potential. The research is based on the coupling of previous theoretical conclusions on vertical greening from across the world with the city of Szombathely's existent building facades. And the foundation of this union is both internal and exterior comfort (Figure 1).

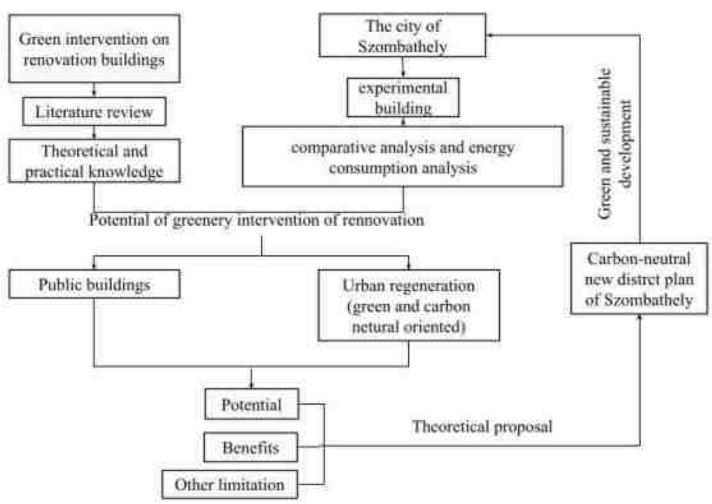

Figure 1: Research methodology diagram

3.panel house

3.1 Buildings in Szombathely

The city of Szombathely is a county town located in the Western Danube Valley region of Hungary. Its ancient predecessor was the capital of the Roman Pannonian Prima province. Through thousands of years of evolution, a number of building and street types existed between the medieval city walls (the historical outline of the city) and the suburbs of the city. The scale of the streets and squares within the medieval city walls has been preserved. The buildings within the medieval walls consist of traditional multi-story buildings, similar to the centuries-old Central European style, and the restored buildings and new buildings are designed in a way that is consistent with the existing tone of the district. Outside the medieval walls, there are four main types of buildings; first, 3-4 story brick houses (apartment buildings or a combination of commercial and residential), second, 4-6 or 11 story slab houses, third, single-family houses, and fourth, in the second half of the nineteenth century, when it became the most important railroad center of the Western Danube due to the construction of the railroad and its population began to grow rapidly, as well as the Art Nouveau style of architecture that defines the city's image to this day were built at that time. They are connected to adjacent streets and public open spaces, each with its own character. 3-4 story brick houses consisting of row houses are directly connected to the pedestrian passageway of the street and can be seen with no or limited greenery in between. Some of the slab houses form apartment blocks and exist in clusters. Some of them are directly connected to the pedestrian access to the main street, while others lie in a separate street block, coexisting with some garden infrastructure. Single-family residences are either freestanding on the parcel, maintaining a buffer garden from the street, or directly aligned with the street façade, with no setback connected frontage. However, the new cultural building retains a well-planned front or side green open space from the pedestrian access.

3.2panel house

The panel house is an apartment building system introduced from the Soviet Union in the 1920s (EX ANTE 2021, 2021). Between the 1950s and the 1980s, it peaked. The majority of residential structures in the city of Szombathely, in Hungary, and even in Central European nations are panel houses (Csaba, 2020). Panel homes are created with numerous generations of construction systems and shapes as a prefabricated apartment structure. They feature a fairly set apartment arrangement and are made of concrete-insulated composite panels. As a result, panel houses are more effectively planned and built than typical brick homes with three to four stories, and they are more appropriate for the Hungarian environment and current housing demands. Slab houses can be divided by height into multi-story apartment buildings and high-rise apartment buildings and multi-story public buildings; and as far as the building composition is concerned, there are buildings consisting of single staircases, double staircases and triple staircases. Observational studies show that the facades of slab houses in the same area tend to

be painted in similar colors or compositions. Light gray, light yellow and blue-green are the most common colors used for exterior plastering. The diversity of balcony forms offers more possibilities for collaboration in vertical greening interventions on slab facades.
Based on the study of the model of slab facades in szombathely city (Figure 2), it was possible to carry out window opening rates (total window and balcony area per total facade area). The results show that the window opening rates are (35%-47%) for multi-story slab houses and (22%-30%) for high-rise slab houses (Table 1). The remaining portion is the plaster surface and, if applicable, other surfaces of the ground floor. The plastered part is a precast concrete slab with integrated insulation. Depending on the year of construction, different panel systems were applied, where the thickness of the wall composition ranged from 19 to 27 cm (Csaba, 2020). The area ratio of vertical green intervention potential can also be calculated as (53%-78%).

Figure 2: Panel house model facades in Pécs (Illustrated by authors)

Table 1: Panel building solid and opening ratio

	Opening Ratio	**Solid Ratio**	**Type**
A	**43%**	**57%**	**Multi-Storey**
B	**47%**	**53%**	**Multi-Storey**
C	**35%**	**65%**	**Multi-Storey**
D	**46%**	**54%**	**Multi-Storey**

E	**22%**	**78%**	**High-rise**
F	**30%**	**70%**	**High-rise**

4. The role of the photovoltaic façade

Solar panels, sometimes referred to as PV panels, are commonly mounted on a building's roof or any other flat or sloping surface. However, the market for PV panels today permits installation on a range of building surfaces. An example of a technology that may collect solar energy from a building's façade is building-integrated photovoltaics (BIPV). Due of their versatility, BIPVs can save total material costs. (Raugei & Frankl, 2009; Jelle, et al., 2012) . This implies that, if the panels are carefully put, vertical surfaces also have the potential to create considerable quantities of energy. The findings indicate that it is promising to place PV panels on high-rise buildings' vertical surfaces. (Liang, et al., 2015; Salimzadeh, et al., 2020). It's crucial to use vertical surfaces effectively to collect sustainable energy on big structures. In general, the term "façade PV" refers to the vertical face of a building or other facility where PV panels are used in place of standard finishes. One of the finest clean energy sources for replacing fossil fuels in the built environment and for supplying local energy is photovoltaic (PV) solar energy. (Kåberger, 2018). This paper focuses on vertical PV design. Researchers around the world have categorized urban vertical PV on building facades with varying emphasis and purpose, which can generally be divided into installation technology, function, material type application, and aesthetics.

5. The experimental building

5.1 Simulation method:

Three environmental factors—temperature, net surface solar radiation, and near-surface wind —have an impact on how nonlinearly solar PV panels respond, and panel characteristics have a big influence on how well the panels function. Because of variables such as their temperature response factor, capacity factor, and cell temperature, an increase in incoming radiation does not necessarily result in a rise in power generation. These conditions must be met in order to determine the actual maximum PV power output (PVO). Calculate the cell temperature using the equation. (1) PVO calculations are then done (Equation 2) using features and temperature response parameters for cutting-edge monocrystalline solar panels and the usual average efficiency rating (17%) currently available on the market. WRF provided the sun radiation, air temperature, and surface wind speed information. Formula 1 To make sure that the base calculations were carried out at the maximum spatial and temporal resolution available for the model output, Equation 2. power curves and equations were applied to hourly and grid cells before any further processing. Comparisons of power production are given as cumulative differences per RES-E every season, whilst variations in wind speed and solar radiation are displayed as median and mean percentage different $cell = c1 + c2\ Tambien + c3\ G + c4\ ws$ Equation 1

$PVO = G * \eta p * [1 + \mu\ (Tcell - Tr)]$ Equation 2

The power curves and equations are applied to each hourly and grid cell before any additional processing to ensure the most effective spatial and temporal resolution of the model output for the base calculations. Variations in wind speed and solar radiation are displayed as median and mean percentage differences, respectively, whilst power output comparisons are depicted as cumulative variances per RES-E per season. The area of the building's south elevation that can be fitted with PV panels is 162.4 m2 (excluding openings and ground clearance of 60 cm) Based on the above calculation, the PV panels can generate: 1200kWh/m2 times 162.4 m2 = 194,880kwh/year of electricity on the building.

The reference model proposed to renovate is located in Szombathely, which is situated in the western of Hungary (Figure 3). The latitude of Hungary is between 45°45'N and 48°35'N and its climate is erratic due to the combined influence of continental climate, oceanic climate and Mediterranean effect (Hungarian Meteorological Service, 2022). In Szombathely, the climate is continental and has been classified as Cfb by Köppen and Geiger; namely, warm temperature, fully humid and warm summer (CDO, 2022). The average annual temperature in Szombathely is 11°C, and summer usually starts from late June to the end of September, in which July is the warmest month. In addition, Szombathely has abundant rainfall, raining heavily even in the driest months.

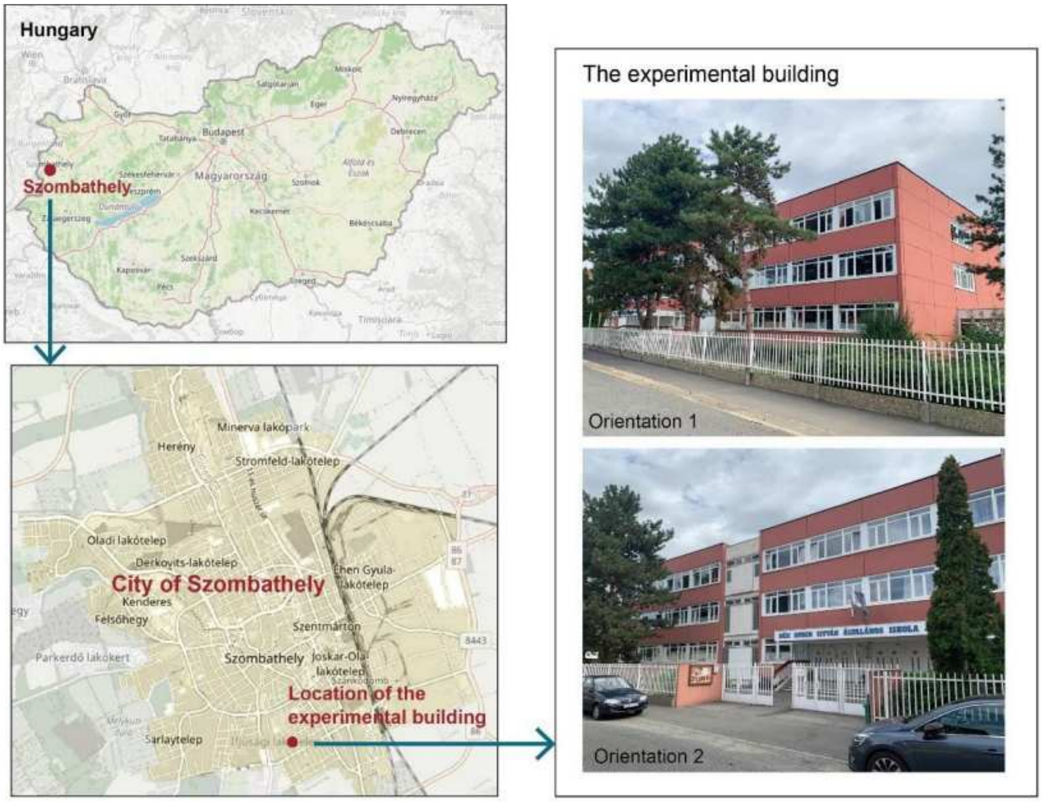

Figure 3. Location of Szombathely and the experimental building

Source from: and the experimental building (Photo by Author)

The building selected for energy consumption analysis is located in the outer area of the city, approximately 1.5 km from the city center (Figure 3). The surrounding area of this building has a tranquil atmosphere as the adjacent area consists mainly of flats and family houses. This building was built in 1980 and faces the southwest direction. It is one of the primary school buildings and has three stories. The building has bare walls and roofs, of which the roof covers an area of nearly 940 square meters. There are 6 scotch pine trees (Pinus sylvestris) planted in front of the buildings, which partly decreased the solar radiation in the summer period. Furthermore, for the energy consumption simulation of the case study, specialized software was utilized in the design and thermal analysis of the building. Although there are many software available for energy consumption simulation analysis, EnergyPlus is the most popular. As it provides a specific module for modeling green roofs, allowing to set vegetation physical properties, such as height, minimum stomatal resistance, leaf area index, thermal properties (albedo and leaf emissivity); etc. This module, therefore, helps in accurately simulating the energy demand before and after the implementation of green roofs.

To explore the energy consumption changes before and after the installation of green roofs, two scenarios were formulated in this study. Scenario 1 maintains the original condition of the experimental building. Scenario 2 refers to the installation of extensive green roofs on the experimental building. Therefore, the difference between Scenario 2 and Scenario 1 lies in the utilization of extensive green roofs, while the rest of the features remain the same. Table 2. Shows the characteristics of the layers of the extensive roof construction systems.

Table 2. Main characteristics of the layers of the extensive roof construction systems.

	Thickness [m]	**Thermal conductivity (W/mK)**
Vegetation: sedum	**0,05**	**-**
Anti-root sheet	**0,001**	**0,33**
EPDM Waterproof sheet	**0,0012**	**0,25**
XPS Thermal insulation	**3,5-14,01**	**0,033**
Plastic nodular drainage layer	**0,04**	**0,33**
Filter sheet	**0,001**	**0,038**
Substrcture	**0,10**	**0,435**

5.2 The results of building energy simulation

The results of building energy simulation in Szombathely is shown in figure 4 to 5,6.

- No green roof

Month/ Electricity (kWh)	1	2	3	4	5	6	7	8	9	10	11	12	Annual	Total (kWh)	Energy used/ ㎡
Cooling	0	0	0.2	0.7	68.9	6207.9	10422.5	9284.3	4491.2	7.4	0	0	30483.72	64407.33	12.63/ ㎡
Heating	10031.8	7420.3	908.1	0	0	0	0	0	0	0	4958.7	10604.7	33923.61		14.06/ ㎡

- Extensive green roof

Month/ Electricity (kWh)	1	2	3	4	5	6	7	8	9	10	11	12	Annual	Total (kWh)	Energy used/ ㎡
Cooling	0	0	0	0.2	47.8	4771.4	8075.1	7137.6	3530.6	7.9	0	0	23570.64	55474.25	9.77/ ㎡
Heating	9554.7	6638.7	833.7	0	0	0	0	0	0	0	4732.1	10144.4	31903.61		13.23/ ㎡

Figure 4. The annual building energy demand between two different scenarios

Figure 4 illustrates the annual energy use of the experimental building in two different scenarios. It is clear that the annual energy consumption for heating exceeds that of cooling in both scenarios. In the scenario of no green roof, heating consumes nearly 3,440 kWh more electricity per year than cooling. However, this difference expands to 8333 kWh per year in the scenario of applying extensive green roof. This is because the cooling energy demand is significantly reduced by installing an extensive green roof on the experimental building. Specifically, the annual cooling energy consumption was decreased by 6913.08 kWh. In addition, compared with the scenario of without green roof, the scenario of applying green roof saves 8,933 kWh electricity of total energy demand, which represents 13.9%. Moreover, the average energy consumption per square meter decreased from 26.69/m² to 23/m². (Hungarian Meteorological Service, 2022).

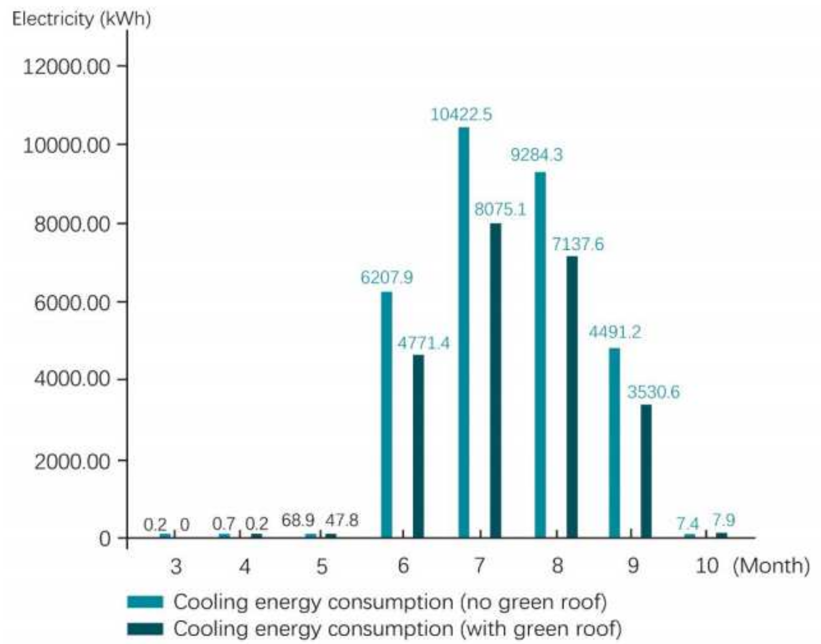

Figure 5. Annual cooling energy consumption of experiment building in two different scenarios

According to figure 4, there is a significant difference between these two scenarios. It is clear that the scenario of using green roof demands less energy for cooling than the scenario of without applying green roof. In addition, the cooling period of this building mainly starts in June and ends in September, in which the largest cooling energy demand occurred in July. The electricity consumed in this month is over 10 thousand kWh in the scenario of without applying green roof, which rose by 40.4%, compared to June. Instead, the energy consumption dropped to 8075 kWh by applying an extensive green roof. During the main cooling period (June, July, August and September), experimental building saves 23.1%, 22.5%, 23.1% and 21.4% cooling energy by using extensive green roofs, respectively. Moreover, compared with the bare building roof, the annual cooling energy saving rate is more than 22%; also, the cooling energy demand per square meter is reduced from 12.63/m² to 9.77/m².

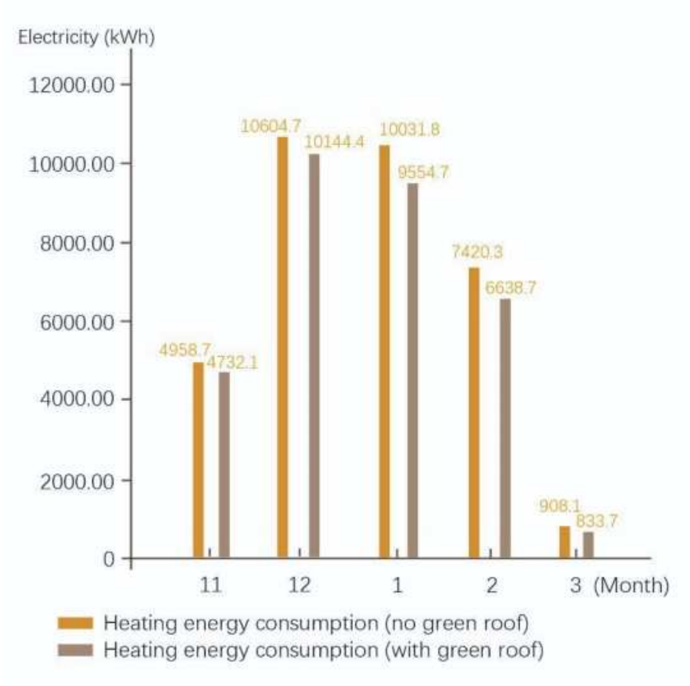

Figure 6. Annual heating energy consumption of experiment building in two different scenarios

As shown in Figure 6, by applying the green roof, the heating energy demand of the experimental building was also reduced compared to the original scenario. The energy consumption after the installation of green roofs decreased by 4.6%, 4.3%, and 4.8% in November, December, and January, respectively, compared to the energy consumption without green roofs. The largest energy savings occurred in February, reaching 10.5%. Similarly, the heating energy consumption was reduced by 8.2% in March through the use of green roofs. In addition, by using the extensive green roofs, the annual heating energy saving rate of the experimental building reached 6.0%, and the heating energy consumption per square meter was reduced from 14.06 per square meter to 13.23 per square meter.

6. Conclusion：

Green interventions and photovoltaic façades play a role in building design to increase the amount of urban greenery and effectively reduce building energy consumption. This study emphasizes interventions on existing building facades and urban renewal, and investigates the impact of greening intervention systems on the energy consumption of Szombathely public buildings in a Central European town, which is a typical prefabricated building. From the comparative measurements, it is clear that it is possible to reduce the overall building energy consumption throughout the year by applying photovoltaic panels on the façade.

This effect, based to this article, results in reduced consumption of energy for air conditioning and might perhaps lessen the impact of the urban heat island. It should be mentioned that the installation of a PV facade on a floor slab encourages the reduction of noise and interior thermal regulation, which may be used to modify the quality of the public space and improve the quality of the home environment. A quantitative analysis of the interior and outdoor thermal comfort in summer and winter, the choice of the range of solar panels that may be used, the flexibility of the installed system, etc. are also crucial after the study of the building's annual energy usage.Szombathely's extensive distribution of solar facades and green roofs is anticipated to result in a universal method of sustainable urban regeneration and a more active and resilient style of life through a comprehensive sequence of greening initiatives.

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Visualising carbon in the design and delivery of buildings – A review of the evidence

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Abstract

Reducing carbon emissions has become a goal for international climate change and decarbonisation policy initiatives, particularly in the built environment. Setting and addressing these goals and accounting for how targets are being met poses a major challenge for professionals in the UK and internationally. Industry working groups, think-tanks and newly formed organisations are developing new guidance on techniques, tools and approaches. This paper reviews evidence within academic journal articles of visualisation practices associated with carbon reduction in the design and delivery of buildings. The review uses a narrative method to review academic literature published in the last 5 years. Findings show visualization tools can be categorised as supporting the refinement of design solutions with regards to carbon performance, by aiding the understanding of carbon contributions of different building elements, decision making, benchmarking and enhancing interactions with carbon related data. The implications of the review are twofold. First, the evidence collated enables a new understanding of the implications of different ways of conceptualising and visualising carbon on the design and delivery process, by categorising the functions of visuals and their prevalence within the literature. Second there are implications for future research on carbon reduction in the built environment and associated domains.

Keywords – built environment, carbon reduction, design, delivery, visualisation.

1. Introduction

In recent years new policy and industry guidance on decarbonisation in the built environment has proliferated (He and Prasad, 2022; Prasad et al., 2023; Satola, et al., 2022). This includes a significant increase in consultation efforts focused on achieving net-zero building standards and addressing embodied carbon within building regulations, specifically Part Z (Nikologianni et al., 2022). Furthermore, there is a substantial amount of policy involvement, target setting, and the utilization of environmental assessment models aimed at promoting a comprehensive approach towards achieving net-zero goals. This multifaceted movement towards carbon reduction affects a broad range of professionals within the built environment, including architects, engineers, quantity surveyors, and other individuals involved in the design and delivery of buildings (Martinez et al. 2023).

Underlying these efforts is the use of visual representations to convey how targets, measures and assessment of carbon reduction may be achieved. While images are an accepted part of communication, there has been little or no discussion of the visual artifacts drawn upon, whether diagrams, charts, graphs, simulation screen shots or similar. An overview and discussion of the visual artifacts used provides a novel review of how what visualisations are being used to represent carbon (Quattrone et al., 2021) as well as how carbon reduction is abstracted within a particular context (Ravasi 2017). As argued by Messaris and Abraham "pictorial framing is worthy of investigation not only because images are capable of conveying unverbalized meanings, but also because awareness of those meanings may be particularly elusive" (2001, p. 225). Design of buildings in particular is characterised by a reflective, tacit and highly visual design practice (Schon 1984), and though emerging work is starting to analyse how design professionals visualise energy in buildings for instance (Oliveira et al., 2023), there have been no analytical accounts or reviews of visual practices for carbon reduction.

We review built environment academic literature that has engaged with carbon reduction issues not just in terms of what authors have written but also how they have visualized carbon.

2. Methods

The paper employs a loose systematic, narrative literature review approach (Eykelbosh and Fong, 2017) to evidence how carbon reduction is approached visually in-built environment literature.

This approach allows for a comprehensive examination by including a wide range of sources that may not fit within a strict systematic review framework. The narrative strategy employed here enables the synthesis and analysis of this diverse body of knowledge (Anthony, 2023; Vågerö and Zeyringer, 2023), allowing for the inclusion of various types of evidence, including empirical studies, case studies, theoretical frameworks, and conceptual discussions. Lastly, visual approaches to carbon reduction in the built environment often involve contextual and conceptual aspects, including design intent, user experience, and socio-cultural considerations. A narrative review approach facilitates the exploration of these contextual and conceptual dimensions, allowing for a deeper understanding of how visual representations are employed to address carbon reduction in real-world settings.

To identify relevant articles, a search was conducted using academic databases and search engines, namely Science Direct, Scopus, and Google Scholar. The search located original articles and reviews written in English within the past five years, ensuring the inclusion of recent research. This time period was selected due to the significant increase in carbon related discussion surrounding construction projects and associated research, driven by research agendas and changes in national policy (SW Energy Hub, 2019). As such a five-year period permits sufficient incorporation of this period.

To construct effective search queries, specific keywords were combined to form customized strings, comprising the terms carbon visualization, carbon representation, net-zero visualization, and net-zero representation. The search criteria were designed to be internationally inclusive with results filtered to prioritise the most relevant evidence. After conducting preliminary searches to assess the effectiveness of different search terms. Criteria to select documents were applied in two screening stages. Stage 1 involved screening based on abstracts, while Stage 2 involved screening full documents. At Stage 1 articles found amounted to 1112; after filtering for relevance and duplication a total of 116 articles were included. The review included using a transparent and reproducible search to identify studies, and explicit and objective methods to select, extract, quality appraise and synthesise the evidence.

Documents that passed the quality assessment were then analysed. Analysis looked for 1) visual signs and narrative on carbon reduction; 2) materialisation of visual themes; 3) conveyed use of visual artifacts (Pradies et al., 2023). The 116 final sample papers (table 1) were then grouped under according to the function of the article (e.g., review article) (table 2), and specifically how carbon is being discussed (e.g., embodied carbon, whole life carbon), along with the build stages (RIBA 0-7) with which they were concerned.

Table 1. Review of built environment literature - key search terms and number of documents.

	Carbon representation	**Carbon visualisation**	**Net zero representation**	**Net zero visualisation**
Scopus	7	26	4	1
Science Direct	10	41	0	2
Google Scholar	6	10	3	6

Table 2. Visual techniques used in sampled literature and its use.

Name and example references	Frequency	Functionality	Type of article
Bar chart	54	- Comparison of embodied carbon across materials and replacements. - Tracking emissions over time. - Representing of total emission of materials or components. - Comparison of embodied carbon calculation with different present or predicted standards.	• Research papers comparing carbon implications of different design options, materials, or technologies (e.g., Rock et al., 2020). • Whole life carbon research presenting the carbon emissions associated with different life cycle stages or building components (e.g., Meneghelli, 2018). • Performance analysis, investigating the carbon performance of existing buildings or building systems use bar charts to visualize energy consumption, greenhouse gas emissions, or carbon intensity over time (e.g., Ji et al., 2019).
Line graph	21	- Comparison of carbon emissions across buildings or projects.	• Time-series analysis papers examining the carbon performance of buildings or building systems over time often use line graphs (e.g., Eberhardt et al., 2019). • Energy modelling and simulation studies, displaying the carbon intensity or emissions profiles of different scenarios or design alternatives, allowing for easy comparison and identification of the most effective strategies (e.g., Rock et al., 2020).
Box plot	9	- Benchmarking building elements. - Representation of how building may meet incoming carbon related standards.	• Sensitivity analysis research, employing box plots to investigate the sensitivity of carbon emissions to different parameters or variables (e.g., Cang et al., 2020). • Performance benchmarking against standards (e.g., Pasanen and Castro, 2019)
Scatter graph	24	- Plotting numerous embodied carbon calculations for different buildings and building configurations/material specification.	• Simulation modelling using scatter graphs to analyse the relationship between input parameters (such as building characteristics, occupancy profiles, or energy systems) and carbon emissions (e.g., Schmidt and Crawford, 2018).

Cascading target chart	5	- Compartmentalisation of building elements based on carbon (e.g., operational or embodied carbon.	• Performance benchmarking: cascading target charts can be utilized in research papers that compare the carbon performance of different buildings, building systems, or design alternatives (e.g., Jusselme et al., 2018).
Pie chart	19	- Division of building carbon origin (e.g., materials, energy consumption, end of life).	• Carbon footprint research: using pie charts to assess the carbon footprint of buildings (e.g., Marsh et al., 2018).
3D colour-coded images	8	- Division of building elements to show magnitude of carbon per element class or area.	• Building energy simulation, using 3D colour images to represent energy performance, including carbon emissions (e.g., Rock et al., 2018). • Embodied carbon assessment using 3D colour images can be used to represent the embodied carbon of different materials, components, or building systems (e.g., Alwan et al., 2021).
Virtual and augmented reality	4	- Overlaying of energy data from energy services with VR.	• Building performance assessment research, using VR/AR to simulate and visualize the carbon performance of buildings (e.g., Kamari et al., 2020). • Energy management and monitoring research, exploring how VR/AR can enhance the visualization of real-time energy consumption and carbon emissions within buildings (e.g., Chen et al., 2020). • Stakeholder engagement and education research, looking at how VR/AR can facilitate stakeholder engagement by providing interactive and engaging experiences to communicate the carbon impact of design choices (Caldas et al., 2022).
Flowchart	23	- Outlining of environment assessment process for determining material choices.	• Carbon management strategies, using flowcharts to outline the various strategies and measures implemented to reduce carbon emissions in buildings (e.g., Li et al., 2021). • Carbon accounting and reporting, using flowcharts to illustrate the process of carbon accounting and reporting, showcasing how carbon emissions are quantified, tracked, and reported for a building (e.g., Li et al., 2022).

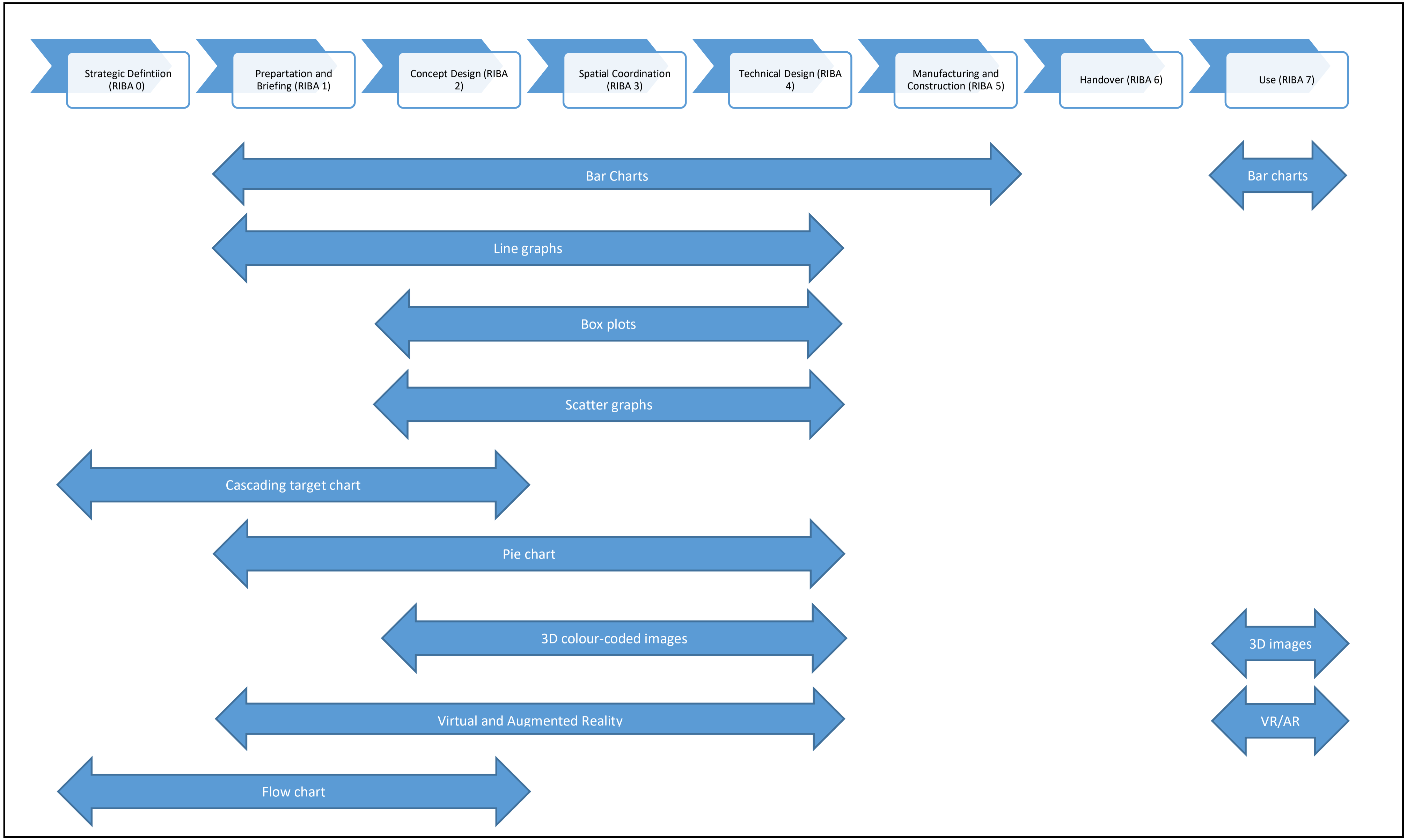


Figure 1: Use of Carbon visualisation techniques across the RIBA stages of a project.

3. Findings

3.1 How is carbon visualised- methods.

Across the 116 number articles and documents reviewed visualisation techniques comprised charts, graphs, and more complex digitised visualisation such as virtual and augmented reality. There was a dominance of certain techniques and methods of visualising, such as pie and bar charts, along with scatter and line graphs, which may be attributed to their simplicity and familiarity with users (Fang et al., 2023). Plus, flowcharts feature in our reviewed articles, highlighting how procedural and process driven carbon research is also present.

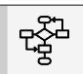
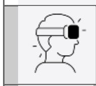
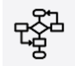
Bar charts, including variations such as grouped or stacked bar charts, are also commonly used as visualizations of carbon information. They are employed in more than 54 articles, making them the prevalent choice for representing carbon-related information. More complex visualizations that involve a large amount of information, such as scatter plots or parallel coordinate plots, are less commonly employed in the analysed research and documents. These types of visualization may offer a more nuanced and detailed representation of carbon data but are currently less prevalent in their use. It is worth noting that the use of 3D colour code visualizations, which provide a three-dimensional representation of carbon-related information, is primarily seen in tools developed by researchers and presented in only a handful of articles (12).

Importantly, in the case of flowchart visualisation, which were identified across 23 articles, the process of understanding carbon in buildings was highlighted. This tool is used to provide a structured representation of the steps involved in assessing and managing carbon-related aspects. They are shown in the literature to indicate the sequence of steps or activities involved in understanding carbon in buildings. This helps stakeholders visualize the logical progression and dependencies between different stages of carbon assessment and management. Plus, flowcharts are seen to incorporate decision points, feedback loops, statements of roles and inputs and outputs associated with each step or activity in the process. This display of carbon therefore differs from other detected here, by assigning actionable points, and processes of delivery of low carbon related activities.

With a significant proportion of authors focusing on the early design stages, many of the visualisation methods were seen to be used across the different design stages (figure 1). For instance, bar charts were used within initial embodied carbon calculations for proposed different materials, and also for post occupancy reviews of monthly energy usage. This suggests that some visualisation techniques are not strongly tied to specific stages of the design process but rather span across multiple stages (figure 1). However, it is noted that although similar visualisation techniques were used to show information from varying build stages, the information within each visualisation did vary due to differing demands at different stages.

Specifically, visuals looked to; compare the potential designs and material choice of a building, specifically their carbon impact, represent the carbon contributions (whether embodied or operational) of specific building elements, aid decision making via the presentation of comparative options, benchmark building options against present and future regulations and legislative standards or targets, communicate carbon related information to audiences such as clients or members of the public, and displaying how the challenge of understanding a building’s carbon implications has been approached (table 3).

Table 3: Overview of message of carbon visualisation detected.

Message of visualisation			
Comparing designs of building or material choices			
Understanding carbon contributions from building elements			
Decision making			
Benchmarking			
Communicating carbon information in an interactive manner			
Displaying the process of understanding carbon			

3.1.1 Bar charts

Bar charts were detected regularly across the reviewed literature, for multiple purposes.

Researchers used bar charts to compare carbon emissions across different categories or scenarios. Each bar represents the carbon emissions of a particular category, such as different building elements, materials, or stages of the construction process.

For example, Resch and Andersen (2018) (figure 2) use a bar chart to detail embodied emissions for different materials and replacements for a variety of building case studies.

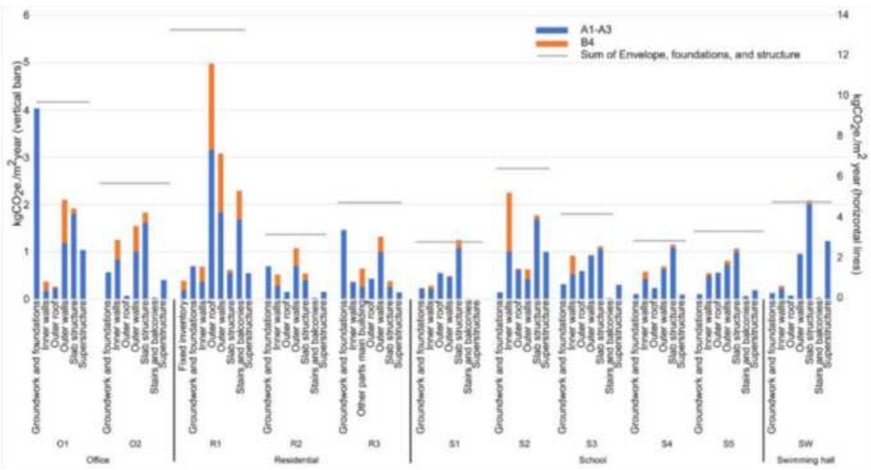


Figure 2: Resch and Andersen (2019); Embodied carbon bar chart.

This visual representation allows for a comparison of the embodied emissions of different building elements across multiple buildings, providing insights into the relative contributions of specific elements to the overall embodied emissions of "Envelope, foundation, and structure" (Resch and Andersen, 2019). By quantifying the emissions in kgCO2e per square meter per year, it allows for a standardized comparison of emissions intensity between different buildings and typologies.

Bar charts can show variations in carbon emissions over time. This allows for tracking changes in emissions over time and identifying trends, seasonal variations, or the impact of interventions (Grant Wilson, 2016). For instance, Ren et al. (2018) utilise bar charts to detail how the carbon footprint of a building element changes over the life cycle of a project (figure 3).

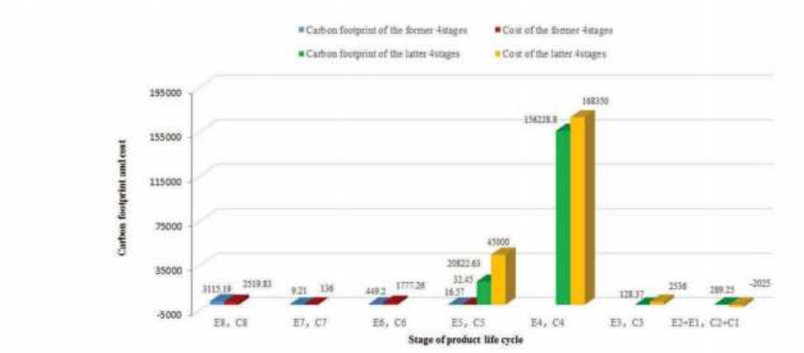


Figure 3: Ren et al., (2018); Carbon footprint of a building component over time

Plus, bar charts used to benchmark carbon emissions against established standards or targets. The bars represent the carbon emissions of different projects, buildings, or components, allowing for easy comparison and assessment of performance against predefined goals. Röck et al., (2020), display this by using bar charts to detail embodied greenhouse gas emissions of buildings against existing and new standards (figure 4).

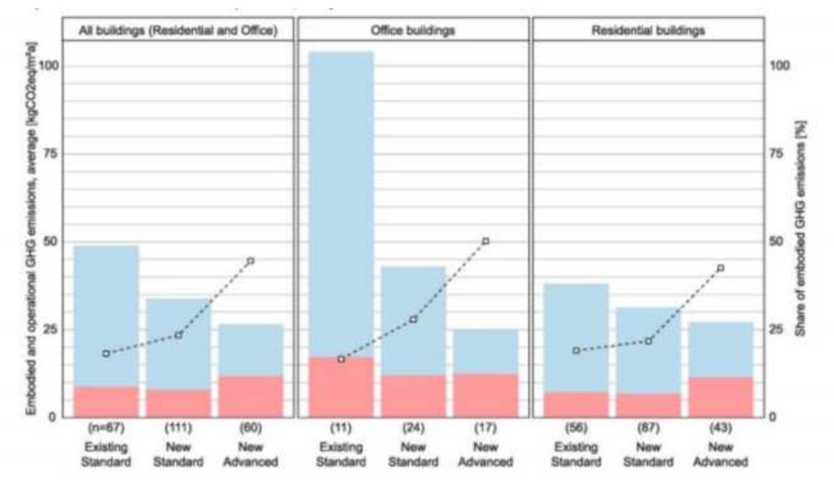


Figure 4: Röck et al., (2020); GHG emission reduction performance against incoming targets

3.1.2 Line graph

Line graphs are utilised to visually represent carbon in buildings by plotting the carbon emissions or carbon-related data over a specific time period. They are used to show the trend of carbon emissions from a building over a specific period, along with being used to compare carbon emissions between different buildings or building projects. For instance, Eberhardt et al., (2019) utilise line graphs to detail the accumulated embodied carbon within a building across its lifespan (in this case 80 years) (figure 5).

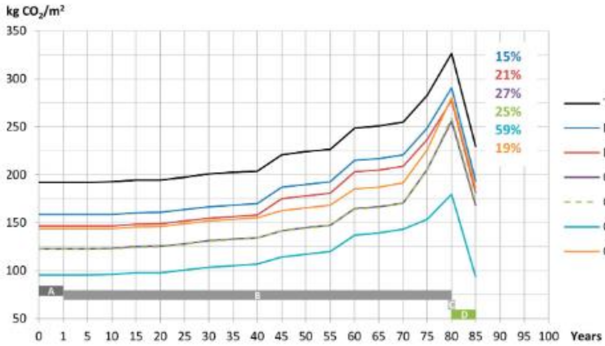


Figure 5: Eberhardt et al., (2019); line graph charting accumulated embodied carbon.

Additionally, line graphs are seen to show how the impact of specific interventions or measures implemented to reduce carbon emissions in a building. By plotting carbon emissions before and after the implementation of a measure, such as energy efficiency upgrades or renewable energy installations, the graph visually demonstrates the effectiveness of the intervention in reducing carbon emissions.

3.1.3 Box plot

Box plots within the literature database are used to provide a concise summary of the distribution and variability of carbon-related data. As such box plots are employed to display the distribution of carbon emissions data within a building or a group of buildings. Plus, they are utilised to help identify outliers, which are data points that significantly deviate from the overall pattern. In this sense box plots provide addition insight that bar charts for instance by highlighting outliers in carbon emissions data and indicating anomalies or areas of concern that require further investigation. By visually identifying these outliers in a box plot, exemplars of box plots are used to aid building professionals in focusing on understanding and addressing the factors contributing to high or low carbon emissions. For instance, Hollberg et al., (2019) use a box plot to benchmark individual elements of a building (figure 6).

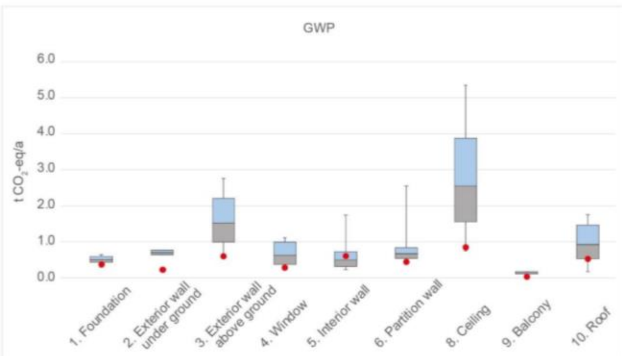


Figure 6: Hollberg et al., (2019); box plot for building component carbon benchmarking.

Box plots can also be used to track changes in carbon emissions over time or assess the impact of interventions. By comparing box plots at different time points or before and after the implementation of measures, one can observe shifts in the central tendency, spread, and presence of outliers, providing insights into the effectiveness of carbon reduction efforts. This is demonstrated by Röck et al., (2020) in their representation of how office and residential buildings may meet new standards (figure 7).

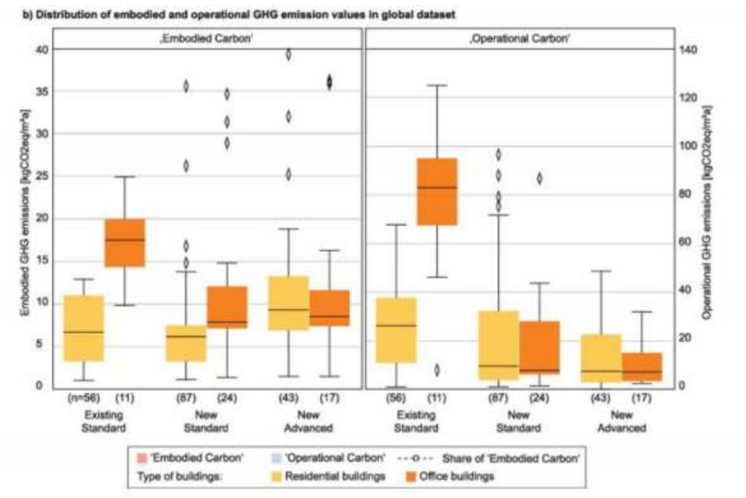


Figure 7: Röck et al., (2020) box plot graph for building performance against future standards.

3.1.4 Scatter graphs

Scatter graphs are identified to visualise carbon by focusing on a relationship between carbon emissions and another variable of interest, such as building area, occupancy, or energy consumption. By plotting these points and examining their patterns, trends, or clusters, one can gain insights into the relationship between carbon emissions and the other variables.

For instance, Płoszaj-Mazurek et al., (2020) utilise scatter plots to detail embodied carbon calculations for different buildings based on height (figure 8).

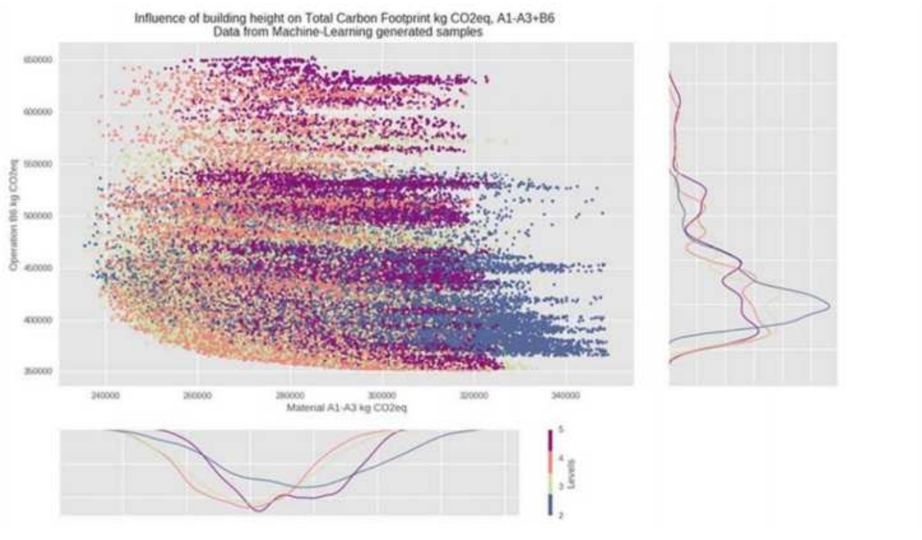


Figure 8: Płoszaj-Mazurek et al., (2020): scatter plot for embodied carbon scenarios.

As such scatter plots permit the identification of outliers or extreme values, along with the indication of how strong a correlation is between variables, or how prevalent groupings are.

3.1.5 Cascading target chart

Cascading target graphs were identified in the literature as a mechanism to visualize carbon in buildings by illustrating the breakdown of carbon emissions into different components or stages. They involve the decomposition of carbon emissions into various contributing factors or stages, permitting the identification of high-impact areas, and the tracking of changes over time. Jusselme et al. (2018) utilise a cascading target chart to compartmentalise the carbon associated with housing, including details of operational carbon, embodied carbon, along with further segmentation into component level figures (figure 9).

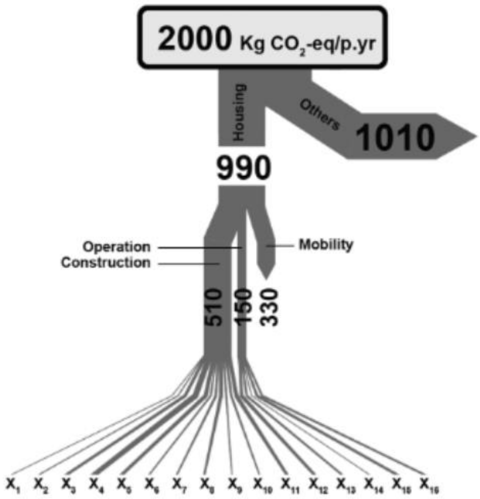


Figure 9: Jusselme et al., (2018); Cascading target chart for carbon emissions.

The layout of cascading target graphs allows for the identification of improvement opportunities. Positive segments represent reductions or improvements in carbon emissions, while negative segments indicate increases or areas of concern. This visual representation helps stakeholders identify areas where efforts should be directed to achieve carbon reduction goals, along with providing a clear and concise visual representation of the carbon emissions breakdown, making it easier to communicate complex information to diverse stakeholders. The visual format allows for a quick understanding of the relative contribution of different components, facilitating discussions and decision-making processes related to carbon reduction strategies.

3.1.6 Pie charts

Pie charts were used by researchers to visualise illustrate the proportion of carbon emissions contributed by various components or sources within the building. For example, slices can represent emissions from energy consumption, transportation, materials, operations, or specific building systems (e.g., Resch, E., & Andresen, I. (2018), figure 10 below).

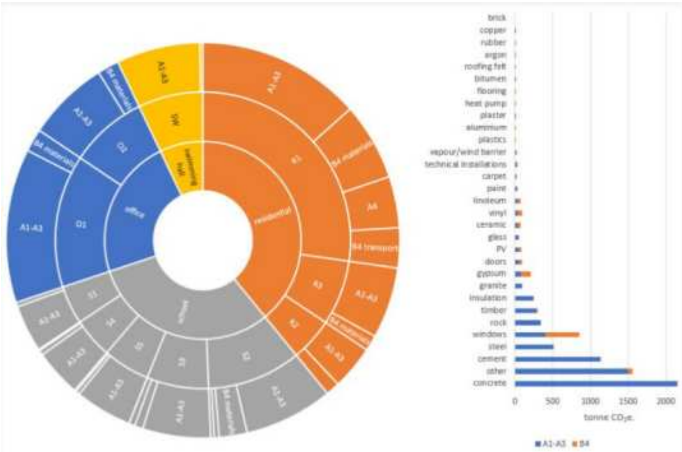


Figure 10: Resch, E., & Andresen, I. (2018); Pie chart displaying carbon emission contributions.

Pie charts such as figure 11 allow for easy visual comparison of the relative contributions of different components to the total carbon emissions. With pie charts providing a clear and intuitive representation of proportions, they make it straightforward to understand the relative contributions of different components and their relationship to total carbon emissions. This makes pie charts effective in communicating carbon-related information to stakeholders, including building owners, designers, and occupants, who may have varying levels of familiarity with carbon footprint analysis.

3.1.7 3D colour-coded images

3D color-coded images can help visualize carbon in buildings by providing a visual representation of carbon emissions of carbon-related data in three-dimensional space. These images allow for the spatial representation of carbon emissions within a building and the intensity or magnitude of emissions in different building areas.

Röck et al. (2018) produced figure 11, detailing a 3D visualization that assigns specific numerical values to indicate the magnitude of the contribution for each building element class. In this case, the values are given in terms of kilograms of CO_2 equivalents per square meter of gross floor area (kgCO2eq/m2GFAa). This provides a precise measurement of the embodied carbon impact associated with each building element class.

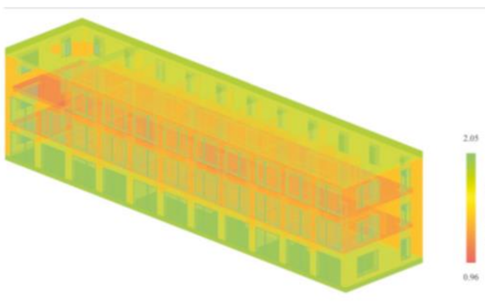


Figure 11: Röck et al., (2018). 3D colour model visualisation (embodied carbon).

Interactive 3D color-coded images enable stakeholders to explore the building and its carbon emissions from different perspectives. Users can manipulate the image, which enhances the understanding of carbon emissions within the building and allows for a more engaging and immersive visualization experience. This interrogation is detailed in work by Mousa et al., (2016), showing in figure 12 how electricity and gas sensors can input data into 3D images to highlight key areas of increased carbon.

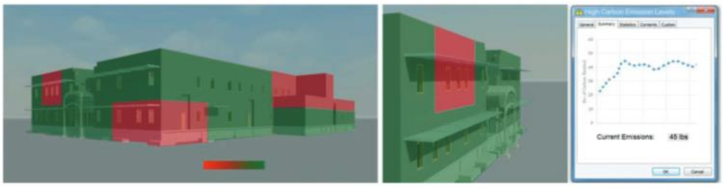


Figure 12: Mousa et al., (2016); interactive 3D image.

3.1.8 Virtual and augmented reality

Virtual reality (VR) and augmented reality (AR) were utilised in the reviewed literature to provide immersive and interactive experiences that help visualize carbon in the built environment by simulating various carbon scenarios in real-time, where users can visualize the carbon footprint of different building designs, materials, and systems by virtually exploring and interacting with 3D models. Suryawinata and Mariana (2022) provide an example of this by using AR to overlay energy information in buildings to aid in decision making (figure 13).

Figure 13: Suryawinata and Mariana (2022); AR energy visualisations.

In the context of carbon reduction VR allows architects and designers to visualize and analyze the energy systems of a building in a virtual environment. By examining the building model and analysing energy data, building professionals can identify opportunities for optimizing the energy system. This includes determining the appropriate equipment and devices needed in the building to minimize energy consumption and maximize energy efficiency. By optimizing the energy system, unnecessary energy use and carbon emissions can be reduced (Suryawinata and Mariana, 2022). Plus, by observing the virtual representation of the building and analysing energy data, architects can identify areas where energy consumption may be excessive or inefficient. This insight enables them to make design modifications, such as optimizing insulation, improving ventilation systems, or incorporating energy-saving technologies, which can lead to reduced energy use and associated carbon emissions (Chudikova and Faltejsek, 2019).

3.1.9. Flowchart

In contrast to the aforementioned visualisation methods, flowcharts were also utilised but I the sense of detailed the process of addressing carbon in buildings. Flowcharts are detected as tools used to visualize carbon in buildings by identifying the key processes or stages within the building's lifecycle that contribute to carbon emissions. We observe literature that uses these to visualise carbon associated with material production, construction, operation, and end-of-life stages. Plus, for each process, they are overserved to aid the determination of the inputs and outputs that contribute to carbon emissions. Inputs which can include raw materials, energy sources, and transportation, while outputs can include emissions such as CO2, CH4, or other greenhouse gases. Consequently, a flowchart is used to visually represent the flow of carbon emissions between the different processes and their corresponding inputs and outputs.

For instance, Gerilla et al., (2007) use a flow chart to detail the environmental assessment of wood and steel reinforced concrete housing construction (figure 14).

Figure 14: Gerilla et al., (2007); flow chart wood and concreate environmental assessment.

3.2 Overview of visualisation techniques

In the selected journal articles, the general goal of the visualizations is to show the relation between design variables or design alternatives and their relative carbon impact. Most building level carbon visualizations focus on the pre-construction stages of a build (figure 1). This suggests that within the research articles reviewed here, much of the temporal context in within earlier project stages. However, there are also papers that address the early design stages, indicating a recognition of the importance of considering carbon impacts at the outset of the design process. Carbon visualizations for early-stage design and detailed design stages differ in both purpose and detail. In the early-stage design, the focus is on exploring and generating design concepts, understanding the overall carbon implications, and identifying potential areas for carbon reduction. The visualizations at this stage are more conceptual and exploratory, aimed at generating ideas and informing design decisions. In contrast, in the detailed design stage, the focus shifts towards refining and implementing the design, optimizing specific components or systems, and ensuring compliance with performance targets. The visualizations at this stage are more detailed and specific, aimed at evaluating and fine-tuning the design for carbon reduction. Additionally, early-stage design visualizations tend to provide a broad understanding of the carbon implications and identifying key design strategies or areas of concern. Detailed design visualizations, on the other hand, require more precise and quantitative information, including specific data on materials, systems, and operational parameters. They may involve detailed calculations, simulations, or parametric models to assess the carbon impact accurately. As such different stakeholders and decision-makers are typically involved in early-stage and detailed design processes.

3.3. Use of visualisations

Overall carbon visualizations are used to help make informed decisions and selecting designs that have lower carbon footprints, by making complex carbon-related information more accessible and understandable, facilitating discussions and raising awareness about carbon reduction strategies. As such they permit the evaluation of different scenarios, trade-offs, and interventions related to carbon reduction in the built environment.

Specifically, the following four areas are detected in the literature as core reasons or uses as to why visualisation are utilised.

3.3.1 Identification of areas of high carbon emission

Carbon visualisations identified are used to detect the areas or activities within a building or construction project that contribute significantly to carbon emissions. This helps in prioritizing efforts for mitigation and improvement. For example, cascading target charts and multi-level pie charts permit the detection of specific building elements which are possibly causing significant impact on carbon projections (possibly in terms of embodied or operational carbon).

3.3.2 Decision making

Visualisations enable the comparison of different design alternatives or strategies in terms of their carbon footprint. This allows decision-makers to assess the environmental impact of various options and make informed choices to reduce carbon emissions. Bar charts offer an example of this, which is well-used within the literature. Numerous research publications utilise bar charts and box plots to compare different options which present themselves in the design process. Plus, carbon visualisations assist decision-makers in evaluating trade-offs between carbon reduction objectives, cost considerations, and other project requirements. By visually representing the carbon impacts of different options, visualisations facilitate informed decision-making and support the identification of optimal solutions. Flowcharts offer a key example of this representation, offering a route to trace how a solution could be optimised and reduced carbon.

3.3.3 Establishing aims and objectives.

Visual representations of carbon performance can be used for benchmarking purposes, comparing the carbon footprint of a building or project against established standards or industry averages. Visualisations facilitate the setting of carbon reduction targets and tracking progress towards achieving those targets. Key visualisations aiding this are line and bar charts expressing explicitly routes of most preferable outcome/performance.

3.3.4 Communicating carbon.

Carbon visualisations aid in effectively communicating carbon-related information to stakeholders, including clients, design teams, and policymakers. They help engage stakeholders in discussions about carbon reduction strategies, foster awareness, and encourage collaborative decision-making. In communicating with stakeholders, visualisations such as 3D colour coding, VR and AR provide increased pathways for interaction with data by stakeholders, providing visuals that are self-explanatory to practitioners and possibly non-practitioners alike.

4. Implications and recommendations

The literature review show evidence of using carbon visualisation for not only building professionals but also for stakeholders involved in the design process who may not have detailed carbon knowledge. Consequently, the role of visualizations is particularly relevant in the context of activities such as participatory design is particularly vital, made even more so by the increased level of carbon related data being used as KPIs in design processes (Wilberg, 2019).

The prevalence of bar and pie charts, along with line graphs, along with their variations, suggests that they are considered effective by their authors in conveying carbon-related data due to their simplicity and ease of interpretation. However, while bar charts are a useful tool for visualizing carbon in architectural design, they have certain limitations and may not offer a complete solution for all aspects of the design process. For instance, they primarily focus on representing quantitative data, such as carbon emissions or energy consumption, but they do not inherently convey spatial information. In building design, spatial considerations are crucial, and it may be necessary to integrate other types of visualizations, such as floor plans, 3D models, or diagrams, to understand the spatial distribution of carbon impacts within a building or across different design options. Plus, bar and line charts provide a high-level overview of carbon data, but they often lack contextual information that is essential for building decision-making. Designers need to consider various factors, such as building function, occupancy patterns, climate conditions, and material properties, which may not be adequately captured in a bar chart or similar. What is more building design involving intricate systems and interdependencies between various elements, such as building envelope, HVAC systems, renewable energy integration, and material selection. As such some simplified visualisations may struggle to represent the complexity of these systems and their interactions. The same can be said for charts and graphs being static representations of data and not offering interactive or dynamic features. In building design, it is often valuable to explore different scenarios, compare design alternatives, and assess the impact of various interventions in real-time, taking into account the experiential knowledge of designers. As such interactive visualizations, such as interactive dashboards or simulation tools, can provide more flexibility and allow designers to manipulate and explore the data in a dynamic and responsive manner. Consequently, we propose a key area of research moving forward is to ascertain the content, role and the extent to which these more interactive visualisation are valuable. Valuable to which stakeholder groups, at which time, and in which research contexts could be add to the visualisation methods such as charts and graphs, and how they may not be appropriate.

5. Conclusion

Visualisations and their need have been widely discussed in the literature. The importance of making carbon understandable for built environment professionals is growing as carbon is increasingly present in the design process. This paper presents a review of carbon visualisation tools, which shows that the majority use common visualisation options (e.g., pie charts or bar charts). In addition, we systematically reviewed the scientific literature and found a variety of visualisations and more complex visualisation options such as 3D imaging and Virtual Reality.

Carbon visualizations are shown to play a crucial role in facilitating informed decision-making and supporting the selection of designs with lower carbon footprints, along with assisting in detail the process of low carbon activities. By making complex carbon-related information more accessible and understandable, visualizations enable the identification of areas of high carbon emission, informed decision making, the establishment of aims and objectives and the communication of carbon to a wide audience. Implications of this research suggest a research agenda is needed, to explore the extent to which visualisations need to take into account the need for design to be responsive and take into account the experiential nature of construction and tackling carbon in buildings.

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Towards a City Sustainability Hub: Advancing Urban Sustainability Governance Through a Participatory Approach

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Abstract: The growing threat of climate change has created an urgency for cities to reduce their carbon footprints. Local governments play a critical role in this challenge and in creating the most liveable communities and sustainable urban environments. In an effort to advance a more proactive sustainability agenda at the subnational level, cities are experimenting with alternative forms of governance. Izmir Metropolitan Municipality ("IMM") is one of the leading local governments in Turkey that adapts a diverse set of strategies, action plans, and policies with respect to climate change in line with the sustainable development goals. It further pursues a participatory and multi-stakeholder form of urban sustainability governance through an original "city sustainability hub" which will also have a physical space for aligning and supporting sustainability-oriented NGOs, public and private institutions, researchers, practitioners and citizens that are already working on a wide range of related fields. The aim of this article is to examine the collective conceptual development process of the "Izmir Sustainability Hub" as a case study. In order to achieve a better understanding of the tendencies of the city stakeholders, an online workshop in four sessions was held with 140 participants focusing on scaling local and global sustainable development targets, working areas, governance and financial model of the Hub and urban/spatial scenarios. During the workshop, local tendencies and priorities were systematically identified and described. The results provided the general framework for the Izmir Sustainability Hub and also a basis for the building scenario of the zero-carbon architectural project competition, which will be the first of its kind in Turkey.

Keywords: sustainability transition, participatory approach, workshop, city hub, carbon reduction

1. Introduction

Cities of the era are expected to meet multi-scale sustainability goals ranging from economic and environmental to social aspects while trying to cope with important challenges such as climate change, population growth, pollution and resource consumption (Sharifi, 2019). Within these challenges, climate change as a global phenomenon is already causing migrations, outbreaks, disasters, and environmental destructions in different ways, speed, and shape worldwide. While urban areas are key contributors to climate change and environmental issues account for 70% of the global GHG emissions and 78% of the world's energy use, they are also a key part of the solution with a significant potential to lead the way to a resilient future (UN-Habitat, 2022).

Therefore, cities implement many strategies to reduce their impact on the global ecosystem and to ensure urban sustainability transition which is essential for a radical shift. Several studies have been conducted to understand the sustainability transition mechanisms and dynamics in cities versus these systemic challenges, that neither individual technological solutions nor individual policy tools can effectively solve alone (Coenen et al., 2012; Geels and Schot, 2007; Gorissen et al., 2018; Larbi et al., 2021; Mabon and Shih, 2018; Markard et al., 2012).

Transitions toward sustainability require concerted, strategic efforts to link and synchronize multiple interrelations. Local governments play an important role as they are responsible for translating ambitious national and global goals and visions into local practices (Palm et al., 2019). To facilitate these shifts, local governments have increasingly adopted novel forms of sustainability governance (Smedby and Quitzau, 2016).

The concept of governance has been a central topic in sustainability discourse for two decades, defined in various ways. In its broadest sense, it is referred to the transition to novel dynamics from traditional governing, grounded in complex multi-actor interactions at multiple levels involving the state, market, and civil society (Evans et al., 2006). Several studies have conceptualized "governance" as the interaction of structural, procedural, and content-related factors in collective action production, to build an understanding of the complex character of the current governance systems, of which collective interest in this context is sustainability (Lange et al., 2013; van der Heijden, 2013; Van Zeijl-Rozema et al., 2008).

Within the cities' sustainability transition efforts, a local government as the intermediator of these interventions can play a leading role by paving the way for advancing urban sustainability governance that scales from global, national, to local levels. Given Turkey's centralized national context, IMM has been a leading local government in the sustainability transition. This has been achieved by preparing climate and green city action plans for local implementation, granting international green funds, incorporating international sustainable networks, implementing SDGs in IMM Strategic Plan that is broadened with ten additional local goals, supporting sustainable urban development network and developing sustainability-oriented strategies, local policies, and practices.

Sustainability and climate adaptation planning and implementation have progressed across diverse fields and projects, with varying effectiveness. Despite progress, adaptation gaps exist through the complex character of sustainability governance. The city of Izmir faces contextual constraints that impede its sustainability transition, including restricted jurisdiction of municipalities and extensive state supervision. Additionally, issues with the applications in complex metropolitan context, such as insufficient coordination among various municipal departments and stakeholders, challenges in socio-technical translations, and a lack of continuous participatory mechanisms, serve as barriers to progress (Kadirbeyoglu and Kutlu, 2023).

Therefore, IMM proposed a novel initiative to accelerate local sustainability transition and advance governance through a city sustainability hub that will also have an institutional space that is a need for sustainability transitions supporting a diversity of formats for multi-stakeholder interaction (Frantzeskaki and Rok, 2018).

This article presents the process of development of a new form of consensus that constitutes a "city sustainability governance" through a participatory approach, focusing on the description of the process that led to the set-up and start of the "Izmir Sustainability Hub". The aim of this article is to examine the collective conceptual development process of the "Izmir Sustainability Hub" as a case study. In order to provide a participatory process forming a new sustainability governance model for the city, an online workshop in one general and simultaneous 3 sessions was held with 140 participants focusing on scaling local and global sustainable development targets, working areas, governance and financial model of the Hub, and urban/spatial scenarios. During the workshop, local tendencies and priorities were systematically identified and described. The results provided a preliminary sustainability governance framework for the Hub and also a basis for the building scenario of the zero-carbon architectural project competition, which will be the first of its kind in Turkey.

1.1 IMM in Pursuit of Sustainability

Izmir Metropolitan Municipality adopts a holistic approach to sustainable urban development. All strategic works and priorities of IMM include a comprehensive vision for a greener and more sustainable Izmir. The Green City Action Plan (GCAP) and the Sustainable

Energy and Climate Action Plan (SECAP) were developed together and are significant reflections of this approach. With these strategies, Izmir aims to increase environmental performance, reduce greenhouse gas emissions and improve climate resilience.

Together with GCAP, which offers a comprehensive plan to improve Izmir's environmental sustainability with 47 actions proposed in the fields of infrastructure, policy, capacity building, and advocacy, SECAP aims to increase climate resilience by reducing emissions by 40% until 2030.

IMM's 2020-2024 Strategic Plan is further aligned with the SDGs of the UN. Moreover, the plan includes ten localized SDGs for the city of Izmir. Along with the Strategic Plan, which includes measures for sustainable management of urban services, natural resource efficiency, and sustainable urban development, a Green Infrastructure Strategy has been developed to promote and expand sustainability throughout the city. In addition, many climate change and energy efficiency-focused projects are implemented within the municipality.

Izmir Sustainable Urban Development Network was established as a city coalition that endorses these objectives as a means of governance.

Figure 1. Izmir +10 Goals in Strategic Plan integrated with 17 SDG

2. Methodology

The conceptualization process for the "Izmir Sustainability Hub" is evaluated as a novel sustainability initiative for the "sustainability governance" of Izmir. This study adopted a multi-stakeholder workshop as a case study in data collection, analysis, and interpretations of the key findings. Both quantitative and qualitative research methods were used in conducting the aforesaid multi-stakeholder "workshop" and assessing the results to identify the optimum framework for the Hub.

Ørngreen and Levinsen, (2017) identify workshops as a means, workshops as practice, and workshops as a research methodology through literature review and also highlight that the term "workshop" has frequently been associated with the term "participation" since the

1990s. Adoption of workshops is a prevalent strategy in order to strengthen the participatory approach, augment stakeholder connections, foster reliance, and collaboratively generate viable resolutions for the objective of sustainability (Bertella et al., 2021). There are multiple implementation models for interactive workshops each with its own tools, possible group types, and capacities for facilitation. A specific workshop methodology is constructed systematically in 7 steps as given in detail in Table 1.

Table 1. Workshop methodology

Step 1: Workshop Design: Participatory approaches have been used to foster an attitude that is open to innovation and change, as well as to involve stakeholders in the process of decision-making. With this regard, first an internal team leading the project designed a framework for the workshop by taking into account the topics, expected outcomes, potential groups of participants, the optimum number of sessions, moderators, facilitators, online platforms, and tools.

The topic of the workshop was the development of a conceptual framework for the "Izmir Sustainability Hub" as a multi-stakeholder sustainability transition initiative and also a knowledge and collaboration space. The workshop aimed to explore the available research evidence related to three main guiding questions:

What are the potential domains of work for the Izmir Sustainability Hub? (a)

What would be the optimal governance and financial model for the Izmir Sustainability Hub? (b)

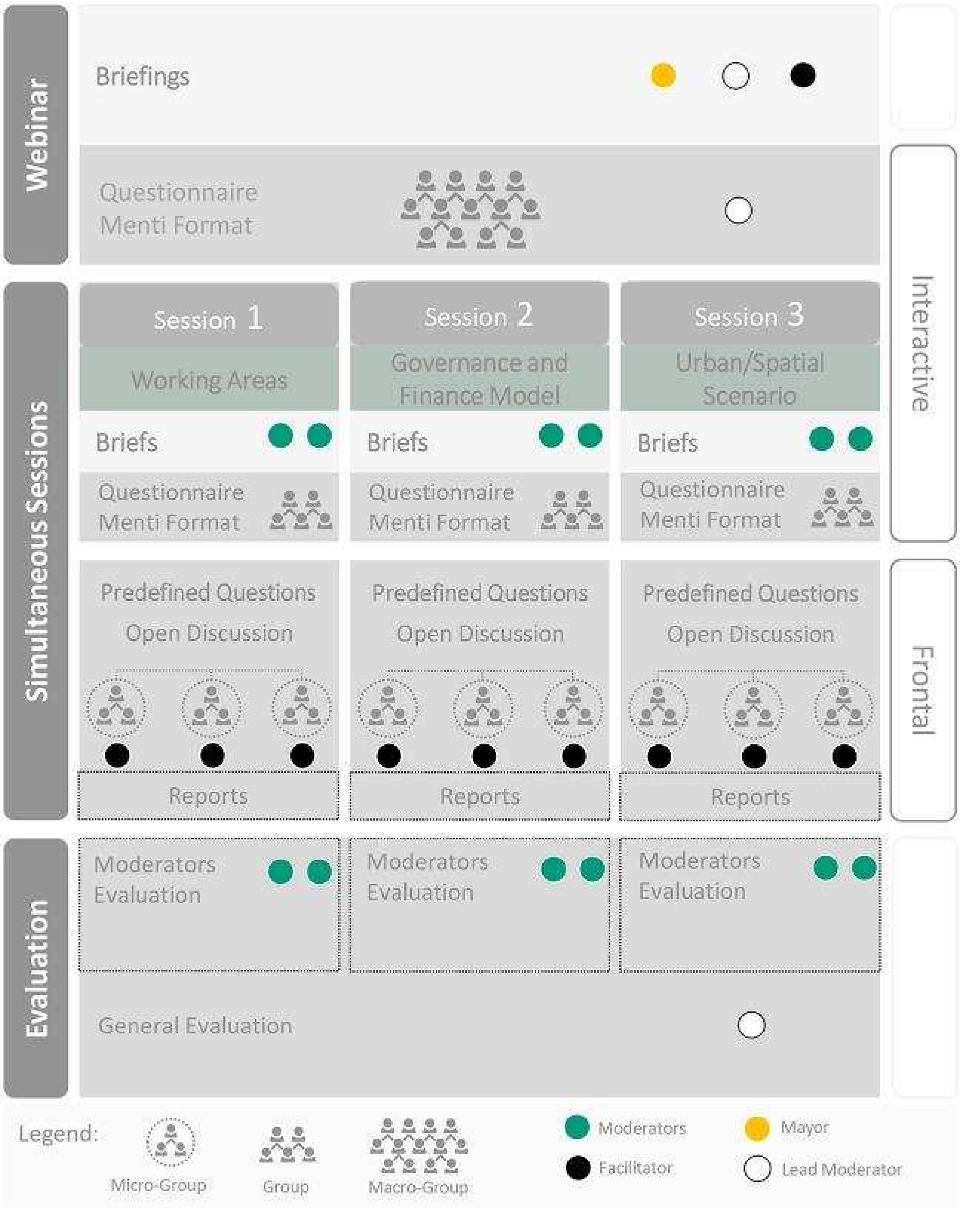
How can urban/spatial scenarios be on the axis of the Izmir Sustainability Hub? (c)

Given these questions, it was planned to hold 1 plenary session and 3 simultaneous sessions on an online platform considering the post-COVID conditions.

Step 2: Actors Organisation and Participants: The executive team for the workshop was composed of a sufficient number of relevant specialists depending on the size and content of the sessions: the chairman and eight moderators were prevalent academics and professionals in their field. Additional ten facilitators were engaged as an expanded internal professionals' team within the IMM to ease communication and future collaboration. A core internal project team with three professionals provided the overall execution of the workshop.

Participants from mainly 9 different groups representing different functions of the IMM, municipal companies, district municipalities, universities, foundations/associations/agencies, research centres, chambers, various platforms, and other sustainability-oriented institutions were invited. Priority was given to institutions in Izmir, but institutions operating in other geographies of the country that can contribute to sustainability were been invited through the facilitation of the online platform.

Table 2. Workshop structure



Step 3: Webinar: The first session of the workshop was designed in two parts: briefings and an ice-breaking questionnaire with Menti which is an interactive interface. Briefings focused on the sustainability pursuit of Izmir, the background and vision of the S-Hub Project, and the workshop procedure. Three questions on general sustainability connotations, local SDG priorities, and urban environmental sustainability priorities were asked via Menti to the macro group.

Step 4: Simultaneous Sessions-interactive: The aim was to explore the core research topics (a.b.c) of the workshop in three concurrent interactive sessions based on the questions in Table 3 circulated through the Menti interface to harness the topic group's collective intelligence and higher participation. The types of questions asked consisted of word clouds, choices, and responses to gain insight with multiple depths.

Step 5: Simultaneous Sessions-frontal: This step aimed to expand exploration efforts with an open discussion oriented by predefined questions given in Table 3. Participants of the previous macro-group were divided into micro-groups of approximately ten. A facilitator for each group shared the questions and took notes for internal reporting purposes. Each participant was encouraged to contribute effectively and share ideas.

Step 6: Reporting and Evaluation: Following completion of the frontal part, notes from the micro-group were collected by the sessions' moderators to produce comprehensive session reports. These reports were produced and presented by moderators to the macro-group and the chairman of the workshop performed an overall evaluation to the audience.

Step 7: Dissemination of the Final Report: A workshop report including briefing documentation and reports from all the sessions held was produced and shared with all participants.

Table 3. Workshop inquiries

	Session 1	Session 2	Session 3
	GSQ1-What is your first notion regarding sustainability? GSQ2-Which of the United Nations' Sustainable Development Goals are of higher priority for the city of Izmir? GSQ3-What are the primary areas of focus for urban-environmental sustainability in Izmir?		
Interactive	S1IQ1-If you choose another word instead of sustainability, what would that word be? S1IQ2-What should be the main working fields of the Izmir Sustainability Hub? S1IQ3-What should the action areas of the Izmir Sustainability Hub be? S1IQ4-What could be the constraints in the Hub's realization process? S1IQ5-What other working fields and Components could be required in the future?	S2IQ1-Which of the SDGs are of higher priority for the Hub? S2IQ2-What are the key principles that should guide the establishment of the Hub with an efficient governance model? S2IQ3-Who are the potential stakeholders of the Izmir Sustainability Hub? S2IQ4-What areas of expertise should be envisioned for the Izmir Sustainability Hub? S2IQ5-What could be the Hub's performance indicators?	S3IQ1-What do you consider to be the most significant challenge that the world will encounter within the next half-century? S3IQ2-What are the fundamental criteria that make structures sustainable? S3IQ3-What are the qualities that are required for urban environments to be sustainable? S3IQ4-In what ways can sustainable buildings contribute to the development and transformation of their urban environment? S3IQ5-How can the Izmir Sustainability Center transform its innovative solutions for the city into an urban-spatial interface experience?
Frontal	S1FQ1-What should be the main working fields of the Izmir Sustainability Hub? S1FQ2-What should the action areas of the Izmir Sustainability Hub be? S1FQ3-How should the monitoring evaluation step and organization be involved in the activities of the center? S1FQ4-What are the challenges that the center may encounter? S1FQ5-What mechanisms and methods are required to be repeatable and measurable in order to carry out these steps elsewhere? S1FQ6-Which partnerships and mechanisms should the Hub engage with?	S2FQ1-What is the purpose of the Izmir Sustainability Hub and who determines it? S2FQ2-What are the potential configurations for the alternative organizational charts of the Hub? S2FQ3-What strategies can be employed by the center to effectively engage with urban stakeholders, the IMM and district mmunicipalities? S2FQ4-What should be the alternative sources of financing for the center, the revenue model for financing sources, and the performance metrics for its managerial units? S2FQ5-What should be the fundamental orientations and main objectives in the Hub's long-term policies and development strategies?	S3FQ1-What areas do you consider sustainability should be represented in? S3FQ2-What are the qualities that are required for urban environments to be sustainable? S3FQ3-What structural and technical features could the Hub's building possess to trigger a sustainable future in an old industrial area? S3FQ4-What are the strategies needed to initiate a transformation in the vicinity of the sustainable and zero-carbon building of the Hub?

3. Results and Discussion

Further analysis of the workshop outcomes was performed to construct a preliminary framework for the city sustainability hub. Besides quantitative questionnaire results collected through the Menti interface, a qualitative content analysis was also conducted for the open discussion sessions. Content analysis provides a concentrated explanation of a phenomenon from verbal, written, or visual language (Chang et al., 2017; Elo and Kyngäs, 2008).

Workshop session outcomes were evaluated for every 4 sessions (General, S1: Working Areas, S2: Governance and Financial Model, S3: Urban Spatial Scenario).

General Session

The chairman of the workshop led the general session using the Menti interactive tool, and three questions were posed to the macro-group to identify the general tendencies of the participants on sustainability conception, prior local SDGs, and urban-environmental sustainability issues. According to the responses from the general session on question 1 (GSQ1); the word “sustainability” was connotated to participants respectively: nature, future, environment, continuity, and life. The top five targets within the local priorities of Sustainable Development goals were determined through a vote o question 2 (GSQ2), with emphasis placed on Good Health and Well-Being-SDG3(12%), Sustainable Cities and Communities-SDG11(11%), Affordable and Clean Energy-SDG7(10%), Clean Water and Sanitation-SDG6(10%) and Climate Action-SDG13(9%) targets. Workshop participants evaluated energy, transportation, water, green areas, and construction issues as local priorities in the field of urban-environmental sustainability in question 3 (GSQ3).

Simultaneous Session1: Working Areas

After the webinar section with general participation as a macro-group, the participants moved to the simultaneous sessions in which they were assigned to particular session groups. One of these simultaneous sessions was the "Working Areas Session". It was held in two sections: an interactive section and a frontal, open discussion.

Session 1 interactive part topic groups responded to five Menti questions given in Table 4. S1IQ1 the initial inquiry pertains to the identification of a suitable alternative term for sustainability. Findings indicated that the attendants mostly established a correlation between the notion of sustainability and the concepts of continuity, resilience, harmony, and circularity. The main working areas of the Hub questioned in S1IQ2, were revealed respectively as energy, waste management, water management, climate, and buildings, as indicated in the responses provided. S1IQ3 was given as an eight-option choice question; data-collection/analysis (22%), policy/strategy development (19%), implementation (15%), monitoring-evaluation (13%), and research (9%) were listed as priority action areas in quick responses to action areas while international knowledge exchange (8%), education (8%) and the development of urban indicators (6%) are following. Responses to S1IQ4 regarding limitations revealed that constraints related to financial resources, policy, legislation, planning, and skilled workforce were considered the most significant. By taking into account the potential for the development of the Hub, question S1IQ5 was about what additional activities and components the Hub might have in the future. The fact that the Hub itself could be a mechanism that can develop and fund the city’s sustainability efforts was ranked first as an important headline. Cooperation, education and transportation were also seen as areas expected to emerge and expand in the future.

Table 4. The list of the top five responses in the Session1 interactive part has been arranged in order of their respective weights.

Session 1 — Interactive

	1	2	3	4	5
S1IQ1-If you choose another word instead of sustainability, what would that word be?	continuity	resilience	harmony	coherence	circularity
S1IQ2-What should be the main working fields of the Izmir Sustainability Hub?	energy	waste management	water management	climate	buildings
S1IQ3-What should the action areas of the Izmir Sustainability Hub be?	(22%)data-collection/analysis	(19%)policy/strategy development	(15%) implementation	(13%)monitoring-evaluation	(9%) research
S1IQ4-What could be the constraints in the Hub's realization process?	financial resources	policy	legislation	planning	skilled workforce
S1IQ5-What other working fields and Components could be required in the future?	funding	collaboration	education	transportation	

Session 1 frontal part was conducted in three micro-groups as open discussion directed by predefined questions, to use time effectively and promote participation. The first two questions S1FQ1 and S1FQ2 which were also posed in the interactive part were redirected to gain a broader insight from participants. 6 common questions on the working areas of the Hub and the areas of action, the monitoring/evaluation steps required in the operation of the Hub, difficulties in the execution of the activities, possible mechanisms and partnerships so that the work of the Hub is repeatable and measurable were discussed collectively. A content analysis was carried out by the researchers, combining the results of the 3 micro-groups.

Simultaneous Session2: Governance and Finance Model

Four micro-groups conducted the second session's research on governance and financial model prospects for the Hub in interactive and frontal parts. The interactive part contained 5 questions asked through the Menti tool. According to votes in S2IQ1, SDGs that are expected to be a priority for the Hub appeared as SDG3(16%)-SDG6(12%)-SDG11(11%)-SDG7(11%), and SDG13(10%). A similar question was asked in the general session for the city, where SDG3-SDG11-SDG7-SDG6- SDG13 came to the fore. It is possible to say that parallelism has been seen. The concepts of participation, transparency, inclusion, technological approach, and integrity came to the fore for the main principles of the Hub, as inquired in S2IQ2. When asked about potential stakeholders in S2IQ3, universities were ranked first, followed by chambers, the private sector, NGOs, research centres, IZKA(Izmir Development Agency), citizens, and international initiatives. Renewable energy, environment, agriculture, transportation, and architecture/city planning fields are seen as the fields of expertise envisaged by the participants of this session through the S2IQ4. As the performance indicator of the Hub posed in S2IQ5, the carbon emission reduction was ranked first (20%). Adaptation to climate change (19%), development of sustainable production and consumption in the city (19%), conservation of urban ecology and biodiversity (15%), sustainable buildings and urban development (14%) are identified as prominent performance indicators for the Hub, while circular economy transition (9%) and socio-cultural development (5%) are the following indicators.

Table 5. The list of the top five responses in Session 2 interactive part has been arranged in order of their respective weights.

Session 2 — Interactive

	1	2	3	4	5
S2IQ1-Which of the Sustainable Development Goals (17 SDGs) should the Izmir Sustainability Hub prioritize?	(16%)-SDG3	(12%)-SDG6	(11%)-SDG11	(11%)-SDG7	(10%)-SDG13
S2IQ2-What should be the main principles for the center to be established with an effective governance model?	participation	transparency	inclusion	technological approach	integrity
S2IQ3-Who should be the stakeholders of the Izmir Sustainability Hub?	universities	chambers	private sector	NGOs	research centres
S2IQ4-What should be the areas of expertise envisaged to be included in the Izmir Sustainability Hub?	renewable energy	environment	agriculture	transportation	architecture/city planning
S2IQ5-What could be the performance indicators of the hub?	(20%)carbon emission reduction	(19%)adaptation to climate change	(19%)development of sustainable production and consumption in the city	(15%) conservation of urban ecology	(14%) sustainable built environment

During Session 2, the frontal part of the workshop was divided into four micro-groups, where an open discussion was held. A total of six inquiries were posed regarding its organizational structure, its collaboration with urban stakeholders, its financial model, and long-term policies and developmental goals. Considering the participant groups' expertise on governance and finance, S2FQ1 on the objectives of the Hub highlights a more holistic view slightly differing from the session one results, such as localization and implementation of the 17 SDGs, supporting the transition to the circular economy, improving urban health, safety, and aesthetics, and creating a multi-stakeholder public platform. Multi-stakeholder, participant, and horizontal associations (Hub) are proposed essentials to the formation of the organizational structure, according to answers to S2FQ2. Expertise and research sections on working areas of the Hub, the advisory board, volunteering support, and citizen engagement are also prevalent in the organization. An autonomous or semi-autonomous structure is also proposed. S2FQ3 aims to explore prospects for the Hub's relationship with city stakeholders. Besides represented institutions and municipalities within the governance structure, a collaboration of regional actors by specific theme projects, participation of different stakeholders by workshops, unit for business and project development, idea development competitions, citizen science, online platform, and network are distilled as instruments of integration of wider city stakeholders. The financial model of the Hub is crucial for continuity and was discussed around S2FQ4. Establishing a city sustainability fund, devising a membership mechanism, allocating budgetary funds from local governments to create SDG shares, receiving support from the business associations of Izmir, and obtaining international and project-based funds are the main components of the financial model. S2FQ5 on long-term trends in policies and development strategies reflects the prospects on more harmonised sustainability transition acts.

To achieve a common goal, it is imperative to integrate distinct efforts and mechanisms. An emphasis on the sustainability of the urban environment and buildings has emerged underlying the need for local certification for carbon reduction and sustainability assessment in the built environment. Continuous data collection and an accessible database to prepare a scientific background for decision-making and policy development are considered priority issues for both short and long-term development. It is vital for the Hub to prioritize sustainability education and facilitate cross-disciplinary and cross-expertise knowledge sharing.

Simultaneous Session3: Urban/Spatial Scenario

The establishment of a city sustainability hub with an architectural common space is vital for facilitating sustainability transitions at the local level. This Hub space will serve as a platform for multi-stakeholder interaction, accommodating diverse formats to advance governance and promote local sustainability. Gaining insights into the urban spatial possibilities of the Hub, which serves as a preliminary step toward architectural reflection, was the main objective of this session.

In the interactive part of the session, queries through the lenses of urban/spatial perspectives were examined. The introductory query sought to identify the foremost challenge that the world will confront in the next half-century. Water, food, global warming, energy, and migration have emerged as prominent problem areas. In S3IQ2, the fundamental factors that determine the sustainability of buildings were considered, with emphasis respectively placed on energy efficiency, waste management, water management, sustainable materials, and passive design criteria. When the same question was addressed for the urban scale in S3IQ3; while energy efficiency was in the first place as a common criterion, it was seen that concepts such as green areas, recycling, accessibility, and environmentally friendly structures came to the fore. The S3IQ4 addressed the sustainable buildings' potential to transform their vicinity. Model building, improving the quality of life, increasing the feeling of belonging to the place, reducing the carbon footprint, and creating a healthy environment were prioritized transformative effects. The primary answer to the inquiry in S3IQ5 of how the Hub can translate its inventive solutions into a spatial interface involved implementing Interactive experience areas and a living laboratory. Technology/research and innovation ecosystem, innovative architectural design, real-time data interfaces, education, co-working, project development and accommodation facilities for researchers were the highlighted topics.

In the studies conducted by three micro-groups during the urban and spatial scenario frontal session, four queries were posed in common as given in Table 3. The areas of representation of sustainability focused on the characteristics of a sustainable environment, the technical/spatial features of the building, and what could be done to initiate environmental change.

Table 6. The list of the top five responses in the Session3 interactive part has been arranged in order of their respective weights.

Session 3 — Interactive

	1	2	3	4	5
S3IQ1-What do you think is the biggest problem the world will face in the next 50 years?	water	food	global warming	energy	migration
S3IQ2-What are the basic criteria that make buildings sustainable?	energy efficiency	waste management	water management	sustainable materials	passive design
S3IQ3-What characteristics do you think the urban built environment should have in order to be sustainable?	energy efficiency	green areas	recycling	accessibility	environmentally friendly structures
S3IQ4-In what ways can sustainable buildings improve and transform the urban environment in which they are located?	Model building	improving the quality of life	increasing the feeling of belonging to the place	reducing the carbon footprint	creating a healthy environment
S3IQ5-How can the hub transform the innovative solutions it will offer to the city into an urban-spatial interface experience?	interactive experience spaces	technological research and innovation ecosystem	creative innovative architectural design	real-time data interfaces	training, co-working, project production, accommodation

S3FQ1 opened a discussion on which areas the sustainability should be represented through the Hub. Climate responsive design, demonstrative interactive spaces and Hub building as a pilot on sustainable and resilient architecture were prominent outcomes expressing the session targets within diverse topics and actions of sustainability. Local strategies in sustainability, integration and coordination of different fields of expertise and professional groups were also supporting results in session 1. Climate change was further seen as one of the main challenge areas of the Hub. Participants evaluated the features of the sustainable building environment through S3FQ2. Design with a life cycle approach, material selection priorities in natural, low-cost, local, digitalization to smart architectural/urban design and implementations, zero energy/zero carbon buildings supported by passive design technics, and a local sustainable building certification program were essentials for the micro-groups of the session. S3FQ3 directed the discussion to the suggested urban environment for the building of the Hub which is a former industrial area near the coast. Circularity, resilience, reversibility, brownfield, climate mitigation, and risk management emerged as concepts to be addressed together. An alternative perspective was also considered whereby the Hub was conceptualized as a decentralized network rather than a singular Hub.

The inquiry into how the development of a sustainable hub building can serve as a catalyst for transformation within its vicinity was raised through S3FQ4. The development of a pilot building that operates with zero carbon emissions was evaluated as a potential catalyst for transformative change. The building can hold a multifaceted and multilevel function of awareness spanning from the initial design phase to its end-of-life stage. A hub with the potential for children and youth-friendly experience and attraction can be established with interactive interfaces and focused programs. Experimental architectural and urban implementations can pave the way for local sustainable architectural innovative solutions. The Hub space has the potential to facilitate citizens in acquiring knowledge and demand about sustainability and sustainable architecture.

This study provided an impact that reinforced local support for the Hub, thereby ensuring that all potential city stakeholders were adequately informed and engaged in collaborative considerations from the project's inception. While the outcomes obtained from a single-day online study are simplified and broad in nature, they have generated adequate data to guide the development of subsequent procedures. The need for conducting frontal focus group studies has been identified due to the complex nature of the subject and the importance of ensuring the readability and depth of the final results.

The overall findings of this online workshop provided a general mapping of the potential stakeholders' approaches and recommendations for a ‘city sustainability hub’ for Izmir. Ensuring the alignment between current practices/policies/organizations on urban sustainability and the workshop’s future recommendations on given strategic themes is of paramount importance for the subsequent stages of the process.

4. Conclusion

Participants of the workshop having expertise in diverse fields with broad perspectives on sustainability, presented various solutions and strategies to encourage sustainability transition and governance and also provided a valuable resource and source of motivation for the establishment of the “city sustainability hub”.

The Hub’s proposed working areas emerged in diverse domains encompassed by the city context. However, the present dynamics have promoted an increased focus on the matter of energy, resource management, climate change, and the building environment. The proposed main action areas for the Hub include data collection, which is regarded as a crucial requirement also for Turkey, the establishment of policy and strategy-making mechanisms, integrated with monitoring and evaluation mechanisms for sustainability, are considered significant areas of operation. Alignment and harmonization of the multi-level sustainability-oriented projects is one of the prominent proposed actions. The Izmir Sustainability Hub (S-Hub) is a novel model for Turkey, which is expected to prioritize Sustainable Development Goals, particularly SDG3, SDG6, SDG7, SDG11, and SDG13 with a particular focus on the urban context. It is defined as a hub that operates based on transparency, participation, and inclusivity principles, which will foster the development of the city's collective intelligence. Improvement of urban sustainability culture, development of knowledge and innovation for sustainability transitions, and promotion of city sustainability research, analysis, and assessment are considered overall functional outcomes.

The evaluation highlights the main stakeholders including universities, NGOs, municipalities, chambers, research centres, the private sector, and international organizations, with the IMM. The establishment of the "Sustainable City Fund" has been identified as a potential approach to enhance the economic sustainability of the Hub by facilitating collaborative financing among stakeholders. Joint projects can be funded through contractual arrangements. The allocation of resources from ministries and municipalities towards sustainability initiatives has been deemed crucial, with a particular emphasis on directing these resources towards S-Hub as part of national endeavour. Additionally, the assessment of financial resources in the form of grants through international project calls is recommended.

It is projected that the Hub will contribute to the sustainable transition and transformation of the city which will be strengthened by the Hub’s communication and engagement with citizens under the theme of sustainability. SDG 11, which is directly related to the building sector, emphasizes the necessity of designing a Hub space in line with the goal of “Sustainable Cities and Communities” that can be demonstrative of where improvements can be made in the building sector which is responsible for a significant share in global energy consumption, resource consumption, waste production and global greenhouse gas emissions.

The method of learning by experiencing has been proposed to increase the involvement of building users through innovative interfaces and spaces designed to transfer these experiences to citizens and stakeholders.

Further research will be conducted to reinforce the organizational framework of the Izmir Sustainability Hub based on the initial study. A series of workshops with local and international participants will be organized with a specific focus on each strategic theme, targeting narrowed-down groups. A national competition process with a focus on sustainable architecture is currently underway, aimed at exploring and generating a sustainable spatial response for the Hub, as the first zero-carbon public building in Izmir.

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Impact of Location Selection on Whole Life Carbon of a Multi-National Manufacturing Facility

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Abstract: Global companies locate new facilities to suit their market opportunities and budgetary costs, however, with increasing expectations to cut emissions and with expectations to meet net-zero commitments, selecting sites based on resulting whole-life emissions is becoming a realistic consideration for business decision-making.

This paper documents a series of scenario-based whole-life carbon modelling studies undertaken to review the design and carbon emissions implications of geographical choices that a multinational manufacturing corporation might consider when selecting locations for new product expansion.

Initially, a new UK-based manufacturing facility was modelled at RIBA stages 4 to 5, then the same production line parameters were "transported" to five other plausible locations based on the company's anticipated market outlet for the product. The building was modelled with alternative key supply chain environmental product declarations for embodied impact, considered energy performance expectations to meet local regulatory mandates, solar power potential and grid energy mix.

Considerable variation was found to result over a 60-year design life depending on the choice of location for a proposed new facility development. The findings will be of interest to businesses that wish to strategize energy consumption and emissions globally and design teams delivering their projects.

Keywords: Energy, Whole Life Carbon, Location, Manufacturing Facility, Carbon Intensity, Design

1. Introduction

The contribution of operational energy use emissions to climate change within the built environment is well established (UK and global). The United Nations Environment Programme (UNEP, 2019), reports that the manufacture of building materials makes up 11% of global greenhouse gas emissions.

Increasingly, multinational companies have recognised the climate emergency and presented targets for territorial decarbonisation of facilities (scope 1 and 2 emissions) and supply chains (scope 3) (GGP, 2004). There is a tendency of a corporate organisation to utilise sustainability information for marketing purposes opening the validity of the underlying data to scrutiny. Many companies may have made reduction strategy declarations and will anticipate the necessity of off-setting budget requirements in the drive towards net zero business operations.

Large companies that procure buildings however do report their scope 1 and 2 emissions via the Streamlined Energy and Carbon Reporting (SECR, 2019) which has been introduced through the Companies (Directors' Reports) and Limited Liability Partnerships (Energy and Carbon Report) Regulations 2018. This supplements existing narrative reporting requirements under the Companies Act 2006. An organisation will fall within the scope of the SECR if it is a quoted company, a large unquoted company or a large limited-liability partnership incorporated in the UK (SECR, 2019). Reporting scope 3 emissions remains a voluntary decision.

This research considers corporate decisions for capital expenditure in a global setting. It assumes that a new product line will require manufacturing in a variety of international locations to supply an identified market. Ultimately the manufacturer should strive to provide carbon labelling of their products and want to achieve parity on all product labelling or set a precedent target at the best factory for declarations across their entire estate.

This paper aims to review what embodied and whole-life emission outcomes would be probable if constructing a new manufacturing facility in global locations suited to capital investment. This will allow testing of the hypothesis that locations with a lower or higher whole-life carbon emissions prognosis may drive future investment decisions. The study is conducted by measuring the life cycle impacts of a real project as a baseline. This involves the assessment of energy consumption for the "regulated" parts of the building such as welfare and offices and the recognition of the consistent unregulated component of energy use which is consumed as the core purpose of a manufacturing facility. The balance between all operational and embodied impacts was considered to recognise which are the biggest impacts. Finally, strategy indicators were identified to reduce the embodied impact of future capital investments in any global location.

Measuring to manage is a familiar concept and recognising where a proposed building design sits concerning published benchmarks and targets for UK construction is a key metric. Targets are set such as the RIBA 2030 climate challenge (RIBA, 2021) and the UK Green Buildings Council Race to Zero initiative (UKGBC, 2021a). However, whilst regulation of operational energy has been successful in reducing regulated emissions in new buildings, national standards for embodied impact in the UK are shortly anticipated.

Two parallel initiatives are currently competing to lobby the UK government to address this gap. LETI (2023) is addressing a cap on embodied emissions on Greater London Authority for new development over 10,000m^2 GIA, meanwhile, Part Z (2023) seeks to have the consideration of embodied impact brought into the suite of building regulations. Both of these initiatives would see local authorities applying new standards during existing and well-established planning application and construction compliance processes. There is no anticipated commencement for either of these options and the construction industry relies on a combination of voluntary reporting through framework agreements and materials assessments as part of BREEAM certification (UKGB, 2021 c).

The standard for lifecycle assessment of buildings (BS EN 15978:2011) with life cycle stages defined to allow clear alignment with Environmental Product Declarations for construction materials is used. Assessment Boundaries of the UK are guided by professional bodies RIBA and RICS with a convention of using a 60-year design life is assumed. And RICS Whole Life Carbon modules A1-A5, B1-B5, C1-C4 including sequestration are used. Analysis should include a minimum of 95% of the cost, substructure, superstructure, finishes, fixed furniture, fixtures, equipment, building services and associated refrigerant leakage.

2. Baseline Project Lifecycle Assessment

The study uses a high-tech manufacturing building project which had reached RIBA stage 5 and was under construction as a baseline. There was no client-driven policy to offset emissions for capital investments although the current RICS guidance methodology does allow absorption of CO_2e from carbonisation of exposed concrete and trees included in landscaping. This potential offset has been excluded from the calculations.

The embodied impact was addressed intuitively by a design team focussed primarily on the significant reduction of regulated and unregulated energy loads. For example, choice of cladding to achieve thermal properties and airtightness, utilisation of off-site fabrication to reduce the impact of waste on site, and on-site generation installations to contribute to renewable energy supply. The design incorporated conventional steel frame with offsite manufacture of the services and plant space ceiling void to reduce the construction programme and reduce waste on site. Efficient and airtight envelope were provided by a composite panel system, good quality glazing and doors. Specification of finish materials which are recognised as reduced impact and materials also that have recyclable end-of-life credentials. Compliance with building regulations in the UK prior to the most recent regulatory uplift of 2022 had been undertaken by the incumbent project design team. Building management systems were specified to minimise regulated energy load with dedicated facilities management support through commissioning and operation to maintain exacting environmental conditions within the manufacturing areas and best practice comfort and energy performance for occupied zones, area defined on BRUKL (NCM:SBEM, 2021) document as 7561m^2.

Initially, the proposed manufacturing facility was modelled using parametric software (Revit) by the architectural team. The export of parametric data to Life cycle assessment software (OneclickLCA) allowed the assembly of all constituent parts to be documented. A series of information refinement workshops with the architectural designers allowed an accurate and realistic model to be developed and clarified the elements which were excluded from the study. Technical literature was provided by the architect to clarify the material specifications; Specialised cleanroom internal linings systems, metal grating walkway decks in the service voids and external cladding for walls and roof.

Fabricators were asked to confirm the quantity of steel in the main frame and the source of steel components. It was found that the import of some elements had been renegotiated by contractors following recent geopolitical situations in Ukraine and China. A small element of biogenic carbon is stored in plywood and some other timber fixtures. LCA models capture this separately and only include it in whole life, timber framing or packing around doors, for example, has not appeared in the model and therefore not accounted for.

External works were excluded from the parametric model; although there were works to pavements, they are largely repairs to existing hard landscaping and as no parallel information would be available for the proposed scenarios, so it was considered more appropriate to eliminate the site context from the study. Below-ground drainage was not shown on the parametric model and utilised existing installations from the previous development of the site. It is a consistent necessity of public health regulations for sanitary and safe drainage, therefore, assumed to be consistently required in any international location.

The manufacturing equipment and associated specialised water purification was present in the parametric model but excluded from the assessment. Loose equipment such as furniture and vending machines, decorative materials such as noticeboards, posters, clocks, recycling bins, staff lockers and other interior elements were present on the parametric model but removed from the assessment because the client supplies and installs such items themselves.

Transport (A4) has generally assumed a reasonably local source for all materials (this is a pre-set UK range of 30-130km depending on material and manufacturer). Secondary journeys (supplier and subcontractor depot) have not been added. No delivery distance data was requested from the contractors all estimates are based on regional distances allocated to the materials.

The LCA Modelling software has utilised a UK average rate for the construction process (A5) based on a project value of £30m (£4000/m^2). This is a proxy rate and not representative of the actual contract value as the project was being delivered using construction management and not a procurement route with an identified contract value. Waste data assumptions are also based on this contract value where they were on-site installed elements.

This resulted in an A5 assumption of 420tonnesCO_2e. The building structure and substructure were predominantly off-site constructed. A reduction of 30% was theorised to represent the probable benefits of programme reduction reduced by 127 tCO_2e to 294tCO_2e.

Most major contractors in the UK will monitor their energy consumption emissions under ISO5001, ISO14001 or SECR and will therefore record underlying energy consumption data after a project is completed. The Considerate Constructors Scheme also prompts best practice energy management, target setting and monitoring. Due to the limited amount of supply chain data on off-site manufacturing waste at the factory, this element of calculation retained default settings.

The energy-using systems were designed and modelled for national calculation methodology and also a planning condition that has prompted the inclusion of solar panels. The modelled data utilises BRUKL for the building area of 7561.1m^2 as shown in table 1.

Table 1 Calculated operational energy consumption based on BRUKL output (B6)

Energy Consumption			**7561.1**	**m^2**
	Actual kWh/m^2	**Annual kWh**	**BRUKL %**	**Total %**
Heating	**3.36**	**25,405**	**9.37%**	
Cooling	**9.65**	**72,965**	**26.91%**	
Auxiliary	**11.28**	**85,289**	**31.46%**	
Lighting	**8.24**	**62,303**	**22.98%**	
Hot water	**3.34**	**25,254**	**9.31%**	
BRUKL Total regulated	**35.86**	**271,141**		**16.61%**
Equipment	**180.05**	**1,361,376**		**83.39%**
Total consumption	**215.91**	**1,632,517**		
Energy Production				
Photovoltaic installation	**5.96**	**45,064**	**16.62%**	**2.76%**
On-site CHP	**0**	**0**		

The baseline building has been designed to achieve a Building Emissions Rate (BER) of 14kgCO_2/m^2/year for regulated emissions with air permeability of 5m3/(h.m^2) @50 Pa and an allowance of 18.05kWh/m^2 for equipment. These annual energy consumption values have been used in the LCA model. An alternative option is to add a contingency to this figure based on the end user’s expectations of energy load or typical consumption per m^2 for the client's other manufacturing buildings in the client’s estate. Manufacturing operational loads are high; the envelope of the building is required to protect the manufacturing process from external and uncontrolled environments. Just 15% of the building is designed for the comfort of human occupants (welfare accommodation, toilets, changing, rest areas, offices). A highly serviced and specialised building of this nature is not readily supported by energy benchmarks so CIBSE TM54 (2022) is the preferable calculation method in practice and used by the designing consultant. R1234ze is a low Global Warming Potential (GWP) refrigerant, used as a replacement for R134a in medium temperature refrigeration and air conditioning, with 265kg total charge (per chiller) in three units. The total impact of this charge is 81tCO_2e over 60 years.

LETI has published guidance for the utilisation of future energy mix factors for the UK (LETI, 2023). These were not used in the baseline assessment or the scenarios to maintain comparability with other nations but would have an impact on reducing the whole-life emissions of the building. This would not affect the modelled embodied emissions.

The baseline building has performed above the benchmark for LETI and RIBA for office buildings; for the embodied impact of 510kgCO_2e/m^2 and whole life impact of 39,774tCO_2e. The most significant materials (A1-A3) were primary (55%) and secondary steel frames (17%), concrete (6%), wall and roof cladding panels (8%), and solar panels 2.8%).

Table 2 Calculated materials impact (A1-A3) of the baseline model

A1 – A3 by element	Total tCO_2e	kgCO_2e /GIFAm^2	%
Substructure	202	26.716	6
Superstructure	1852	244.973	55
Cladding and roof	360	47.556	11
Interior and finishes	639	84.452	19
MEP services	153	20.181	5
Total	3369	511	100

2.1. Discussion of Baseline Model Findings

The building has two floors. However, the significant and walkable plant space within the ceiling voids represents a servicing floor with a high volume-to-floor area ratio and it artificially inflates the calculated embodied impact rate. If the treated floor area is a true floor of plant space, the building area is closer to 11,341m^2. This is significant where performance for embodied and operation carbon emissions is determined by area as a denominator.

The building was noted to have a significant impact from refrigerant gas, despite the lower global warming potential choice. Replacement of many finishes such as flooring and building services at typical intervals were also of concern. For example, solar panels have a high embodied impact as a product but would displace few emissions for the building operator in a close-to-zero grid mix by 2050, however, maintaining panels on large commercial roof spaces will be a critical part of the drive to achieve a decarbonised grid in the UK (CPRE 2023).

The building is assumed to be dismantled following conventional process with a high recycling rate after 60. Alternatively, the building may be reconfigured to suit alternative manufacturing processes and equipment. The very high steel content was noted as a potential material bank for the future building owner to exploit in due course. The structural frame alone is worth £117,000 at current UK scrap rates (Let's Recycle, 2023).

2.2. Potential Improvement to the Baseline Design

A review of the baseline was undertaken to identify if any beneficial design changes should be considered. Reducing regulated emissions to have met Part L 2022 – minimal saving possible from improved specification but air tightness performance should be targeted to have the potential to reduce operational emissions. This would be representative of achieving BRUKL A rating and less than 10kgCO_2e/m^2/year for regulated emissions. Potentially a saving of 30tonnesCO_2 annually which would have reduced regulated emissions by 1815tCO_2e over whole life (UKGBC, 2021d).

Alternative flooring specifications were reviewed but the specified product was found to be the best option for emissions and critical to meet stringent performance requirements. Plasterboard, rockwool and high-pressure laminate supplier EPDs did not vary widely so swapping suppliers would have an insignificant impact. GGBS/PFA replacement concrete could have reductions of 10-20% depending on mix design, however, there is reduced availability of these products in the UK currently (IStructE, 2023). Sandwich panels thickness and U-value were already optimised for operational performance, but a built-up system represented 86% saving with stonewool core, this is heavier than the specified cladding and would add further steel to the frame so the savings will be reduced in practice. This structural design variation was not modelled. The circularity benefits of a built-up system are acknowledged due to much easy separation and recycling of the layers at deconstruction. Overall, a 2.4% absolute reduction of and benchmark to 509kgCO_2e/m^2 could have been achieved.

The influence of design life for replacement is apparent in B modules in table 3. If the building were dismantled at 25 years, before the replacement of some significant installations, there is a 47% reduction in the embodied impact. Although reference period choice has been based on historical data gathering (Anderson and Negendahl, 2023), and desires for international harmonisation (Zimmerman et al 2021), there is also a case for alignment with model B replacement cycles (typically 15, 20 and 25 years) to support better circularity. The impact of the replacement facility should also be recognised to avoid short-term avoidance (Lamb et al 2020).

Table 3 Design life sensitivity and Reference Period

Reference period	**Module A1-A5 (excl. biogenic carbon) kgCO_2e/m^2**	**Module B1-B5**	**Module C1-C4 (excl. biogenic carbon)**	**TOTAL kg CO_2e**
60 years	**511**	**82**	**15**	**5,201**
25 years	**511**	**18**	**15**	**2,457**

3. Global Scenario Models

Five geographical locations (Brisbane, Toronto, Mumbai, Helsinki and Buenos Aires) were selected to represent possible centres of manufacturing expansion. Spread across several continents and in cities with good export transport networks to provide coverage of key markets in Europe, the Americas, Asia and Pacific regions. Influence of other socio-political drivers, such as land costs, utility costs and taxation, employment costs, and various geographical and economic risks of disruption to production influence business decisions. These commercially sensitive considerations were intentionally excluded from the framing of the study to focus solely on CO_2e emissions.

The parametric data of the model building was retained but other variables were adjusted to represent the materials supply chain, local climate and solar potential. Local baseline energy performance regulations for regulated loads given that passive energy design optimization of the modelled building should be undertaken in depth during the design stage. The methodology aimed to adjust the models as follows.

1. Adjust national energy mix for nation/state.
2. Review energy demand in relation to climate, latitude solar potential and building standards.
3. Adjust key higher-impact materials groups to local Environmental Product Declarations (EPD).
4. Adjust the majority of bulk materials to local EPD.

5. Review frame options based on EPD.

Grid carbon intensity for the locations was identified within the OneClick database, except for Argentina. Our World in Data (2022) was utilised to identify a proxy rate comparable to Germany in 2021. A review of predicted decarbonisation based on the Paris Agreement National Determined Contributions in 2023 suggests that there is variability in the anticipated speed and investment approaches to be taken. These are noted in Table 4 but were not utilised in modelling.

Table 4 Grid Carbon Intensity at time of modelling and future scenarios

	B6 Energy Mix (source used in LCA software)	B6 Grid Intensity modelled in 2022 kg CO_2e / kWh	Future scenario references	Whole life impact if discounted tCO_2e
UK	National SAP 10.1 rating	0.14	Decarbonised by 2050 (GOV.UK, 2022)	2,445
Australia	Queensland (Green Star)	0.96	Decarbonised by 2050 or sooner, (NABERS,2022) (Australian Government, 2021	9,586
Argentina	Proxy (2021)	0.57	Decarbonised by 2050 (UNEP, 2022)	5,953
Finland	National average	0.15	Carbon neutral projected by 2035 (Fingrid consultation report 2023)	6,891
India	National average (Noted that localised generation is preferable due to the unreliability of grid)	1.01	Decarbonised by 2085 (McKinsey, 2022)	20,381
Canada	National average (also available for each state)	0.12	95% decarbonized by 2050 (CER, 2021)	1,672

3.1. Energy Demand in Relation to Climate, Latitude and Standards

Additional loading on the building environmental management was replicated by adjusting the regulated energy requirements using building energy consumption intensity based on climate and standards. The methodology using best practice Climate 2030 ASHRE code, a scoping tool has been used to estimate energy use for a notional healthcare building in each of the cities. Healthcare has been used rather than industrial, due to the very highly serviced nature of the manufacturing process.

The benefit of solar panels varied widely between counties at extreme or more equatorial latitudes. This is important to note considering the panels are identified as 93tCO_2e; where the grid mix is already decarbonised nationally, they have a much-reduced benefit over the whole life of a building taking 15 years to reach emission paybacks in Canada, but just over one year in Mumbai. Note that B8 emissions from manufacturing equipment remained identical for all locations. Compensation for heating and cooling demand was simulated using ASHRAE guidance (Architecture 2030). The unregulated energy intensity of the manufacturing process was assumed to be consistent regardless of location.

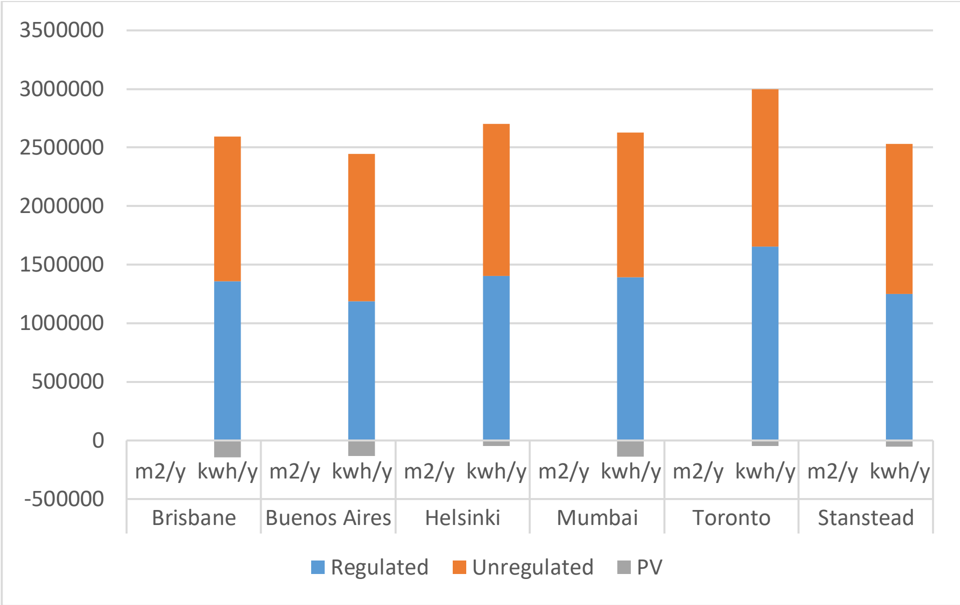

Figure 1 Annual Consumption and generation including photovoltaic installation (B6)

Quantities from the parametric model were replaced with the most locally sourced as closely equivalent performance as possible.

1. Steel frame in all locations
2. Concrete foundations
3. Pre-cast concrete
4. Plasterboard or drywall
5. Glass
6. Cladding or sandwich panels
7. PVC flooring

Materials of less than 2% contribution in the UK model have not been considered significant for substitution. The design of concrete foundations was assumed to be consistent throughout and did not additionally allow for structural design for ground conditions and earthquake risks.

3.2. Discussion of Global Model Findings

Significant variations in electricity emissions were found in the six nations selected, this had an impact on the whole life emissions over 60 years (figure 2), but also on the environmental performance of key materials manufactured locally. The national energy mix has a significant impact on the overall emissions in counties that still rely on fossil fuels. Where this is the case, more on-site renewable energy generation (I.e. solar or hydrogen) is preferable. The benefit of installing solar power on the roof of the building was found to be greatest in India and Australia. Where solar is maximised by latitude, it would be likely that a larger area than the roof of the facility should be considered for installation. This is particularly beneficial if sub-premium value land is available close by. Increased fabric performance and airtightness and the use of heat recovery from the manufacturing process will be beneficial in Canada and Finland where heating demand is high.

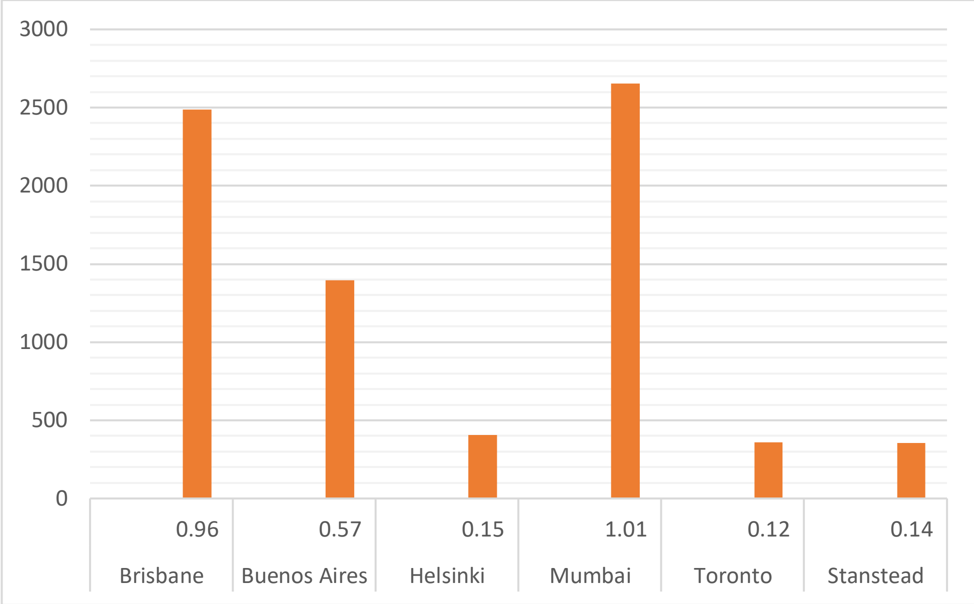

Figure 2 Annual emissions tCO_2e if constructed in the year of modelling and grid intensity $kgCO_2e$/kwh (B6)

The database associated with the Oneclick software had limited information for a variety of materials in some geographical regions. This is a fast-changing arena, with manufacturing companies rapidly adopting the Environmental Performance Declaration as a competitive marketing tool where WLC is already legislated (BPIE 2021a and b). Materials science developments and decarbonisation of complex and engineered assemblies require ongoing monitoring by localised designers.

Bulk materials such as sand and aggregates have a similar impact in all locations due to energy being related to diesel fuel consumption in basic processing and transport with heavy machinery which is similar globally. Some of these constituents are increasingly from recycled sources, but this trend is not reflected in the database used for the modelling.

Structural frame choice is significant in embodied impact; steel is so conventionally anticipated in the UK that it is rarely questioned for large commercial buildings. Australian concrete and steel have a similar impact to the UK but there are wider variations between production plants in different Australian states. Concrete is the main structural system in India, it may also be preferable for thermal mass properties. Steel has a significantly lower impact in Canada (saving of 1000tCO_2e in comparison to the UK), concrete had lowest impact in Finland. Pre-cast concrete flooring and plasterboard have very similar impact in all locations. Rockwool has limited EPD available globally but is low-impact insulation in comparison to plastics-based products. Timber sector is very advanced in Finland and would be the likely choice of the structural frame.

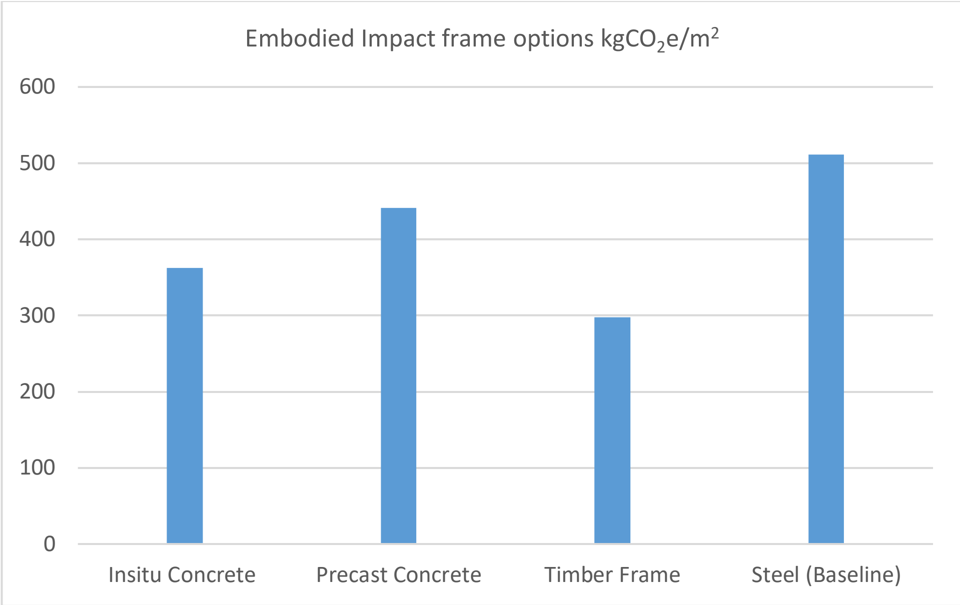

Figure 3 Embodied Impact of frame options using International average data $kgCO_2e/m^2$

Danish building control adopted a new metric for absolute whole life impact (Whole life $KgCO_2e/m^2$/50 years) for all new buildings, those over 1000 m^2 must comply with the limit value of 12 (BPIE, 2021). This single indicator (figure 4) could be utilised in global comparisons over 60 years can give an alternative metric for whole-life carbon, however without discounting clarity and comparable industry data the numeric rate currently lacks meaning for decision-makers. The baseline design might not be compliant if built in Denmark despite grid intensity and decarbonisation scenarios being currently comparable to the UK.

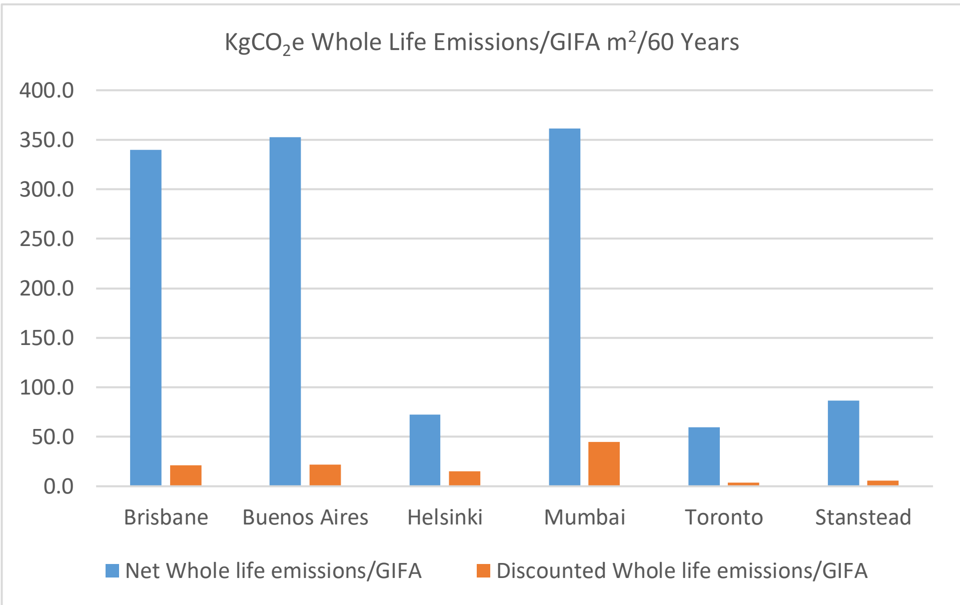

Figure 4 Using a singular rate for whole-life emissions $kgCO_2e/GIFAm^2$/60 years

4. Recommendations

Corporate manufacturing companies will require to site new facilities across global markets so must consider decisions around all carbon emissions scopes considering energy and materials supply chain alongside product carbon foot printing. Establishing a clear strategy for performance evaluation and targets are being established for each new capital investment.

4.1. Recommendations for the End-User

Five steps to take carbon emissions out of future high-intensity projects in any location;

1. Scope opportunities and constraints for local decarbonisation and energy reduction adaptations
2. Model operational energy targets and design life with local grid emissions both with and without proposed national decarbonisation
3. Test frame selection impact including construction methodology (i.e. offsite)
4. Refine modelling with materials for the envelope, cladding and internal finishes
5. Engage suppliers and contractors in the EPD and fuel consumption conversation alongside procurement pathways.

Parametric models can utilise life cycle assessment modelling process to identify opportunities to reduce the impact as early as practical. Design decisions should be based on a full and locally referenced design and be coordinated with fire safety and engineering requirements. Making a separate parametric model for off-site constructed elements for comparison with more conventional construction could be beneficial at the design stage but is time-consuming for a practice to resource unless the cost is allowed within the service fee structure. An approach to this problem can lie with the module suppliers providing their models with embedded LCA data for integration early in the design process. Liaising with consultants and subcontractors with design portions in parametric modelling could assist greatly with streamlining this process. Challenging the improvement of airtightness at completion testing is important for operational savings in the UK. It will also be hugely beneficial in climatic zones where heating and cooling energy demands are high.

4.2. Recommendations for the Construction Industry

Further recommendations leading from gaps in available data found within this study were identified, particularly monitoring of energy consumption, delivered materials, deliveries distance and waste should be standard practice for contractors, and written into procurement documentation.

Embodied impact benchmarks to compare a high-tech manufacturing facility UK baseline project against did not exist for the UK, however, it did meet the current RIBA2030 climate challenge and LETI benchmarks despite being an intensively serviced commercial building (services were 5% of A1-A3). Construction of the UK benchmark project (UK NZCBS, 2022) is due to complete in 2024 and commissioning is expected to take a further 12 months, ultimately post-occupancy evaluation would be beneficial to compare predicted B6 energy use with actual monitoring. Life cycle evaluation tools would benefit from a graphical mapping function as part of the user interface showing where modelled materials came from visually. This would be a useful addition to considerations for a live design stage project where this is an opportunity to discuss risks and vulnerabilities with a client and procurement team.

Operational emissions of the building are likely to be monitored by a major corporate client in-house for reporting and a dedicated on-site facilities management service should support commissioning. The client is likely to prioritise the exact provision of environmental conditions for manufacturing compliance rather than primary energy consumption on a day-to-day basis. Utilising annual energy consumption records where possible; either through facilitated post-occupancy evaluation or as part of annual energy reporting statistics for the client's property portfolio. This is probably most pertinent for understanding how the building reacts to sudden variations in manufacturing intensity or occupancy and deviation from model weather data such as heatwaves.

The sensitivity of frequent replacement of shorter design life elements is an ethically problematic finding in terms of the promotion of long-life flexible buildings. As noted by

Pomponi et al (2018), should be further researched to prevent it from becoming a reason to demolish sooner rather than promoting adaptive reuse.

4.3. Proportionality of Embodied to Operation Impact and Discounting Electricity

The speed at which all nations achieve decarbonised grid will have a significant impact on design decisions in coming years. It is critical to understand the first period of building services design life, however difficult to speculate on the nature of the equipment that replaces it due to rapid technological advancement. Considering the absolute embodied impact proportionality identify the prioritisation of low carbon energy design over materials selection with grid intensity. Figure Figure 5 demonstrates that Brisbane and Mumbai would have that characteristic based on the models in this study. A longer reference period may result in the use of decarbonising grid factors effectively pushing the problem into the future. The expectation of the technological pace of change, focus (Technological optimism in Lamb, 2020) should be on emissions that will happen in the procurement phase.

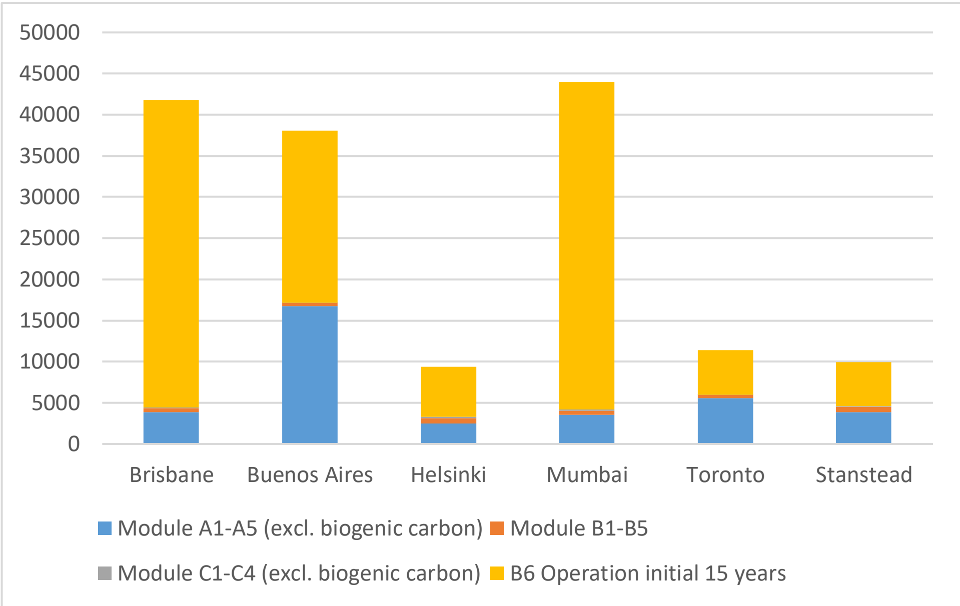

Figure 5 Proportionality of embodied impacts on operation in the first 15 years (kgCO_2e)

Identifying an acceptable cap on the absolute level of emissions for any capital investments may need to be locally, rather than globally defined. Flexible and time-bound target structures that take account of the state of construction product supply chain EPD evolution and grid decarbonisation in regions of their global market. Presenting absolute totals at any stage as indicative (Fieldson et al 2009) and offer clarity on a range (as a +/- % tolerance). This is particularly important if local regulations impose maxima that a design team must achieve, or the client must allocate a monetary budget for offsetting (UKGBC 2021 b). Conversely, successful rapid grid-decarbonisation will radically bring forward the impact of focus on A1-A5 emissions prioritised for inspection over B modules.

Any rate presented is made more sensitive by the denominator used, in this case, the gross internal floor area excluded plant void in the ceiling. Where there is any comparison being made, the internal or treated floor area as the unit of useability of a building should be very carefully considered. Figure 6 shows the addition of the plant space.

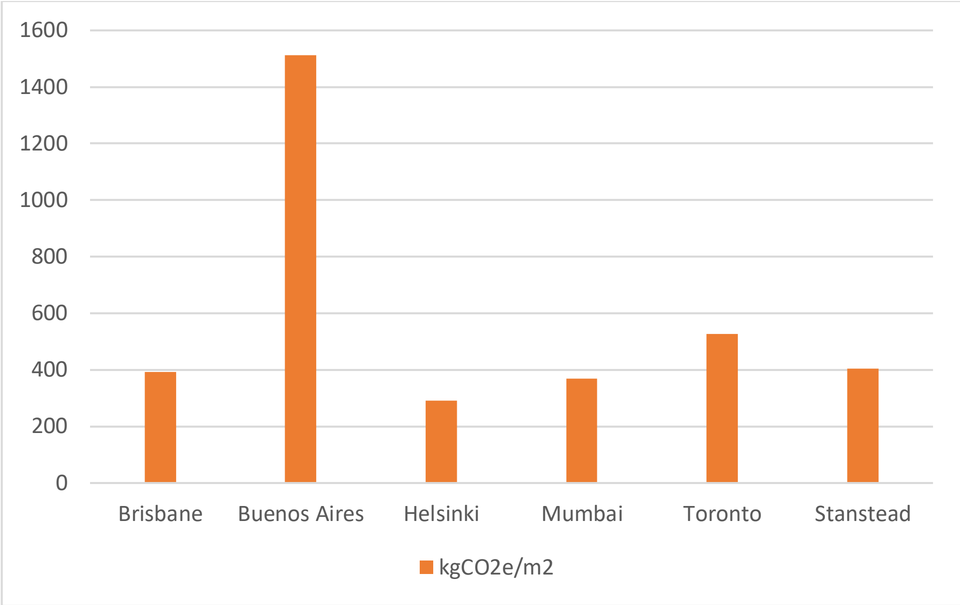

Figure 6 Using an embodied impact rate with a denominator reflecting true treated floor area ($kgCO_2e/m^2$)

5. Conclusions

Multi-national companies may already pay close attention to the existing emissions intensity for kWh of power across their existing international manufacturing sites. They should also review frequently, how each nation is planning to decarbonise and the risks of delay to those projections as part of their sustainability strategy. Identifying clear metrics and communication of absolute emissions and performance rates expectations are key to achieving this aim.

Where embodied impact outweighs the operational impact must be highlighted to shift the focus of local design teams to include the scope 3 element of emissions measurement. Transparency is fundamentally important to decision-makers and design teams and LCA should be commissioned from feasibility stage and reviewed until post-occupancy evaluation stage. The potential fee cost of this consultancy role should be offset against the value of savings generated from carbon offsetting costs or competitivity of carbon labelling on products.

Design life uncertainty for building services is particularly acute for the manufacturing sector; the tendency to design for bespoke provision with a focus on, high productivity efficiency in the first instance in preference for flexibility in the long run, is unlikely to change. Global corporates must monitor and reflect on all of these issues of procurement and investment strategy.

5.1. Significance

The findings for local grid mix and supply key materials supply chain are significant for large corporations and international developers and their designers, contractors and supply chains to consider the implications of geographical site selection over the lifetime of buildings. Criticality of the useable floor area must develop definition as a denominator for embodied impact as metrics become embedded in regulation.

5.2. Limitations

The research was funded by an industrial productivity voucher and the anonymity of the case study has been preserved to protect the third-party interest of the case study provider. This experiment would have been difficult to complete without the extraction of volumetric data from the parametric model and international database provided by the software tool.

Replication of the experiment outside of a software environment of this nature would be complex and time-consuming to conduct.

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Carbon evaluation considering a hygrothermal performance comparison of stone wall retrofits

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Abstract: Improving the thermal performance of walls by adding or increasing insulation is one of the first considerations for reducing heat loss in existing buildings. In most situations, the selection of materials is determined by the cost and reduction of thermal conductance, most likely choosing high embodied carbon materials used reduce becoming a counterintuitive process increasing the building's overall retrofit carbon intensity.
Through this research, hygrothermal performance for specific solid stone walls and the selection of insulation materials, whether they are synthetic or natural in their origin, were evaluated by comparing the embodied carbon of the products from cradle to grave boundary conditions. In addition, the research explores the potential benefits of using natural insulation products manufactured in the UK and the carbon intensity benefits it presents.
Two scenarios were evaluated involving a minor retrofit (MiR), with a U-value of 0.50 W/m²K and a major retrofit (MaR) with a U-value of 0.22 W/m²K. The distinction between the thermal improvements depended on the selected insulation type and the thickness required to meet the established U-values and hygrothermal considerations. The comparison included wood fibre insulation products using 100% softwood (100SW) fibres and one with a blend of 80% softwood and 20% hardwood (80SW-20HW) fibres, against PIR insulation boards.
The research demonstrates the advantages of using hardwood insulation (80SW-20HW), with a 16% saving in material thickness against the 100SW boards to reach the same U-values, and with the lowest level of moisture accumulated on the wall when compared to both traditional wood fibre and PIR boards.
The benefits of using the 80SW-20HW are explicated when the GWP is taken into account, with a saving of 29% and 24% against 100SW, respectively for MiR and MaR. In comparison with PIR, the 80SW-20HW boards guarantee a saving of 15% for MiR, and 52% for MaR. However, wood fibreboards are mainly imported, and greater advantages on the GWP will be achieved if the products are manufactured locally. This study shows how the GWP could be further reduced, up to 60% against PIR boards, if the 80SW-20HW is made in the UK.

Keywords: wood fibre insulation; condensation risk; embodied energy; carbon footprint.

1. Introduction

Of total UK GHG emissions, 18% are associated with housing (LETI, 2021), mostly attributed to poorly delivered new homes and high energy demands of older existing housing. Improving the performance of these existing homes is a crucial action of the UK Government's strategy towards net zero performance of the built environment. The highest heat loss across a building envelope is attributed to the external envelope, 35% according to Yaman (2021), most of which could be reduced by adding insulation.

The benefits of natural fibre insulation products have been widely explored, with different studies demonstrating its adaptability and hygrothermal benefits as well as its lower global warming potential (GWP), also known as embodied carbon.

Densley Tingley, *et al*. (2015) have shown that, with or without taking into account the carbon sequestration of these materials, wood fibre boards present the lowest GWP when compared to PIR, Rockwool, expanded polystyrene and phenolic foam. Similar results were confirmed by Grazieschi, *et al.* (2021), analysing the embodied energy of products, identifying wood fibre boards as being the highest energy consumers during its production stages relying on up to 70% of renewable primary energy (PER).

Despite the GWP benefits of certain natural products, a preference for products with lower thermal conductivity values is adopted for optimal retrofit projects as shown by Walker and Pavía (2015). However, work by Volf, *et al.* (2015) confirms that thermal conductivity should not be the only consideration in the selection of insulation products, as indoor benefits such as humidity and temperature buffering improve better delivered by natural fibre materials can contribute significantly to homes indoor air quality and thermal comfort of occupants.

Previous studies focus on analysing specific characteristics of the insulation materials such as environmental impact, thermal conductivity, etc.). Meanwhile, Lee *et al.* (2019) suggested pursuing a holistic approach that takes into consideration a range of variables.

Considering the above, this study aims to explore the benefits of using wood fibre boards made with a blend of softwood and hardwood as suggested by Imken, Kraft and Mai (2021). This paper explores various objectives focused on not just reaching a similar thermal performance (U-value), but equally considering condensation risk analysis and the embodied carbon of such product from cradle to grave. To achieve this, results and analysis seek to demonstrate the distinctions between the manufacturing and delivery of such products, with the end-of-life showing disposal, recycling and re-use of such insulation materials.

2. Methodology and materials selection

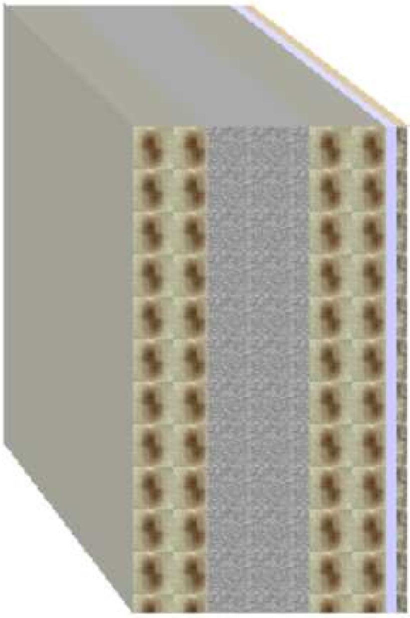
2.1. Methodology

To accomplish the evaluation of this study a pre-1919 tenement flat is used as a common, often poorly performing, archetype in Scotland; as described by the Scottish Government (Scottish Government, 2019b) and by Piddington *et al.* (2020). Often the external walls of these buildings used traditionally built masonry made of 600mm local sandstone and interior lath and plaster finishing, presenting a typical U-value of 1.0 ±0.2 W/m^{2}K (Baker, 2011; Jenkins and Curtis, 2021).

The existing wall was modelled using the BuildDesk-U software. Taking into consideration the inconsistency of the wall due to the stones' sizes and the presence of the mortar, a simplified stratification was used, with 30% of sandstone, 40% mortar, and 30% of sandstone, see Figure 1. In accordance to Baker (2011), and Jenkins and Curtis (2021) the final U-value of the wall is 1.13 W/m^{2}K.

Figure 1. Final configuration of the existing wall

Existing wall



U= 1.13 W/m²K

RT= 0.89 m²K/W

Wall Build Up	**Thickness [mm]**
Sandstone	180
Limestone mortar	240
Sandstone	180
Unventilated air layer	25
Render, lime and sand	25
Total thickness	650

The holistic approach of this study looked at the U-value of the upgraded wall as the independent variable.

Following the Scottish Government directives, section *6.2.11 "Alterations to the insulation envelope"* of *Scottish Technical Handbook – Domestic* (Scottish Government, 2022), a U-value of 0.22 W/m²K may be achieved in case of envelope alteration. However, this value should be reached if "*reasonably practicable*" (Scottish Government, 2022). In light of the above a higher U-value, of 0.50 W/m²K, was also selected, having two main scenarios, Minor Retrofit (MiR), with U=0.50 W/m²K and Major Retrofit (MaR) with U=0.22 W/m²K.

The insulation materials under investigation were selected based on the knowledge of the benefits of using wood fibre insulation products for retrofit projects (Jenkins and Curtis, 2021). The study conducted by Imken, Kraft and Mai (2021) suggests wood fibre boards made with 80% softwood and 20% hardwood (80SW-20HW) have a 16% lower thermal conductivity value than the traditional wood fibre boards (100SW), consequently, the two products have been compared. In addition, PIR boards were selected as a sample, due to their low value of thermal conductivity, U=0.02 W/mK, and taking into consideration their presence in the UK insulation market.

For the 100SW, variations in the density and thermal conductivity are recorded for different thicknesses. 100SW boards, with a thickness lower than 80mm, have a thermal conductivity of 7%, and a density of 38% higher than 100SW boards with a thickness above 100mm (Suprema, 2022). The same proportions were applied to the 80SW-20HW boards.

The U-values of the upgraded wall were undertaken using the software BuildDesk-U. The two wood fibre boards, 100SW and 80SW-20HW were modelled as directly applied to the existing wall with a breathable adhesive. Mechanical fixings, 6/m², were selected for the simulations, as suggested by the Wood Fibre Insulation Academy (2023). With PIR boards, the existing render was removed, and the boards were installed mechanically to timber battens.

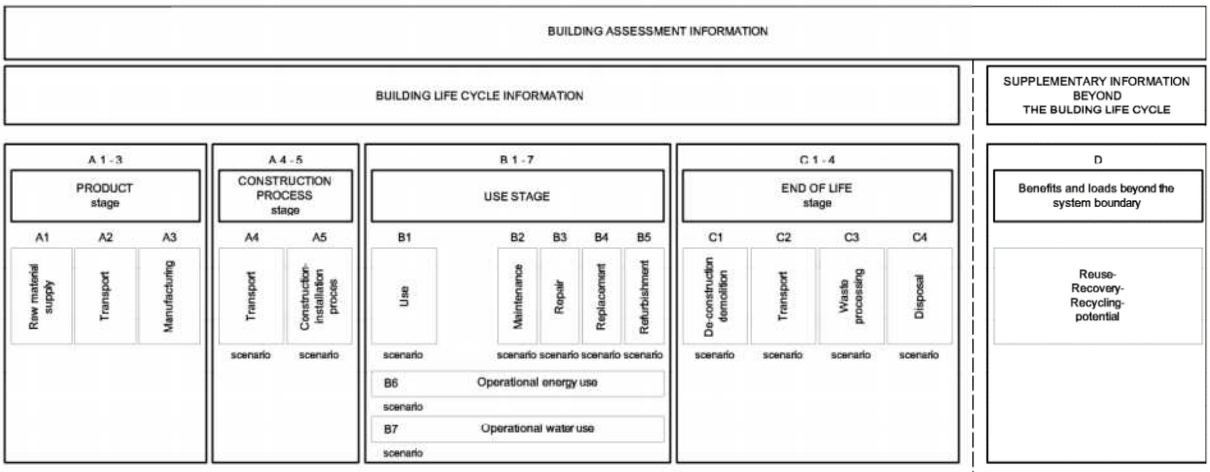
With the BuildDesk-U software, a hygrothermal evaluation of the upgraded wall was also undertaken, considering the presence and absence of an air and vapour control layer

(AVCL). This evaluation allows an understanding of the condensation risks that may occur when a wall is insulated internally.

The CRAs were assessed with the Glaser method, according to the BS5250 and BS EN ISO 13788 standards. The approach of the Glaser method has its limitations. In fact, it is based on a simplified static approach of condensation behaviour in building components, highlighting the most impermeable option. The research by Little *et al*. (2015) shows how with the Glaser method none of the insulation products under investigation passed the risk assessment when the AVCL was not applied. However, with the numerical simulation, it was possible to establish that the RH on the wall, upgraded with phenolic foam, is accumulating during the time. The case study conducted by AECB (2016) proves how the Glaser method overestimates the RH that may occur on the external wall when wood fibreboards are in place. Nonetheless, the in-situ measurements of the AECB (2016) case study, point out that moisture may occur between the cold side of the wood fibre insulation.

To evaluate the effects of the retrofit interventions in terms of embodied carbon (EC), the life cycle analysis (LCA) was conducted covering stages A1-A5, and C1-C4 and D of the BS EN 15978 standard (BSI Standards Publication, 2011). Supporting guidance by the Royal Institution of Chartered Surveyors (RICS) (2017), and the Institution of Structural Engineers (Gibbons and Orr, 2022) were also used.

Figure 2. System boundaries according to BS EN 15978



Finally, to understand the impact of Module A4, transportation, two extra scenarios were set, considering the wood fibre insulation products manufactured first in Europe, and then in the UK. Module A4 was calculated according to the following formula (RICS, 2017; Gibbons and Orr, 2022):

- A4= Material mass (a) x transport distance (b) x carbon conversion factor (c).
- Embodied carbon factor (ECF)= b x c

The default ECF values for Module A4 for the UK were selected according to Table 1.

Table 1. Default EFC values for Modula A4 for the UK (Gibbons and Orr, 2022)

A4 transport scenario	Km by road	Km by sea	ECF A4 ($kgCO_2e/kg$)
Locally manufactured e.g. concrete, aggregate, earth.	50	-	0.005
Nationally manufactured e.g. plasterboard, blockwork, insulation	300	-	0.032
European manufactured e.g. CLT, façade modules, carpet	1500	-	0.160
Globally manufactured e.g. specialist stone cladding	200	10,000	0.183

ECF selected for this study

For the LCA, data were extrapolated from the Environmental Product Declaration (EPD) of existing products on the market. Data of the 80SW-20HW were taken from the 100SW EPD, Pavafrance SAS (2020). The declared functional unit of the 100SW EPD is $1m^3$, with a conversion factor to 1kg equal to 0.005 (Pavafrance SAS, 2020). The above conversion factor was applied to the 80W-20HW boards, considering so the different densities of the two products. In addition, an area of $50m^2$ was hypostatised to be covered by the insulation materials. The initial operational energy, B-6 was calculated considering the Energy Performance Certificate (EPC) of an existing building in Scotland, as reported in Table 2.

Table 2. Building characteristics

Total floor area (FA)	Operational energy consumption	Annual energy consumption
84 m^2	295 $kWh/m^2/year$	24780 kWh/year

Following the (Scottish Government (2019a) guideline, the average household consumption by end-use has been calculated as shown in Table 3.

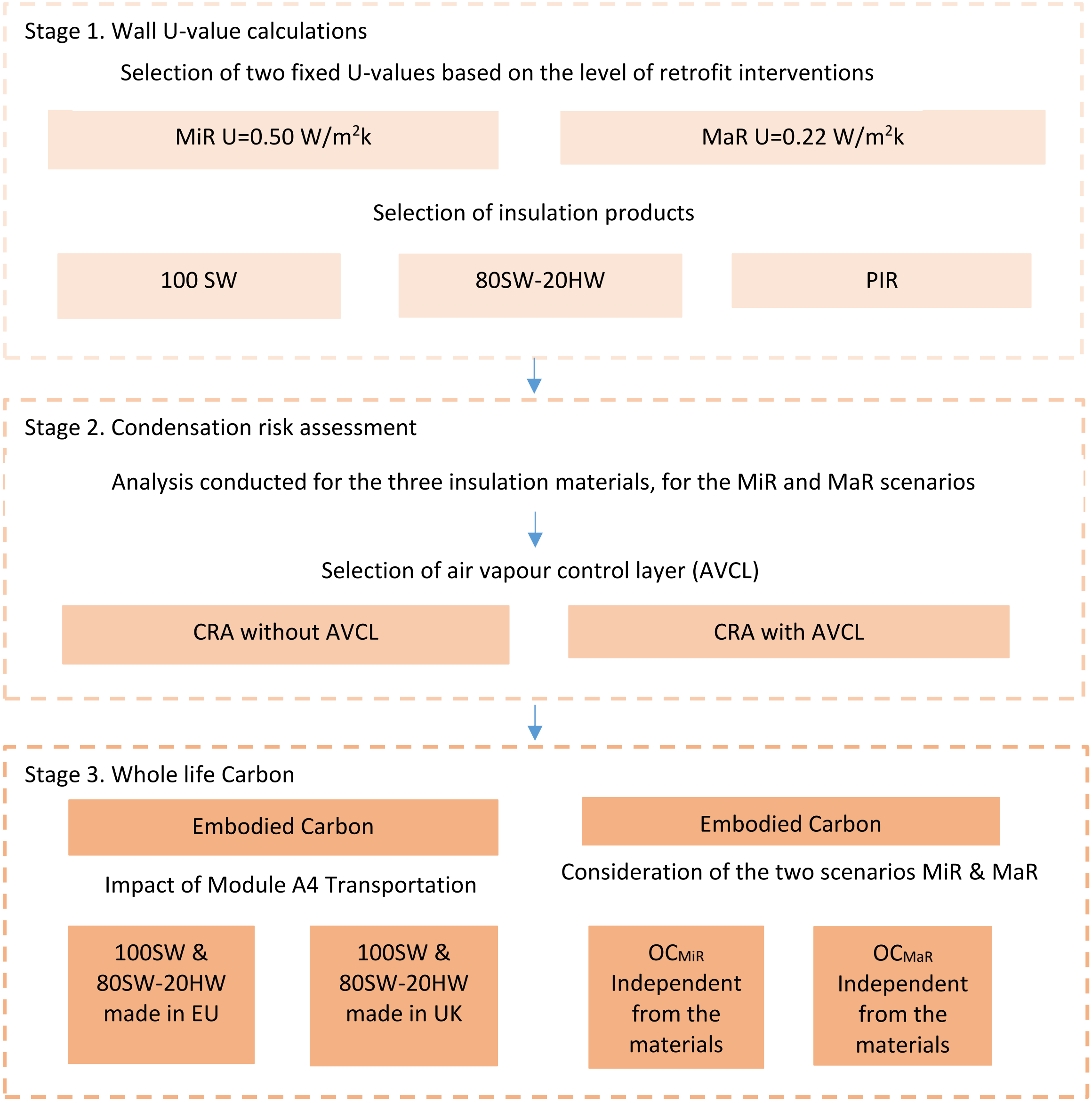
Table 3. Annual energy consumption breakdown

	Annual energy consumption [kWh/year]	Energy consumption	Carbon Intensity Factor [kgCO2e/kWh/year]	Operational Carbon [kgCO2e/year]
Space heating (74%)	18337.2	Natural gas	0.18486	OC_h=3390
Water heating (13%)	3221.4	Natural gas	0.18486	OC_w=596
Appliance (10.5%)	2601.9	Electricity	0.23314	OC_a=607
Cooking (2.5%)	619.5	Electricity	0.23314	OC_c=144

Having the fixed U-values for the two scenarios, OC_h will be reduced with circa the same significance, independently of the insulation material applied. For the above reason, the operational carbon (OC) of the upgraded building, has been considered constant for MiR, OC_{MiR}, and for MaR, OC_{MaR}.

A summary of the research methodology is reported in Figure 3.

Figure 3. Research Methodology summary



2.2. Material characteristics

The characteristics of the 100SW were selected after reviewing the existing products on the market. The 80SW-20HW board features were taken by the study conducted by Imken, Kraft and Mai (2021). PIR board values were selected using the BuildDesk-U catalogue.
Table 4 shows the different features of each insulation product.

Table 4. Insulation products characteristics

Insulation products	Density [kg/m3]	Thermal Conductivity [W/(mK)]	Water vapour diffusion resistance value µ	Specific heat capacity [KJ/(kg K)]
100SW Thickness 30-80 mm	200	0.044	3	2.1
100SW Thickness 100-200	145	0.041	3	2.1
80SW-20HW Thickness 30-80 mm	177	0.037	5	2.1
80SW-20HW Thickness 100-200 mm	129	0.035	5	2.1
PIR	32	0.020	50	0.92

The values for AVCL were also designed by using existing products. The same AVCL was applied to the 100SW and 80SW-20HW products, see Table 5 for further details.

Table 5. AVCL characteristics

AVCL	Water vapour diffusion equivalent (Sd) [m]	Thickness [mm]	Water vapour diffusion resistance value µ
AVCL for 100SW & 80SW-20HW	6	0.40	15000
AVCL for PIR	1500	0.40	$3.75E10^6$

3. Results & analysis

3.1. U-values and thickness of the upgraded wall

Having settled the two scenarios, MiR and MaR, and selected the three insulation products, six simulations were undertaken in total for the U-values calculations. The results of the simulations are reported in Table 6.

Table 6. U-values and thicknesses of the wall upgraded with the different insulation products.

Product ID	Insulation products	Targeted U-value [W/m²K]	Scenario ID	U-value [W/m²K]	Required thickness [mm]	Final wall thickness [mm]	Thickness increment [%]
1	100SW	MiR=0.55	1.1	0.47	60	725	12
		MaR=0.22	1.2	0.22	160	825	27
2	80SW_20HW	MiR=0.55	2.1	0.48	50	715	10
		MaR=0.22	2.2	0.21	140	805	24
3	PIR	MiR=0.55	3.1	0.43	30	667.5	3
		MaR=0.22	3.2	0.19	100	737.5	13

The 80SW-20HW boards offer a minimum saving on the final wall thickness when compared to the 100SW boards. However, up to 17% of insulation material can be saved when using the blended boards.

The advantages of the 80SW-20HW boards are explicated when looking at the comparison of the 80SW-20HW VS PIR boards, and 100SW VS PIR boards. In fact, despite the higher increment of thickness of the natural products, when compared to the PIR boards, up to 33% of insulation material can be saved for the 80SW-20HW boards against the 100SW. In addition, the 80SW-20HW boards offer an increment of the wall thickness equal to 7% for MiR and 9% for MaR when compared to PIR boards, against the 9% and 12% increment of the 100SW boards. The direct comparisons, between the insulation products, are shown in Table 7.

Table 7. Direct comparison of the insulation products

Insulation products	Targeted U-value [W/m²K]	Thickness of the insulation comparison [%]	Thickness of the wall comparison [%]
80SW-20HW VS 100SW	MiR=0.55	-17	-1
	MaR=0.22	-13	-2
80 SW-20HW VS PIR	MiR=0.55	67	7
	MaR=0.22	40	9
100 SW VS PIR	MiR=0.55	100	9
	MaR=0.22	60	12

3.2. Condensation risk analyses of the upgraded wall

Firstly, the analysis of the existing wall without any improvements was undertaken to record the initial conditions. The stone wall, due to its nature, presents interstitial condensation during the winter months, but all the condensate is predicated to evaporate during the summer months, with a total of 8 months free of moisture, and with a maximum of accumulated moisture content per area equal to 23 g/m², see Table 8 for further details.

Table 8. Monthly moisture content per area gc [g/m²] and the accumulated moisture content per area Ma [g/m²] for the existing wall

		Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Sandstone / Limestone Mortar	gc	7	10	5	-9	-14	-	-	-	-	-	-	-
	Ma	7	18	23	14	-	-	-	-	-	-	-	-

Afterwards, the condensation risk analysis was undertaken, for both scenarios MiR and MaR, and considering the absence and presence of the AVCL, with a total of twelve simulations.

For the 100SW, without AVCL, the upgraded wall did not pass the assessment for both MiR and MaR. The maximum accumulated moisture content per area (Ma) recorded for MiR, is equal to 2013 g/m².

When the AVCL is applied the wall maintains its initial conditions for MiR with a Ma of 15 g/m², and 8 months free of moisture. For MaR, despite the presence of the AVCL the wall has a Ma of 73 g/m^2, 387% higher than the original conditions, with just 4 months free of moisture.

Similar results were recorded for the 80SW-20HW boards with the accumulated moisture content per area during the months slightly lower than the 100SW boards. The major differences were recorded for MiR without AVCL, with the highest accumulated moisture content (Ma) 13% lower than the 100SW, and a final Ma on the wall 19% less than 100SW.

The data reported above, indicates how pushing the boundaries to reduce at the minimum the U-value of the walls could increase rapidly the risk of moisture, having an average of moisture free half time shorter than the walls had originally.

As for the previous insulation materials, the PIR boards did not pass the risk assessment when the AVCL was not applied. Nonetheless, the accumulated moisture content per area Ma, was 52% and 81% lower respectively for MiR and MaR when compared to the 80SW-20HW board. However, when the AVCL was applied the results showed no moisture content on the wall, with a total of 12 months free from moisture.

In reality, an AVCL is always applied in PIR boards, with the majority of PIR insulation products on the market having a vapour control layer integrated with the panels. The consequence of this result is that the existing wall loses its ability to let the vapour pass through, the moisture movement is not therefore allowed, with higher risks of decay in case of any infiltrations.

The results of the CRAs for the three insulation materials for scenarios MiR and MaR, with and without the AVCL are reported in Figures 4 to 7.

Figure 4. CRA results for MiR without AVCL

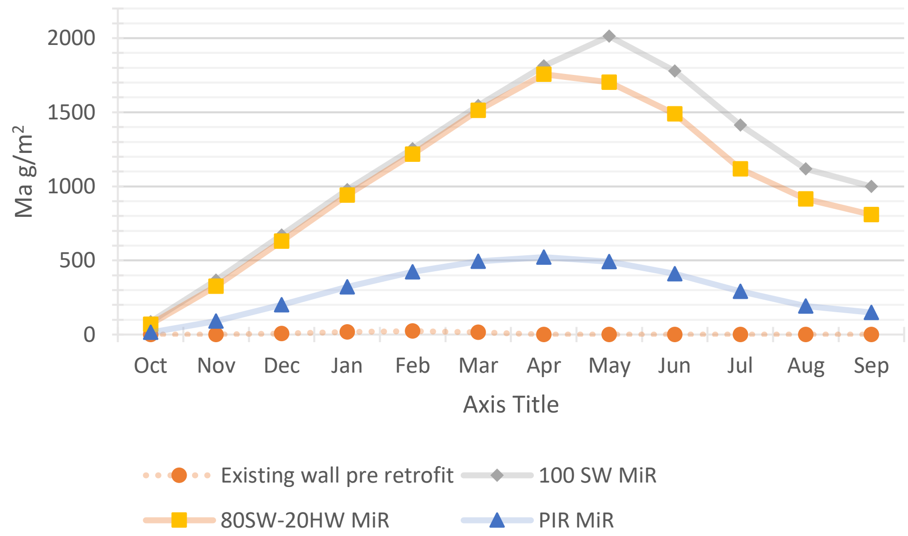


Figure 5. CRA results for MiR with AVCL

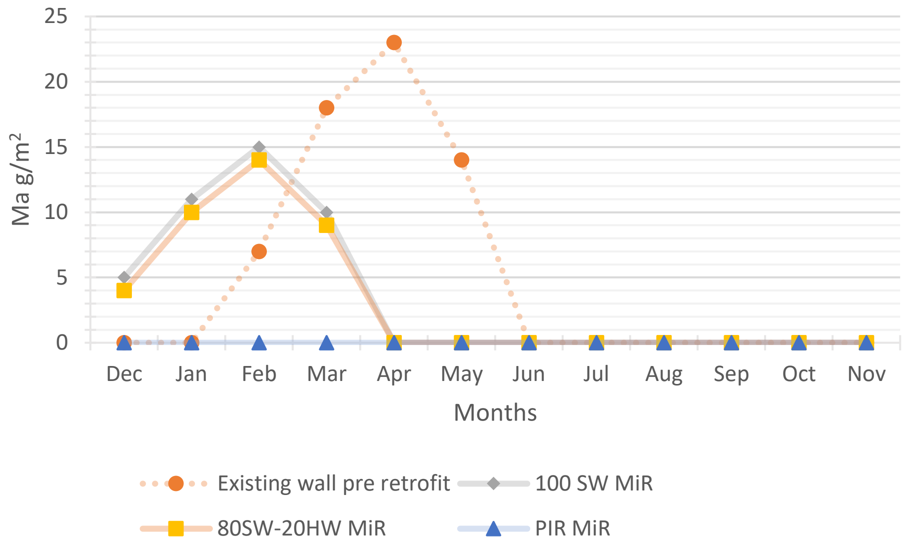


Figure 6. CRA results for MaR without AVCL

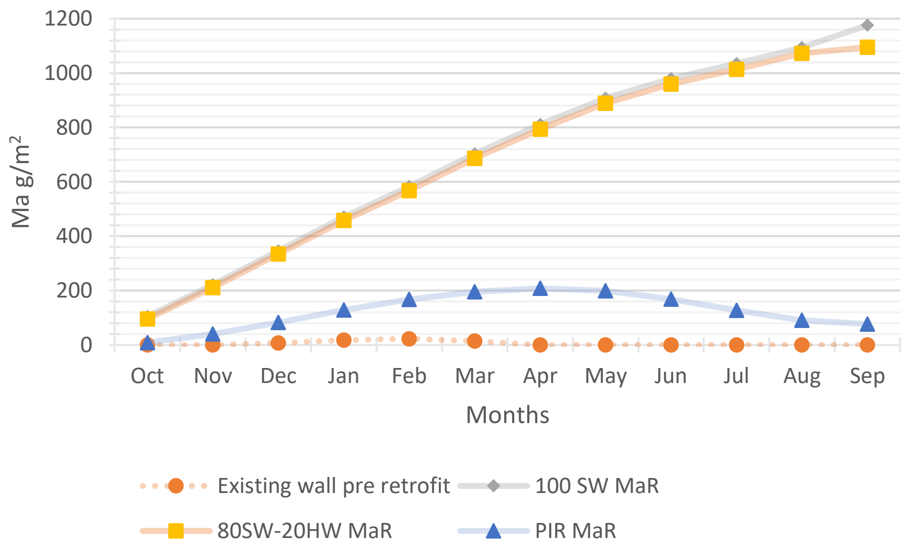
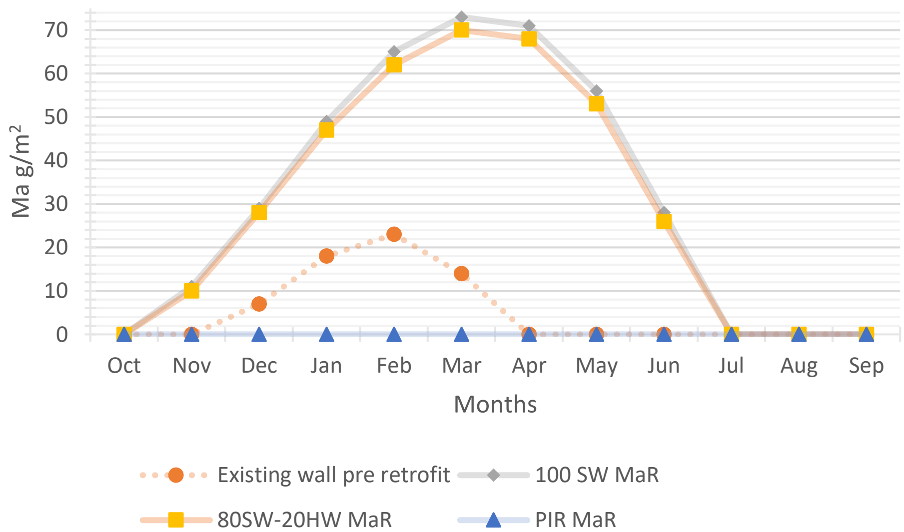


Figure 7. CRA results for MaR with AVCL

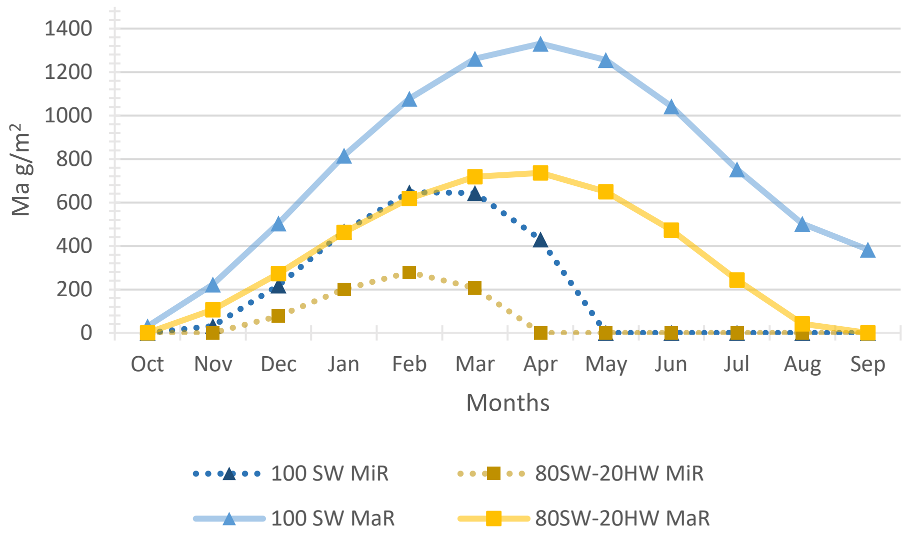


This study was limited to the use of the Glaser method, however, as mentioned in Section 2 Methodology, previous research have shown that with the dynamic simulation, which takes into account the permeability of the material, and the actual weather conditions, the relative humidity (RH) of the upgraded walls with wood fibre board is balanced during a period of time, and there is always an equilibrium of state (Little *et al*., 2015; Baker, 2016). On the contrary, when no hygroscopic insulation products are applied internally the RH accumulates during the time (Little *et al*., 2015; Baker, 2016). In addition, AECB (2016) showed that for wood fibre boards, the Glaser method overestimated the level of RH when compared to in situ measurements.

It should be also noted that the AVCL selected for the PIR boards, has a water vapour diffusion equivalent (Sd), 250 times higher than the AVCL selected for the natural insulation materials. Both the 100SW and the 80SW-20HW boards rely less on the AVCL. Moreover, this study was limited to the use of the Glaser method.

Both, 100SW and 80SW-20HW boards, recorded moisture on the cold side of the insulation materials when the AVCL was not applied. For MiR the 80SW-20SW boards have the maximum accumulated moisture content per area (Ma) 57% lower than the 100SW boards. For MaR the risk of moisture within the insulation materials increases exponentially with a maximum of two months free of moisture for the 80SW-20HW, and an equivalent moisture content of up to 16%, see Figure 8.

Figure 8. Comparison of the accumulated moisture content per area Ma (g/m^2) for 80SW-20HW and 100SW on the cold side of the insulations



The results are in line with the AECB (2016) case study where in situ measurements have shown 15% moisture content on the cold side of insulation boards, when the wall was upgraded with 200mm wood fibre boards without AVCL, and with a final U-value of 0.156 W/m^{2}K.

The findings of this study alongside the AECB (2016) suggest that when using natural fibre insulation products, the masonry wall may need to be treated with rain screen or a protecting layer, to reduce the effects of the rain loads. If treatments of the walls are not possible, the use of the AVCL may help in reducing the risk of rot of the insulation materials. Lowering excessively the U-value should be also avoided.

3.3. Whole Life Carbon (WLC)

3.3.1 Embodied Carbon (EC)

The EC of the insulation products was conducted considering the two main scenarios MiR and MaR, plus an evaluation of the impact of having the wood fibre boards, 100SW and 80SW-20HW manufactured in the UK. A total of 10 scenarios were evaluated.

Table 9 shows the materials' quantities required to reach the wall U-value. To take into consideration the different densities of the natural insulation materials the functional unit used in this study is the mass.

Table 9. Quantity of insulation required for each scenario

Insulations & scenarios	Density [kg/m3]	Thermal Conductivity [W/(mK)]	Wall U-value [W/m^{2}K]	Insulation thickness [m]	Area [m^2]	Volume [m^3]	Total Mass [kg]
100SW MiR	200	0.044	0.47	0.06	50	3	600
100SW MaR	145	0.041	0.22	0.16	50	8	1160
80SW_20HW MiR	177	0.037	0.48	0.05	50	2.5	442.5
80SW_20HW MaR	129	0.035	0.21	0.14	50	7	903
PIR MiR	32	0.020	0.43	0.03	50	1.5	48
PIR MaR	32	0.020	0.19	0.10	50	5	160

Data for the 100SW were extrapolated from the Environmental Declaration of Performance (EPD) of an existing product. The characteristics of the material, and the LCA declared by the company are reported in Table 10 and Table 11.

Table 10. 100SW specifications

Name	Value, Unit
Declared unit	1.00 m^3
Declared Density	200.00 kg/m^3
Conversion Factor to 1 Kg	0.005

Table 11. EPD 100SW boards (Pavafrance SAS, 2020)

Declared unit 1 m^3	A1-A3	A4	A5	C1	C2	C3	C4	D
GWP [kgCO_2eq.]	-2.35E+2	-	1.04E+1	0.00E+0	5.19E-1	3.22E+2	0.00E+0	-2.62E+2

Data for the EC of the 80SW-20HW were taken from the 100SW EPD (Pavafrance SAS, 2020), and adapted according to the product density, using the conversion factor to 1kg of 0.005, as reported by the 100SW EPD.

Finally, also the data for the PIR EC were extrapolated by using the EPD of an existing product on the market, reported in Table 15.

Table 12. EPD PIR boards (Finnfoam oy, 2021)

Declared unit 1 kg	A1-A3	A4	A5	C1	C2	C3	C4	D
Global Warming Potential (GWP) ($kgCO_2eq.$)	2.66E+0	1.83E-02	-	0.00E+0	6.08E-3	0.00+E0	2.59E+0	0.00

Module A5 in this case was calculated according to the following formula (RICS, 2017; Gibbons and Orr, 2022):

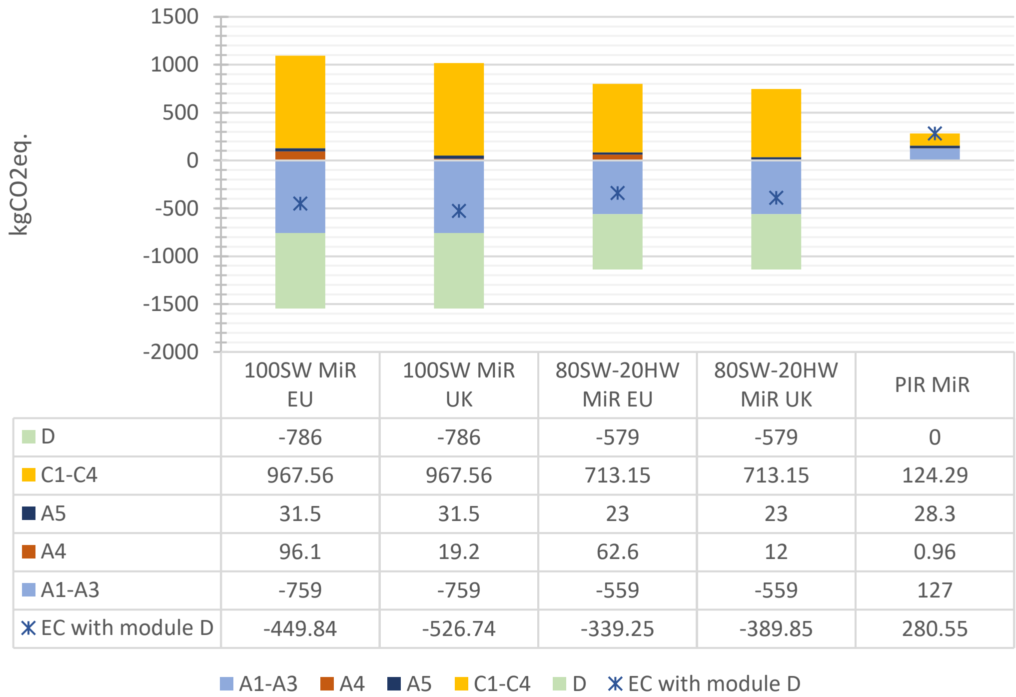
- $A5 = WF \times (GWP_{A1\text{-}A3} + GWP_{A4} + GWP_{C2} + GWP_{C3\text{-}C4})$
- WF= Waste factor

Considering a waste rate for PIR equal to 10%, the WF for this study has been assumed to be 0.111 (Gibbons and Orr, 2022).

3.3.2 EC comparison of the different insulation products

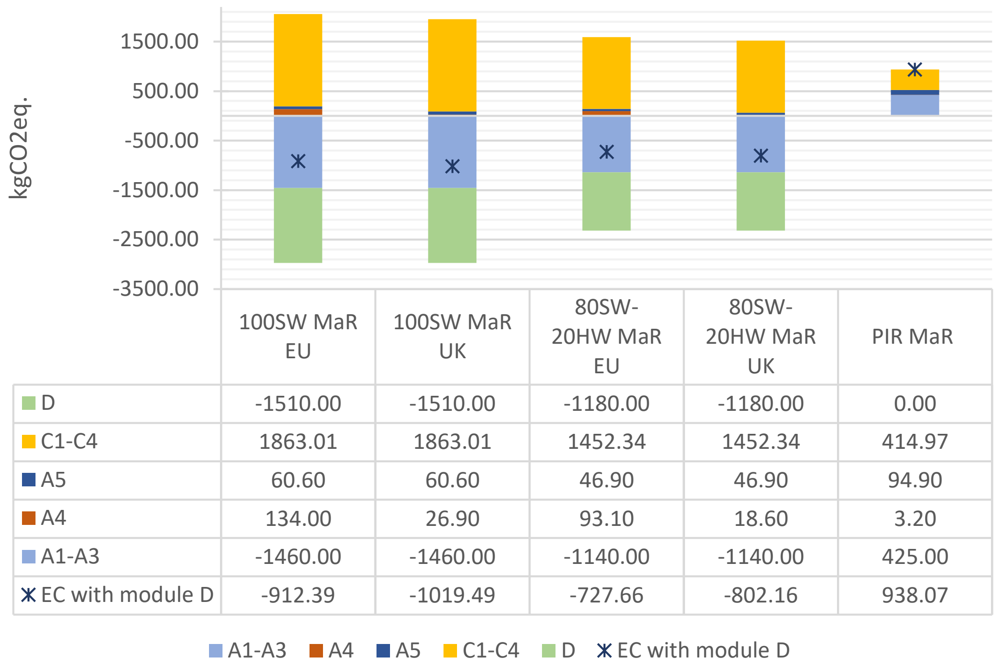
The LCAs for MiR and MaR of the different products are shown in Figures 9, and 10 with Module A1-A3 and Module D offering the major saving in terms of CO_2 emissions for the wood fibre boards, due to their nature, and the opportunity to recycle the materials at the end of life.

Figure 9. LCAs comparison for MiR



	100SW MiR EU	100SW MiR UK	80SW-20HW MiR EU	80SW-20HW MiR UK	PIR MiR
D	-786	-786	-579	-579	0
C1-C4	967.56	967.56	713.15	713.15	124.29
A5	31.5	31.5	23	23	28.3
A4	96.1	19.2	62.6	12	0.96
A1-A3	-759	-759	-559	-559	127
EC with module D	-449.84	-526.74	-339.25	-389.85	280.55

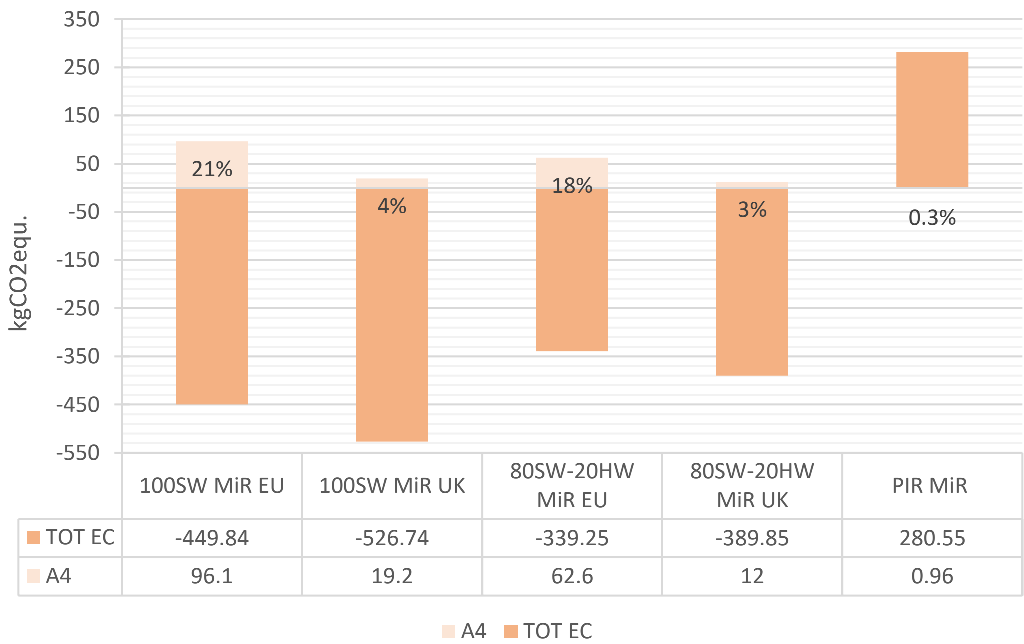
Figure 10. LCA comparison for MaR



	100SW MaR EU	100SW MaR UK	80SW-20HW MaR EU	80SW-20HW MaR UK	PIR MaR
D	-1510.00	-1510.00	-1180.00	-1180.00	0.00
C1-C4	1863.01	1863.01	1452.34	1452.34	414.97
A5	60.60	60.60	46.90	46.90	94.90
A4	134.00	26.90	93.10	18.60	3.20
A1-A3	-1460.00	-1460.00	-1140.00	-1140.00	425.00
EC with module D	-912.39	-1019.49	-727.66	-802.16	938.07

For both natural insulation products, 100SW and 80SW-20HW, Module A4 has an impact of 21% and 18% circa respectively on the total EC, against the 0.3% of PIR boards. With the wood fibre boards made in the UK, the impact of Module A4 could be potentially reduced by up to 4%, see Figure 11.

Figure 11. Module A4 impact on the total EC

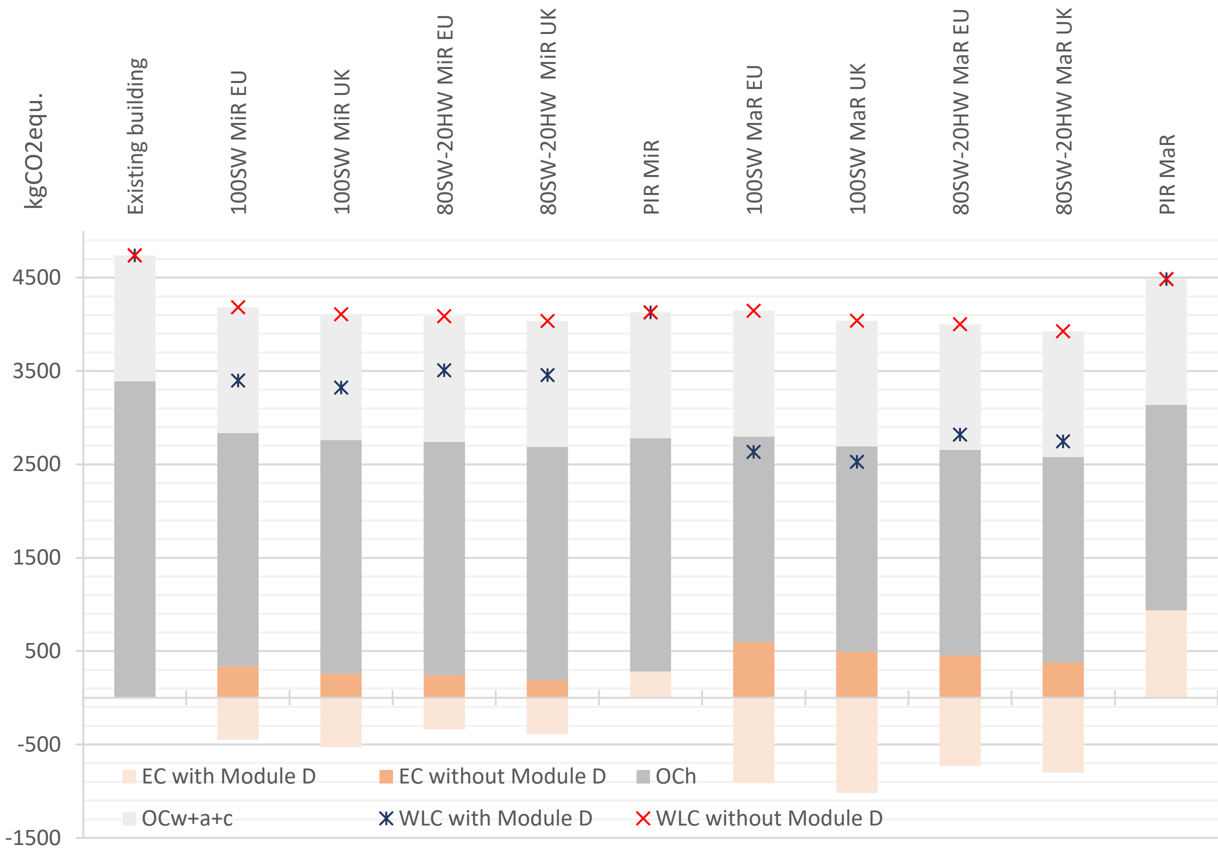


	100SW MiR EU	100SW MiR UK	80SW-20HW MiR EU	80SW-20HW MiR UK	PIR MiR
TOT EC	-449.84	-526.74	-339.25	-389.85	280.55
A4	96.1	19.2	62.6	12	0.96

3.3.5 WLC comparison

The whole life carbon of the different scenarios has been evaluated against each other and against the existing building pre-retrofit, see Figure 12.

Figure 12. WLC of the different scenarios



If the 100SW and 80SW-20HW boards have benefits explicated in Module D, the 100SW insulation product guarantees the lowest level of WLC, being 45% for MiR, and 81% for MaR less than WLC of the PIR boards. When compared against the existing building a saving of 28% in carbon emissions for MiR, and 44% for MaR are recorded for the 100SW boards. On the contrary, for the PIR boards, 13% of MiR, and 5% of MaR of carbon emissions are saved in comparison to the existing building.

When Module D is not taken into account, for MiR, the 80SW-20HW boards guarantee the highest savings in terms of carbon emissions, -3% against the PIR boards, and -6% against the 100SW. Looking at the MaR, 100SW and 80SW-20HW have WLC values of 15% and 21% respectively lower than the one for PIR. An extra 5% could be saved if both wood fibre boards were made in the UK. In comparison with the existing building, for MiR all three insulation products offer a saving of carbon emissions that ranges between 12-15%, with the 80SW-20HW boards having the highest saving rate. On the other hand, for MaR, the scenarios change drastically with the PIR boards having a WLC value just 5% lower than the existing building, contrary to the 100SW and 80SW-20HW that are offering a saving of carbon emissions of respectively 13% and 16% against the original status quo. See Table 13, and Table 14 for further details.

Table 13. WLC comparison between insulation products

Scenarios	Carbon emissions saving with Module D [%]	Carbon emissions saving without Module D [%]
100SW MiR EU VS PIR MiR	-45	3
100SW MiR UK VS PIR MiR	-50	-1
100SW MiR EU VS 80SW-20HW MiR EU	-11	6
100SW MiR UK VS 80SW-20HW MiR UK	-14	5
80SW-20HW MiR EU VS PIR MiR	-38	-3
80SW-20HW MiR UK VS PIR MiR	-41	-6
100SW MaR EU VS PIR MiR	-81	-15
100SW MaR UK VS PIR MaR	-86	-20
100SW MaR EU VS 80SW-20HW MaR EU	-30	8
100SW MaR UK VS 80SW-20HW MaR UK	-40	7
80SW-20HW MaR EU VS PIR MaR	-73	-21
80SW-20HW MaR UK VS PIR MaR	-76	-25

Table 14. WLC comparison against the existing building (EB)

Scenarios	Carbon emissions saving with Module D [%]	Carbon emissions saving without Module D [%]
100SW MiR EU VS EB	-28	-12
100SW MiR UK VS EB	-30	-13
80SW-20HW MiR EU VS EB	-26	-14
80SW-20HW MiR UK VS EB	-27	-15
PIR MiR VS EB	-13	-13
100SW MaR EU VS EB	-44	-13
100SW MaR UK VS EB	-47	-15
80SW-20HW MaR EU VS EB	-40	-16
80SW-20HW MaR UKVS EB	-42	-17
PIR MaR VS EB	-5	-5

4. Conclusions

There is a need to upgrade the existing UK building stock, and any choices made will have an impact as well on the UK Government's strategy of reducing the carbon emissions associated with the construction industry. Insulating the building envelope is the key point for reducing the heating demand of existing structures, and the selection of those materials has an overall impact on the emissions generated by those interventions.

Considering the above, the aim of this research is to understand the impact on the whole life carbon of upgrading a pre-1919 tenement flat, with three different insulation materials applied internally, 100SW, 80SW-20HW, and PIR boards. In doing so, a holistic approach was undertaken.

Firstly, considering two different scenarios, Minor Retrofit (MiR), with U=0.50 W/m²K and Major Retrofit (MaR) with U=0.22 W/m²K, the influence of the different levels of thermal conductivity on the final thickness of the upgraded wall was evaluated. The reduction of the thermal conductivity value, with a product made with a blend of softwood and hardwood, offers a saving in terms of final insulation thickness material equal to 17% and 13% against the traditional 100SW boards. However, when compared to PIR, both wood fibreboards offer an increment of the total wall thickness between 7-12% higher.

Nevertheless, the hygroscopic nature of the PIR boards may put the existing building at a higher risk of moisture. The condensation risk analyses, undertaken in this study, show that the application of PIR boards, limits the breathable nature of the existing wall, becoming not permeable after the insulation application. On the other side, the wood fibreboards, 100SW and 80SW-20HW have shown very high levels of moisture content when a layer of vapour control (AVCL) was not applied. However, this study was limited in using the Glaser method for the CRA, with previous research showing that the values obtained with this method are overestimated. The CRA for the wood fibreboards also showed that moisture might occur on the cold side of the insulation, with similar results obtained by AECB (2016) with in-situ measurements. The study suggests that the 80SW-20HW boards have a lower level of moisture content between the wall and the cold side of the insulation, up to 55% when compared to 100SW boards. The application of the AVCL, even if is not generally necessary for natural insulation products, could prevent this risk.

Finally, an evaluation of the materials embodied carbon, and its impact on the whole life carbon was undertaken, considering the different set scenarios, MiR and MaR. In addition, being wood fibre insulation products mainly imported from Europe, this study analysed the impact of that added carbon for transportation to the UK.

The results show great advantages of using the two natural insulation products, up to 45% and 81% for MiR and MaR. Having those products manufactured in the UK could reduce up to 17% the impact of Module A4 on the total embodied carbon.

For this study, the information for the LCAs were taken by EPD of existing products. The wood fibre boards, in this case, have also benefits in Module D, considering that the material is transported to a biomass power plant, with an energy retrieval combustion.

If the above are not satisfied, and there are no gains for Module D, the scenarios change completely. In fact, the research suggests that in this case, the 100SW boards have an EC for MiR, higher than the PIR boards, 20% circa, unless they are made in the UK, -8%. On the contrary, the 80SW-20HW boards have an embodied carbon 14% lower than PIR boards for MiR, and -32% with the product made in the UK.

Conversely, even without taking into consideration Module D, when looking at the whole life carbon against the existing status quo, the differences in savings between the three insulation products for MiR are almost negligible. For the MaR, the PIR boards offer the lowest carbon emissions saving, -5%, against the 13% and 16% offered by the 100SW, and the 80SW-20HW, with a 1-2% extra saving for products manufactured locally.

Overall, the research shows the importance of looking holistically at a retrofit strategy, and that different factors need to be taken into consideration. Despite natural insulation products offering advantages in terms of embodied energy and condensation risk, the boundary conditions of where those products are made and how they are used at the end of life have a great impact on the final whole life carbon.

5. References

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Quantifying the Embodied Emissions of Building Envelope Systems in a Toronto Context

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Abstract: Building enclosure systems consisting of roofs, walls, floors, and windows are crucial for reducing the whole-life carbon emissions from buildings. However, selecting enclosures with the least whole-life carbon emissions is challenging because the embodied carbon (EC) of enclosure systems is poorly understood. This paper addresses this challenge by establishing a methodology for analysing and calculating the EC intensity of commonly-used enclosure systems for Part 3 buildings in the Greater Toronto and Hamilton Area (GTHA) in Ontario, Canada.

A literature review was conducted to understand methods for calculating the EC of enclosures using life cycle assessment (LCA). One Click LCA was used for this analysis because of its database's specificity of available construction materials and adaptability for system or component-level LCA. The EC of twenty-six commonly used enclosure system designs in the GTHA were analysed. These systems were designed to meet a minimum thermal performance of RSI 3.5 (R 20).

The applied methodology provides a straightforward and replicable way for designers to quantify and compare the EC of their design choices. Additionally, the study shows the variations in the carbon intensities of the enclosure systems analysed, with EC intensities of exterior wall systems ranging from 50 to 210 $kgCO_2e/m^2$.

Keywords: Embodied emission, building enclosure, building envelope, life cycle assessment

1. Introduction

About 37% of the world's CO_2 emissions related to processes and operational energy come from the building and construction sectors (United Nations Environment Programme, 2022). In response to this challenge, the construction sector has concentrated chiefly on lowering emissions linked to the total energy used by buildings for their daily operations (operational carbon) (Ecological Building Network et al., 2015). However, the effect of embodied carbon on buildings' whole-life carbon emissions will become the deciding factor as substantial reductions in our operational carbon consumption are accomplished through the design of high-performance buildings and our electricity grids decarbonize (Rock et al., 2020). Embodied carbon emissions are those associated with extracting raw materials for building construction, transportation and manufacturing the construction products and the construction process itself. It also includes the emissions associated with the maintenance, repair, and replacement of building components throughout the building's life cycle and the dismantling, demolition, and eventual material disposal at the end of a building's life (Mayor of London, 2022).

As embodied carbon might account for most of Canada's new building's carbon emissions between 2023 and 2050 (Canada Green Building Council, 2022), Government bodies and industry in Canada have developed legislation and standards to incentivize the reduction of embodied and operational emissions. For example, as part of the revisions to Toronto's Green Building Standard Version 4, the City of Toronto has detailed a new requirement that specifies that certain project types must conduct upfront assessments of embodied carbon emissions. (The City of Toronto, n.d). The CaGBC's (Canada Green Building Council) Zero Carbon Building – Design Standard Version 3 also aims to incentivize embodied carbon reduction.

Although these standards apply to medium to large (Part 3) buildings in Toronto, particular interest is paid to the latter as they comprise 85% of the projected new constructions in Toronto (The City of Toronto, 2021). Large Part 3 buildings, defined by the Ontario Building Code (OBC), include commercial, multi-unit residential, and institutional buildings greater than 600 m^2 and taller than three stories. Compared to low-rise residential buildings, these often have a greater embodied carbon intensity ($kgCO_2e$ per m2). The more carbon-intensive enclosure systems that are frequently utilized in these structures may be to blame for the high embodied carbon intensity (Rock et al., 2020).

Building enclosures consisting of roofs, walls, floors, and windows play a significant role in constructing high-performance buildings that provide optimal thermal comfort to occupants (Llantoy et al., 2020). They act as environmental separators, and choices around the composition of different enclosure layers affect operational and embodied carbon. Therefore, it is essential to understand the balance between these enclosures' operational and embodied impacts (Echenagucia et al., 2022). Most embodied carbon analyses so far have focused on structure and enclosure from a whole-building life cycle perspective (Rodriguez et al., 2020). Up until now, thermal functioning has been the primary consideration in building enclosure design. When considered along with embodied carbon, the primary focus has been on the insulating material layer, as seen in Grazieschi et al. (2021) and Raouf & Al-Ghamdi (2020).

Researchers have used life cycle assessment (LCA) to analyze the whole life carbon impacts (comprising of the embodied and operational carbon impacts) of buildings and building systems (Zigart et al., 2018). Monteiro & Freire (2011) compared different exterior wall options of a single-family house in Portugal using three impact assessment methods. Bin Marsono & Balasbaneh (2015) used LCA to analyse and compare the global warming potential (GWP) of seven combinations of exterior and interior walls using different building construction materials for residential buildings in Malaysia. Choi et al. (2016) analyzed the carbon impacts of steel-reinforced concrete, concluding that early design strategies around the types and proportions of concrete, steel, and rebar can significantly reduce greenhouse gas emissions. It is expected that the same finding as Choi et al. (2016) will apply to building enclosure systems. However, most studies do not analyze the layers of enclosure systems in that much detail. Sierra-Perez et al. (2016) conducted an environmental assessment study of façade-building systems and their thermal insulation materials; however, this was also at a whole-building level as opposed to the enclosure system level only.

Similar to the scope of this research, recent studies have been focusing more on enclosure assemblies. In four temperature zones in the United States, Hong et al. (2020) compare six high-performance external wall assemblies for a residential building, including four assemblies that use light-frame construction (LFC). Lariviere-Lajoie et al. (2022) used cradle-to-grave life cycle assessments to quantify the contribution of upfront embodied impacts to the environmental effects of exterior wall assemblies of an office building in Quebec City (Canada). However, these focus on wall systems and exclude roof and floor assemblies, which also considerably impact buildings' thermal performance and whole-life carbon. For this reason, this research aims to establish a replicable methodology for analyzing and calculating the embodied carbon intensity of commonly used building enclosure systems for Part 3 buildings in the Greater Toronto and Hamilton Area (GTHA) in Ontario, Canada.

2. Methodology

2.1. Assembly Selection and R-value Calculations

The building enclosure systems included in this study focus on some of the most commonly used assemblies in Part 3 commercial, residential, and institutional buildings (as defined by the Ontario Building Code) in the Greater Toronto and Hamilton Area (GTHA). Based on the authors' collective industry experience, a total of 26 building enclosure assemblies, as shown in Table 1, were selected for analysis, prioritizing variety in the materials used to establish a strong data set for comparison and to maximize the usefulness of the data for analysis and industry guidance. Most of the assemblies selected are suitable for new construction projects. However, some assemblies suitable for existing building retrofits are also included.

Table 1. Enclosure Assembly List

S/N	ID	Assembly Description	Type
1	W01	Exterior Insulated CMU with Brick Veneer	Wall
2	W02	Split Insulated Steel Frame with Lightweight Cladding	Wall
3	W03	Split Insulated Steel Frame with EIFS (EPS)	Wall
4	W04	Exterior Insulated CLT wall panel with Aluminum Panel Cladding	Wall
5	W05	Split Insulated Wood Frame with Mineral Wool and Stone Veneer Cladding	Wall
6	W06	Double Wythe Insulated Precast with Kooltherm	Wall
7	W07	Doubly Wythe Insulated Precast with XPS Insulation	Wall
8	W08	Spandrel Panel with 3" Mineral Wool Backpan, Interior Insulated with Mineral Wool	Wall
9	W09	Spandrel Panel with 3" Mineral Wool Backpan, Interior Insulated with Sprayfoam	Wall
10	W10	Insulated Metal Panel with Mineral Wool Insulation	Wall
11	W11	Insulated Metal Panel with Polyisocyanurate Insulation	Wall
12	W12	Architectural Precast with Mineral Wool Interior Insulation	Wall
13	W13	Architectural Precast with Spray Foam Interior Insulation	Wall
14	W(R)14	Existing Masonry with Interior Mineral Wool Insulation	Wall
15	W(R)15	Existing Masonry with Interior Spray Foam Insulation	Wall
16	W(R)16	Existing Masonry with Exterior EIFS Overcladding	Wall
17	W(R)17	Existing Masonry with Exterior Aluminum Panel Overcladding	Wall
18	R01	Conventional Roof with Polyiso on Metal Deck	Roof
19	R02	Protected Membrane Roof with XPS on Concrete Deck	Roof

20	R03	Conventional Modified Bitumen Roof with Hybrid Insulation on CLT Deck	Roof
21	R04	Existing BUR Roof Replacement over Polyisocyanurate Insulation	Roof
22	R05	Sloped Metal Roof Assembly	Roof
23	F01	Parking Garage Concrete Ceiling with Vinyl-faced Mineral Wool	Floor
24	F02	Parking Garage Concrete Ceiling with Fire Resistant Spray Insulation	Floor
25	F03	Parking Garage Insulated Dropped Ceiling (Heated Plenum)	Floor
26	F04	Insulated Soffit with Mineral Wool	Floor

In order to establish reasonable performance targets that both meet the current needs of designers as well as meet future performance requirements of local energy codes such as the Toronto Green Standard version 4, the "*City of Toronto Zero Emissions Building Framework (2017) Appendix C: Parametric modelling results*" was used as a reference point to set recommended baseline target effective R-values and U-values for the roof, wall, exposed floor, and vision glazing. A thermal performance target of R-30 (RSI-5.3) was set for the roof, R-25 (RSI-4.4) for the walls, and R-25 (RSI-4.4) for the floors.

The assemblies were designed to meet the effective R-value targets followed above, and the effective R-value of each of the selected assemblies was calculated following building science best principles as well as NECB-2017 and ASHRAE Fundamentals.

Examples of effective R-value calculations are provided in Figure 1 below for wall W01, which include the assembly description, material thickness, material conductivity, effective R-value and nominal R-value.

W01	**Exterior Insulated CMU with Brick Veneer**								
Assembly Graphic	Assembly description	t_{SI} [mm]	t_{IP} [in]	k [W/mK]	C (USI) [W/m2K]	RSI effective [m2K/W]	R effective (ft2·°F·h/ BTU)	Rnominal (ft2·°F·h/ BTU)	Thermal Degradation (%)
	Interior air film					0.12	0.68		
	Interior gypsum board	12.70	0.50	0.16	27.04	0.04	0.21		
	Steel stud-framed wall	63.50	2.50	0.49	7.75	0.13	0.73		
	Single-wythe CMU wall	203.20	8.00	1.18	5.81	0.17	0.98		
	Self-adhered sheet-applied air barrier and water-resistive barrier (WRB) membrane (vapour impermeable)	1.00	0.03	-	-	-	-		
	Semi-rigid mineral fiber exterior insulation with intermittent stainless steel masonry veneer anchors	152.40	6.00	0.04	0.24	4.09	23.22	25.80	10%
	Air cavity	25.00	0.98	0.03	-	-	-		
	Anchored masonry veneer	90.00	3.54	0.79	8.78	-	-		
	Exterior air film					0.03	0.17		
	TOTALS	547.8	21.6			4.6	26.0	25.8	

Figure 1. R-value Calculation Table for Wall 1 (W01)

2.2. Life Cycle Analysis

The LCA of this study followed the European Standard EN 15978:2011 for whole-building LCA. This standard, based on ISO 14040 (International Organization for Standardization(a), 2006), describes the method for calculating the environmental performance of a building based on Life Cycle Assessment (LCA) and other quantified environmental information and provides a way to publish and communicate the results of the analysis.

This LCA aimed to analyse the embodied carbon of the layers in four building enclosure systems (exterior walls, floors, and roofs). The physical system boundary includes all material components required for the construction of 9 m^2 of enclosure assembly with a thermal performance of R-30 (RSI-5.3) for the roof, R-25 (RSI-4.4) for the walls, and R-25 (RSI-4.4) for the floors. The temporal boundary included life cycle stages A1 to A5, assuming a 60-year building lifespan. Life cycle stages B and C were excluded due to EPD data uncertainty.

The material quantities for each building enclosure component were calculated using Microsoft Excel spreadsheets. For the parts within each assembly, component areas or volumes were calculated for the functional unit 9 m^2 as was appropriate for the corresponding environmental emissions data available or product datasheet.

Using the material quantities calculated, the life cycle impacts of the component materials were calculated using the One Click LCA application. Component EPDs were selected from the One Click LCA database based on the most representative material available for the components' building enclosure purpose and material properties. The TRACI v2.1 characterization for North America was used, which includes the following impact categories:

- Global warming potential (GWP) in kg CO_2e
- Acidification potential in kg SO_2e
- Eutrophication potential in kg Ne
- Photochemical smog potential in kg O_3e
- Ozone depletion potential in kg CFC-11e

GWP was reported separately from the other impact categories, as it was the primary focus of this study. The embodied carbon of the assemblies was presented in absolute (kg CO_2e per functional unit) and carbon intensity (kg CO_2e/m^2). The biogenic carbon of each assembly was also reported separately in the modules they occur per ISO 21930:2017 and the National Research Council (NRC) Whole Building Life Cycle Assessment Guidelines (International Organization for Standardization, 2017; Bowick et al., 2022).

Following the life cycle impact assessment (LCIA), the assemblies were analysed to identify the components with the highest embodied carbon. Further sensitivity analysis was conducted by replacing high-impact materials with lower-impact alternatives in One Click LCA to understand the magnitude of the impact. Finally, the results were presented in graphs and charts showing the GWP impacts and a table ranking the enclosures from lowest to highest impact.

3. Results and Discussion

The findings indicate that the cladding material, insulating layer, and backup structure account for most of the embodied carbon in exterior wall enclosures; the other components have limited impact. The pie size in Figure 3 represents the overall amount of embodied carbon by each wall assembly. Large pies indicate a higher total amount of carbon emissions. The slices display the breakdown of the critical constituents of carbon emissions.

The structural components accounted for most of the embodied carbon in the roof assemblies, except for R04 and R05, as shown in Figure 4. R04, a retrofit assembly, did not

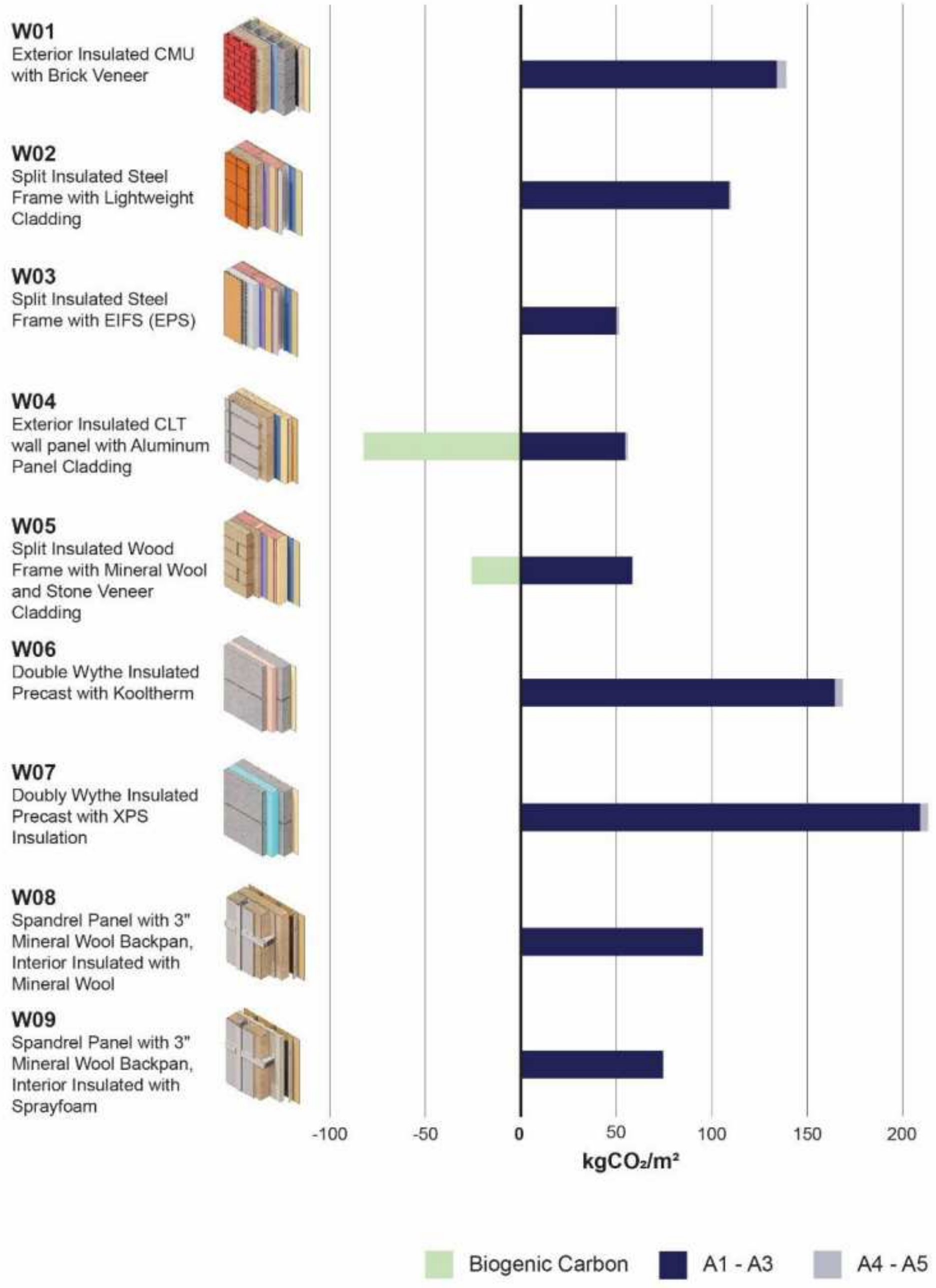


Figure 2. Embodied Carbon of W01-W09

include the emissions from the existing structure, as they would come into the new service life burden-free per Wralsen et al. (2018). The aluminium metal roof of R05 accounted for more than half of the embodied carbon of the roof assembly, and likely due to the carbon-intensive manufacturing process of aluminium.

The floor assemblies were similar to the roof systems, with the structural components accounting for over 60% of their embodied carbon. The insulation was the second-highest, accounting for an average of 10% of the total embodied carbon across all four assemblies.

Therefore, designers should carefully select these components and consider alternatives early in the design process.

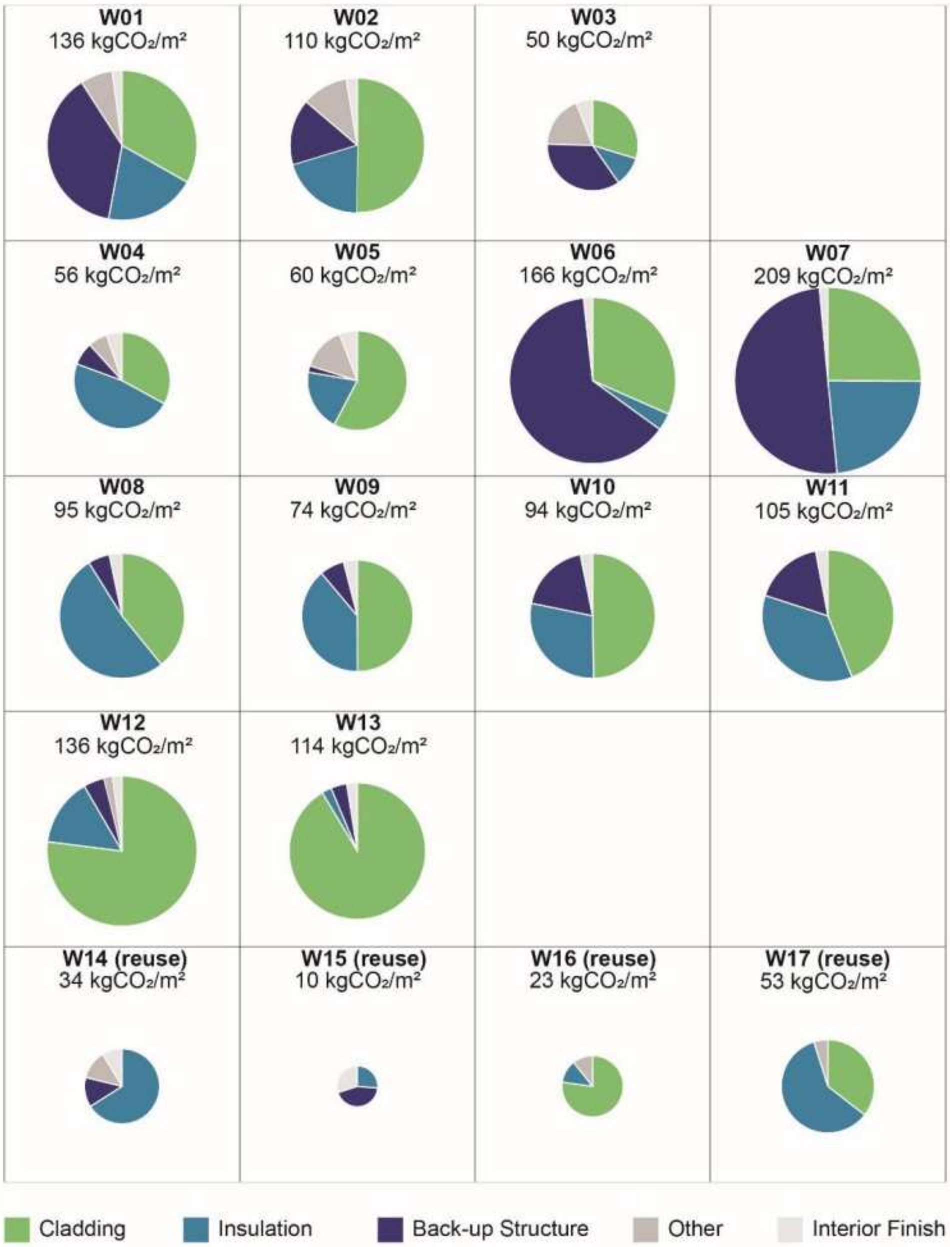
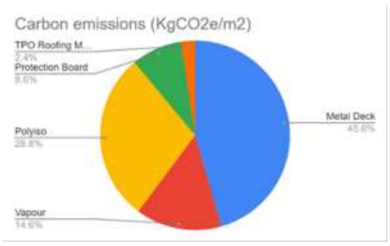
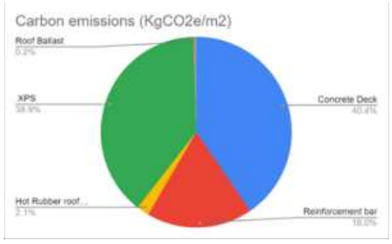


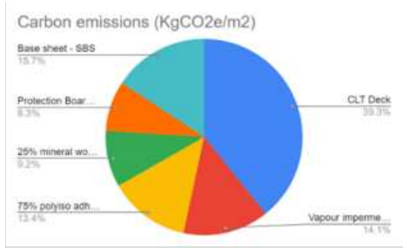
Figure 3. Embodied Carbon of Wall Assemblies Represented by Size



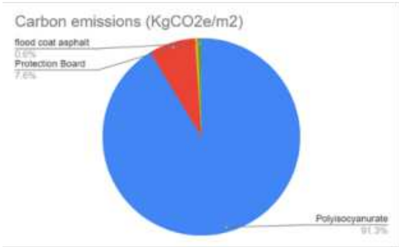
Roof 1 (R01)



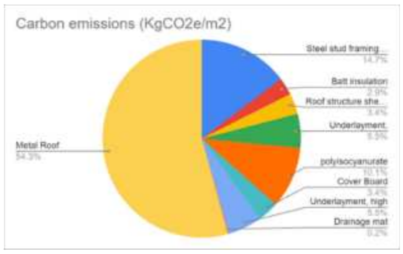
Roof 2 (R02)



Roof 3 (R03)



Roof 4 (R04)



Roof (R05)

Figure 4. Embodied Carbon Emissions of Roof Assemblies (Please zoom in to see figures)

4. Conclusion

Building and component-level embodied carbon analysis is still in its infancy, and data availability is rapidly evolving. The available EPDs in North America are frequently generic industry-level assessments or are not yet available. It is envisioned that additional manufacturer- or even plant-specific EPDs would enable more in-depth material analysis and selection. These evaluations should not be viewed as conclusive solutions for choosing an enclosure but rather as guidance for thinking about the various materials that go into making an enclosure. They also highlight the layers with significant impacts that need more study.

The information utilised in EPDs and databases like One Click LCA is frequently based on regional, national, or even continental averages that do not distinguish between items. The GWP of materials at the product stage is frequently region-specific and influenced by elements like the energy source of local electrical grids, manufacturing techniques, transportation choices available locally, the accessibility of raw materials, etc. The critical systemic differences between provinces and industries within provinces are not considered in the available national averages, and the consequent GWP of the resulting assemblies and materials within these assemblies is subject to change when placed within a particular regional context. The situation is anticipated to improve as more firms develop precise product and production plant data. This will make it easier to choose quality components and materials that are made locally.

The study's method enables the reduction of the whole-life carbon emissions of new constructions in Toronto and can be replicated in other regions. It provides a simple way to integrate thermal performance with embodied carbon analysis early in the design phase. This enables designers and architects to choose materials wisely based on their GHG emissions and thermal efficiency. This interaction encourages the development of more environmentally friendly structures that better reduce whole-life carbon emissions of buildings.

Despite its benefit, this method is limited in that other factors that may affect a building's overall energy performance are not considered. Such factors include the thermal mass and hygrothermal properties of enclosures and their interactions with other building energy systems for efficient operational energy use and adequate indoor environmental quality. Additionally, the study focuses on the GWP impact of the enclosures. Future studies can assign more weight to other environmental impact categories for a more holistic picture.

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Embodied carbon performance gaps in timber production for the UK built environment: A brief review.

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Abstract: The built environment contributes to nearly 40% of global carbon emissions. It is vital that the carbon footprint of building materials is accurately understood. Mass timber construction is widely assumed to be a sustainable approach to the building due to the regenerative and carbon sequestrating capacities of timber among others and is being increasingly employed to reach Net Zero by 2050. Performance Gaps are a widely accepted phenomenon in the Built Environment, with a strong focus on reducing operational gaps but far less consideration for embodied carbon gaps. Several studies have demonstrated shortfalls in the available carbon footprinting methods for analysing the full carbon flux at the point of extraction and the climate change potential of timber production. We highlight three key areas of performance gaps in the static life cycle assessment methods and realistic climate impacts. Firstly, sustainable forestry certification is opaque in its reliability and capacity to deliver regenerative forestry. Secondly, emissions from peat and the forest floor are not considered in static LCA models, yet contribute considerably to woodland carbon flux, and aerosol transfers. Thirdly, the radiative forcing of surface albedo change caused by landcover modifications. We propose further analysis to enhance the capacity of the construction industry to employ dynamic LCA modelling to limit its carbon emissions and recommend forestry activities.

Keywords: Embodied Carbon, Forestry, Dynamic LCA, Carbon flux, Mass timber
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1. Introduction

The global built environment contributes approximately 39% of the planet's carbon dioxide (CO_2) emissions through embodied carbon and operational emissions of buildings (UN, 2021). Construction continues to increase in the UK with private industrial, residential and commercial construction driving annual growth (ONS, 2022). Within this, demand for new timber construction has also continued to grow significantly in the UK in recent years. 2021 saw timber imports grow 15% on the previous year, with concerns of demand-supply gaps emerging as a result of global supply-chain issues (Timber Development UK, 2022).

Calls to further increase the implementation of timber as a building material are growing. Aiming to expand carbon storage threefold, timber construction is seen to be a tool for mitigating climate change and a key component in the journey to Net Zero Carbon 2050 (CCC, 2019). CO_2 is absorbed by trees from the atmosphere as they grow through photosynthesis. This captured carbon element is retained in the wood until it reaches the end of its life, offering an opportunity to lock carbon in the material while the land is used for further carbon sequestration. Figure 1 shows the globally agreed approaches for calculating the sequestered carbon in timber (Hawkins, 2021), illustrating the lumped approach that is normally used in Life Cycle Assessments (LCA) for buildings. However, several studies have shown that the available LCA methods do not consider the full carbon flux and climate change potential of timber production. With continuing uptake of timber for UK construction, this brief review highlights the performance gaps that exist in measuring whole-life carbon performance of timber. The review focuses particularly on the gap between the carbon and greenhouse gas balance of forests and those calculated through standardised Intergovernmental Panel on Climate Change IPCC guidelines (IPCC, 2006) which could result in an overstatement of performance.

Figure 1. Approaches for calculating the sequestered carbon in timber (adapted from Hawkins, 2021)

2. Life Cycle Assessment Performance Gaps in the UK Built Environment

Performance Gaps are generally accepted (in varying capacities) within the Built Environment. The term categorises the inherent discrepancies which arise between the performance of the designed 'idealised' building, and that of the building realised onsite when in its operational phase (AHMM, 2022). Performance Gaps in building operational energy have been discussed in the industry for decades, with Post Occupancy Evaluation and detailed commissioning processes aiming to capture, record and rectify many gaps during the handover and occupation phases. However, a building's operational impact accounts for one key component of a building's life-cycle performance, the other element being its embodied carbon performance (Fig 2). It is anticipated that the embodied component will become incrementally more critical with grid decarbonisation and wider uptake of onsite renewables reducing operational energy emissions.

The concept of Performance Gaps is now being applied to Embodied Carbon too. When combined with the operational gap this provides the whole-life performance gap. A multitude of factors contribute to various project and building life stages, from material extraction and production to initial design stages through to operation (Fig 3). This review focuses on the indirect and hidden gaps present in the A1 Raw material supply phase for timber products, concerning the IPCC approach. However, this is just one small component of a larger issue facing the built environment industry in accurately assessing life-cycle carbon impacts in the move to Net Zero Carbon by 2050.

3. Life Cycle Performance Gaps in Timber

Quantifying the full environmental impact of natural regenerative materials such as timber is inherently complex and has significant scope for uncertainty. Calculations for embodied carbon in construction materials draw upon the methodology that has been developed by the IPPC (2006), and EN15804:2012+A2:2019, which sets out the requirements for developing Environmental Product Declarations (EPD) for construction products. In the UK construction industry, softwood and hardwood products are primarily imported from the European Union (Sweden, Latvia, Finland, Germany) and North America, with UK forests supplying around 31% of our total sawn wood demand (TDUK, 2022; Forest Research, 2022). With such high levels of imported timber sourced from areas with differing forestry practices, EPDs provide a critical source of information for life cycle assessors and wider practitioners. However, current EPD assessment methods for timber have a series of limitations (as outlined below) meaning the embodied carbon performance we are predicting is likely to be better than the true scenario.

3.1. Sustainable Forestry certifications

Amid growing discontent towards the forestry industry in the late 20th Century as a result of high deforestation and other resource management concerns, sustainable forestry certifications emerged from the private sector to recognise foresters that employ practices which limit harm to natural resources and nearby communities. Forestry Stewardship Council (FSC), Programme for the Endorsement of Forest Certification (PEFC), Sustainable Forestry Initiative (SFI) and Canadian Standards Association (CSA) are several of many certifications for forestry approaches.

There are many criticisms of sustainable certifications implementation efficacy and capacity to protect indigenous communities (Earthsight, 2021; Greenpeace, 2021). It is also essential to consider the impact of certified forests on carbon sequestration and emissions. The biogenic carbon stored in tree cells is only incorporated into LCA if the timber has been sustainably sourced (RICS, 2017). In a wide-ranging study across geographic regions, Dietz et al (2022) found that scholarly research into sustainable certifications across agriculture, forestry and aquaculture has a mixed performance at the producer level. Meanwhile, Tritsch et al (2020) found that FSC is one of several factors affecting lower deforestation levels, and is not necessarily the most significant. This uncertainty suggests that it cannot be guaranteed that plots are replanted, or that the same tree is planted after a tree is extracted, questioning the validity of biogenic carbon sequestration and storage calculations dependent on this assumption.

3.2. Emissions from Peat

Peatland is a terrestrial wetland ecosystem in which anaerobic conditions related to the water table elevation prevent the rapid decomposition of plant matter. This results in the long-term storage (millennia) of sequestered carbon from plant photosynthesis and the capture of nitrogen. The intricate interactions with the ecosystem include the release of methane (CH_4) into the atmosphere when the water table is high (Sloan et al., 2018), further contributing to the complex dynamics between the soil and plant composition, the water table and greenhouse gases.

Forestry practices, as with conventional agriculture, require drained land. This impacts the carbon efflux as a result of several processes. Firstly, if the disruption of the vegetated layer of the peatland prevents it from being able to photosynthesise, it is significantly limited in its capacity to sequester carbon into the soil over time (Sloan et al., 2018). This stops the build-up of plant matter in the soil, and the sequestered carbon with it. Secondly, the lowered water table influences the oxidation of organic matter and causes the carbon transfers in the soil to alter. This is due to greater oxygen levels being available to the organisms on the forest floor, which increases the rate of organic-matter decay (Leitner et al., 2016) and causes significant instabilities in GHG balances (Minkkinen et al., 2002). Thirdly, when carbon is carried from the soil by drainage to water bodies, it can be released from the water as CO_2 emissions (Härkönen et al., 2023).

Considerable tracts of large-scale forestry and afforestation occur on peatland landscapes. For instance, in the UK, it is predicted that 18% of peatland is beneath forestry (Evans et al., 2014). Such new planting or tree replacement on peat soil transfers carbon processes from secure storage in the below-ground material, to reliance on the aboveground storage of capacity of trees, limiting the carbon life-cycle to the end use of timber in addition to the carbon lost from the peat into the atmosphere. In most cases, this leads to a considerably shorter storage term (years to decades), together with an overall decline in soil-carbon storage, than if it were locked in the undisturbed, waterlogged peat soil (IUCN UK Peatland Programme, 2020).

3.3. Albedo change

The change to albedo from disturbing forests causes a radiative forcing that can be traced as a source of global warming (O'Halloran et al., 2012). Albedo is an important controlling factor which impacts land surface temperature and subsequent evapotranspiration and release of aerosols (Pielke et al., 2011). Surface albedo is viewed as a crucial area of research for understanding and improving climate change mitigation and adaptation (Bright and Lund, 2021), particularly in the context of forestry products and carbon dioxide sequestration strategies (Boysen et al., 2016; Bright and Lund, 2021).

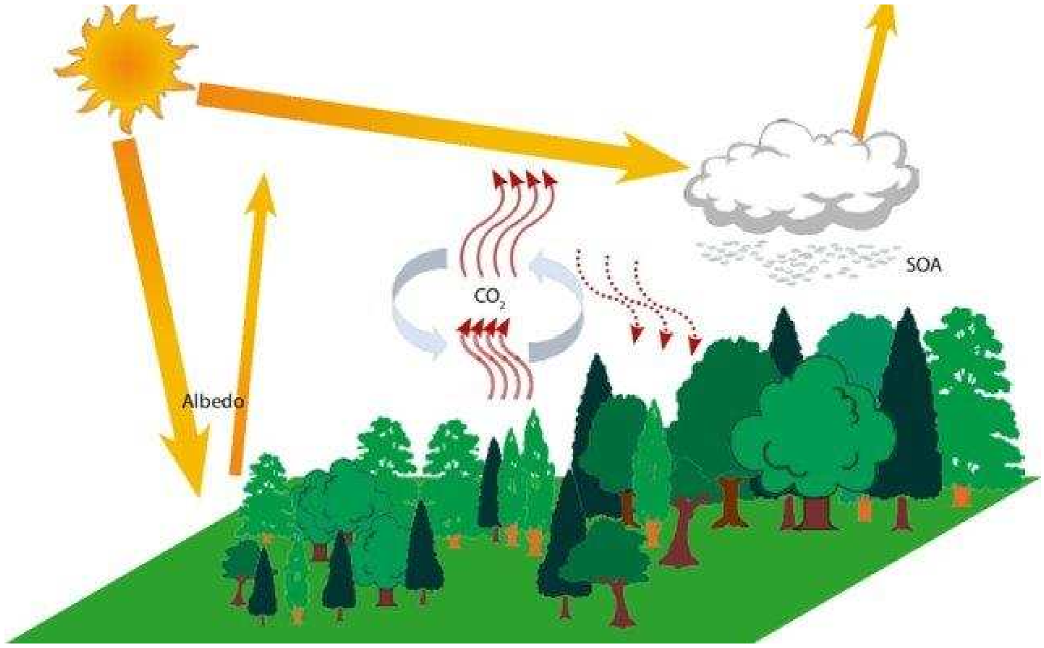

Figure 2. Illustration of the processes influencing radiative forcing: surface albedo, CO_2, and secondary organic aerosols (SOA) (Berndes et al., 2016).

It has been increasingly recognised that surface albedo is not considered in carbon calculators for wood products. The reason may be that the topic presents too many complex dynamics to be interpreted within the scope of most calculations. For instance, the Forest Research report 'Quantifying the sustainable forestry carbon cycle' (Matthews et al., 2022) omits the detail of surface albedo from their modelling scenarios presented. Holtsmark (2015) found that when surface albedo change after harvesting was accounted for in simulations, it was no longer possible to consider biofuels as a carbon-neutral product. Radiative forcing is a highly geographically and climatically specific biogeochemical and biophysical process. For example, albedo values are very different for areas of bare earth compared with areas covered by fresh snow (Weihs et al., 2021), meaning that seasonal changes alone can add complexity to the process of assessing any one product. In another study, Otto et al (2014) studied the effect of species variation and thinning strategies on summertime forest albedo. They found that both variables have a considerable impact on forest albedo, and consequently climate variability, therefore recommending the incorporation of such calculations into Earth System models. Although the IPCC's Sixth Assessment Report (Intergovernmental Panel On Climate Change, 2021) explicitly refers to the biogeochemical and biophysical effect of radiative forcing from surface albedo in changes to forested land, it is not directly included in modern LCA calculations.

Dynamic modelling is understood as an enhanced approach to estimating the carbon footprint and global warming potential of materials through analysing the atmospheric dynamics and heat-trapping ability of GHGs (Hawkins et al., 2021; Wang et al., 2022). This is largely due to the static nature of LCA's methodologies' interpretation of carbon emissions as neutral, referred to as the 0/0 or -1/.+1 approach (Andersen et al., 2021). However, dynamic LCAs offer a temporal analysis of the effects of land use changes over time (Cordier et al., 2022). This consideration of timing is crucial for accurately establishing the varying conditions of change in forest albedo and peat carbon emissions from water table changes. A previous study has demonstrated through dynamic LCAs the need for increased growing periods in forests to achieve climate neutrality, if at all (Wang et al., 2022).

Lately, fast-growing crops such as hemp, straw and sugarcane are increasingly being studied to address problems of carbon forcing in forestry (Caldas et al., 2019). These biomaterials are assumed to be fully regenerated within one year of harvesting in contrast to timber which takes longer to regenerate in the forest (Pittau et al., 2018). In addition, improved sequestration of carbon can be facilitated due to higher annual yields, therefore offering a potentially superior option for achieving Net Zero objectives in comparison to wood products (Lahtinen et al., 2022). Furthermore, such crops present an opportunity for raising the water table through 'paludiculture' to reduce the emissions associated with peat decomposition and subsequently, enhance the capacity of peatlands to behave as carbon sinks (Mulholland et al., 2020; Ziegler, 2020).

4. Conclusion

The carbon flux of forests is a complex mosaic of variables which in many cases are not yet fully understood, particularly in terms of both the interactions between forest and soil carbon and the radiative energy balance. The built environment is shifting towards employing mass timber construction as a method of limiting the carbon footprint of buildings and construction. Whilst this is a broadly positive turn away from other anthropogenic materials, not enough is yet known about the precise impacts on the environment through associated emissions from the extraction of timber and the industry must ensure any benefit is correctly attributed. LCA has been used as a satisfactory calculation of carbon emissions from wood, but research has proven that the methods used do not cover the detail necessary to establish the full, true, sustainability of forestry products. Sustainable forestry certification has contributed to improving environmentally sustainable woodland management, however it cannot be guaranteed that the conditions of certified forests and re-planting restore the biogenic carbon sequestered in trees that have been extracted. Forestry land is commonly drained in much the same way as agricultural land, leading to low water tables and carbon emissions from peaty soils beneath trees. Thirdly, when trees are removed from forests, the surface albedo of the planet changes, thus causing shifts in the radiative forcing of a forested area. Further research is needed to enable the wider improvement and implementation of time-dependant dynamic modelling to close the performance gap of LCAs and understand the true environmental impacts of forestry.

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Case Study: A Low-Carbon, Mass-Timber Arena

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Abstract: As energy codes have driven down the operational carbon of buildings, embodied carbon has become a prominent issue in design and construction. The U.S. Inflation Reduction Act, passed in 2022, made specifying low-carbon building materials and products a vital component of the federal government's strategy to reduce U.S. greenhouse gas (GHG) emissions. After our university's recent construction of a mass-timber sports arena, a team of UI architecture graduate students was invited to participate in a Life Cycle Analysis to calculate the building's embodied carbon. The final LCA report was published in January 2023.
With this exercise completed and the report in hand, we still had many questions. Preeminent among them was, "Is a net-zero carbon arena possible?" Our arena was built of locally sourced timber grown in the university's experimental forest about 10 miles from campus. This timber was used for massive glu-lam beams/trusses that spanned the breadth of the arena and for CLT roof members, as well as various wooden elements in the façades. Sounds like a good start toward net zero, right? However, the global warming potential for the arena's structure is calculated to be 213 $kgCO_2eq/m^2$, not exactly zero. In this paper we will examine the causes of this disappointing result. Although the final LCA report warns against comparing assessments with other buildings, we are also examining the design decisions made in a contemporaneous arena in Zurich made of concrete and steel. Adam Caruso of Caruso St. John Architects said, "If we were to build this today, we would not have built with so much concrete." Our paper will compare and share insights from the two arenas as well as other commercial and institutional buildings.

Keywords: Mass Timber, Life Cycle Analysis, embodied carbon

1. Introduction

When the new ICCU (Idaho Central Credit Union) Arena opened in fall 2021 our team was invited to participate in Athena's Life Cycle Analysis (LCA), under the auspices of the United States Endowment for Forestry and Communities, in spring 2022. The University of Idaho (UI) team took this opportunity as a great means to gain insight as to the value of mass timber construction in reducing buildings' carbon footprints. Our primary question was, "Is a net-zero-carbon arena possible?" When the LCA was finally published in January 2023, we noted that the global warming potential of the building was calculated to be above zero, 213 $kgCO_2eq/m^2$. We also wondered if the carbon sequestration value of the wood used throughout the building were reported. During construction the UI team, using the Canadian Wood Council Carbon Calculator, derived a preliminary sequestration value of 1,141 metric tonnes with an additional 442 metric tonnes of avoided emissions. The LCA report left us with additional questions, commented on below.

1.1. Q1: What were the design intentions and limitations?

The initial vision for the arena project heavily involved the Idaho Department of Ecology and Natural Resources, aiming to celebrate the state's timber heritage through the innovative use of wood sourced from the UI's experimental forest. This approach not only paid homage to local resources, but also brought enthusiasm for generating economic opportunities within the region. To bring this vision to life, the logs were milled into dimensional lumber (lamstock) by Idaho Forest Group, while the architectural team collaborated with local companies, such as Boise Cascade and QB Laminators, to fabricate the glu-lam beams (Opsis Architects, 2021).

Another key aspect of the design focused on identifying the most efficient methods for production and construction. In order to incorporate sustainable systems, the architects reimagined the prototypical, windowless, steel-box arena. Based on discussions with architect Chris Roberts the Opsis team's primary goal was to use mass timber harvested from Idaho's forests to create an innovative, long-span structure. While carbon reduction metrics were not initially used during the design nor construction processes, it was evident that timber structural members could outperform their concrete counterparts in similar sports arena structures.

Through the optimisation of structural components, the project successfully reduced the amount of timber required compared to the first design iteration, thus achieving significant improvements in sustainability. Even though embodied carbon was not a design issue, the resulting structure certainly addressed that issue.

1.2. Q2: What does the LCA's focus on embodied carbon indicate?

Whole building life cycle assessments, as the name implies, are cost explorations of a building's entire lifespan. LCAs systematise a building's lifespan into stages. As shown in Figure 1 below our LCA was performed before the building had completed a full year of use, and measured only embodied carbon for the construction and end-of-life stages. Each of these stages has some associated nontrivial environmental impacts. The System Boundary is drawn around items within the LCA's scope. For instance, the environmental practices of raw material supply and acquisition, an industry in its own right, are quantified as part of the whole building LCA. Sustainable practices in the forest industries in the U.S. and in Canada are neither uniform nor standardised. On top of that, the long-span, glu-lam members used for the roof support were highly specialised products that could not be fabricated locally.

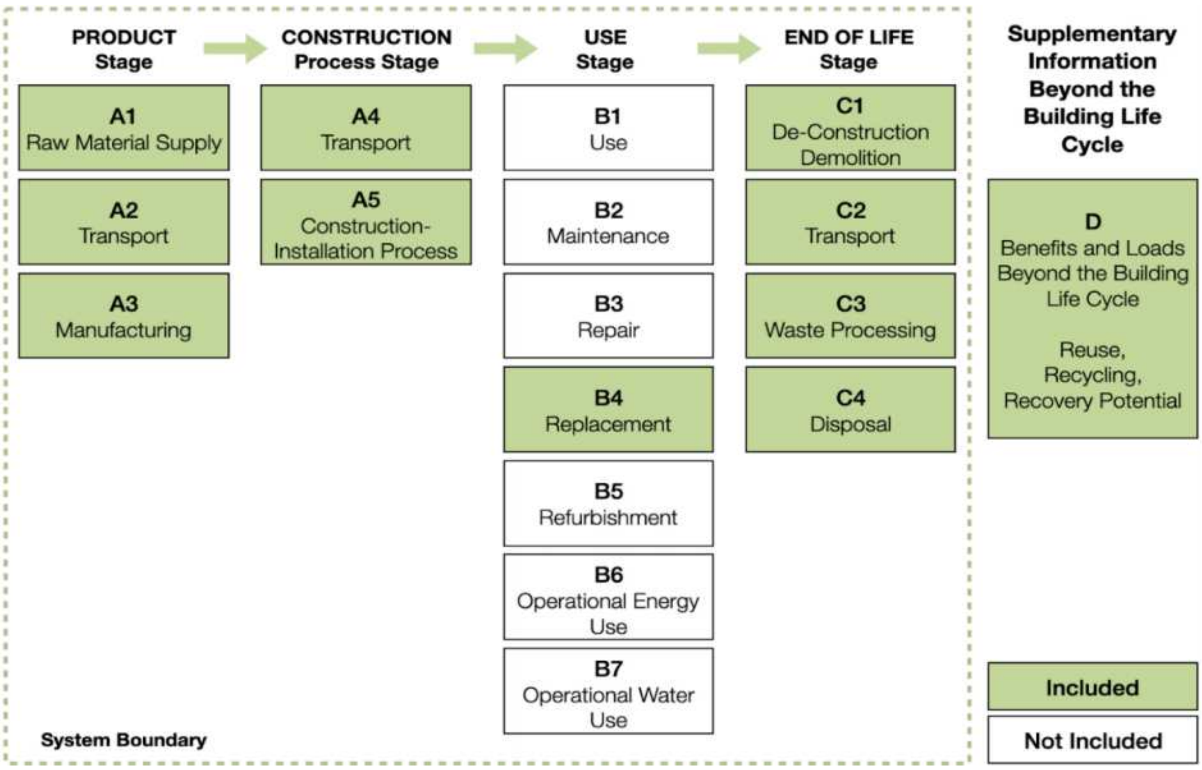

Figure 1. Stages of building life considered for the ICCU Arena (Athena, 2023).

Non-renewable materials, such as Portland cement and steel, require significant energy to extract and transform into usable building products. The manufacturing process for each is dependent on fossil fuels. Yet according to the U.S. Forest Service, mass timber buildings use as much energy to produce as equivalent concrete buildings, indicated by LCAs (Puettmann et al, 2021). That is, the forestry industry uses carbon fuels to harvest, transport, mill, dry, glue, and press lumber to form a usable mass timber product. By delving into the GHG emissions of buildings we can begin to reduce them. Kelly Alvarez Doran, Senior Director of Sustainability and Regenerative Design at MASS Design Group, leads a University of Toronto studio called, “Towards Half: Climate Positive Design for the GTHA.” They use LCAs to make quantifiable comparisons of similar buildings’ envelopes and structural systems. These comparisons can highlight the performance of a building as an expression of the amount of carbon it embodies. The whole building LCA brings us one step closer to paying for the real Dasguptaian value of an item by establishing an environmental as well as monetary cost.

According to Doran, “[t]he ‘AED’ sector is just starting to understand the immense carbon impact of building materials. To drastically reduce this impact, greater knowledge and firm embodied carbon benchmarks and targets must become part of building standards and planning policies that govern construction across Canada” (Doran, 2021). Doran is not calling for yet another layer of codification of building assemblies, but rather the consideration by policy makers and government officials to support industries as they decarbonise and help coordinate disparate processes. In the case of lowering embodied carbon in buildings, it may be a matter of reworking current building codes and re-evaluating forestry practices. The way we shape and manage forests for economic gain plays a large part in the carbon sequestering capabilities of trees and soils as well as the health of ecosystems.

The LCA challenges architects, engineers, and designers to view the creation of any building in a new light. We have passed the point where merely managing the carbon emissions associated with each stage of a building’s lifespan is adequate. The embodied carbon associated with all buildings, revealed by LCAs, indicates the collective effects that our industry has on our planet. The LCA is a crucial tool in decarbonising the AEC industry, which now accounts for a third of world GHG emissions (Puettmann et al, 2021). Tracking and quantifying greenhouse gas emissions is a contemporary burden that could make the difference in a world permanently altered by human-caused climate change.

1.3. Q3: How does the building compare to others?

In a similar pursuit of reducing embodied carbon in buildings, Doran has shared results from his Half Studio research aimed at identifying the major drivers of carbon embodiment in construction. Among the primary contributors were the structural system, particularly cast-in-place reinforced concrete, as well as construction below grade for foundations and underground parking.

Doran’s examples demonstrated that a low-rise structure with a concrete foundation and timber frame superstructure has a 50% lower carbon footprint compared to a fully concrete construction (Doran, 2021). The ICCU Arena follows a similar structural scenario, with a concrete foundation and basement, complemented by mass timber glu-lam beams, wooden roof deck, and wood cladding. The calculated carbon embodied in this structure amounts to 213 $kgCO_2eq/m^2$, which is lower than the values observed in Doran’s comparative case studies (cf. Table 1 below), even for low-rise, wood-frame buildings.

Table 1. Carbon embodiment in different structures (Doran, 2021).

PROJECT ADDRESS	FLOORS	STRUCTURAL SYSTEM	GFA OF STUDY	kgCO2e /m²
538 Eglinton Ave E	G+3	Wood Frame	203	283
571 Dundas St W	G+2	Wood Frame	136	243
318-324 John St	G+3	Wood Frame	342	227
GTHA LOW-RISE AVERAGE				**251**
1075 Queen St E	G+6	Hollowcore & Steel	859	395
2803 Dundas St W	G+7	Concrete	1,522	596
22 Trolley Cres	G+12	Concrete	2,289	366
38 Cameron St	G+13	Concrete	4,529	615
505 Richmond St W	G+14	Concrete	1,911	469
GTHA MID-RISE AVERAGE				**488**
481 University Ave	G+53	Concrete	20,618	494
11 Wellesley St W	G+60	Concrete	10,644	546
GTHA HIGH-RISE AVERAGE				**520**

On the other hand, a contrasting construction type with a similar building use and contemporaneous design–build phase is the Swiss Life Arena in Zurich, Switzerland, designed by Caruso St John Architects. This 70,000 m^2 (753,470 ft^2) arena, accommodating 12,000 seats houses an ice hockey arena, practice rink, business centre, restaurant, and parking. The construction started in March 2019 and completed in November 2022 with a building footprint of 28,000 m^2 (301,390 ft^2). Even though the building is recent, the design phase began a decade ago: Adam Caruso said, “If we were to build this today, we would not have built with so much concrete” (Williams, 2022). Comparing the size of the two arenas side by side, the ICCU Arena is 6,149 m^2 (66,186 ft^2) with a capacity of 4,700 seats, one-tenth the size of the Swiss Life Arena with 2/5 the seating capacity, so the use of concrete cladding is even more concerning than we imagined.

Figure 2. Swiss Life Arena with concrete cladding (Williams, 2022).

The structure is built with 5,700 tonnes of steel and 100,000 tonnes of in-situ concrete (Williams, 2022). The concrete cladding elements, resembling hanging drapery, cover the buttresses and trusses supporting the raised area and associated facilities (Caruso St John Architects, 2019). The ICCU Arena has concrete mainly limited to the basement and the foundation. The roof is supported by huge timber glu-lam beams and doubled plywood decking while the walls are steel studded and wood panelled. Wood is also used in some floor decks, the stairways, and window framing. In comparison the Swiss Life Arena uses significantly more concrete.

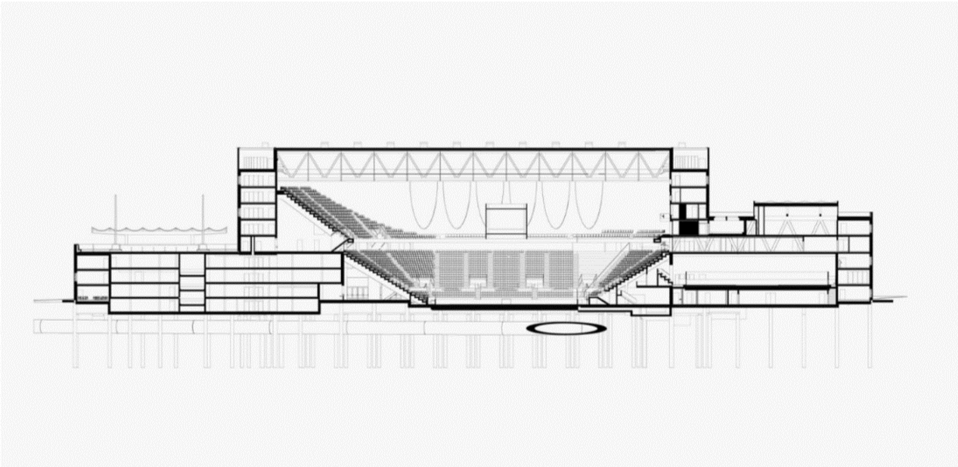

Figure 3. Section view through Swiss Life Arena (Williams, 2022).

1.4. Q4: Where is the embodied carbon in the arena?

According to the U.S. Forest Service we can separately reduce GHG emissions using sustainable wood products in seven different ways, four of which are relevant to the AEC industry: “[1] using local wood sources and products to reduce the effects of transportation; [2] producing wood products for use in long-term service; [3] building for deconstruction with reuse and recycling potential of all wood elements; and [4] replacing fossil-based, energy-intensive materials with wood products in low-, mid-, and high-rise buildings” (Puettmann et al, 2021).

Broadly speaking, much of the building product industry is carbon intensive and carbon storage is as important as the use of renewable energy and local production. The motivation behind replacing materials, like steel and concrete, with mass timber is the biogenic carbon storage of wood. Yet, according to Kelly Doran, “[t]here is currently a lot of debate about how best to account (or whether to account at all) for carbon storage in ‘LCA’ reporting, due in large part to the complexities of forestry practises around the world, and the unknowns of a building’s ultimate service life” (Doran, 2022). In the Athena LCA of the ICCU Arena the carbon sequestration or biogenic carbon of wood products used was included in the calculations. The final report specifies, in a roundabout way, that glu-lam was the only wood product that proved to be carbon negative, and that Athena equates the embodied carbon of every cubic meter of glu-lam wood to be -284kgCO_2 (Athena, 2023). Doran says, “it became clear that responsibly sourced wood, when accounting for bio-sequestration, can be a low-carbon solution for structure, envelope, and interior finishes” (Doran, 2022). In the ICCU Arena wood was used in the long-span trusses, the portal truss, the floors, the curtain wall mullions, and the exterior finish.

While we were hopeful that the arena would be carbon neutral through biogenic carbon storage, achieving such would have been pure luck. To bring the embodied carbon of a building to zero, a more rigorous approach to design and construction is needed. The LCA found insufficient timber to compensate for the concrete foundations and the composite gypsum and steel partitions. We are also concerned that the quantification of embodied carbon of glu-lam, for example, was inexact. Doran put it this way, “In comparison to other materials, the provenance of mass timber has significant and disproportionate impacts on the resulting global warming potential (GWP). Where mass timber supply and manufacturing were regionally abundant, the footprint of the timber was roughly 10-15% less than in projects where the engineered material was sourced transcontinentally or internationally” (Doran, 2022). In other words, transportation of locally sourced wood products drastically cuts down on embodied carbon. Until the carbon footprint of trucking and freight is diminished, architects should seek products that are as locally available and sourced as possible.

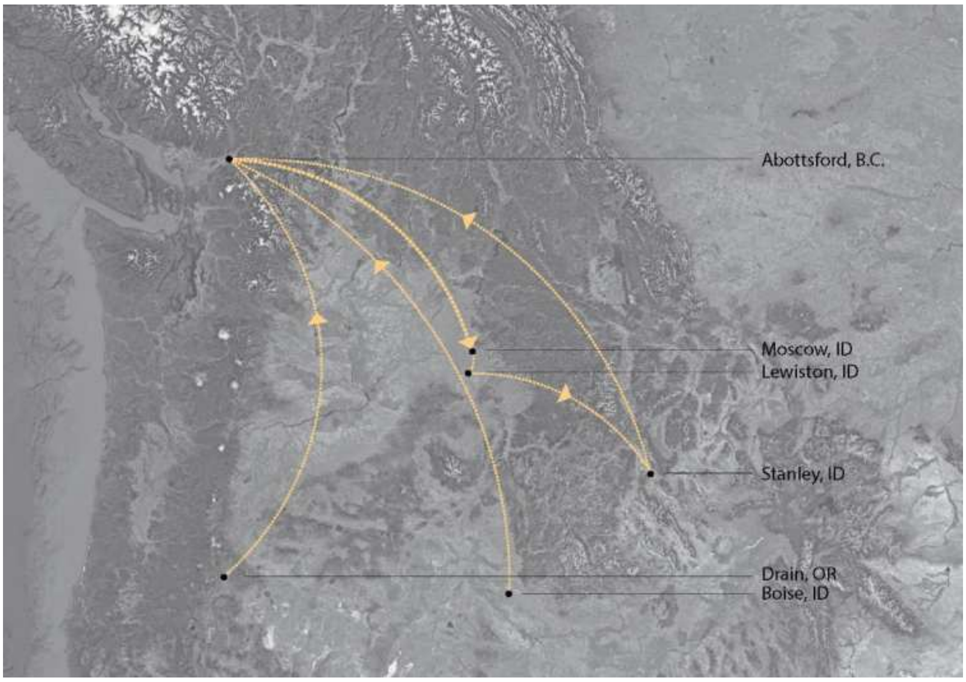

Figure 4. The Pacific Northwest sources and journeys of the ICCU timber.

Unfortunately, even though locally sourced, the wood for the ICCU Arena took quite a journey (Figure 4) from our experimental forest near Moscow, Idaho, to be converted into lamstock in Stanley, Idaho, to be formed into trusses in Abbotsford, British Columbia, Canada, before returning to the University of Idaho in Moscow to construct the arena.

1.5. Q5: What alternatives could have been implemented?

Ultimately, were policy makers to set embodied carbon benchmarks for buildings, the construction industry would consider less carbon-intensive building materials and techniques that achieve the same structural performance as in prior practise. For designers, carbon accounting doesn’t fundamentally alter the design process. Quite the contrary, buildings and professionals become much more marketable, and resultant communities can demonstrate the positive effects. Shaving off kilograms of carbon by making material substitutions is comparable to the choices architects make concerning affordability, buildability, thermal properties, or visual appeal of a building. In one Toronto development, Doran’s studio found that through straightforward material and specification swaps, the project could avoid upwards of 800 tonnes of CO_2eq—roughly 44 years of Canadian per capita emissions (Doran, 2022). But in the case of concrete, there seems to be little alternative. We use so much of it that cement production accounts for 8% of world GHG emissions each year (Ramsden, 2020). To-date, concrete is irreplaceable for foundations in residential and commercial buildings, but research into low-carbon concrete is ongoing.

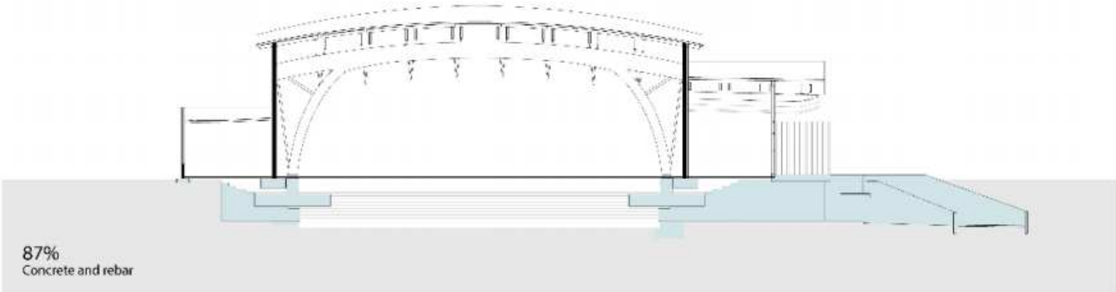

Figure 5. ICCU Arena section highlighting concrete use (in blue).

Concrete takes up the majority of the ICCU Arena's total embodied carbon, nearly 90%. It was used in the below-grade foundation (shown in blue in Figure 5) and above-grade shear walls. Finding a carbon neutral form of concrete is a vital undertaking considering the material's requisite usefulness for below-grade parking and superstructures. Doran's Half Studio uses Oneclick LCA to compare the proportion of CO_2 in each building material, identifying the materials that have a disproportionate impact. His students also found the main carbon culprit or "hotspot" in seven of ten developments to be concrete. These developments all had underground parking structures. The promise of wood is in its biosequestration which occurs while it grows. Similarly, carbonation is a chemical process that can allow certain concretes to absorb and store carbon from the atmosphere. This process depends on the makeup and location of concrete and works less well in structural concrete (Laurent, 2023). This process does not reliably offset the GHG emissions in the life cycle of most concrete buildings and structures. According to the International Energy Agency, there are multiple goals the industry must pursue to reach neutrality. But for architects, the solution simply could be to use less concrete. In the ICCU Arena it could have been possible to redesign the shear walls as CLTs, thus reducing the amount of concrete used by 16.5%.

2. Conclusion

While the ICCU Arena did not achieve the goal of net-zero carbon, it does compare favourably with other low-carbon buildings. It would fare better with the use of CLTs for the shear walls (replacing concrete) and by mindful materials choices as highlighted by Doran. It also sets the stage for future zero-carbon arenas as viable low-carbon concrete alternatives become available.

The arena's design intent was not to be carbon-neutral, but simply to highlight the use of mass timber in long-span structures. However, the construction above the foundation is mainly timber with some steel, except for the shear walls. Local fire code required the use of steel stud walls rather than wood framing for partitions. Designing with a carbon limiting intent could have reduced the embodied carbon content.

Fortunately, because the LCA was calculated before the building was occupied for a full year, Athena's LCA was limited to embodied carbon, totally excluding considerations for operational carbon emissions (a good topic for further study of the arena). It provided a robust way to examine embodied carbon without commingling the issues of embodied vs. operational carbon emissions. It also allowed comparison with other studies, such as Doran's, that focused on embodied carbon emissions. Although Doran's studies focused on commercial and institutional buildings rather than sports arenas, the ICCU Arena matched well with Doran's low-rise, wood-frame institutional buildings. Thus, it is not a carbon hog. We also discovered a contemporaneous sports arena, the Swiss Life Arena in Zurich, a concrete and steel structure with concrete cladding. Although we don't have carbon data for it, the architect regrets his material choices. Even in the ICCU Arena, the vast majority of the concrete is located in the foundation and shear walls, begging for an alternative to high-carbon concrete. Among alternatives to concrete are Amin Taha's suggestion of replacing it with stone, namely post tensioned stone beams and foundations (Taha 2023) and Remy Drabkin's replacement of concrete slabs with Drabkin-Mead Formula concrete that features a carbon sequestering admixture made from biosolids from the waste streams of municipal wastewater treatment plants (Build with Strength 2023). Taha has demonstrated his idea successfully with construction of a 6-story mixed-use building at 15 Clerkenwell Close in London, UK, and Drabkin hers with the carbon negative slab at her Remy Wines building near Dayton, OR, USA. Future timber buildings can explore these alternatives to achieve net zero or better.

Another issue that surfaced is that site carbon is not reckoned in the LCA. This arena has vast areas of concrete paving used as walkways, retaining walls, and a plaza. With carbon in mind, this site design could easily be improved to lower the project's carbon footprint. Overall, the ICCU Arena is a beautiful building and points toward a lower carbon future.

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Accounting for socio-spatial impacts of energy storage technologies – Learning from energy infrastructures literature

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Abstract: Energy storage technologies are seen as critical to meeting decarbonisation policies in the UK as well as internationally. The focus in policy and practice to date has been to make energy storage technically viable, with little attention given to their impact on people, community, and places they inhabit. Studies show that energy infrastructures do have significant implications on people's social relations, energy practices, wellbeing, and health. However, accounting for these impacts in the context of energy storage has been fragmented and poorly defined. The purpose of this review is to bring together the disparate literatures covering impacts of energy infrastructures on people and inhabited places, with a view to draw attention to the multiplicity of effects energy storage may present. The literature review draws on semi-systematic methods, focusing on published international research. The benefits of the review are twofold. First, it provides novel insight for policy makers, practitioners, and academics on the complex impacts (social, technical, spatial) generated by energy infrastructures across sectors and scales, with a view to highlight the potential implications energy storage might have. Second, it helps understand the important role of energy storage systems in reducing carbon emissions and prepare for their predicted substantial growth across the UK and Northern Europe in the next 5 years.

Keywords: energy storage, built environment, carbon emissions, socio-spatial impacts, urban context.

1. Introduction

Renewable energy generation is currently at the forefront of decarbonisation agendas, both in the UK and internationally, with energy storage forming an integral part of these (IPCC, 2018, Simson, 2023). While planning and installation of energy storage technologies are accelerating, their social and spatial impacts are not studied (Sovacool, 2014). There has been established research on the wide range of social and spatial impacts of other energy infrastructures on people, though beyond energy storage. Studies exploring *spatial* changes as a result of local energy infrastructure developments, such as hydro-dams, wind farms and shale gas extraction plants, show impacts through community displacement, change in living conditions and changes in job security (Tilt et al., 2009, Égré and Senécal, 2003). Together with spatial impacts, scholarship also identified *social* impacts such as change in lifestyle and social beliefs, impacts on social equality and community health (Mottee et al., 2020, Stedman et al., 2012).

Theoretical and empirical research on energy infrastructures (e.g., windfarms, large hydro dams, solar farms, electricity lines, etc) characterises and accounts for diverse social and spatial impacts. However, research on energy storage implications to date has mainly focused on matters of social acceptability (Thomas et al., 2019, Devine-Wright et al., 2017). Acceptability studies generally explore reasons behind public support or opposition towards potential energy storage deployment, without accounting for fine-grained social and spatial implications of energy storage installations.

While this area lacks research, there is a critical need to map and account for the likely impacts energy storage may have on people, communities, and places as well as ways this could be studied. This is especially pressing in the context of accelerated energy storage deployment in the UK and Europe which is predicted to grow exponentially in the next five years (Simson, 2023, Mexis and Todeschini, 2020). A review of published literature on the social and spatial impacts posed by energy infrastructures on nearby communities, how these impacts have been accounted for and in which contexts, can help provide not only knowledge on ways energy storage can be examined in future research but also the likely impacts that can be anticipated.

The following sections outline the methodological approach for the review, followed by a discussion on key themes found. The conclusion discusses the likely implications from the review insights and areas for future research.

2. Methods

It is worthy to note that, while over 80 energy storage projects are operational in the UK and more than 300 projects awaiting construction (Department for Business, 2023) there are no studies to date on their socio-spatial impacts. To begin to understand what potential implications these might pose on nearby communities, it is helpful to look at other technologies and their impacts. Thus, the review focuses on broader socio-spatial implications of global energy infrastructures and ways these have been measured.

Literature reviews can generally be classified as systematic, semi-systematic or narrative. Semi-systematic reviews help explore topics that have been studied differently by disparate disciplines (Snyder, 2019). A semi-systematic review was used to map common themes emerging across multiple disciplines covering socio-spatial impacts of energy infrastructures. The review was conducted in two stages. In first stage, a search protocol was developed, conducted, and papers selected. Searches were conducted using multiple databases (Google Scholar, Scopus, Science Direct and Web of Science). First searches focused on general queries: '*energy and social impacts*', '*energy and spatial impacts*', and '*lived experiences of energy infrastructures*'. Three key themes emerged as part of this: sense-making, meaning-making, and place-making. These results led to targeted searches on '*energy infrastructures and sensemaking*', '*energy infrastructure and meaning making*' and '*energy infrastructure and place-making*'. In total, after both searches, 89 papers were found, when searched 'in the title of the article' and in 'key words'. Inclusion criteria set were English-published peer-reviewed papers, all publishing years. Both qualitative and quantitative approaches were included to fully capture the range of methods used in energy and social sciences research. Exclusion criteria were editorials and reviews, studies not focused on social or spatial impacts, studies not grounded in theory, non-peer reviewed papers and non-English published papers. After removing duplicates and implementing exclusion criteria, 24 papers formed the final sample. The second stage was conducted via snowballing, utilising bibliographical references. Both inclusion and exclusion criteria were used to ensure that the review only targets research published in reputable journals (with an Impact Factor > 3), and papers are focused on spatial and social impacts of energy infrastructures. A further 17 papers via snowballing were included.

3. Overview of key themes identified in literature

Three key themes emerged in the review including 15 studies that explore how people make sense of new energy infrastructure technologies (*Sense-making* and *meaning-making* theme); people's identities with place in the context of new energy infrastructures (Place-making theme with 13 studies) and a third theme focused on methodological and theoretical insights (theories and methods theme) with 13 studies.

Sense-making and meaning-making studies on energy infrastructures reveal how people register new energy developments. Such research can provide valuable insight into the social impacts operational energy infrastructures pose on nearby communities and people. As Burdge and Vanclay define them, social impacts refer to any 'social and cultural consequences to human populations' generated by any public or private development, in this case energy infrastructures, which alter the way people 'live, work, play, relate to one another, organize to meet their needs, and generally cope as members of society' (1995:1). In this review, identified papers highlight social changes, such as shifts in attitudes, lifestyle and identity (Jacquet and Stedman, 2013) emerging in relation to new local energy infrastructure developments.

One extensively studied energy infrastructure is wind farms. Kim and Jung (2019) in their study of four Korean wind farms, identified implications on identity and perception: residents see their community as mechanical after wind farm installation, due to noise and visual impact; attitudes: people fear the unknown and the potential implications of wider novel technologies on health and general wellbeing; and lifestyle: some residents, although recently moved to the area contemplated relocation. Similarly, Papazu (2017), in studying the sudden opposition to a new energy development in an energy community, identified lifestyle discrepancies between novel technologies and the community as main reason.

Intertwined with sense-making and meaning-making, studies on *place-making* contribute to a richer understanding of 1) how spatial impacts unfold and 2) the role place identity plays in forming these impacts. One key insight provided by place-making research reveals that in some cases, new energy infrastructures greatly impact on place identity and community perception (Bailey et al., 2016). In doing so, social relations between community members see negative shift (Gailing et al., 2019). Consequentially, social cohesion – the bond formed between residents – can suffer.

Research methods across sensemaking and place making vary, with some papers relying on case-studies (Gailing et al., 2019, Fast and Mabee, 2015), questionnaires, semi-structured interviews (Bergquist et al., 2020), narrative semi-structured interviews (Bailey et al., 2016) and experimental methods (Winthereik et al., 2019, Papazu, 2017). Following up on the first two themes, the theories and methods section addresses how social and spatial impacts are measured and accounted for.

The way people make sense of and give meaning to new energy developments has been studied by different disciplines, using a wide range of theories. To form a comprehensive picture of commonly used theories, the following frameworks were identified: Science and Technology Studies (STS), Social Construction Studies and Social Acceptance. Out of the 15 papers that discussed social and spatial impacts through sense making, 4 drew on analytical concepts found in STS; 3 used social construction theories and 8 focused on social acceptability. Within the second theme of *place-making*, with 13 papers, 1 focused on Territory-Place-Scale-Network Theory (TPSN), 10 papers on place identity and 2 papers on place attachment. To ensure diversity, the review looked at several energy infrastructure technologies, in order of research focus: wind farms, hydro dams, solar farms, hydrogen plant, shale gas plants and electricity lines.

Table 1 illustrates all three themes (sense and meaning making, place making and methods and theories), common paradigms used, as well as the theoretical frameworks utilised and their unit of analysis.

Table 1 Key themes and theoretical frameworks identified in reviewed literature.

Impact	Theme	Field	Theory	Use of Theory	Unit of Analysis
Social	Sense and Meaning Making	Science and Technology Studies (STS)	Actor-network Theory (ANT)	Explores human-technology nexus, under the premise that everything in the social and natural world exists in constantly changing networks	People=Technology (does not differentiate between actors' nature)
		Social Construction Studies	Social Representation Theory (SRT)	Understands information processing mechanisms as a two-step process (anchoring and objectification)	People-focused
			Risk Perception Theory	Studies people's perceptions on rapid change and associated risks	People-focused
		Social Acceptance	Social Impact Assessment (SIA)	Primarily predicts social impacts of infrastructures and other planned developments	Technology-focused
Spatial	Place Making	Socio-Spatial Studies	Territory-Place-Scale-Network (TPSN)	Explores the role of four actors in socio-spatial relations	Multiple foci
			Place Attachment Theory	Studies people-place bonding, accounting for emotions, memories, knowledge, beliefs, and behaviours	People-focused
			Place Identity Theory	Integral part of place attachment, explores the construction of personal identity and physical environments	People-focused

3.1. Theme 1- Sense making and meaning-making

Theme 1 included 15 papers that discuss social impacts generated by energy infrastructure installations as follows: lifestyle (6 papers), attitudes (5 papers) and identity (4 papers). Lifestyle was addressed as disruption to lifestyle and risk of disruption. Attitudes were studied in terms of positive/negative change following energy infrastructure installation. Finally, identity was covered as positive/negative change as well as risk of negative change.

Papers covering *attitudes,* such as acceptability (Devine-Wright et al., 2017, Devine-Wright and Devine-Wright, 2006) or learning to live with novel technologies (Winthereik et al., 2019, Gailing et al., 2019), show that energy infrastructures affect people's perceptions both positively and negatively. General post-installation attitudes can vary depending on 1) local, regional and national scale (Devine-Wright and Batel, 2017), and 2) factors such as demographic (del Río and Burguillo, 2008, Soini et al., 2011), past experiences (Kim and Chung, 2019), media coverage, socio-cultural and economic values (Delicado et al., 2016) or duration of exposure to technology (Sherren et al., 2019). While some studies indicate that attitudes vary from one to technology to another (Irie et al., 2019), other argue that experiences vary from one research participant to another regardless of technology (McLachlan, 2009, Groth and Vogt, 2014, Owens, 2016).

Research on small-scale energy infrastructures, such as electrical substations or similar, are very fragmented (Terrapon-Pfaff et al., 2019). Conversely, studies on the impacts of developments such as wind, hydro and solar energy infrastructures are abundant, and can, at minimum, provide a gateway to exploring other technologies, such as energy storage. In this review, *lifestyle* impacts are covered in terms of disruption (Kim and Chung, 2019) and potential disruption (Papazu, 2017). Disruption to daily routine is related to aesthetic characteristics (large wind farms obstructing views), noise and landscape modifications (residents felt that their area does not look the same anymore; from *natural* to *mechanical* neighbourhood). *Identity* studies encompassed both lifestyle and attitudes. Kim and Chung (2019) and Tilt and colleagues (2009) show permanent residents' identity to their neighbourhood negatively shifted, in light of wind farm and, respectively, large dam infrastructure installations.

Common trends across social implications are disruption to familiar routines (daily life, social relations, change in landscape) and fear of the unknown (change in wellbeing, lifestyle) (Jacquet, 2009). Both trends can have long term implications. One study on shale gas plant installation showed that fear of the unknown led to mental health concerns in local residents, even in pre-installation phase (Stedman et al., 2012). Social impact is also closely linked to implications on *place* (spatial impacts). Impact on identity, for example, is twofold, as it can affect the way residents identify with the neighbourhood both socially and spatially. The following section will elaborate on spatial impacts and how they unfold.

3.2. Theme 2- Place making

Research on place-making mechanisms accounts for the spatial implications of energy infrastructures. As well as reconfiguring the *social* patterns discussed above, energy infrastructures can also re-shape *spatial* configurations. Place attachment, closely linked to place identity, is a complex phenomenon, incorporating feelings, emotions and perceptions formed by residents towards their community (Peng et al., 2020). Studies on energy infrastructures and place-making processes show that the identity formed by an individual for the place they live in highly influences how they see and perceive novel additions to their environment, such as wind farms, dams, solar farms, and others. The 8 papers identified on place-making generally address place identity and place attachment, with identity and attachment are considered interchangeable.

Papers such as Kim and Chung (2019) and Tilt and colleagues (2009), for example, address both place making and sense making. For place making, they identify negative changes to (permanent and new) residents' feeling of belonging, which in some cases turns into relocation. Other papers like Bailey and colleagues (2016), show that in some cases place attachment is stronger in permanent residents, and therefore the impact on these groups is higher. In contrast, further research highlights that longevity is not always relevant, whereas active citizenship and place-bonds are (Bailey et al., 2016). Bergquist and colleagues (2020) show that spatial implications are also connected to residents' lifestyles; for example, for farmers, a wind farm installation might threaten agricultural activities, while for others (Jacquet and Stedman, 2013) there is fear of neighbourhood dynamic change. Culture and heritage also present a main factor in negative attitude shifts, whether related to energy infrastructures, such as power lines (Soini et al., 2011, Bailey et al., 2016), or renewable energy installations (Delicado et al., 2016).

Overall, identity matters tend to be multi-dimensional, with crossovers between social and spatial implications, and span over different cultures, scales (urban, rural, semi-rural), as well as over different technologies, as previously discussed. The next section reviews common frameworks and methods used to measure these impacts and discusses advantages and limitations of each, as well as how these can be used to study the potential implications of energy storage installations.

3.3. Theme 3- Theories and Methods

3.3.1. Sense-making and meaning-making theories

Energy research on social attitudes provides a starting point in investigating the people-technology relationship. Dominant areas of attitude scholarship are social acceptability (Devine-Wright et al., 2017) and risk (Joffe, 2003). Social acceptability is widely studied in relation to renewable energy infrastructures and is most often framed using NIMBY (Not-in-my-Backyard) literature. NIMBY 'describes opponents of new developments who recognise that a facility is needed but are opposed to its siting within their locality' (Burningham et al., 2006:2). However, it received extensive criticism for its over-simplistic nature (Devine-Wright and Howes, 2010, Warren et al., 2005), with scholars showing that *identity*, in some instances, is more important than *proximity to development* in forming attitudes (Phadke, 2011, Wester-Herber, 2004).

For a more comprehensive measurement of social acceptability, some studies use the Social Impact Assessment (SIA) framework. SIA has the overarching goal to create more sustainable transitions, by predicting positive and negative implications of planned infrastructural developments (Vanclay, 2003). Describing best practices, Égré and Senécal (2003) put forward an extensive agenda, covering key stakeholders, demographics, potential impacts and solutions as well as post-installation monitoring. SIA is versatile and could be used for different technologies (like energy storage), however it requires adjustments to account for different settings (Kirchherr and Charles, 2016). Other limitations include large number of stakeholders involved and a lack of willingness to participate.

Although acceptability studies can provide useful insight into public opinion on novel technologies and their deployment, they are most often prospectively used and do not measure impact post-installation (Vanclay, 2012). To gain an in-depth understanding of the people-energy infrastructure nexus, research needs to focus on how people ***experience*** energy infrastructures, including storage (L'Orange Seigo et al., 2014). *Experiences* are deep-rooted socio-psychological mechanisms, through which individuals make sense of and give meaning to reality and associated changes (Weick et al., 2005, Sommer and Baumeister, 1998). In turning the 'unfamiliar into familiar' (Batel and Devine-Wright, 2015:315), like in the case of a new technology, people use images and metaphors. The theory measuring this, Social Representation Theory, is known as SRT (Moscovici, 1988). While most studies use SRT prospectively to understand how sense-making forms opinions (Devine-Wright and Devine-Wright, 2006, Batel and Devine-Wright, 2015), others employ it retrospectively. A study of two hydrogen plants (Scotland and England) showed that the Scottish community used SRT to make sense of the newly installed technology, and attach more positive attributes to it, compared to the English community, where feelings of anxiety towards an unfamiliar technology were greater (Sherry-Brennan et al., 2007). Novel technologies, argues Sherry-Brennan (2007), can be seen as risky. Risk perception can be influenced by media coverage (Scheufele and Lewenstein, 2005), views held by key community actors, cultural values, and previous personal experiences with energy infrastructures (Jacquet and Stedman, 2013). SRT could be a way to understand the origins of perceived risk, and to grasp how a novel technology might be psychologically registered by local communities. However, SRT, in its quest to unpick highly complicated psychological mechanisms, is context-dependent and cannot provide broad insights (Joffe, 2003).

Another field concerned with the relationship between people and new technologies is Science and Technology Studies (STS) (Asdal and Moser, 2012). The Actor-Network-Theory (ANT), developed through STS, questions how technological advances shape social orders (Latour, 2005). The ever-evolving relationship between people and emergent technologies was studied via STS and to some degree, ANT, on Samsø island, Denmark (Papazu, 2017). Here, residents turned Samsø into the first ‘renewable energy island’ (Nader, 2010:504). In a decades-long process, they built (physically and mentally) a renewable energy reality, wherein they lived with the novel technology and assigned positive meanings to it.

Meaning making can equally be as revealing to understand the implications of newly installed energy technologies. Interwoven with sense-making mechanisms, meaning-making helps people process social change. *Memory* (collective and individual) is integral to meaning-making processes (Küpers and Batel, 2023). Memories historically acquired by community members constitute a big part of how their lived experiences with energy developments unfold. Kim and Chung (2019) showed that in light of wind farm developments, four South Korean communities created new place meanings based on individual memories. When residents felt that their familiar environment is disrupted by unfamiliar elements (wind turbines), they developed negative meanings for their community. By contrast, in the face of change in Samsø, people worked collectively to create positive new realities of their island, allowing their memories and place meanings to positively change over time. Similar to this example, in the hydrogen plant study (Sherry-Brennan et al., 2007), the Unst (Scotland) community found positive outcomes and meanings following installation.

3.3.2. Place making theories

Meaning making is closely linked to community (physical and perceptive meaning). A seminal framework for understanding the ‘spatialities of energy transitions’ (Gailing et al., 2019:1113) is Jessop’s TPSN – standing for Territory (inside-outside border), Place (proximity), Scale (hierarchy of social relations) and Network (interconnectivity between nodes of energy and social relations). TPSN argues that the people-energy nexus is multi-dimensional, formed of multiple scales, networks and interdependencies (Jessop et al., 2008). For example, a German study (Gailing et al., 2019) shows how neighbourhoods shifted identity (from *a* neighbourhood to *an energy* neighbourhood) as a result of energy systems installations. However, the framework received criticism for characterising places in only four dimensions without considering other factors (e.g., how people’s lived experiences with place or legislators’ responses to place influence spatiality) (Jones et al., 2013, Tan, 2016).

The question of interdependency between people and their physical environment is further posed by the theory of *place attachment*. Place, as seen by Relph (1976), is constructed by people through emotions, memories, beliefs, behaviours and previous experiences. The notion of place-making is a central concern in the Place Identity Theory (White et al., 2008), for example. The intricacies between place attachment and place identity can be difficult to break down, although it is commonly believed that individuals build place identity using two constructs: internal and external thoughts. Internal thoughts include mental images, metaphors and descriptions applied to the area of residence. External thoughts deal with physical appearance, symbolics shapes (area landmarks, language, etc) and institutional shapes (street, neighbourhood, area, etc) (Peng et al., 2020). In relation to energy projects, place attachment and/or identity can shift both positively and negatively. For example, one study looking at a tidal energy project in Northern Ireland highlighted that, instead of disrupting identity to place, the project enhanced it. This shows that if the energy development is registered mentally by residents as place-enriching, rather than place-destroying, place identity levels can rise (Devine-Wright, 2011). Similarly, Soini's (2011) power lines study also shows that external thoughts can shift from negative (project makes environment less desirable to live in) to positive (seeing project as area enhancing), thus potentially impacting on place attachment levels.

3.3.3: Methods: advantages and limitations for energy storage research

Measuring social impacts through sense and meaning making theories can take different forms. Some of the identified papers draw on traditional methods, such as semi-structured interviews (Kim and Chung, 2019), case-studies (Tilt et al., 2009) and participant observation (Papazu, 2017); while others employ experimental methods: story-telling, poetry (Winthereik et al., 2019), and archival research (Devine-Wright and Devine-Wright, 2006).

Several studies highlight the importance of understanding socio-spatial relations using multi-dimensional methods (Jones et al., 2013, Tan, 2016, Moore and Hackett, 2016). One example of how this might take form is Winthereik and colleagues' (2019) work which uses a mix of storytelling, poetry, walks and experiential imagery to grasp people's emotional engagement with the newly developed marine energy industry in Denmark. Positioned within STS, the *Energy Walk* encourages participants to let *senses* take over rational thoughts. The intentional shift from purely observational methodologies (interviews, questionnaires) to experiential exercises physically places the individual next to energy installation, creating a more dynamic interaction. Experiential methods might provide unique insight into how people make sense of new energy technologies. For energy storage, such methods can help us understand how people *experience* installations. The combination of storytelling, walks and imagery, in particular, can be of great help in 1) understanding whether the installations are visible to residents (Sherren et al., 2019), 2) measuring perception (sense and meaning making) and 3) measuring the effect these have on people's identity with place. While multi-dimensional methods can be a unique measuring tool for a unique setting, they also have drawbacks, and raise questions of prescriptiveness. In other words, how can we distinguish between people's organic experiences and the in-built experiences created by researchers through these methods?

4. Discussion and Conclusion

This review set to explore and highlight the wide range of implications energy infrastructures pose on individuals, communities, and places they inhabit. The social and spatial impacts discussed here, although observed in other technologies, provide a starting point for further research into potential energy storage impacts. By employing semi-systematic methods, the review focused on three key themes found in the disparate literatures on energy infrastructure impacts: *sense and meaning making*, *place-making* and *theories and methods*. Each theme brings different aspects of the people-energy nexus to light. Sense-making and meaning making studies highlight how people experience energy infrastructures, while place-making studies showed place identity and its construction to be crucial to how people make sense of and live with energy infrastructures. Finally, the third theme indicates a diversity of theoretical and methodological insights that are drawn upon in study of impacts of energy infrastructures that would be useful in the study of energy storage effects. Although not without limitations, all methodologies provide a different lens to see not only a highly dynamic world, but the complexities involved in how people live with novel energy technologies. Attempting to understand how emotions, memories, and general attitudes are shaped, can be very beneficial to 1) account for deeper social and spatial implications and 2) attempt to predict future social and spatial implications of other new technologies, such as energy storage. This review acknowledges that no one study can account for how each individual experiences novel technologies (Soini et al., 2011).

In effect, the paper expands knowledge on how energy storage socio-spatial impacts might be accounted for in 3 ways: 1) it presents the different social and spatial implications (changes in lifestyle, attitudes and identity) that other energy infrastructures pose on individuals and their communities in order to 2) highlight the importance of studying energy storage installations socio-spatial impacts, and 3) provides novel insight into how we can account for these impacts, which can better inform policymakers, technology developers and wider academia (Krumm, 2022).

In conclusion, it is widely agreed that energy infrastructures form an integral part of the societal fabric, and it is critical to understand how people 'metabolize' (2007:1) and live with new technologies (Mordini, 2007). In light of decarbonisation agendas and the increasing levels of energy storage installations deployment in the UK, it is crucial to account for their social and spatial implications (Devine-Wright et al., 2017). Accounting for these impacts is critical to community wellbeing, as it provides a richer understanding of how the storage installations impact on daily routines, social relations, and local identities. Ultimately, gaining a richer understanding of these implications allows for a better consideration of their deployment and ensures decarbonisation efforts are more efficient and sustainable long term.

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Achieving zero carbon communities by co-location of marine renewable energy

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Abstract: The CO_2 or carbon intensity of electrical power consumption of communities and households is dependent on power flows from national transmission and local distribution networks. For zero carbon communities, injected electrical power must necessarily be net zero CO_2, and, for remote locations, reliance on potentially constrained national infrastructure may not be sufficient to achieve time-bound, zero carbon targets.

Future net zero energy scenarios for GB typically do not include substantial marine energy capacity (wave and tidal stream). However, these technologies have the potential to deliver a renewable energy mix with lower system costs, higher availability and improved supply-demand matching, while maximising efficient use of existing infrastructure; relevant for the often highly constrained power networks supporting remote communities.

This work explores the emissions reduction potential of marine renewable generation when co-located with remote communities. Power flows and associated CO_2 emissions are computed using the power system modelling tool PyPSA-GB. By comparing National Grid future energy scenarios (FES) with scenarios with higher installed capacities of marine energy, marine energy is shown to further reduce emissions for remote zero-carbon communities.

Keywords: Future energy scenarios, zero carbon communities, power system modelling, marine energy, emissions reduction

1. Introduction

The greenhouse gas emission intensity associated with the electrical power consumption of communities and households is dependent on power flows from national transmission and local distribution networks arising from the national generation mix. For remote, 'zero carbon communities' (where energy consumption is net zero CO_2), locally generated or injected electrical power must necessarily be net zero CO_2, and reliance on potentially constrained national infrastructure may not be sufficient to achieve time-bound, net zero targets.

Future net-zero energy scenarios for GB typically do not include substantial marine energy capacity (wave and tidal stream) based on their current costs and technological readiness (National Grid ESO, 2022b). However, the these technologies have the potential to deliver a renewable energy mix with higher availability and improved supply-demand matching (Pennock et al., 2022). Tidal energy has also been shown to reduce system costs from balancing, reserve capacity and curtailment (Frost, 2022). The presence of marine energy can also maximise efficient use of existing infrastructure relative to a single type of generation (Sun, Harrison and Harrison, 2020), which is particularly relevant for remote communities in the west and north coast of Scotland and nearby islands, where distribution grids are highly constrained, and face lengthy timescales for network expansion. Accordingly, this work explores the emissions reduction potential of marine renewable generation when co-located with remote communities. Bulk CO_2 emissions and associated carbon intensity from hourly power generation are computed by power system modelling (Lyden, 2021) and the impact of co-locating wave and tidal stream with remote, zero carbon communities is investigated by comparing National Grid future energy scenarios (FES) (National Grid ESO, 2022b), with novel scenarios including higher capacities of marine energy using the scenarios and the power generation time-series developed in (Struthers et al., 2022) as inputs to PyPSA-GB.

2. Method

2.1. Overview

Two future energy scenarios from National Grid (Section 2.2) are simulated using an open dataset and power dispatch model (PyPSA-GB) with renewable resource data and 29 bus transmission network model (Section 2.3). PyPSA-GB was chosen as it can represent the power generation mix with a temporal resolution of one hour, in energy scenarios up to 2050 using data input from National Grid FES. Two transmission network nodes (or buses) are selected to represent the transmission system connection to distribution networks potentially supplying zero-carbon communities which are both: remote; and can be co-located with marine renewable energy (Figure 1). Accordingly, the results of this method does not extend into the distribution network or smart-energy system scales, where further innovation for zero-carbon communities can be expected.

As an introduction to this approach, a single year is considered (2045) where decarbonisation is well underway – indeed, beyond the 2035 target for delivering a decarbonised power system (Committee on Climate Change, 2023) – but contemporary with projections for substantive installed capacities of marine energy. The CO_2 emissions metrics of the two buses in FES in the year 2045 are benchmarked as *base cases* (Section 2.2) using carbon intensity data for each type of generation, storage and interconnectors (Section 2.5). The benchmarking considers:

- National energy mixes in each scenario(Section 3.1)
- Bulk emissions of generation nationally (Section 3.2)
- Carbon intensity of generation nationally (Section 3.3 and 3.4)
- Bulk emissions of generation at each bus (Section 3.5);
- Carbon intensity of generation at each bus (Section 3.6).

This process is then repeated using two novel scenarios (Struthers et al., 2022) which replace the installed capacities of wave and tidal stream technologies in the FES. Each element of this method is described in the following sections.

2.2. National Grid Future Energy Scenarios (FES2022)

In the UK, the electricity system on the island of Great Britain (GB) is operated by National Grid ESO (Electricity System Operator). Each year, NG ESO publishes Future Energy Scenarios which represent a range of different, credible ways to decarbonise GB's networked energy system, particularly with a focus on the power system, although whole energy system aspects are included. In 2022, there were four FES with the following characteristics:

- **Consumer Transformation (CT):** primarily electrified heating, consumer behavioural change; high energy efficiency; *demand* side flexibility;
- **System Transformation (ST):** primarily hydrogen for heating, low consumer behavioural change, lower energy efficiency; *supply* side flexibility;
- **Leading the Way (LW):** rapid roll out of electrified and hydrogen heating; significant lifestyle changes; fastest decarbonisation;
- **Falling Short (FS):** slow decarbonisation of heat; minimal behaviour change; slowest decarbonisation.

For the purposes of this study, only two FES were selected for analysis: CT and LW. ST was not selected on basis of high hydrogen heating – independent evidence does not support widespread use of hydrogen for space and hot water heating (Rosenow, 2022) –while FS is not compliant with the UK Net Zero targets.

As a primer, the emissions from the national power sector in 2045 as calculated in FES2022 are -32.3 $MtCO_2eq$/year and -14.2 $MtCO_2eq$/year, as a result of high deployment of bioenergy with carbon capture and storage (BECCS) (National Grid ESO, 2022c). Arguably, the reliance on BECCS itself is motivation for exploring the emissions reduction potential of alternative forms of low carbon generation (including marine energy), as BECCS remains largely unproven (Fridahl and Lehtveer, 2018).

2.3. Introducing the power system model: PyPSA-GB

PyPSA-GB is an open dataset and power dispatch model of the GB transmission network developed at the University of Edinburgh which uses National Grid's Future Energy Scenarios as inputs for future power system modelling. PyPSA-GB is executed in Python and based on the PyPSA open-source python environment (Brown, Hörsch and Schlachtberger, 2018).

This study uses network constrained linear optimal power flow, using a 29 bus network model (Belivanis, 2013) and 2012 as the historic year for renewable resource data, other than tidal lagoon and tidal stream which were predicted directly using the Thetis coastal ocean model (Kärnä *et al.*, 2018; Struthers *et al.*, 2022).

The generator dispatch order is dictated by the marginal cost assigned to that generator. All renewable generators are assigned a zero marginal cost to reflect their generally low costs and prioritise their injected power. Details of PyPSA-GB will be described in an upcoming paper (Lyden *et al.*, no date). BECCS is assumed to always run and not be displaced by renewables such that the negative emissions it captures and stores can be maximised.

2.4. Cases, installed capacities and future energy scenarios

For this study, six cases were considered, over the course of a single year.

- **Nodes:** two nodes were selected to represent remote zero carbon communities adjacent to (and therefore assumed suitable for co-location with) substantive installed capacities of marine energy, as per (Struthers *et al.*, 2022). These were Beauly and South West Peninsula (Figure 1).
- **FES2022 interpreted installed capacity scenarios:** Within FES2022, 'Marine' energy includes wave, tidal stream and tidal lagoon, and is not disaggregated explicitly. This makes it impossible to accurately represent the temporal complementarity arising from the site installed capacity, spatial distribution and diversity of renewable resource (sea surface waves, tidal current and tidal range) without some interpretation. To overcome this, these capacities were interpreted manually according to coordinates from the Regional Breakdown of FES2022 data, which were inspected to deduce the location and installed capacity the Table 1.
- **Novel installed capacity scenarios:** the marine energy installed capacity scenarios were selected from (Struthers *et al.*, 2022). Two scenarios were selected 'Low' and 'High' to bound the maximum possible range of installed capacity of marine energy expected outside of FES2022. For the two FES considered, the wave and tidal stream installed capacities were simply removed and replaced with the installed capacity of the novel scenarios. Note that 'Low' still has significantly more marine energy installed capacity than either CT or LW.

- **Year:** in general, marine energy has lower technological readiness than more established renewable energy technologies such as onshore wind, solar and offshore wind. This can be observed from nationally installed capacities and projections, which exceed GW-scale in the 2040s for wave power. The year 2045 was selected as a compromise to best highlight the impact marine energy could make while aligned with contemporary scenarios for future power system evolution.

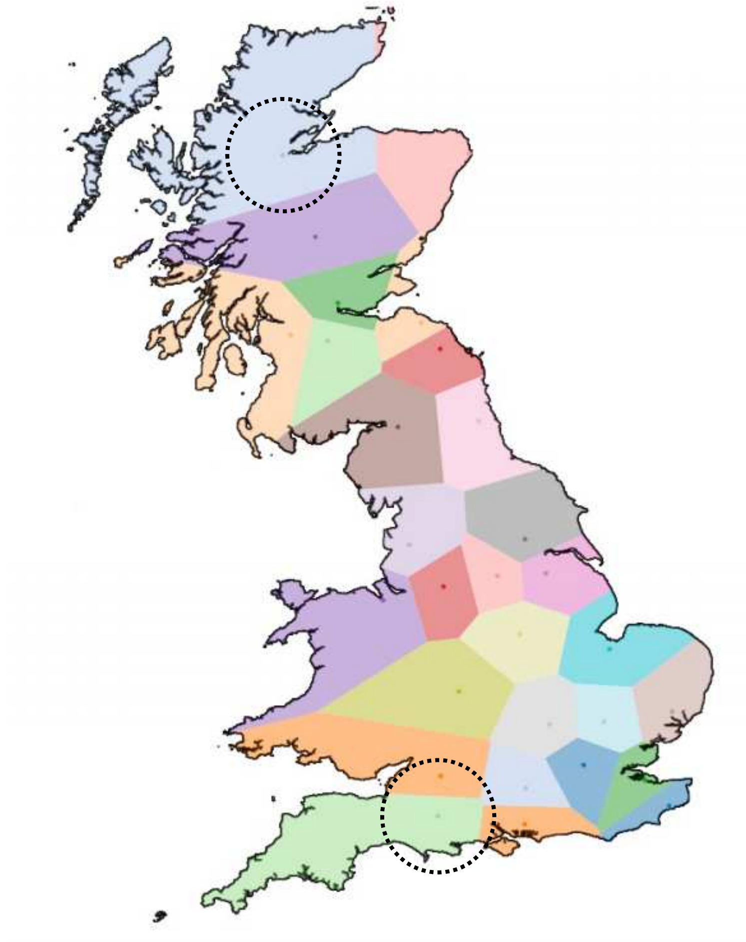

Figure 1. 29 bus network model with associated Voronoi cells. The two nodes representing some of the most remote cells and communities of this network are highlighted by dotted circles: Beauly (top) and South West Peninsula (bottom).

Table 1. Interpreted locations of Marine energy from FES2022. Proximal locations are based on grid coordinates.

DNO License Area (FES2022)	GSP (FES2022)	Latitude (FES2022)	Longitude (FES2022)	Assumed location	Assumed network	Proximal location technology	Proximal site with largest capacity
NGET	Direct(NGET)	Not present	Not present	England/Wales	Transmission	Tidal lagoon	Various
SHETL	Direct(SHETL)	Not present	Not present	North Scotland	Transmission	Tidal stream	(Struthers *et al.*, 2022) (MeyGen)
SPTL	Direct(SPTL)	Not present	Not present	South Scotland	Transmission	Tidal lagoon	(Mackie *et al.*, 2021) (Solway)
SHEPD	Port Ann	56.026	-5.350	West coast Scotland	Distribution	Tidal stream	(Struthers *et al.*, 2022) (Sound of Islay)
South Western	Alverdiscott	51.006	-4.137	South west England	Distribution	Wave energy	(Struthers *et al.*, 2022) (Scarweather)
SEPD	Chickerell	50.624	-2.489	South England	Distribution	Tidal stream	(Struthers *et al.*, 2022) (Portland Bill)
NPgY	Elland	53.695	-1.823	Midlands	Distribution	Tidal lagoon	(Mackie *et al.*, 2021) (Liverpool)
SEPD	Fawley	50.821	-1.330	South England	Distribution	Tidal stream	(Struthers *et al.*, 2022) (Isle of Wight)
SHEPD	Lairg	58.008	-4.395	North Scotland	Distribution	Wave energy	(Struthers *et al.*, 2022) (Farr Point)
SEPD	Melksham	51.392	-2.150	South west England	Distribution	Tidal lagoon	(Mackie *et al.*, 2021) (Cardiff)
South Wales	Pembroke	51.682	-4.987	South Wales	Distribution	Wave energy	(Struthers *et al.*, 2022) (PDZ)
South Western	Taunton	51.017	-3.153	South west England	Distribution	Tidal lagoon	(Mackie *et al.*, 2021) (Watchet)
SHEPD	Thurso	58.572	-3.509	North coast Scotland	Distribution	Tidal stream	(Struthers *et al.*, 2022) (Brims)
SPM	Wylfa	53.414	-4.482	North Wales	Distribution	Tidal stream	(Struthers *et al.*, 2022) (Anglesey Skerries)

Figure 2. Visual comparison of the installed capacities of wave power (blue) and tidal stream (orange) between 'Low Marine' (top left), 'High Marine' (top right), CT (bottom left), LW (bottom right). There is only a very slight difference between CT and LW. Installed capacity is indicated by the area of the bubble.

2.5. CO_2 emissions modelling and assumptions

This analysis uses the 'carbon intensity' of each generator type to represent the operational carbon dioxide (CO_2) emissions for the power system in each time step (one hour). Carbon intensity is measured in gCO_2 per kWh of electricity generation, and is dependent on the carbon content of the fuel, and the net generator efficiency averaged over some period of time (Staffell, 2017).

A wide range of generation and storage technologies are included in PyPSA-GB and FES2022. In FES2022 the CO_2 emissions by fuel type are input to the BID3 power market dispatch model (National Grid ESO, 2022a), for which the carbon intensity assumptions were provided directly by National Grid (Powar, 2022) in personal communication. For this study, these were compared with other sources (IPCC, 2014; Staffell, 2017; Rogers and Parson, 2022) and amended where significant differences existed. In general, more conservative (higher) values for carbon intensities have been used relative to BID3 (Table 2). No data on BID3 carbon intensities of storage or interconnectors were provided.

The carbon intensities of all types of energy storage are assumed as zero, in lieu of a more detailed treatment, such as (Pimm *et al.*, 2021). Biomass is assumed to have a non-zero, or non-climate-neutral carbon intensity (IPCC, 2014). BECCS is assumed as carbon negative as per (Powar, 2022) and on the basis of the balance of literature – especially (IPCC, 2014). However, it should be noted that the life cycle climate impact of biomass combustion remains an active area of research, where assumptions of climate neutrality could underestimate the impact of biomass consumption and long-term CO_2 storage (Cherubini *et al.*, 2011; Ventura, 2022; Adetona and Layzell, 2023). Alternatively, some sources attribute even larger negative emission potential to BECCS (García-Freites, Gough and Röder, 2021; Zhang *et al.*, 2022).

The energy delivered from BECCS to the grid is not trivial in some scenarios, and the dispatch order of the plant is significant for emissions accounting. When BECCS is assumed as negative emission technology with negative carbon intensity, the dispatch order must account for this such that the *decrease* in carbon capture and storage and power generation from BECCS resulting from the dispatch order favouring variable renewables does not cause a net *increase* in emissions.

Carbon intensity data for interconnector imports are challenging to obtain, especially at a time horizon of 2045: 2022 data has been used where alternatives were unavailable (Electricity Maps, 2023), which is likely to be a conservative assumption, as future power system carbon intensities are expected to fall significantly as climate change targets are pursued. Any unmet load is assumed as zero emissions, as are interconnector exports from GB.

Table 2. Table of operational carbon intensity of generation used in this analysis. FES2022 inputs are shown in braces where different.

PyPSA-GB Generator Type	Carbon intensity [gCO_2/kWh]	Reference
AGR	**0**	**(Powar, 2022)**
Anaerobic Digestion	**354**	**(Powar, 2022)**
Biomass (co-firing)	**120 {0}**	**(Staffell, 2017)**
Biomass (dedicated)	**120 {0}**	**(Staffell, 2017)**
CCGT	**394 {182}**	**(Staffell, 2017)**
BECCS	**-329**	**(Powar, 2022)**
CCS Gas	**57 {18}**	**(IPCC, 2014) ***
Coal	**937 {322}**	**(Staffell, 2017)**
Diesel	**935 {n/a}**	**Oil (Staffell, 2017)**
EfW Incineration	**117**	**Waste (Powar, 2022)**
Hydro	**0**	**(Powar, 2022)**
Hydrogen	**11**	**(Powar, 2022)**
Landfill Gas	**300 {117}**	**Other (Rogers and Parson, 2022)**
OCGT	**651**	**(Staffell, 2017)**
PWR	**0**	**(Powar, 2022)**
Sewage Sludge Digestion	**300 {117}**	**Other (Rogers and Parson, 2022)**
Solar Photovoltaics	**0**	**Renewable (Powar, 2022)**
Tidal lagoon	**0**	**Renewable (Powar, 2022)**
Tidal stream	**0**	**Renewable (Powar, 2022)**
Wave power	**0**	**Renewable (Powar, 2022)**
Wind Offshore	**0**	**Renewable (Powar, 2022)**
Wind Onshore	**0**	**Renewable (Powar, 2022)**

*** IPCC AR5, Annex III, Table A.III.2**

Table 3. Table of carbon intensity of electricity supplied from GB interconnectors used in this analysis

Interconnector	Carbon intensity [gCO_2/kWh]	Reference
BritNed	513	Netherlands (Rogers and Parson, 2022)
EastWest	426	Northern Ireland (Rogers and Parson, 2022)
Moyle	426	Northern Ireland (Rogers and Parson, 2022)
Nemo	132	Belgium (Rogers and Parson, 2022)
IFA	48	France (Rogers and Parson, 2022)
IFA2	48	France (Rogers and Parson, 2022)
NSL	9	Norway (Rogers and Parson, 2022)
ElecLink	48	Assumed as IFA/IFA2
Viking Link	231	West Denmark 2022 (Electricity Maps, 2023)
Greenlink	426	Assumed as EastWest
GridLink	48	Assumed as IFA/IFA2
NeuConnect	494	Germany 2022 (Electricity Maps, 2023)
NorthConnect	9	Assumed as NSL
FAB Link	48	Assumed as IFA/IFA2

3. Results and Discussion

3.1. Comparing national energy mix of base FES2022 scenarios

To begin the discussion of the results, it is first of all instructive to consider the differences in the delivered mix of energy generation between the scenarios. For the base cases, in general, CT has more BECCS, and slightly less interconnector imports than LW, but otherwise the differences are fairly minor (Figure 3). With increasing marine renewables, the largest changes are only observed in thermal dispatch (which decreases with more installed capacity of marine) and renewables (which naturally increases with more installed capacity of marine energy). The breakdown can be seen by technology in Figure 4. Of note is that unmet load is always reduced (up to around a third in the high marine scenarios) by the increased installed capacity of marine energy. This is an operationally advantageous outcome, echoing findings from (Pennock *et al.*, 2022) – however for LW unmet load is still significant (around 4% of the total energy demand).

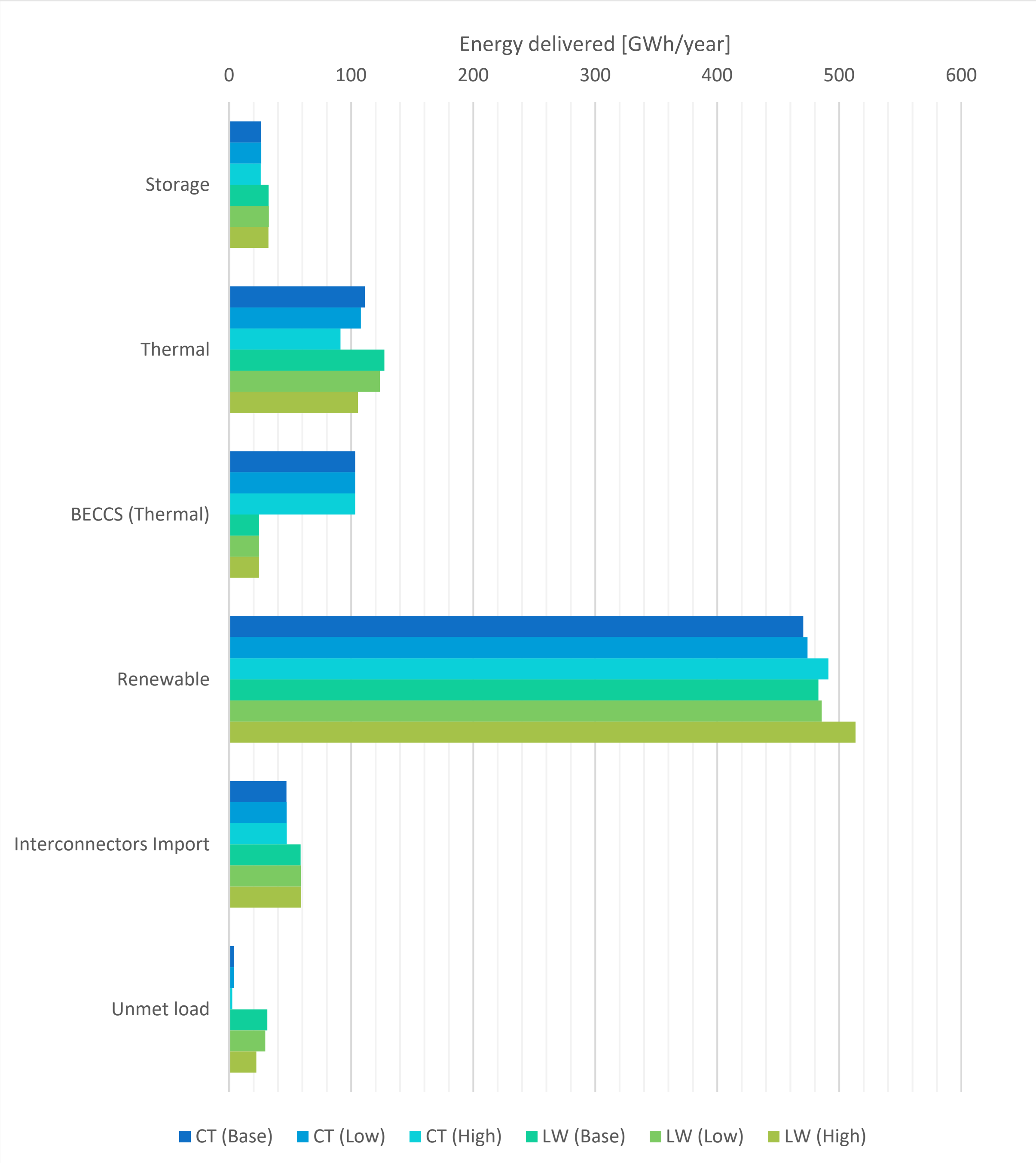

Figure 3. Comparison of energy delivery by technology categories between scenarios in 2045.

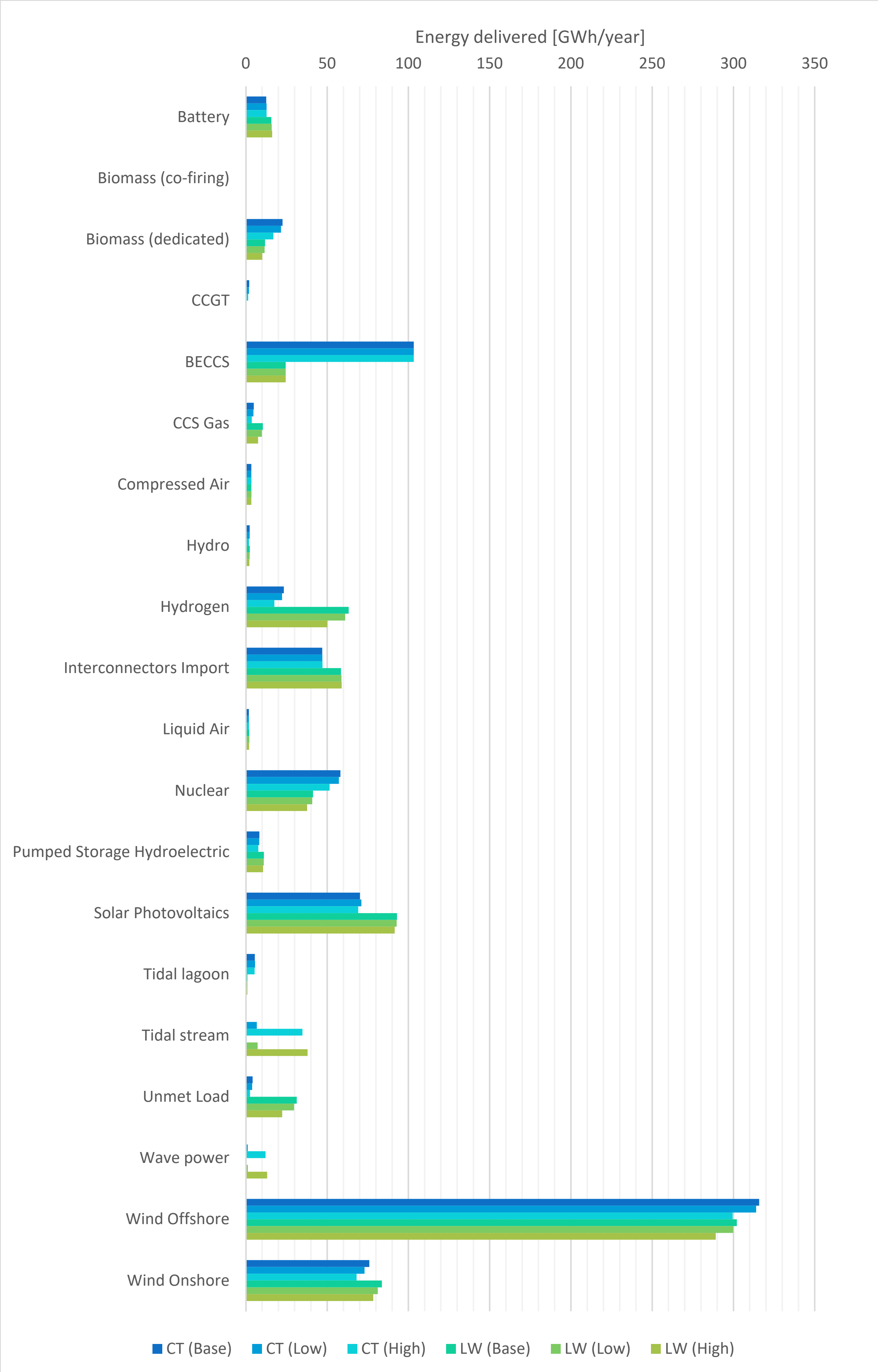

Figure 4. Comparison of energy delivery by technology between scenarios in2045.

3.2. National power sector total emissions

Moving to the emissions from these cases, the aggregate emissions from the GB power sector in the year 2045 were negative (due to operation of BECCS plant), and this deepened in all cases with the addition of marine renewables; as much as 1.1 and 0.6 $MtCO_2$ for the high marine cases of CT and LW (Figure 5).

Note that when the BID3 carbon intensities are used the PyPSA-GB results for CT is +3% of the BID3 calculated value – "FES2022" compared to "Base (BID3)" in Figure 5 – but for LW the difference is much larger (-49%). This could arise from PyPSA-GB network constraints which does not include a pan-European model for interconnectors, or the different accounting of emissions from imported power itself, and could necessitate further investigation.

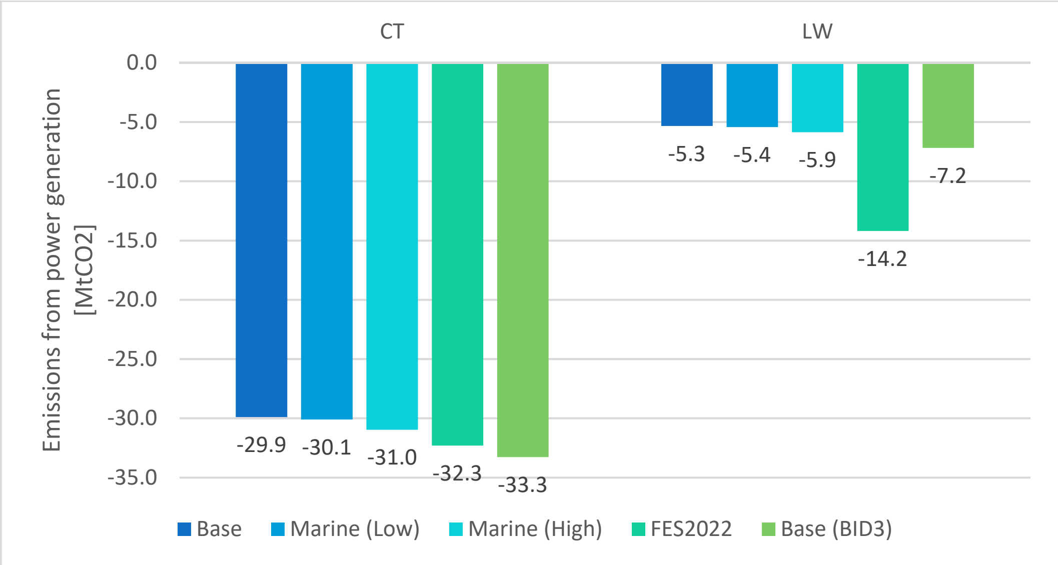

Figure 5. National emissions for the year 2045 in various cases.

3.3. National carbon intensity

Looking then at carbon intensity across GB, similar patterns between Base, Low and High scenarios are seen, where higher installed capacities of marine energy deepened the negative carbon intensity of the power sector (Figure 6). However the FES2022 reported values ("FES2022") are more deeply negative than those calculated in PyPSA-GB, even when the BID3 carbon intensities (Table 2) are used in PyPSA-GB ("Base (BID3)").

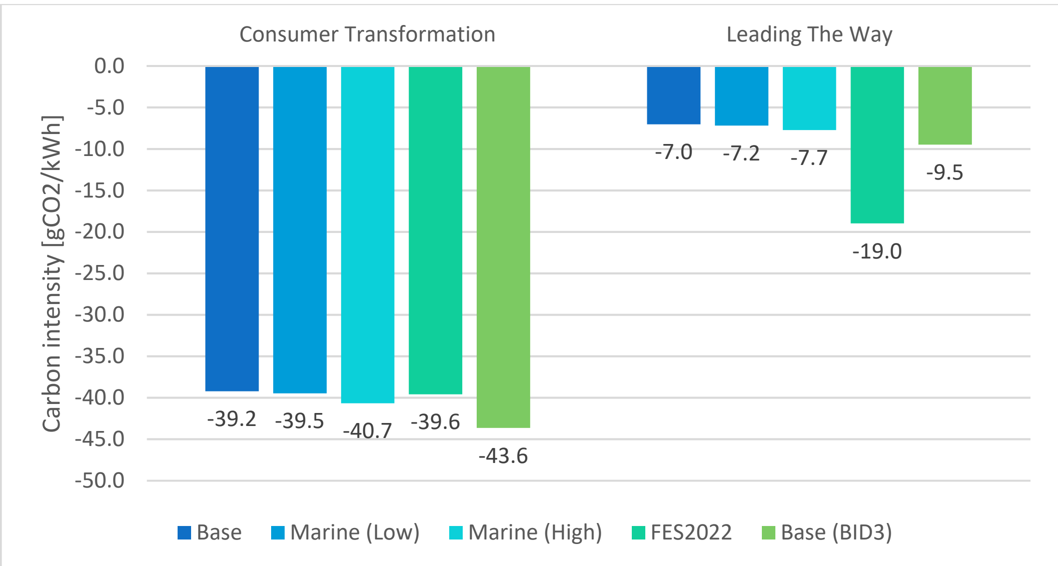

Figure 6. National carbon intensity for the year 2045 in various cases.

3.4. Nodal carbon intensities between base and high cases

Moving towards an assessment of zero-carbon communities adjacent to the nodes of interest, the spatial distribution of carbon intensity was investigated. Spatially, while reductions in carbon intensity of generation at each node are observed in the high cases, the changes are relatively minor (Figure 7, Figure 8) and quite localised – with limited impact on adjacent nodes – when averaged over the year. Further analysis in PyPSA-GB could reveal seasonal aspects to the carbon intensity changes.

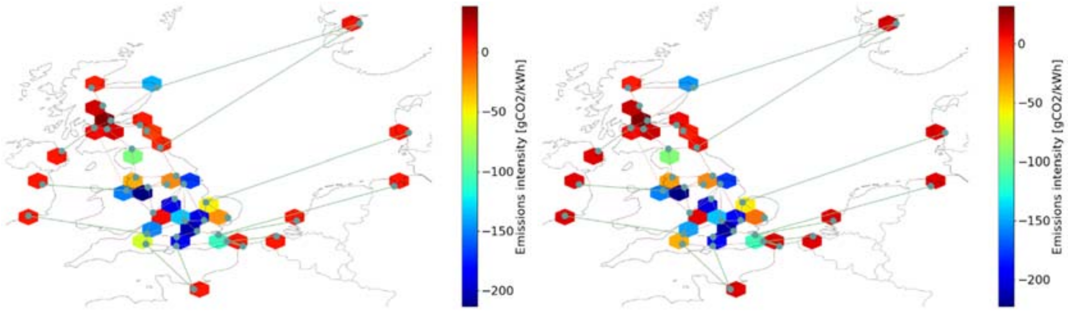

Figure 7. Spatial distribution of carbon intensity of generation in CT 'Base' (left) and CT 'High' (right)

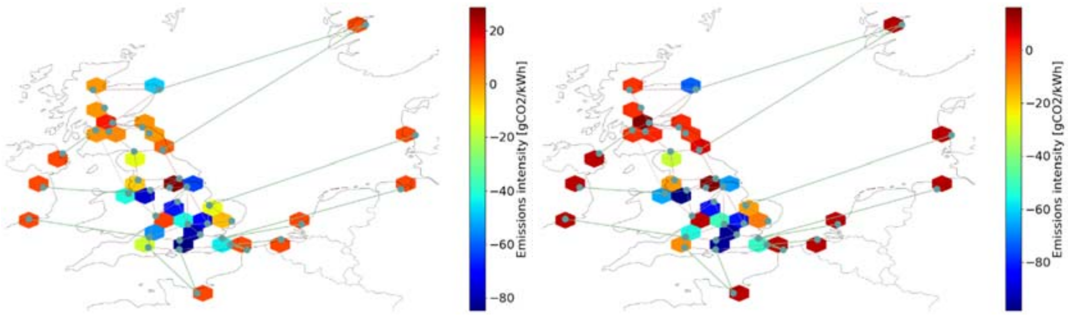

Figure 8. Spatial distribution of carbon intensity of generation in LW 'Base' (left) and LW 'High' (right)

3.5. Beauly and SW Peninsula total emissions

The generation mix at the network node of Beauly is characterised by multiple types of renewable generation and some dedicated biomass. By contrast, SW Peninsula has more dispatchable thermal plant including – crucially – BECCS. For communities adjacent to Beauly, the absence of any negative emissions BECCS means that the co-location of marine energy reduces emissions in all scenarios. For Beauly, the carbon intensity of generation fell by more than 75%, and by more than 50% in LW between the base and high marine cases. For SW Peninsula, the negative carbon intensity is deepened, although the improvements are less significant at only around 1% for CT and 5% for LW between the base and high marine cases (Figure 10). This suggests that there are more dispatchable carbon intense, thermal plant at Beauly, which are obviated by more marine renewables, while at SW Peninsula, there are fewer –reducing the carbon reduction potential of co-location with marine energy.

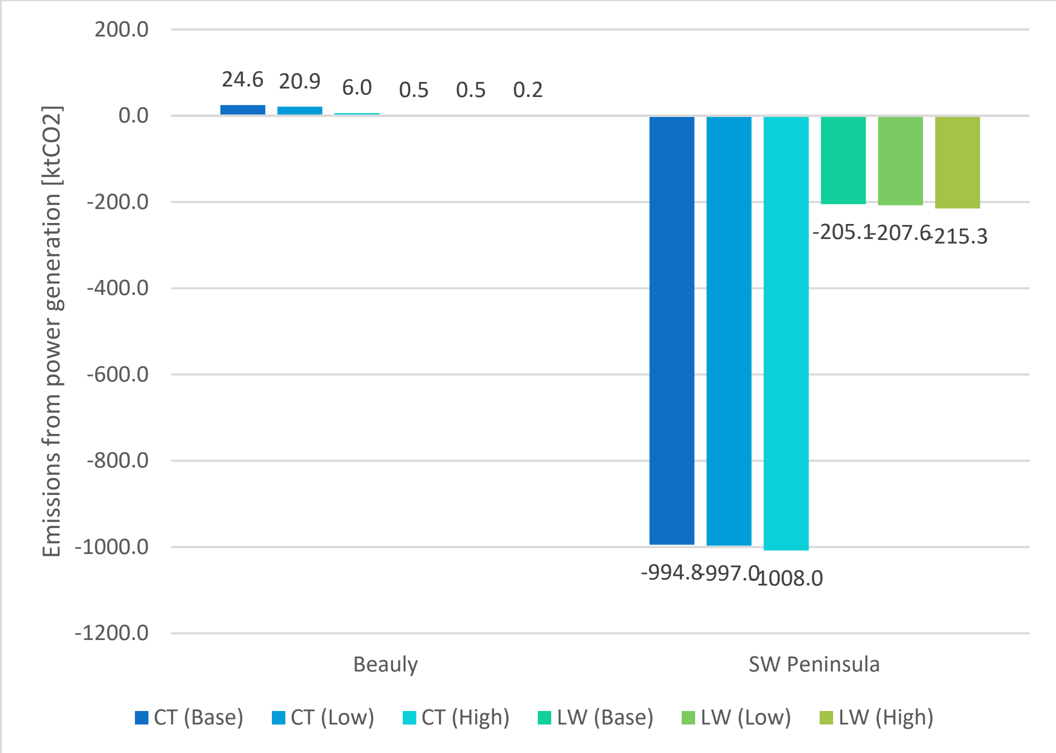

Figure 9. Emission from power generation at Beauly and SW Peninsula in 2045 determined in PyPSA-GB

3.6. Beauly and SW Peninsula carbon intensity

This pattern is replicated for the carbon intensity of generation at Beauly which falls significantly in high marine cases. However, for SW Peninsula, the negative carbon intensity becomes more positive. This implies that some zero carbon intensity marine is displacing at least some negative carbon intensity BECCS, requiring further investigation.

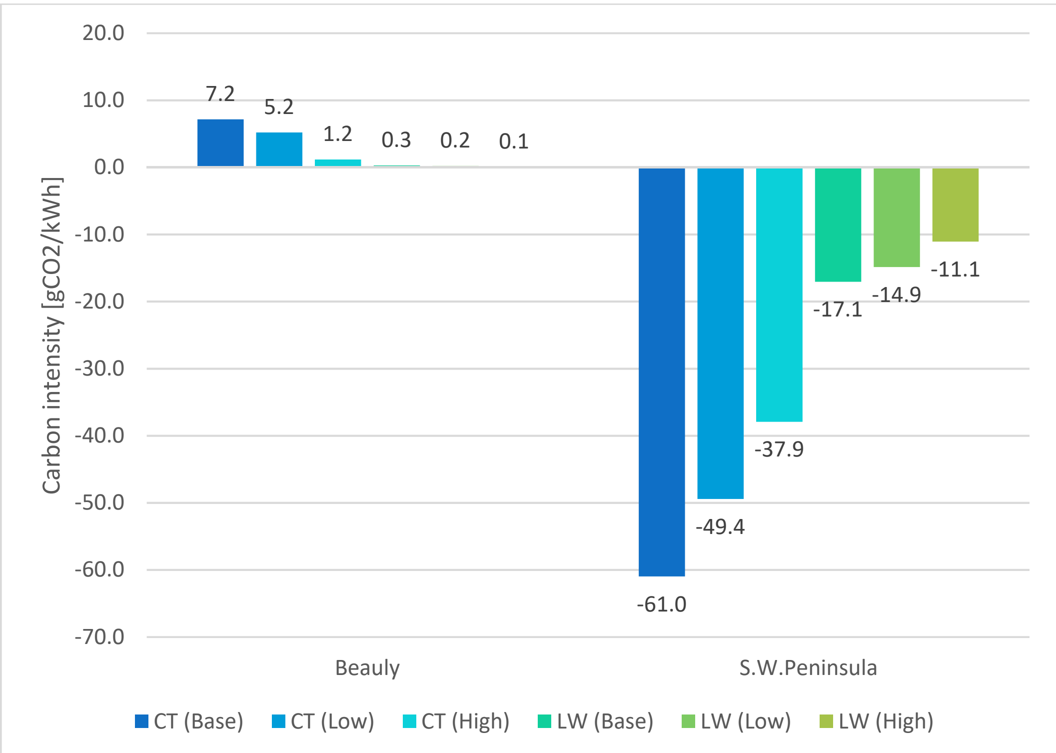

Figure 10. Carbon intensity of power generation at Beauly and SW Peninsula in 2045 determined in PyPSA-GB

4. Conclusion

4.1. Implications of co-locating marine renewables with zero-carbon communities

This work has investigated the change in carbon emissions nationally and locally due to the co-location of marine energy with remote communities in 2045 using future energy scenarios from National Grid. The results show that higher installed capacities of marine renewables in future energy scenarios always reduces carbon emissions from the power sector on a national scale and local scale, but can lead to a local increase in carbon intensity when interacting with BECCS plant. Scenarios with increased marine energy also have less unmet load indicating the value of this technology to future power system operation.

For zero carbon communities for which co-location of marine energy is a credible option, marine energy can therefore improve bulk emissions and carbon intensity reductions and facilitating the race to net zero.

4.2. Limitations and further work

This study has a number of limitations which could be investigated in further work.

- The 29 bus transmission network model is assumed here as a proxy for zero carbon communities, when fundamentally this is a simplification of the complexity of the distribution and domestic energy systems expected in the future. The advantage of this methodological choice is that the national network can be observed for systemic impacts, such as national emissions and spatial impacts. The results of this method therefore cannot not extend into the distribution network or smart-energy system scales, where further innovation for zero-carbon communities can be expected.
- This study does not include any investigation into whether simply overbuilding other forms of renewable energy or storage are as effective, and does not disaggregate the effects between the two temporally distinct technologies: wave from tidal stream.
- The results do not align exactly with the BID3 findings even when BID3 carbon intensity inputs are used. The similarity of the results varies between scenarios, with CT results typically more similar. There are a number of possible explanations of these differences to be determined: for example, network constraints and interconnector modelling are central differences between the models and BID3 explicitly models more demand side flexibility such as V2G. Further work is required to understand the source of this discrepancy.
- Only two FES are considered, and only for one year: 2045. In a larger scope the other FES would be considered and over a wider temporal coverage.
- It is assumed that the carbon intensity of generation local to a node is equal to the carbon intensity of consumption at a node. In reality the power flows *between* nodes will change this, with particular nodes have an excess/deficit of generation/consumption. Work is ongoing by the authors on this topic.
- Unmet load is not belaboured upon: in reality unmet load is a significant issue for power system operation, although it is observed that scenarios with higher installed capacities of marine have less unmet load than the base scenarios.
- Further work could explore the seasonal component in energy delivery and the relation to the historical year selected in High marine scenarios.
- The intercomparison of CO_2 and CO_2eq is not examined.

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How circular is a renewable energy supply of existing buildings? Case study of the use of PV in an apartment block to increase self-consumption

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Abstract: To achieve the projected building stock decarbonization, large efforts are needed. The renovation rate in Europe remains well below the targeted annual 3% (Artola et al. 2016; Laffont-Eloire et al. 2019). Some of the main barriers to invest in decarbonization have to do with the decarbonization costs and access to finance, as well as complexity, awareness, stakeholders' management, and fragmentation of the supply chain (BPIE 2011; 2016; Seddon et al. 2004). In energy planning of buildings, it is often unclear to what extend circularity is emphasized with focus on energy supply options and what influence different technology options have.
This work deploys the use of various renewable energy sources, optimizes self-consumption and storage capacity. In particular, the question of how circular the investment in the renewable energy supply option is, was of interest. For this purpose, various simulations were carried out in Polysun and Sympheny (photovoltaic systems, small wind power plants and energy storage systems) to examine which of these options are most suitable in terms of economic efficiency and degree of self-sufficiency (Bollinger et al., 2019).
The case study showed that the solar panels pay off after just a few years. Without the use of energy storage, a self-consumption rate of 30% is expected.

Keywords: PV system, self-sufficiency, energy autonomy, economic evaluation

1. Introduction

The energy supply of the industrialized world has undergone several fundamental changes and developments in the last centuries, which correspond to the requirements of a dynamic industrial society (Göllinger, 2021). According to Göllinger (2021), we can now speak of the "energy turnaround", which is the popular term for a politically initiated structural change in the field of energy supply. The role of the customer is changing: the classic customer is becoming a "prosumer" - a contraction of the words "producer" and "consumer" - and therefore an individual who actively intervenes in the value chain of the energy supply (Herbes & Friege, 2015). Photovoltaic technology has made great strides in recent years in terms of cost and performance (Frey, 2019). Therefore, according to Frey (2019), completely new possibilities of use are opening up (Swisssolar 2023).

This is in particular interesting in terms of circular principles. The amount of self-consumed electricity from the own PV plant does not have to be fed into the grid, does not have to distributed to other consumers and does not "generate" CO2 emissions from operation. At the same time it enhances the distributes renewable energy production which is planned to become the backbone of our future energy system (Parlament 2022).

On the other hand, Schulz (2015) emphasizes the problem of decreasing feed-in tariffs for electricity from photovoltaic systems. The existing framework conditions have created impulses for new business models for the supply of household customers). The newly created business model aims to make optimal use of electricity by maximizing household self-consumption (Schulz, 2015). Goeke and Kürkel (2017) call this topic: self-sufficiency in the building, which generally means self-sufficiency with electrical energy and heat. Consequently, facility management is an important building block, because according to Kummert, May and Pelzeter (2013), it is necessary for optimal management of buildings.

1.1. Literature review

The word "prosumer" combines the words "producer" and "consumer" (Klimaschutz, 2016). It therefore refers to people who can produce and consume a certain good (Klimaschutz, 2016). Driven by the energy transition, the old structure of producer and consumer is being overcome and the new type of "prosumer" is emerging (Climate Protection, 2016). Prosumers actively participate in the energy market by simultaneously consuming electricity from the grid and feeding electricity into the grid through their own production (Klimaschutz, 2016). This is done, for example, with a solar system on the roof of the private household (Climate Protection, 2016). According to Zafara et. al (2018), the concept of the prosumer is consequently represented, as can be seen in Figure 1.

This new development in the energy sector takes into account the growing demand for energy while addressing important economic, environmental, and social issues (Zafara, et al., 2018). By sharing their surplus energy with others, prosumers help reduce carbon emissions and promote the use of renewable energy (Zafara, et al., 2018). In addition, they can also gain economic benefits by selling their surplus energy to the grid (Zafara, et al., 2018). Overall, the prosumer strategy offers a promising alternative to traditional energy consumption and helps to create a sustainable energy supply (Zafara, et al., 2018).

In the literature, the terms energy self-sufficiency, energy autonomy, and energy independence are often used as synonyms (McKenna, Jäger, & Fichtner, 2014). Broadly speaking, the principle refers to local or regional energy production rather than importing energy (McKenna, Jäger, & Fichtner, 2014). The concept can be found in individual buildings as well as entire regions (McKenna, Jäger, & Fichtner, 2014).According to McKenna, Jäger & Fichtner (2014), the definition depends on the degree of self-sufficiency sought. To this end, they have come up with three rough definitions (McKenna, Jäger, & Fichtner, 2014, pp. 242-243):

1. Tendential self-sufficiency: decentralized, regional energy supply, i.e. there are tendencies towards a regional energy supply that covers, for example, more than 50% of annual demand, although self-sufficiency is not (necessarily) explicitly defined as a goal here.
2. Soft or on-grid self-sufficiency: on-grid, i.e. the municipality or region is self-sufficient in energy over the year, but the existing supra-regional grid infrastructure (for electricity, gas, heat, etc.) is often used to compensate for discrepancies between supply and demand. In this case, only some energy applications and areas are usually covered.
3. strong, hard or complete autarky: completely off-grid: the municipality or region is energetically separated from its surroundings and covers its own energy demand constantly and completely by itself.

McKenna, Jäger & Fichtner (2014, p. 243) quote the authors Rae and Bradley, who give the following definition of energy self-sufficiency: "a situation in which the energy services used for sustaining local consumption, local production and the export of goods and services are derived from locally renewable energy sources". Unlike McKenna, Jäger & Fichtner (2014), Rae and Bradley do not make an sub-division of the definition as mentioned above. Their definition deals with the extent and degree of autonomy (McKenna, Jäger, & Fichtner, 2014). The extent refers to the self-sufficiency approach; i.e., how many residents, buildings, and associated land area should become self-sufficient (McKenna, Jäger, & Fichtner, 2014).

The following is a brief further discussion of the definition of residential energy self-sufficiency. According to Frey (2019), it is necessary to rely much more on decentralized and sustainable energy production than before in order to ensure energy supply in the long term. This means that energy self-sufficient buildings are needed, which generate the electrical energy requirements internally as far as possible (Frey, 2019).

1.2. Scientific gap

From the initial situation, these three questions arise:

- Which economic factors and business developments influence photovoltaics in residential construction?
- Which indicators are relevant for homeowners: inside regarding the degree of energy (degree of autonomy/economy)?
- Which prerequisites must be created in order to optimize the business models of photovoltaics?

1.3. Objectives

The aim of this work is to give a comprehensive insight into photovoltaics in residential buildings and to examine various aspects of this topic. In doing so, the economic and business factors, the relevant indicators for homeowners regarding the degree of energy efficiency and the role of photovoltaic models in the integration of solar power systems in existing properties will be considered. It will be shown how the current framework conditions and developments in the field of solar energy affect the economic viability of photovoltaic systems in residential buildings and what obstacles and solutions exist in the implementation of photovoltaic projects.

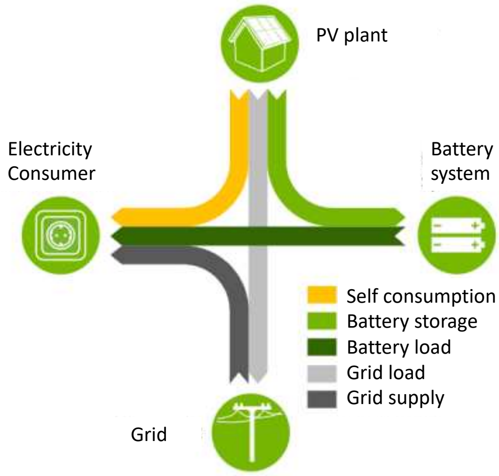

Figure 1. Concept of prosumer (HTW)

2. Methodology

In 1996, the construction of the Wingertstrasse project was started. Three apartment houses were built, each with two times three and one with four units. The electricity supplier in Zurich (EKZ) approached the condominium owners in 2012 about producing their own electricity through a photovoltaic system. The flat roofs with a rough orientation to the south were ideal for an installation, the implementation was limited to only one residential unit in the initial phase. The photovoltaic system was planned in such a way that it would only produce electricity, without the energy obtained being used for self-consumption. The specifications of the PV system are summarized in Table 1.

Table 1. specification of the base case PV system

number of modules	45 modules
area of PV modules	75 m^2 (area of modules)
energy production per year	11188 kWh/y
CO2 savings per year	5594 kg/y
inverter efficiency	96%

With the help of scientific literature and expert interviews with specialists in the field of photovoltaics and energy consulting, the questions posed above should be answered. Furthermore, an interview was conducted with an interested homeowner in order to identify the main knowledge gaps and questions regarding the topic. In addition, a model was created using Polysun (software for photovoltaic simulation), which can be related to the Wingertstrasse project (paradigmatic case). The goal is to draw a comparison from the simulation data and to be able to derive statements related to the degree of self-sufficiency and the economic efficiency of the plant.

Therefore, four different cases were evaluated with the Polysun solar calculator. For all four cases, the technical data was taken from the offer, only the inverter had to be determined by an automated determination (in the "Wizard"). In relation to the consumption per person (76 kWh/month), an average value was used, which comes from the smart meter data of the EKZ tool. For the calculation of the remuneration, the remuneration rate from the offer was used and for the calculation of the electricity costs, the EKZ electricity tariffs 2023 for private customers were used, thereby one calculated with an average value from the high and low tariff (Elektrizitätswerke Zürich, 2023). For the calculation of the payback period, a period of 25 years was considered and an inflation rate of the electricity of 8.5% per year was included, which was derived from the last year's inflation.

3. Results

The results of each case are summarized in Table 2.

Table 2. results of simulations for the four cases

	base case	case 1	case 2	case 3
Average self-sufficiency ratio per year (%)	-	37.0%	46.5%	72.9%
Average self-consumption ratio per year (%)	-	67.9%	84.7%	50.2%
Average feed-in ratio per year (%)	100%	32.1%	15.3%	49.8%
Photovoltaic system yield per year (kWh)	11’800	11’800	11’800	35’421
Self-consumption per year (kWh)	-	7’097	9'291	15’191
Grid feed-in per year (kWh)	11’800	4’703	2’127	17’540
Electricity purchase per year (kWh)	20’064	12’967	10’773	4’873
Remuneration per year / Case (CHF)	4’708.20	1’876.50	848.67	6’998.46
Electricity costs per year / Case (CHF)	4’314.76	2’788.55	2’316.73	1’047.94

3.1. Base case

The base case scenario represents the current situation and how the photovoltaic system is currently operated. This scenario is considered the general baseline. 100% of the electricity production is fed into the grid at a compensation rate of 0.399 Fr/kWh. The most important key data are shown in Table 2.

Annually the plant produces 11'800 kWh, and thus 4'708.20 CHF are earned per year. The profitability calculation states with regard to the amortization of the plant that it is profitable after 8.5 years.

3.2. First case – with consumer

The first case scenario differs in the inclusion of the consumers. The consumers are three apartment buildings with a total of 22 residents. The yields of the photovoltaic system are constant. Table 2 shows the most important key data.

In this scenario, the electricity generated is both fed into the grid and used directly by the residents. The amortization of the plant in this case takes 9.7 years, more detailed information follows in another subchapter.

3.3. Second case – with consumer and storage

The second case scenario is supplemented with the use of a battery (10kWh), the other initial situation is the same. However, it should be mentioned here that a new investment was made through the use of the battery. Here, 1400 CHF per kWh of storage capacity was calculated, which is a good benchmark according to Energie Schweiz (Energie Schweiz, 2020). Table 2 shows the key data for the second case scenario.

By using a battery in this case, the electricity produced is temporarily stored and can be used at another time. In this case, the plant would be amortized after 12.8 years.

3.4. Third case – with consumer and storage and larger PV system

For the third case scenario, the initial situation was adapted, and a reference is made to a possible expansion on site. As already mentioned in the Wingertstrasse project chapter, the system is limited to only one apartment building. Therefore, the system was calculated to be three times as large, so that each apartment building is equipped with one system. This means that 135 modules were installed and the dimension of the battery was also adjusted, namely to 45 kWh. Table 2 shows the most important key data.

This case produces 35'421 kWh per year and would be amortized after 13.5 years, since a large part of the produced electricity can be fed into the grid.

3.5. Comparison of four cases

The following page shows a graph that compares the yields of the photovoltaic system, the self-consumption, the grid feed-in, the electricity demand and the electricity purchase.

Here it is noticeable: When it comes to the use of a battery, the self-consumption can be increased at least by one third, depending on the dimensioning of the system. However, if more is used by the customer or stored temporarily, correspondingly less is fed into the grid. However, even in this case it depends on the size of the plant. If the yield exceeds consumption, more is fed into the grid or sold.

Another interesting development can be observed in the purchase of electricity. The better the own electricity is used, the less has to be purchased on the electricity market to cover possible gaps in the power supply. Here again, the dimensioning of the system plays a major role, because the larger the system is dimensioned with a correspondingly large battery, the less electricity has to be purchased. In the case of the third case, the purchase amounts to just under a quarter of the annual requirement.

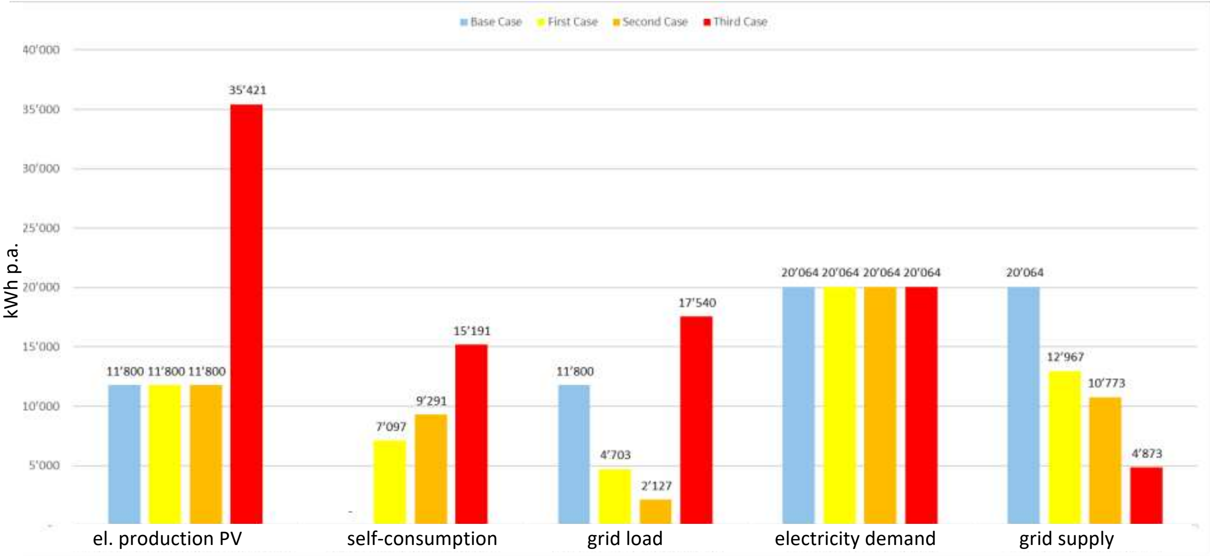

Figure 2. key data of electricity for the four cases

Figure 3 shows the level of self-sufficiency, the self-consumption ratio and the feed-in percentage per year. It can be seen that the use of a battery in the second case helps to increase the degree of self-sufficiency. However, there is a countermovement with respect to the feed-in ratio. In addition, the self-consumption ratio can be increased with the use of the battery and through the intermediate storage of the electricity. In this comparison, the size of the plant must also be taken into account, because this can lead to a large difference, see third case scenario.

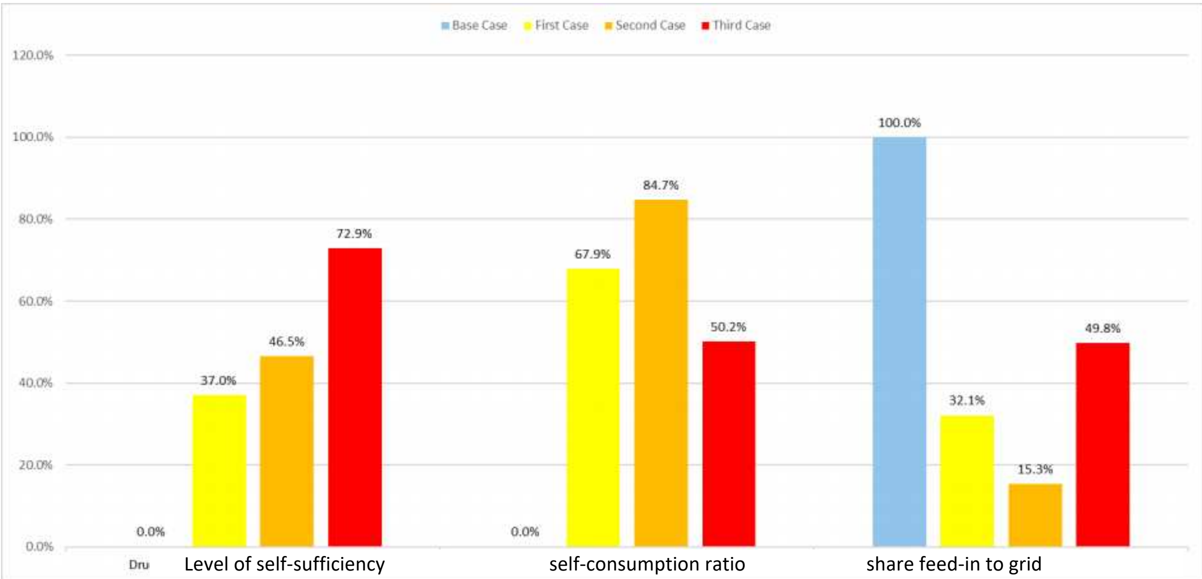

Figure 3. level of self-sufficiency, self-consumption and feed-in percentage of the four cases

The savings are calculated from the company's own electricity production. This is because the electricity that was produced in-house did not have to be purchased on the market and thus represents a positive business. For the calculation of the total profit, the key figures of the profit or loss are summed up with the savings, which finally represents the total profit per case (Figure 4). If the profit distributions are compared, it becomes clear that the inclusion of consumers and a battery represent a profitable advantage. Thus, about one third more profit can be generated. If we refer to the third case, we can speak of a very lucrative model, which generates about 9,000 francs per year.

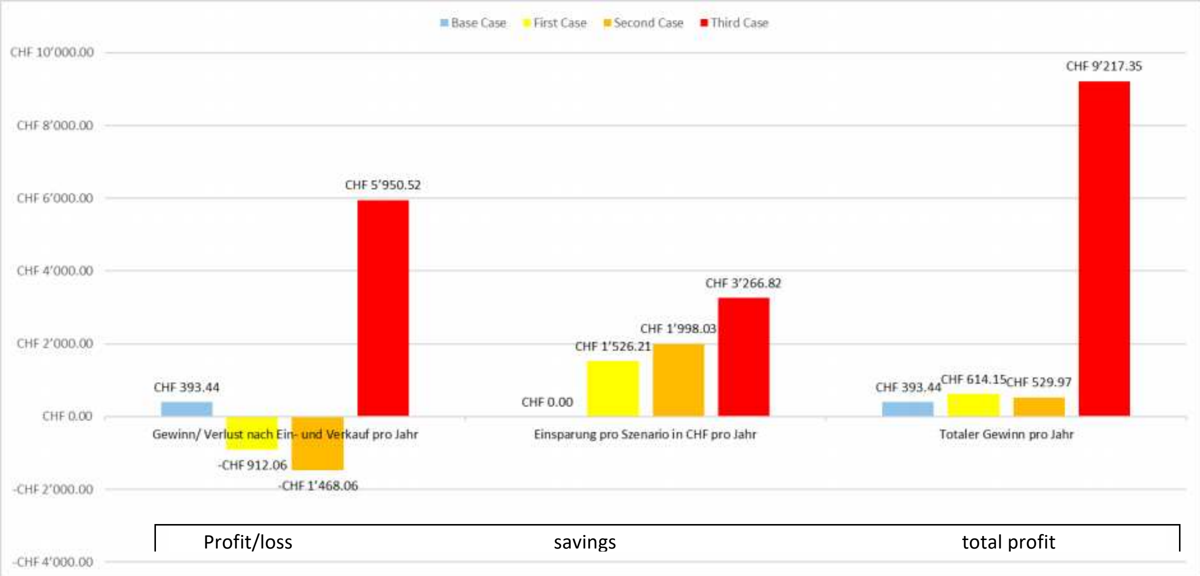

Figure 4. profit/losses, savings and total profit for the four cases

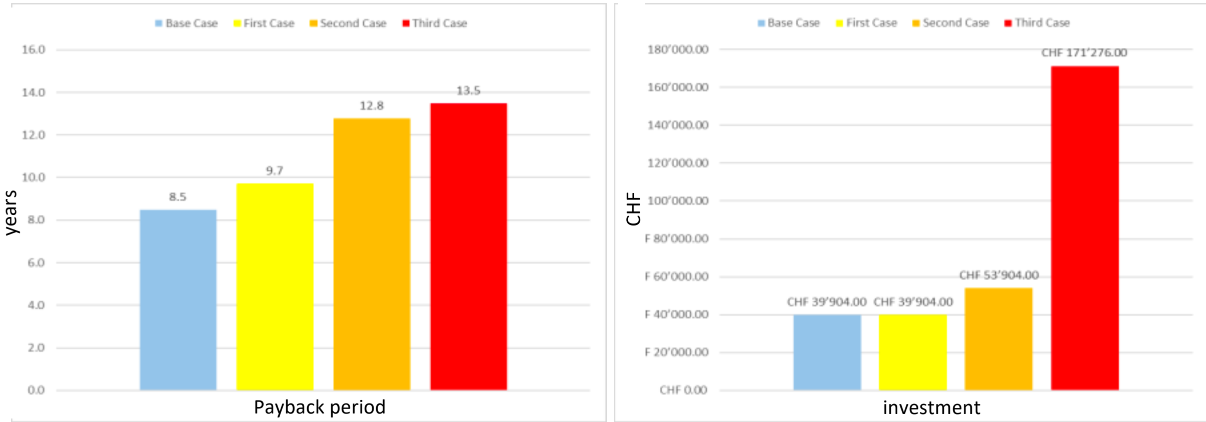

Figure 5. payback (left) and investment (right) for the four cases.

For the calculation of the payback period, a period of 25 years was considered. The investments were compared with the annual returns from the compensation and the savings. The electricity price increase over the course of the period was also taken into account. The average inflation rate was derived from a price comparison of electricity costs in the municipality of Illnau-Effretikon from 2018 to 2023 (Admin Switzerland, 2023). Figure 5 compares the payback periods of the different scenarios. The intersection points with the zero line represent the payback period in each case.

4. Discussion

The following can be derived from the comparison of key data on electricity (see Figure 2): If a battery is used, the self-consumption share can be increased by a third or more. With regard to the grid feed-in, a countermovement can be seen: The higher the self-consumption, the lower the grid feed-in. Another interesting fact is that the higher the self-consumption, the lower the costs for purchasing the electricity.

However, with all these statements, the dimensioning of the plant must be taken into account, because this can lead to significant changes, which can be easily seen from the grid feed-in. If the comparison of the self-sufficiency is considered (see Figure 3), it is clear that the use of a battery has a significant influence on the degree of self-sufficiency of the scenarios. What can also be increased by their use is the self-consumption ratio. However, there is a decreasing movement depending on the size of the plant. The same applies to the feed-in ratio in reverse. With regard to the economic efficiency of the scenarios (see Figure 4), it can be seen that the scenarios with the inclusion of consumers and a battery are the most financially worthwhile. Compared to the Base Case, the First Case scenario can generate the most profit (if the Third Case with much higher investment is excluded). Therefore, the dimension of the plant continues to play a large role. In Figure 5, comparison of payback period and investment, a counter movement can be seen. The higher the investment, the longer the payback period. Nevertheless, it must be said that this increase is limited and does not increase proportionally. Another factor influencing the payback period is the varying returns from the feed-ins and the savings in the scenarios.

5. Conclusions

First of all, it was important to clarify which economic factors and business developments influence photovoltaics in residential construction. The economic viability is influenced, among other things, by the subsidy measures, which are intended to create a financial incentive.

However, this influence is limited. Rather, the strong demand can be attributed to the attractive production of own electricity, which increases own consumption. In addition, it is easier to achieve economic success with the current operation of a photovoltaic system, insofar as customers are not already deterred by the high investment costs that have to be made. In terms of business developments, technological development is one of the biggest drivers. Switzerland is currently promoting projects that are looking for solutions in various areas of photovoltaics. This development relates primarily to the intelligent use and control of solar power. Another driver is the use of batteries. With their use, the produced electricity can be ideally redistributed and adapted to the consumer profile.

Regarding the second question, the analysis of the case study shows that the main indicators are the dimensioning and the use of a battery of the plant. The greater the energy yield, the more can be generated and the degree of self-sufficiency improved. However, it should be noted that the system must always be compared with the corresponding consumer profiles. Furthermore, the investment sum must not be neglected. A high energy yield also requires a high investment, which has an influence on the payback period.

Finally, the question is addressed as to which prerequisites must be created in order to optimize the business models of photovoltaics. First, the dimensioning of the system should not be based on self-consumption, but on the optimum that can be achieved on site.

In addition, new solutions should be pursued, such as models that are based on sharing with neighbours (ZEVs or LEGs), which, however, require a transparent agreement between the system operator and the electricity grid company with regard to the grid usage costs. The digitalization of metering can create new models that are more lucrative for system operators. Active intervention in the electricity market would be the logic next step. With regard to regulatory measures, better conditions must be created in the area of the use of PV barrels and the integration of photovoltaic systems into existing infrastructure. PPA are often mentioned as an attractive financing model. Here, the financial risks lie with the investor and not with the consumer.

In the long term, this model could be used in large developments to supply surrounding consumers as well. For further optimization, better disclosure of product supply chains and compliance with European standards for new products should be in focus. In conclusion, it can be said that a lot will have to change in the future with regard to photovoltaics so that Switzerland can achieve the energy transition by 2050. Nevertheless, these are good approaches that must be pursued further.

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Energy use, CO2 emission, and emission reduction potential of cooking fuel substitution in Nepal

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Abstract: Clean energy access is key to socio-economic progress and an important issue for developing countries. The availability and affordability of clean commercial fuels have been a serious problem in most rural households in developing nations. Though energy consumption patterns vary widely over geographies and the type of fuel used, the variations in their usage patterns remain poorly understood. Thus, an energy use survey was conducted for 515 households in three climatic regions of Nepal in 2018. To analyse the energy consumption and associated CO_2 emission patterns of traditional, mix, and commercial fuel using households, this study assumed a TMC model based on the available cook stoves in investigated households. In addition, this study further analysed the CO_2 emission reduction potential of cooking fuel substitution by liquified petroleum gas and electricity under the business-as-usual scenario, moderate emission scenario, and low emission scenario. The results suggested that 25% households rely on traditional cooking fuels without using any other clean cooking fuels, 67% households add clean cooking fuels to their energy systems, and only 8% households rely on commercial cooking fuels. This study also highlighted that substituting cooking fuels substantially reduced indoor CO_2 emissions. Compared to business as usual, the CO_2 emission decreased by 0–57% and 65–100% in moderate emission and less emission scenario, respectively.
Keywords: Energy use, Emission reduction, cooking fuel, Energy access, Energy poverty.

1. Introduction

1.1. Overview

Access to clean energy is key to socio-economic development and one of the basic issues of developing countries. Nepal is a small country situated in the Himalayan Mountain range between India and China. It has high geographical diversity, which makes it difficult to develop modern energy infrastructure in all parts of the country. The unavailability and unaffordability of clean commercial fuel has long been a serious problem in rural households. Access to clean cooking fuels is essential for promoting human well-being as it improves the quality of life (Kurniawan et al., 2018). The enormous potential of renewable energy resources of the country, such as hydropower, solar power, and wind power, can be utilised for improving the living conditions of people through clean energy development. However, due to economic and other social constraints, most of these resources have remained underutilised, and thus, a large number of households have to rely on traditional fuels (Gurung et al., 2011; Islar et al., 2017; Ghimire et al., 2018). Approximately 70% of the total households, including urban and rural areas, and 90% of rural households in Nepal depend primarily on traditional fuels for daily cooking (CBS-Nepal, 2011).

Firewood is the major source of cooking and heat energy and provides 78% of the total energy demand of the country (IEA, 2016; Poudyal et al., 2019). In addition to using firewood, many households add different types of fuels, such as liquified petroleum gas (LPG), electricity, kerosene, and biogas, to fulfil their everyday cooking energy demand. LPG is the second most widely used cooking fuel, with a total annual consumption of 1.4 million tonnes (Poudyal et al., 2019). Electricity is still unreliable with a high frequency of load shedding and is mostly used for lighting and other electric appliances. Approximately 90% households have access to electricity either from grid or off-grid supply, with per-capita electricity consumption of 146.5 kWh/year.

The substitution of traditional cooking fuels by LPG and electricity may offer great potential to reduce indoor CO_2 emissions as well as other associated emissions. Thus, several countries have implemented nationwide cooking fuel substitution programs. For example, the Indonesian government initiated the world's largest exercise to substitute kerosene with LPG in 2007, where 58 million LPG packages were distributed to reduce dependency on kerosene (Kurniawan et al., 2018). Since the 1970s, the government of Ecuador has heavily subsidised LPG and fixed household LPG prices at 1.60 USD per 15 kg cylinder. As of 2014, more than 90% Ecuadorian households were primarily cooking with LPG (Gould et al., 2020). The government of India has also initiated several policies to promote LPG accesses and has provided huge subsidies for low-income Indian households (Gould and Urpelanien, 2018; Sharma and Jain, 2019).

The use of clean cooking fuels has substantial health, climatic, and environmental benefits of reducing indoor air pollution. Moreover, it increases the energy consumption efficiency of the household sector, which plays a significant role in reducing indoor CO_2 emissions (Kurniawan et al., 2018). To determine the effectiveness of various policies directed towards the development of clean cooking fuels in the household sector and draw necessary improvements for future consideration, it is necessary to understand the complex energy use and associated emission patterns of different fuels used in households.

1.2. Literature review

Several studies have investigated energy use patterns in Nepal (Islar et al., 2017; Poudyal et al.; 2019; Rijal et al., 2018; Pokharel et al., 2020; Shrestha et al., 2020; Acharya and Adhikari, 2021;). For instance, Malla (2013) studied household energy consumption patterns and their environmental implications in Nepal. Joshi and Bohora (2017) assessed the impact of various socio-economic factors on household cooking fuel preference and the motive for making a transition towards cleaner fuels. Rupakheti et al. (2019) monitored indoor levels of black carbon and particulate matter and found that the commonly used improved cook stove might help in reducing particulate matter emissions but may not reduce black carbon emissions. Das et al. (2019) estimated the time required and human energy expenditure for the production of cooking fuel for four alternative cooking energy systems and found that human energy expenditure and time had a significant influence on the selection of cooking fuel. Bartington et al. (2017) assessed the patterns of domestic air pollution and found that air quality levels associated with biomass fuel consumption exceeded WHO indoor air quality standards and fell in the hazardous range for human health. Pradhan et al. (2019) analysed the biogas and electricity-based cooking practices and found that the use of cleaner cooking fuels can reduce the firewood consumption by 12–24% in the residential sector (Pradhan and Limmeechokchai, 2017, Pradhan et al., 2019). Other comprehensive studies on energy use have been conducted in several countries, including India (Gould and Urpelainen, 2018; Ravindra et al., 2019), Bangladesh (Baul et al., 2018), Myanmar (Win et al., 2018), and Indonesia (Kurniawan et al., 2018). While assessing the potential of CO_2 emission reduction using clean cooking fuels, it is necessary to conduct comprehensive studies that focus on the heterogeneous energy use patterns of different fuels used in households across regions.

1.3. Objectives

This study assessed existing household energy use and associated direct CO_2 emission patterns of households in traditional, mix, and commercial using households in three regions in Nepal. It also explored the CO_2 emission reduction potential of households by substituting traditional cooking fuels with LPG and electricity. Furthermore, this study also analysed the emission reduction potential by considering the business as usual (BAU) scenario and two other hypothetical alternative scenarios, moderate emission scenario (MES) and low emission scenario (LES).

2. Methodology

2.1. Study area and Climate

Field studies for household energy use surveys represent cold, temperate, and sub-tropical regions in Nepal. To capture the variations in geographical conditions, population demographics, socioeconomics, and local cultures, three non-adjoining districts, Solukhumbu (cold), Panchthar (temperate), and Jhapa (sub-tropical), were selected in this study. Within these districts, altitude ranges from approximately 60 m above sea level in the southern terai region to the highest peak of 8848 m and Mount Everest in the northern region. Table 1 presents the physical and demographic characteristics of the study areas.

Table 1. Demographic and physical characteristics of the study area.

Study area (district)	Area (km^2)	Climate	Population (individual)	Population density (individual/km^2)	Access to grid electricity	Access to black topped road
Solukhumbu	3312	Cold	105,885	39	no	yes
Panchthar	1241	Temperate	191,817	150	yes	yes
Jhapa	1606	Sub-tropical	812,650	510	yes	yes

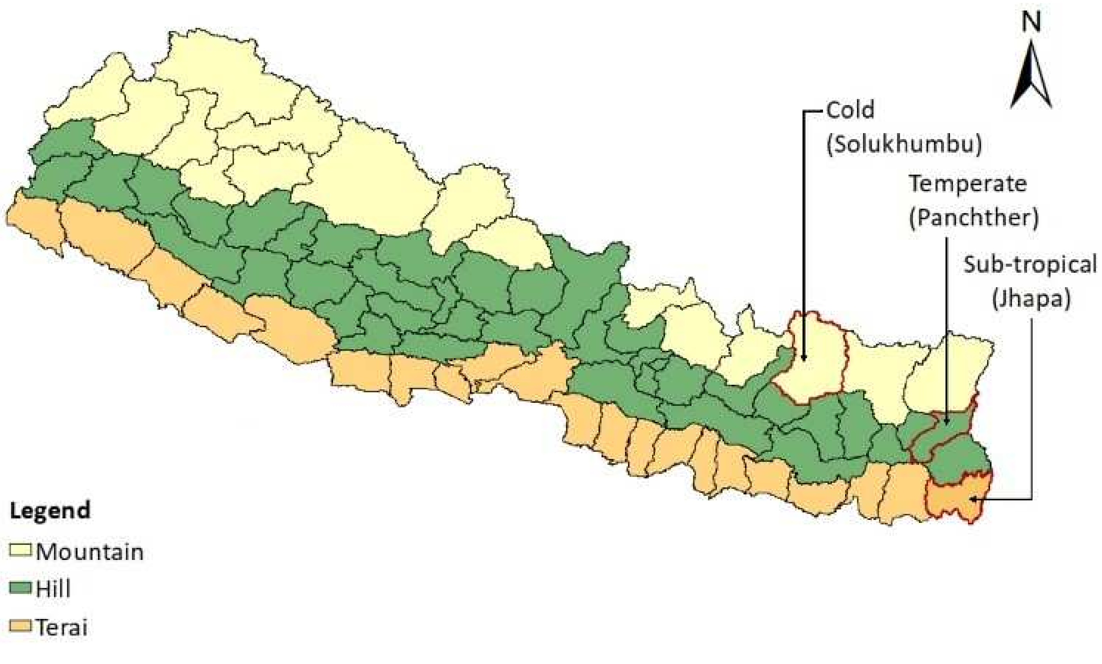


Figure 1. Locations of the study areas.

2.2. Household survey

A household questionnaire survey was conducted in the winter of 2018 for 515 households. A total of 76 households in cold, 261 in temperate, and 178 in sub-tropical regions were interviewed to collect necessary information using the questionnaire.

Estimation of household energy use

Monthly electricity bills provided by the local electric power company were used to estimate household electricity use. These electricity bills were measured in kWh/(household·month), which was converted into MJ/(household·day). The amount of LPG used was obtained by asking the specific duration on how long a LPG cylinder would normally last in a family. In Nepal, metallic cylinders containing 14.2 kg of LPG are available in grocery stores. To estimate the household firewood consumption, the person responsible for cooking was asked to answer the total amount of firewood used in kg for each cooking time per day. Finally, using the conversion factor of all respective fuels, the energy data obtained were converted into MJ. The energy conversion units used were assumed as follows: LPG 48 MJ/kg, electricity 3.6 MJ/kWh, and firewood 16 MJ/kg (Nansaior et al., 2011).

Estimation of energy use for cooking

Estimating the energy used only for cooking purposes in the surveyed households is challenging as the activities of cooking, heating, and preparing animal feed are often combined. Five households in the sub-tropical region were selected for experimental measurements to estimate per capita firewood used for cooking as these households did not use any fuels for space heating due to favourable thermal environmental conditions during the survey period (Pokhrel et al., 2020). For this measurement, firewood used for other purposes, such as space heating and animal feed preparation was excluded. This firewood was measured using the weight survey method (Fox, 1984; Bhatt et al., 1994). In this study, it was assumed that the per-capita firewood used for cooking is similar in all regions. Per-capita LPG used for cooking was also estimated using the data of five LPG consuming households in the sub-tropical region. Although no households were fully dependent on electricity for cooking, it was assumed that the per-capita LPG and electrical energies used for cooking were equal.

2.3. Characterisation of the assumed TMC model

To analyse the heterogeneous energy use patterns, a simple three-step TMC model based on available cook stoves was assumed in this study. We assumed that traditional (T) fuel using households gradually add clean cooking fuels in their energy system and become mix (M) fuel using households. Thereafter, these mix fuel using households intensify the usage of clean fuels and leave traditional fuels, turning into commercial (C) fuel using households. In each of the three steps (of this assumed TMC model), households can rely on multiple cooking devices and fuels. On the basis of the assumed TMC model, the energy situation of any society can be explained at three levels. The first level is the abundance of traditional cooking mode, second is the abundance of mix cooking mode, and third is the abundance of commercial cooking mode.

All surveyed households were categorised into three categories: traditional, mix, and commercial fuel using households. Households having cook stoves only for traditional fuels were classified as traditional fuel using households, households with cook stoves for both traditional and commercial fuels were classified as mix fuel using households, and households having cook stoves only for commercial fuels were classified as commercial fuel using households. The cooking modes of traditional, mix, and commercial fuel using households were considered traditional, mix, and commercial, respectively. Figure 2 shows the categorisation of the fuel using households and cooking modes based on cook stoves.

We assumed that households will switch from traditional mode through mix mode to commercial mode with the changes in income and access to modern commercial energy services. However, in rural societies of developing countries, the adoption and rejection of clean cooking fuels is a continuous process that depends on various socio-economic circumstances and cultural behaviours of the people, which determines the position of these households in the TMC model. We expect this model to be helpful in identifying the state of existing energy situations and to predict possible changes in the household energy systems in developing countries like Nepal. Figure 3 shows the existing cook stoves in studied area.

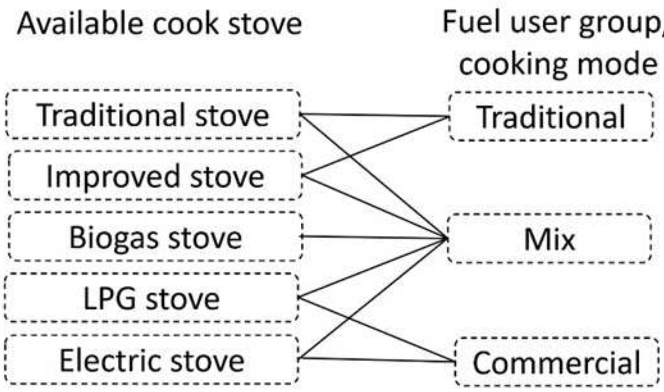


Figure 2. Categorisation of fuel using households and their cooking modes.

(a) (b) (c)

Figure 3. Improved cook stove found in the study area: (a) cold, (b) temperate, and (c) sub-tropical regions.

2.4. CO_2 emission calculation

CO_2 emissions from the fuels used were calculated from equation 1 (Bhattacharya et al., 2000; Baul et al., 2018). The results of the emissions from fuel use were expressed in kg CO_2 e /(household · month).

Emissions = ∑ (EFab × activityab) (1)

where EF is the emission factor of the fuel (in kg CO_2 e/kg or kg CO_2 e/kWh), activity is the amount of fuel used (kg or kWh), and a and b are the types of fuel and activity, respectively (Baul et al., 2018). The emission conversion units used were 0.241 kg CO_2 e/kWh for LPG and 1.163 kg CO_2 e/kg for firewood. Direct emissions from electricity used in this study were assumed to be zero as almost all electricity generated in Nepal is from renewable hydropower plants, micro hydropower plants, and photovoltaic solar power.

2.5. Estimation of CO_2 emission reduction potential

To estimate the indoor CO_2 emission reduction potential of substituting cooking fuels, we considered three scenarios: the BAU scenario and two hypothetical scenarios (MES and LES). The two alternative scenarios, MES and LES, analysed the implication of diffusion of LPG and electricity as clean cooking fuels, respectively. These three scenarios represent three different levels of indoor CO_2 emissions: high, medium, and low, respectively. Total household CO_2

emissions from these fuels were calculated using equation (1). The details of these scenarios are described as follows:

1) BAU scenario:

This scenario represents the existing fuel use patterns of all the investigated households. In this scenario, households in traditional mode use only traditional cooking fuels. Households in mix mode use either traditional or commercial fuels, and households in commercial mode use only commercial fuels such as LPG or electricity to fulfil their everyday cooking energy requirements.

2) MES:

This is an alternative hypothetical scenario with lower emissions than the BAU scenario. In this scenario, per-capita firewood used for cooking in all households was replaced by per-capita LPG. In Nepal, most people living in rural and semi-urban areas rely on subsistence agriculture in which people use firewood for various purposes such as space heating, animal feed preparation, and domestic alcohol preparation. Therefore, the substitution of firewood, particularly in cold and temperate regions, is very expensive and is not always practical. Therefore, this study replaced only the amount of firewood used for cooking. The total CO_2 emissions in this scenario included emissions from LPG as a regular cooking fuel in all households and emissions from firewood used for purposes other than cooking.

3) LES:

This is an alternative hypothetical scenario with the lowest emissions among the three scenarios. In this scenario, per-capita firewood and LPG used for cooking were replaced by electricity as a clean cooking fuel. As the hydroelectricity used in Nepal does not emit any CO_2, we assumed that this scenario has the lowest emissions. Total CO_2 emissions in this scenario include emissions from firewood and LPG used in all households for purposes other than cooking.

3. Results and discussion

3.1. Household characteristics

In the study area, the number of household members ranged from 2 to 12. The family size in this study varies slightly across the three climatic regions and among the three fuel using household categories. The family size was 5.9, 5.6, and 5.2 persons in cold, temperate, and sub-tropical regions, respectively, and 5.7, 5.5, and 4.6 persons in traditional, mix, and commercial fuel using households, respectively. Approximately 80% households cooked meals thrice daily, whereas 20% households cooked meals twice daily. Cooking activity was generally carried out by female members, and fuel collection (firewood and LPG) was carried out by both male and female members. Nearby community forests and private plantations were the main source of firewood, whereas the local source of LPG was some of the grocery stores in nearby markets, for all regions. Approximately 45% households burn firewood inside their houses, while 55% households burn firewood outside their houses.

3.2. Proportions of households in traditional, mix, and commercial modes

We estimated the proportion of households that belong to either traditional, mix, or commercial modes on the basis of the assumed TMC model. As shown in Figure 5, a similar tendency was observed across all regions, and all regions were dominated by the mix mode followed by the traditional mode. The percentage of households that belong to traditional mode was high in temperate, medium in cold, and low in sub-tropical region. The high percentage of traditional mode in temperate regions might be due to the low income and limited accessibility of commercial cooking fuels, as a majority of the residents rely on subsistence agriculture.

The percentage of households belonging to the mix mode was high in sub-tropical, medium in cold, and low in temperate region. Commercial fuel using households were marginally smaller in all regions. However, the percentage of households that belong to commercial mode was also high in the sub-tropical region. The high percentage of mix and commercial modes in the sub-tropical region may be attributed to the increased accessibility and affordability of commercial fuels.

Figure 4 also indicates that 25% households were in traditional mode, 67% households were in mix mode, and 8% households were in commercial mode. This reveals that 25% households rely on traditional cooking fuels without using any other commercial cooking fuels, 67% households rely on both traditional and commercial fuels for cooking, and only 8% households use clean cooking fuels regularly. From this result, we can speculate that 25% households either do not have access to clean cooking fuels or they do not have the ability to purchase clean cooking fuels and rely entirely on traditional cooking fuels. This also indicates that 76% households add clean cooking fuels such as LPG and electricity to some extent in their cooking systems without giving up traditional fuels. However, the frequency and quantity of clean cooking fuel consumption varies depending on socio-economic circumstances and cultural behaviour.

Reportedly, households with sufficient income and without agricultural activities prefer to use clean cooking fuels regularly, whereas medium- and low-income households involved in subsistence agriculture prefer to use LPG and electric rice cookers together with firewood. The most common reason reported for non-adoption of LPG as a regular cooking fuel in all regions was high installation cost, irregular supply, and high regular expenditure than firewood. The unavailability of regular electricity supply, high installation cost, high regular cost of cooking, and lack of knowledge about electric cooking technology have been reported as barriers to the adoption of electricity as a regular cooking fuel. It was also observed that firewood was easily available either from nearby community forests or from plantations in agricultural fields. Thus, most of the households preferred using firewood as their primary cooking fuel. The findings of this study are consistent with the findings of earlier studies conducted in India (Ravindra et al., 2019).

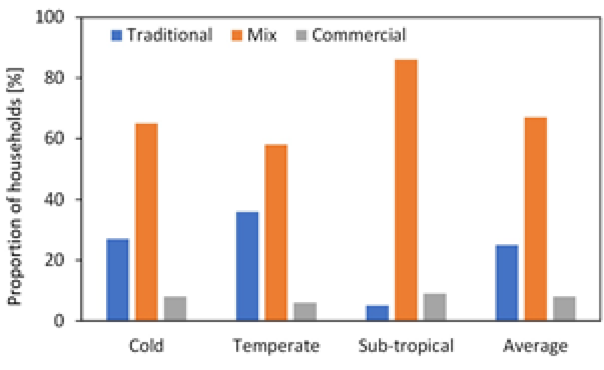


Figure 4. Proportion of traditional, mix, and commercial fuel using households.

3.3. Total household energy use

Most of the households used more than one type of fuel simultaneously, and a large proportion of household energy was used for cooking, heating, and lighting. Firewood and LPG are the most common sources of cooking, whereas electricity is the primary lighting fuel in all households. No household in the study area used kerosene and animal dung as cooking fuel. Access to grid electricity was uneven in the three regions. However, most of the households fulfilled their lighting energy demand either by grid electricity, micro hydro power plants, or standalone photovoltaic solar systems (Shrestha et al., 2019).

Figure 5 shows the per-capita energy used by the households in cold, temperate, and sub-tropical regions, and the overall average in traditional, mix, and commercial modes. In the cold region, total household energy used in traditional, mix, and commercial modes was 40, 35, and 8 MJ/(capita·day), in temperate region it was 37, 28, and 5 MJ/(capita· day), and in sub-tropical region it was 21, 18, and 5 MJ/(capita· day), respectively. This shows that households in traditional mode in all regions used high, those in mix mode used medium, and those in commercial mode used low amounts of energy.

In traditional mode, most of the energy was provided by firewood, and only a small amount was provided by electricity, which was used for lighting and for charging mobile phones. The high energy use in the traditional mode might be due to the use of traditional cooking fuels in highly inefficient cook stoves. The conversion efficiency of cook stoves varies substantially. For example, the residential burning of firewood has an 18% efficiency and that of LPG has more than 60% efficiency, whereas the efficiency of using electricity is even higher (Li et al., 2019). Another reason for the high energy use in traditional mode might be the rearing of livestock, which requires extra energy for the preparation of animal feed. Li et al. (2019) concluded that considering both commercial and non-commercial sources, rural residents consume 90% more per-capita energy than urban residents, which comes from non-commercial sources. This study also showed that households relying mostly on traditional fuels, which are considered as non-commercial fuels, consume significantly higher energy.

In the mix mode, due to the occasional use of LPG and electricity as cooking fuels, a slightly lower amount of energy consumption was observed as compared to that of the traditional mode. Here, most of the energy was provided by firewood, and only a small amount was provided by electricity and LPG. Comparatively low firewood used in mix mode than in traditional mode might be due to the smaller number of livestock reared.

In the commercial mode, all energy required for cooking, heating, and lighting was provided by commercial fuels such as LPG and electricity. These households, which were connected to the grid electricity, preferred to use rice cookers together with LPG stoves. The households not connected to grid electricity always used LPG as their cooking fuel. Thus, these households used the highest amount of LPG and electricity among the three modes. The significantly low amount of per-capita energy used in commercial mode might be attributed to the use of efficient cooking technology and low frequency of energy use.

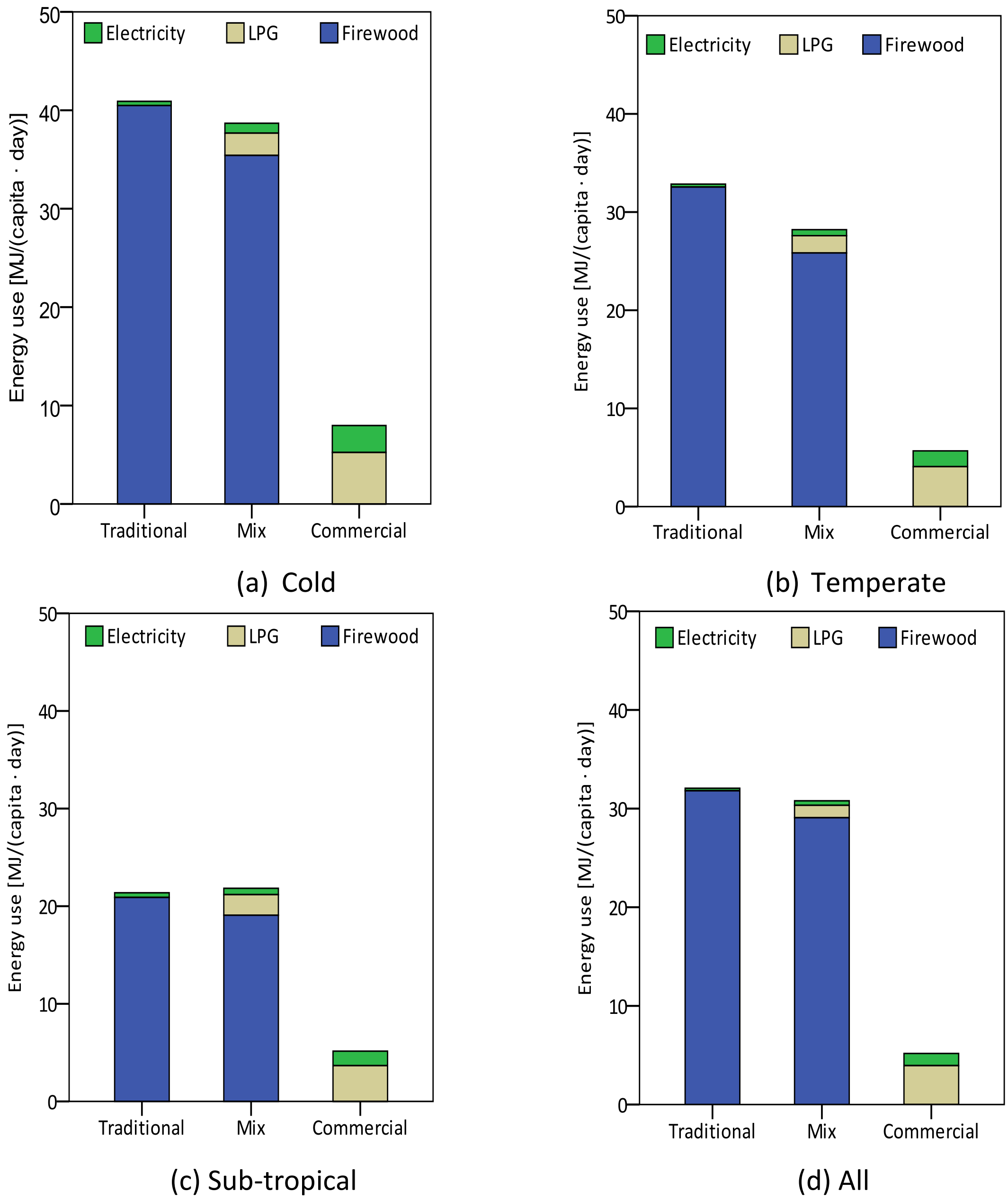


Figure 5. Total household energy used in traditional, mix, and commercial modes: (a) cold, (b) temperate, (c) sub-tropical, and (d) average of all regions.

3.4. Household CO_2 emissions

Household CO_2emissions depend on the type and amount of fuel used. We analysed direct CO_2 emissions using the emission coefficient for each fuel type. Figure 10 shows the household CO_2 emissions in traditional, mix, and commercial modes in the three climatic regions.

In the cold region, the household CO_2 emissions in traditional, mix, and commercial modes were 460, 440, and 50 kg CO_2 e/month, respectively. Evidently, the CO_2 emissions in the traditional and mix modes were similar but significantly higher than the emissions in commercial mode. There are two main reasons for the high CO_2 emissions in traditional and mix modes. First, households in traditional and mix modes rely heavily on traditional cooking fuels with highly inefficient cook stoves. Second, these households practice subsistence agriculture with animal rearing, which requires extra fuel to prepare animal feed and leads to additional CO_2 emissions as compared to households in commercial mode. The slightly lower emissions in mix mode than in traditional mode might be associated with occasional use of commercial cooking fuels and a lower number of animals reared in mix fuel using households. A similar tendency can be observed in temperate and sub-tropical regions. In temperate regions, the household CO_2 emissions in traditional, mix, and commercial modes were 400, 340, and 40 kg CO_2 e/month, whereas in the sub-tropical region, these were 360, 340, and 30 kg CO_2 e/month, respectively.

The household CO_2 emissions are high in cold regions, medium in temperate regions, and low in sub-tropical regions. This is probably due to the variation in the amount of fuel used in the three regions. Previous studies have reported high household energy requirements in cold regions due to the indoor thermal environmental conditions of the households (Pokharel et al. 2020). Therefore, the higher energy requirement in the cold and temperate regions might be the cause of higher CO_2 emissions as compared to the sub-tropical region.

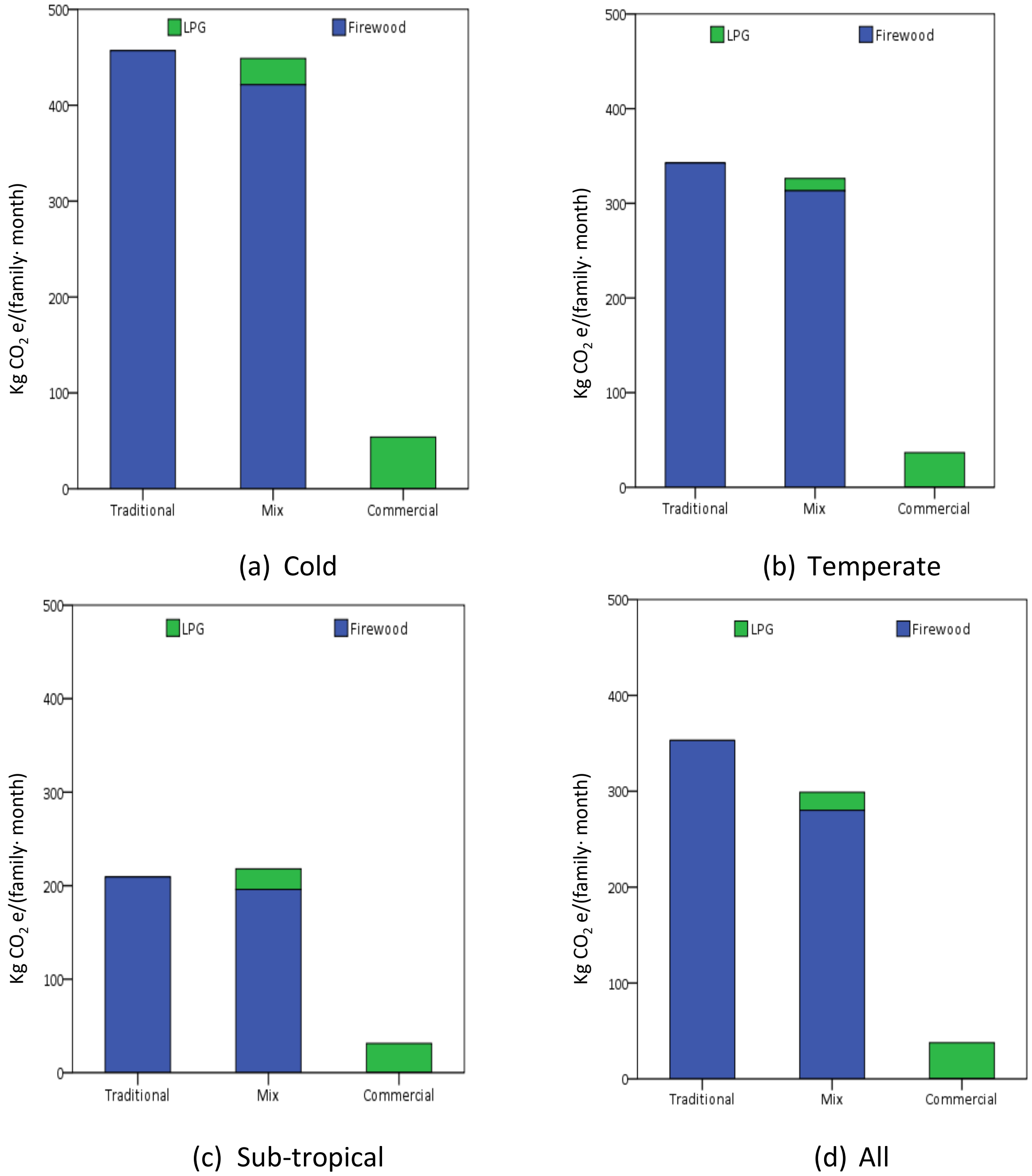


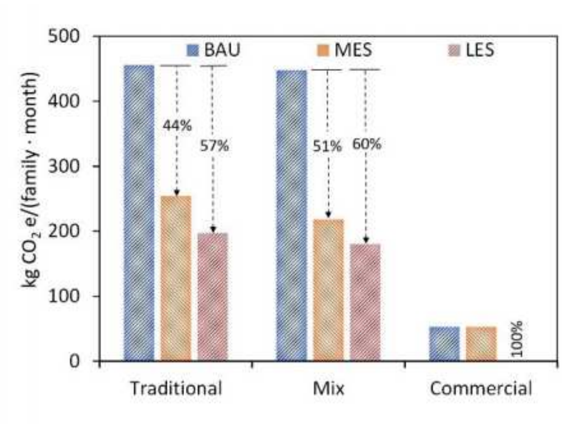
Figure 6. Household CO_2 emissions among traditional, mix, and commercial modes: (a) cold, (b) temperate, (c) sub-tropical, and (d) average of all regions.

3.5. CO_2 emission reduction potential by clean cooking fuel substitution

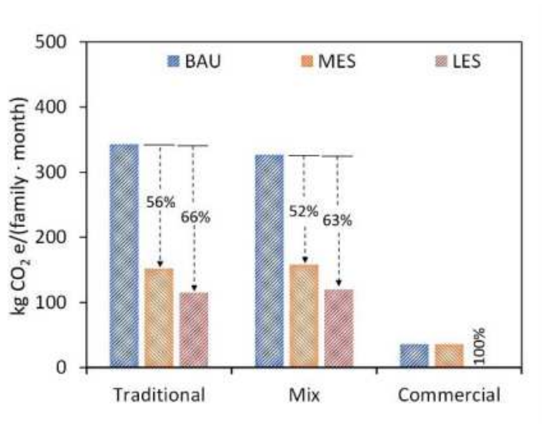
Figure 8 shows the reduction potential of household CO_2 emissions in cold, temperate, and sub-tropical regions among the households in traditional, mix, and commercial cooking modes. The CO_2 emissions will decrease significantly in traditional and mix modes due to the substitution of cooking fuels in the two alternative scenarios, whereas a decrease may not occur in commercial mode under MES, though emissions could be decreased by 100% in LES.

In the cold region, the CO_2 emissions in MES will decrease by 0–44% and by 57–100% in LES. In the temperate region, the CO_2 emissions in MES will decrease by 0–56% and by 66–100% in LES. Similarly, in the sub-tropical region, the CO_2 emissions in MES will decrease by 0–73% and by 91–100% in LES.

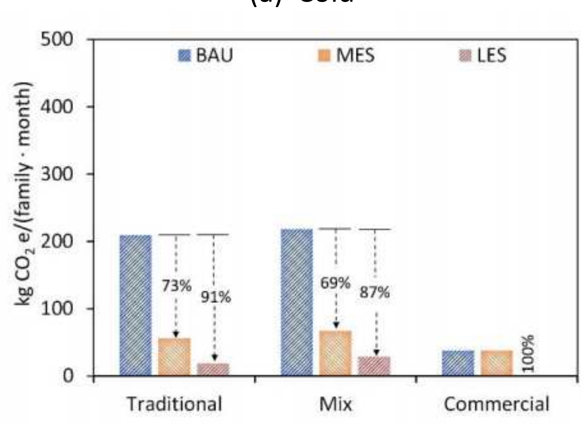
Among the three regions, high CO_2 emission reduction potential was found in the sub-tropical region followed by the temperate region, and a low CO_2 emission reduction potential was found in the cold region. This result seems reasonable as sub-tropical households do not require any heating energy due to the favourable climatic conditions, and cooking fuel substitution significantly reduces direct CO_2 emissions. On the other hand, households in the cold region require extra energy (mainly firewood) to maintain their indoor thermal environment conditions, and this extra energy emits extra CO_2. Thus, the emission reduction potential of substituting cooking fuels in the cold region seems lower than that in the other two regions. Masera and Saatkamp (2000) have also found that the temperature is the crucial factor influencing energy consumption and CO_2 emission.



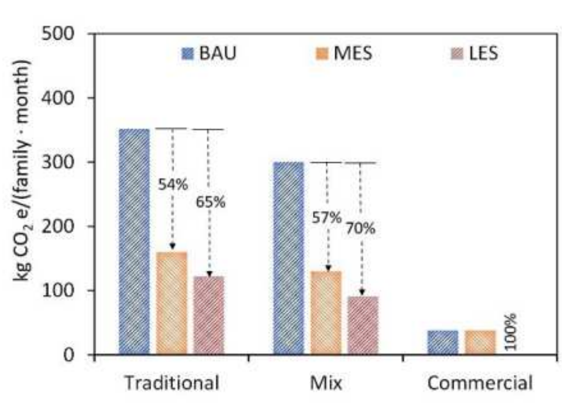
(a) Cold



(b) Temperate



(c) Sub-tropical



(d) All

Figure 7. Emission reduction potential of clean cooking fuels among traditional, mix, and commercial modes: (a)cold, (b) temperate, (c) sub-tropical, and (d) average of all regions.

3.6. Conclusions

Based on this study the following conclusions were made:

The results of this study suggest that 25% households rely heavily on traditional cooking fuels without using any clean cooking fuel, 67% households add clean cooking fuels to their energy systems, and only 8% households rely on commercial fuels to fulfil their daily cooking fuel requirements.

Due to the use of inefficient cooking technology, traditional and mix fuel using households use more household energy than commercial fuel using households and emit more CO_2 than commercial fuel using households. Additionally, traditional and mix fuel using households spent significantly longer time in cooking than commercial fuel using households.

The CO_2 emission reduction potential was high in sub-tropical region, medium in temperate region, and low in cold region. The CO_2 emissions would decrease in MES by 54%, 57%, and 0% and by 65%, 70%, and 100% in LES in traditional, mix, and commercial fuel using households, respectively, as compared to the BAU scenario.

We concluded that regular cooking fuel substitution would be the ideal option, and it is beneficial for residents' health and the environment. Information on the ground reality of the energy use patterns of different fuel using households in different regions is essential to formulate an effective energy policy. This study identified that households with easy access to clean cooking fuels were also found to be dependent on solid biomass fuels to fulfil their daily cooking energy demand, which indicates that a complete transition to clean cooking fuels is not only associated with fuel accessibility but also associated with many other socio-economic and cultural aspects. The study stresses the need for policy makers and stakeholders to synchronise the information of heterogeneous energy use patterns among different regions and among different fuel using households for formulating effective interventions and energy policies.

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The Sustainable Campus - Working towards a Carbon-Neutral University

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Abstract: The main task of a university is to conduct scientific research, accommodate scientific education, and transfer knowledge. Within this environment, new models, approaches, strategies and technologies can be tested and investigated safely. Simultaneously these processes can be monitored, evaluated and adjusted and enhanced when needed. Due to these characteristics, universities and other institutes of higher education can and should be at the forefront of sustainable development and climate action. Universities should pave the way for other organisations, companies, and cities and show how to reach the climate goals.
A Vision, Ambition and Action Plan with 5 specific goals for Delft University of Technology (TU Delft) and was adopted by the university's executive board. In 2030, the university wants all activities on and from the campus to be carbon neutral, circular and climate adaptive, and to contribute to the quality of life for its users and nature and demonstrate sustainable innovations on campus. This paper will show which steps TU Delft has taken to set these ambitions in place and how they want to become a Climate University and example for others. The main elements addressed are Sustainable Operations and Behavioural Change.

Keywords: Climate action, sustainable university, campus as a living lab, sustainable operations, carbon neutral

1. INTRODUCTION

The current global warming is likely caused by human actions between and within counties, and among individuals, which release greenhouse gases. The amount of emissions has increased over time and is still ongoing due to activities such as use of fossil fuels, land use changes, unsustainable lifestyles and the growth of consumption and production (IPCC, 2023). Changes can already be seen in weather patterns – more extremes – which has a negative impact on nature and people. In all sectors, immediate action is needed to reduce the amount of greenhouse gas emissions to stay between the limited warming of 1.5°C-2.0°C. These numbers will be exceeded if we do not take action and only follow the currently implemented policies (figure 1) (IPCC, 2023). The threat will become more complicated the longer we postpone action.

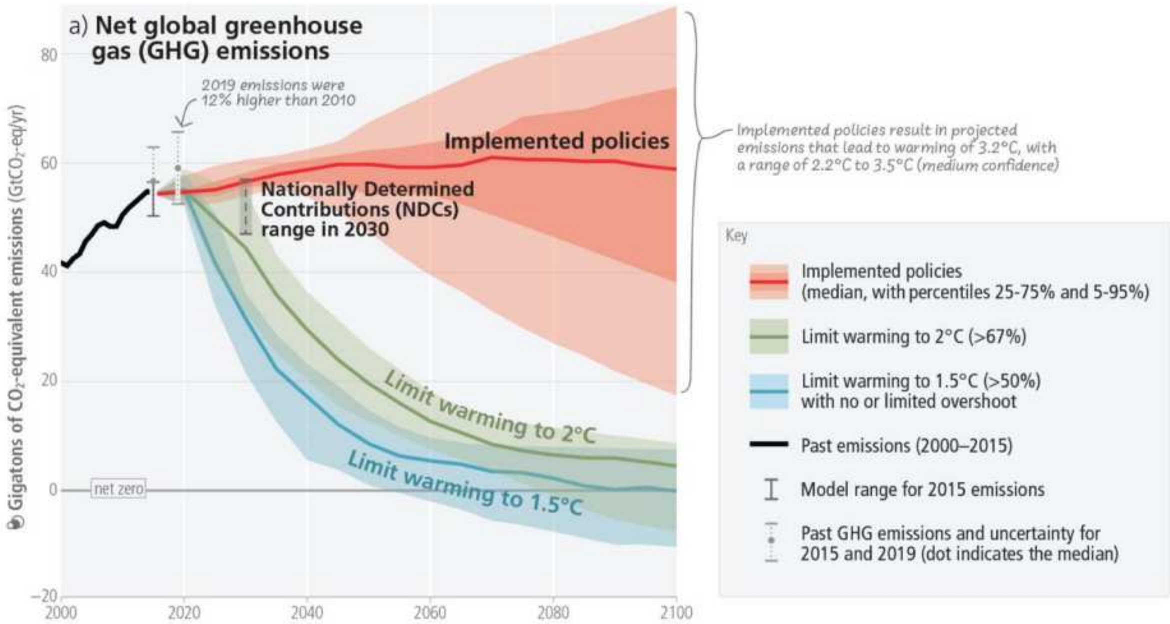


Figure 1. Limiting global warming to 1.5°C and 2°C involves rapid, deep and in most cases immediate greenhouse gas emission reductions (IPCC, 2023)

1.1. Pave the way

The main task of a university is to conduct scientific research, accommodate scientific education, and transfer knowledge. Within this environment, new models, approaches, strategies and technologies can be tested and investigated safely. Simultaneously these processes can be monitored, evaluated and adjusted and enhanced when needed. Due to these characteristics, universities and other institutes of higher education can and should be at the forefront of sustainable development and climate action. Universities should pave the way for other organisations, companies, and cities and show how to reach the climate goals.

1.2. TU Delft

In April 2019, The Delft University of Technology (TU Delft) published its vision on climate change and the need for drastic climate action. The university acknowledges that the living environment is changed by anthropogenic greenhouse gases and states that it will use its innovative character to power the transition. Climate action is both limiting the amount of greenhouse gases emitted – climate change mitigation – and adapting to the new environment, climate change adaptation. Together with climate science and climate governance, these are the four pillars the Climate Action Programme is focussing on.
Beside contributing to society by doing research on climate action the university also wants to become an example in its operations. In 2021, a Sustainability Coordinator and Sustainability Project Manager were appointed who set the ambition to become among other things carbon neutral[1] and climate adaptive. However, becoming sustainable does not only mean becoming carbon neutral and being able to adapt to the new environment. The university also wants to become circular, to reduce the depletion of rare earth metals and improve the biodiversity of nature and people. To reach these goals, new policies have been set in place.

[1] With carbon neutral or CO2 neutral the authors mean climate neutral, referring to all GHG Emissions.

2. TU DELFT'S SUSTAINABILITY APPROACH

2.1. Stepping stones

Vision on Climate Action and Climate Action Programme. In 2019 the university published its vision on climate action and acknowledged that climate change is also caused by human actions. This statement was the beginning of the Climate Action Programme that started in 2021. The university allocated 22 million euros for this programme. The programme focusses on four research themes: Climate Science, Climate Change Mitigation, Climate Change Adaptation and Climate Governance.

CO_2 Roadmap. The university expressed its intentions to become carbon neutral and circular by 2030 in the Strategic Framework 2018-2024 (TU Delft, 2018). To be able to become carbon neutral, an organisation must know its current footprint. To get a grip on this, a carbon analysis of the campus was performed focussing on energy, water, mobility, food, waste, buildings, and green (Blom and Dobbelsteen, 2019). The final result was an overview of the immense challenge we have as a university to become zero carbon, the CO_2 Roadmap for TU Delft.

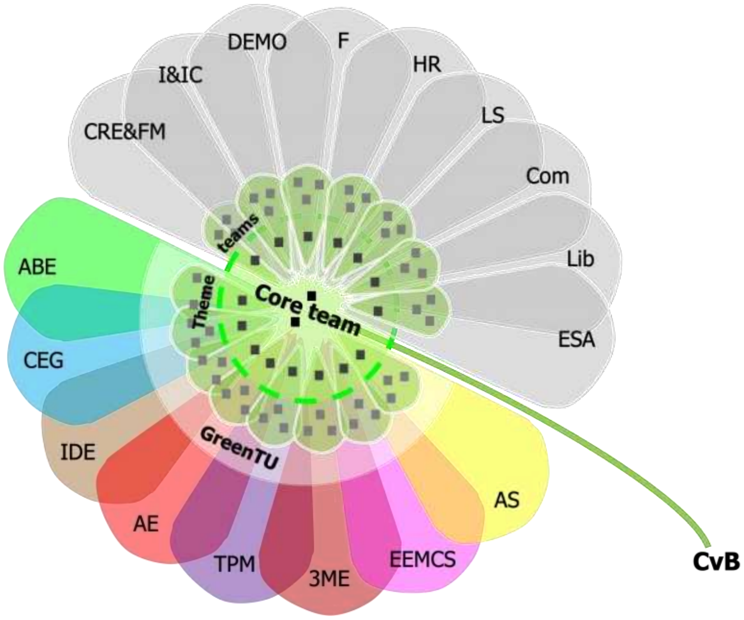
Carbon accounting. The carbon analysis of van den Blom and Dobbelsteen (2019) was a one-time analysis to get a grip on the starting situation of TU Delft. However, to become carbon neutral and to be able to steer on these results continuous carbon accounting is needed. The university has delegated this task to the finance department, which is already used to producing similar annual reports. This department follows the 'CO_2-Prestatieladder', a Dutch translation of the International Greenhouse Protocol (Tax, 2020). The financial department took over the graphical visualisation of Blom & Dobbelsteen, an illustration that shows how much forest area TU Delft needs to sequester greenhouse gas emissions. This study shows that the campus of TU Delft should need a forest area of 1.5 the size of the city of Delft (figure 2).

However, during the carbon accounting of Blom & Dobbelsteen and the financial department, there was still insufficient information about procurement. Afterwards, Herth and Blok (2022) conducted an in-depth study into everything TU Delft purchased in 2019. The impact of procurement turned out to be equal to everything else together, doubling the forest area to a size of 3 times the city of Delft. At the moment, the university is working on a system that calculates the carbon footprint based on financial data. Everything the university consumes, uses, operates, or purchases can be traced back to the financial overview.

Figure 2. The carbon footprint of TU Delft in the year 2019, expressed as forest area needed to sequester all CO_2-equivalent emissions, with the city borders of Delft (grey lines) and TU Delft domain (white patch) visible underneath (Tax, 2020); procurement makes the area twice as large

Sustainability Coordination. At this point in time, the university has the ambition to become carbon neutral by 2030 and has an image of the current footprint. To reach these ambitions a Sustainability Coordinator was appointed from 2019-2020 who focussed on streamlining sustainability initiatives within the business operation and who coordinated GreenTU, a student association focussing on sustainability within the university. In January 2021, a new Sustainability Coordinator was appointed together with the Sustainability Project Manager who both directly work under TU Delft's Executive Board.

Action Plan. In the first year, the new Sustainability Coordinator and Project Manager developed a vision, ambition and action document (Dobbelsteen and Gameren, 2021). This report was subdivided into six elements: 1. Vision & Ambition, 2. Education, 3. Research, Valorisation & Technology Transfer, 4. Community, 5. Operations, and 6. Action. First, a clear overall ambition and vision were formulated, this ambition was then superimposed on the primary processes (education, research and valorisation), community and operations. The final chapter described the way forward. To be able to set up this document the Sustainability Coordination team developed a first governance structure (Figure 3) with a core team representing all students, faculties and university services. In addition, theme teams were developed from people with relevant academic knowledge and operational responsibilities from within the entire organisation. Their input and advice were used as content for the vision, ambition and action document.



The Figure 3. Flower illustrating the collaboration of TU Delft faculties (coloured petals) and supporting divisions (grey petals) in sustainability theme teams and the core team; students are organised under GreenTU (Dobbelsteen and Gameren, 2021).

Sustainability goals. The vision, ambition and action document of van den Dobbelsteen and Gameren (2021) states 5 main goals:

1. Carbon neutral by 2030
2. Climate adaptive by 2030
3. Circular by 2030
4. Contributing to the quality of life, including biodiversity
5. Demonstrating TU Delft's excellence and sustainability on the campus

Financial means. In January 2022, the report was officially approved by the Executive Board. The university showed that becoming sustainable is at the core of its heart. This was also the moment that the report could be shared externally. To realise these ambitions, the Executive Board allocated 100 million euro to the sustainability project in September 2022. The largest share, 95 million, is needed for the buildings and the energy system, a smaller part, 5 million, is allocated for awareness, innovation, food, etc. To stimulate innovations and living labs on campus, 20 million was set aside from the 95 million. A separate Campus Innovation Taskforce was created to fasten the procedural process and asses proposals. If a project is awarded the university will provide co-funding.

Line responsibility. Sustainability should be at the core of all activities to reach such high goals set by the TU Delft. These goals cannot be reached with a Sustainability Coordination team only. The goal of the sustainability team is to make themself redundant and to ensure sustainability is part of the daily tasks and activities of all employees and preferably done from intrinsic motivation. Faculties and University Services were made responsible for specific tasks. Deans and Directors were asked to appoint a Local Sustainability Coordinator (LSC) and to set up their own local sustainability action plan. The LSC works in close collaboration with the local GreenTeams and Faculty students councils. The Sustainability Coordination teams facilitated a first workshop to connect the LSCs, who are working on the same topic, and to create positive energy for this project. After that, workshops were set up on specific themes such as Mobility, Campus & Real Estate, and Education. For example, to realise sustainable travel, multiple departments such as Legal, HR, and the faculties need to work together. Becoming sustainable cannot be realised by just one department, collaboration between departments is needed together with a conscious community. The appointment of an LSC at every faculty and university service stimulates to work pass these borders. In addition they are also the ones who know their community best and can inform and stimulate them to implement sustainability into their daily tasks and behaviour.

2.2. Steering CO_2 with TCO_2

To become carbon neutral a clear picture is needed of the current footprint of the university. These numbers can be seen within the vision, ambition and action document (Dobbelsteen and Gameren, 2021). For some elements, assumptions were made. To get this more accurate, TU Delft asks their suppliers in every new contract to report on the carbon emissions the university has for using or buying their product or service. In addition, steering on reducing carbon emissions is also needed. According to Peter Bakker of the World Business Council for Sustainable Development (WBCSD) (Buitenhof, 2023) a new economic model should be used that also includes other values than just financial profit. The university is implementing Total Cost of Ownership. This model looks at all costs and benefits of a service or product over its whole lifespan. In addition, the university wants to use a carbon price. First as shadow price and later as real price, possibly a carbon tax. After reviewing various scientific sources the university decided to calculate with € 150,- per tonne of CO_2-equivalent (Dobbelsteen and Gameren, 2021). At the moment the university is already considering to increase this value. TU Delft coined the combination of a carbon price and TCO, TCO_2. TCO_2 is used during the selection of suppliers but also as a bonus/malus for products sold on the campus. In addition, when suppliers do not reach their specific goals they need to pay € 150,- per tonne of CO_2-eq they emitted above the agreed baseline. TU Delft invests this money into carbon compensation such as planting trees and increasing biodiversity.

3. SUSTAINABLE OPERATIONS

Beside becoming carbon neutral in 2030 the university also states that it wants to demonstrate its actions regarding sustainability on campus. In other words “Practise what you teach and preach”. As a university, we can test new approaches, models and techniques on our campus and simultaneously learn from them by monitoring and measuring. The effect of these measures on operations can be made visible in such a way that the university can steer on it. This makes Sustainable Operations the focal point of the Sustainability Coordination group.

3.1. Theme teams

The coordination team developed multiple theme teams that focus on a specific theme related to operations. These teams consist of academic staff, supporting staff and students with different horizontal and vertical backgrounds from within the whole organisation. Every team tries to reduce the carbon footprint from that specific theme by for example testing and implementing new models, projects, or techniques.

<u>EcoCampus.</u> The university strives to become a natural, self-sufficient, biodiverse, climate-positive campus where people and nature can co-exist. The university should not be seen as a demarcated area but tries to embed and connect with the green and blue structures around it. By doing this the campus will become more climate adaptive and less affected by extreme weather conditions such as flooding, drought and heat. A positive consequence is that the

university also becomes more sustainable over time. The campus will be a living lab where students and researchers can test how the environment should be designed to withstand the changes due to climate change. Beside providing cooling and a place for insects and small animals, greenery also absorbs carbon and nitrogen. However, only a small percentage of the carbon footprint of TU Delft can be absorbed by greenery on campus. More should be planted elsewhere. Every year the university organises a tree planting day. During the last event thereof, 40 trees were planted. In addition, a biodiversity zero measurement study was done by Royal Haskoning BV. This study will be used to further increase the biodiversity on campus.

Construction & Renovation. The task of this team is twofold: construction of newbuilds and renovation of the current building stock. New buildings – faculties, laboratories and shared educational buildings – are currently developed on the South Campus. Constructing a new building has a higher carbon footprint than renovating an existing building (Blom and Dobbelsteen, 2019). That is why the Sustainability Coordination team prefers to renovate the current building stock instead of demolishing or repelling it. However, if a new building is needed it should comply with the highest sustainability standards: carbon neutral, climate adaptive, circular, and contributing to the quality of life of nature and health.
Most buildings on campus were built around 1970, which means they should be renovated within the coming years. For renovations the New Stepped Strategy from Zero-Energy Design (Dobbelsteen, 2021) is leading: research the local circumstances, reduce the demand by passive and smart & bioclimatic design, reuse residual flows, and produce from renewable energy sources. In addition, Fremouw et al. (2021) studied the potential of solar productivity of TU Delft. This research is currently being used by Campus & Real Estate department for the PV roll-out plan.

Energy System. The energy system should be capable to keep up with future demands, regulations and carbon neutrality. The university is looking into generating energy – heat, cold and electricity – on campus. Electricity should be generated by for example PV systems on the roofs, facades and parking garages. In addition, the university is also looking into the generation of electricity via hydrogen and wind turbines on campus. The basis of the university's heat demand will come from a geothermal heat system. The university started with the construction of the geothermal heat wells in June 2023. The high-temperate (HT) heat will be used for districts in Delft that are hard to renovate. The mid-temperature (MT) heat – the return temperature – and low-temperature (LT) heat will be used in the renovated buildings at the campus.
At the moment a large share of the electricity comes from Dutch wind farms on the North Sea. According to the CO_2 Prestatieladder, the carbon impact related to that is 0 tonne of CO_2-eq (Tax, 2020). The current carbon footprint related to energy comes from the purchase of gas. To become carbon neutral and independent the university is looking into renewable energy.

Mobility. Within the mobility team, the focus lies on 3 different types of travel: commuter travel of staff and students, business travel (national and international), and international student travel. Within the CO_2 Prestatieladder these emissions fall within scope 3, upstream and downstream. To become fully zero-carbon for mobility the university should avoid travel at all costs. Although this is impossible the travel frequency can be reduced and a more sustainable travel mode should become the standard.
Coming on foot or by (e-)bike should become the standard travel option for people that live near the campus. The standard option for people who live further than 25 km away should be public transport or a combination of foot or bike and public transport. The university is

looking into the possibility to stimulate those facilities within the employee arrangements with HR. In 2030, the campus will be a fossil-free area. In this case, if students, staff and suppliers want to use a car it should run on electricity or other forms of energy such as hydrogen.
International travel by staff and students, especially flying, has the greatest impact on carbon emissions. Currently, 3 faculties have implemented a new travel policy as a pilot. Focussing on travel time or travel distance. Within a certain period or distance the train should be the standard instead of the airplane. The university is looking into implementing a carbon tax if someone still chose to take the airplane. The carbon tax will be used for carbon-saving projects. A special train map is already made for students to help them compare different forms of travel within Europe (figure 4).

The Figure 4. Student travel map comparing time and emitted carbon emissions per location (TU Delft, 2021)

<u>Food and Beverage.</u> Food and beverage make up a large part of TU Delft's carbon footprint. Multiple studies show that animal-based food has a greater carbon impact than plant-based food, a recent study that confirms this comes from ten Caat et al. (2022). The restaurant in the Faculty of Architecture and the Built Environment was the first one to serve vegetarian and vegan products in its restaurant and banqueting map. This choice was made after participating several times in the 'Week without Meat' and in close consultation with students, staff and caterer. A study done by an external party at the request of TU Delft shows that the carbon footprint of the Faculty of Architecture is now half compared to a standard menu (Greendish, 2022). Recently, an extra luxury restaurant and a standard restaurant were opened which serve only vegetarian and vegan food.
In the year 2022/2023 the university worked on a tender for catering implementing multiple requirements regarding sustainability. One requirement is that the new catering should report monthly on the products they buy. Together the university and the caterer will

calculate the related carbon emissions. The contract stipulates that these emissions must decrease annually.

Procurement & waste management. 50% of the total footprint of TU Delft is caused by procurement which falls within scope 3. However, every organisation needs products and services to fulfil their work activities. The university proposed a new policy following the R-Ladder (RVO, 2020). The first step of the R-ladder is to avoid purchasing new products (figure 5). The question that should be asked is, do we need this? And if so, do we need this new or is it already somewhere on the campus? To make this work, an organisation wide inventory method is needed. As with the tender regarding food additional requirements regarding carbon accounting, circularity, and partnership are included in the new policy. Currently, the university is working on a new tender for waste management. Previous requirements are implemented into the document. To become carbon-neutral the entire supply chain should join our mission.

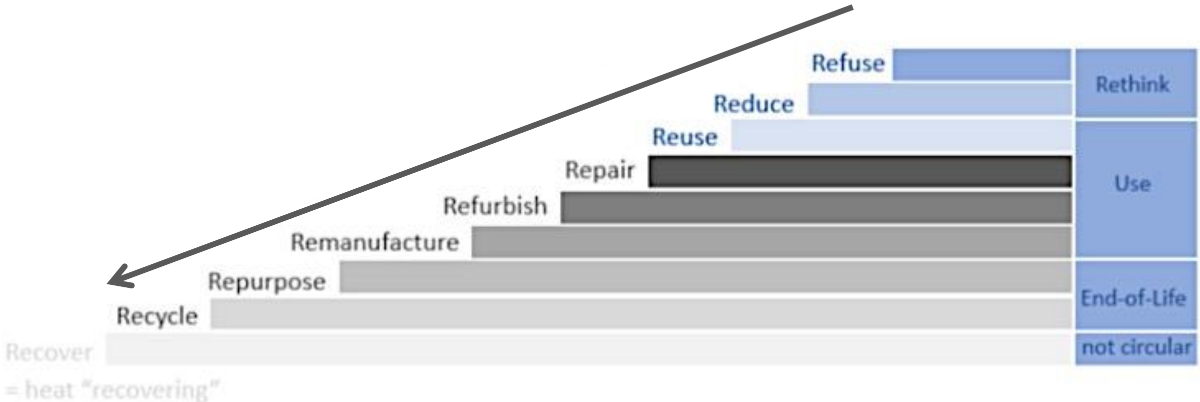


Figure 5. Graphic illustration of research and actions on the theme of mobility (RVO, 2020)

IT, AI & Data management. The positive side of IT, AI & Data Management is that it can make products and services more energy efficient and smarter. However, the process itself also uses a lot of energy. This team looks into the optimisation of both. The university wants to measure the current energy usage and when possible subdivided it per type of consumption, e.g. building energy versus user energy. It can be seen that for example, datacentres use more energy than educational buildings. To reduce energy usage, this team looks into computation processing, server management, and waste heat usage. Data management, looking into the amount and type of data that is stored is also needed beside monitoring and steering on energy usage. Other measures related to this theme are the collection of e-waste, providing e-learning facilities and deep learning.

4. BEHAVIOURAL CHANGE

To become a sustainable university implementing sustainability into the operations and the daily task of employees and students is not enough. The right governance and technical systems can be put in place but as the community does not act sustainable TU Delft will not reach its goals. A behaviour change is needed. TU Delft tries to establish this by informing the community about its goals and engaging them. De Vries (2019) states that the accumulation of hassle people encounter can lead to stress. That is why people often delay or do not show sustainable behaviour to prevent this from happening. The university should take this "hassle factor" into account and help its community to overcome this by giving clear, concise and credible information.

4.1. Communication

A collaboration between the different communication departments is set up to create a unified and recognisable flow of information regarding sustainability. Multiple platforms are used such as the sustainability website, TU Delft news(letter), and social media platforms such as LinkedIn, Instagram and Twitter, to teach and inform the community. It is important to engage the community, introduce them to the topic of sustainability, let them learn and discover at their own pace, and gradually make them aware of their behaviour.

4.2. Climate Conversations

To help the LSCs with engaging their community, the Sustainability Coordination team offered them to follow the Climate Conversations course. Within this course, the LSCs learn how to open up meaningful conversations about climate change. In the future, the LSCs will facilitate these kinds of conversations to create a safe place for the community to talk and learn about climate change and related feelings. Often, people engaged with climate change, feel that they are in a quandary. "I want to act sustainable but then I cannot fly anymore, I cannot, I cannot barbeque anymore, I cannot … anymore." These conversations are a place to talk about those feelings and struggles with others. It could be a chance to change the thought of "having to" to "wanting to".

5. NEXT STEPS

Becoming a Sustainable University or a Sustainable Organisation requires hard work. A lot of organisations are saying that they want to become sustainable but do not put their money where their mouth is, and then the ambition becomes greenwashing. This paper discusses the steps TU Delft is taking on Operations and Behavioural Change to become more sustainable and to set an example so that others can learn from it.

5.1. Lessons learnt

- Ambition and support from the highest level, the executive board
- People willing (change managers) to get the initial work done
- Measuring is knowing: a zero assessment as the starting-point
- A roadmap – preferably via backcasting – to reach the desired goal
- It is a technical and personal transition. Inform and engage the community
- Start small and share those small wins. This will reduce the resistance and create a ripple effect.
- Communicate in various ways to reach the whole community
- Be prepared for resistance and see this as something positive

5.2. The way forward

As stated in the beginning immediate climate action is needed to limit the warming of 1.5^{o}C-2.0^{o}C (IPCC, 2023). As starting-point, TU Delft focusses on reducing carbon emissions because this can be measured in numbers. The university also focusses on becoming circular, climate adaptive, and biodiverse but this is more difficult to express in numbers. A first-time schedule is made towards 2030 to showcase to the managers that action is needed now on all themes (figure 6).

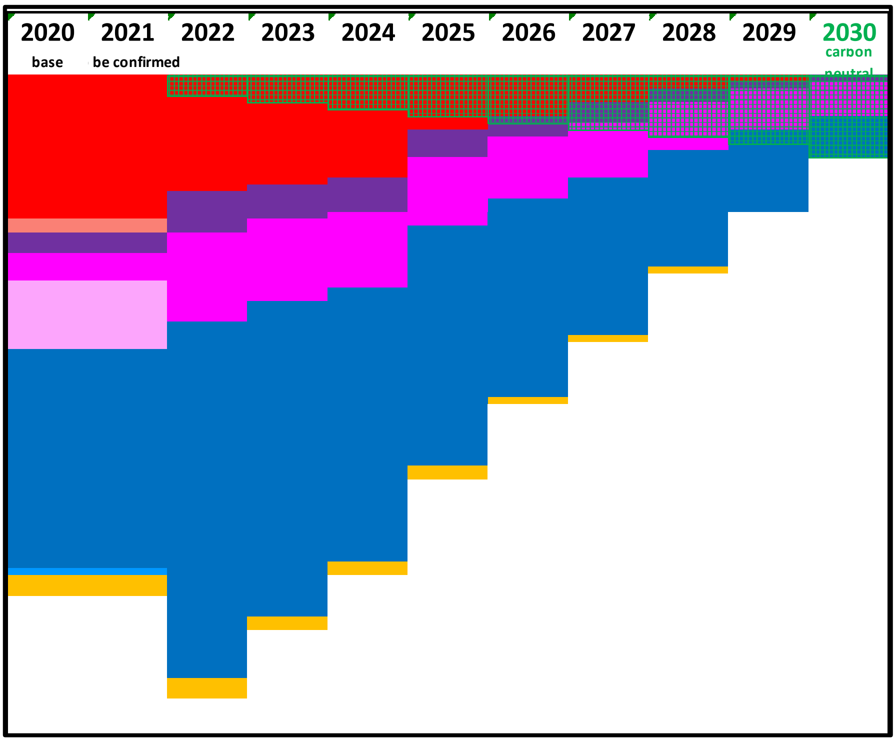


Figure 6. Carbon emission reduction towards the year 2030 (Dobbelsteen and Gameren, 2021)

It is impossible to be fully carbon neutral because there will always be unavoidable emissions. For example, even vegan food has a small footprint and there will always be a need to buy some new products. The university is going to compensate for those remaining emissions by means of reforestation in areas that need it. Currently, the university is having the final conversations with some candidate organisations that offer these services.

6. Conclusion and evaluation

It can be seen that TU Delft is striving to become a sustainable campus and wants to pave the way for other organisations, companies, and cities and show how to reach the climate goals. In 2019, the university acknowledged that the environment is changing by anthropogenic greenhouse gases and stated that it will use its innovative character to power the transition. This acknowledgement can be seen as the kick-off of the transition. After this acknowledgement, the university expressed its intentions in the Strategic Framework 2018-2024 and delegated the task of continuous carbon accounting to the finance department. To be able to reach the ambitions the executive board appointed a Sustainability Coordinator and Sustainability Project Manager who developed the 'Vision, Ambition and Action Plan' and created a team around them to execute the plans. The transition gained momentum when the Executive Board officially approved the report and allocated 100 million euros to realise these ambitions. By doing this, the Executive Board showed that becoming sustainable is at the core of its heart, which was an important signal to the community. We learned that the sustainability goals can only be reached when sustainability is part of the daily tasks and activities of all employees and students. The core team established this by making Faculties and University Services responsible for specific tasks and asked the Deans and Directors – with backup from the Executive Board – to appoint a Local Sustainability Coordinator (LSC) and to set up their own local sustainability action plan. The LSCs work in close collaboration with each other, the local GreenTeams, Faculty Student Councils and the Sustainability Coordination team. It is important to realise that sustainability is something that passes all borders. Collaboration between every Faculty, University Service, supplier and municipality is needed.

The start of the transition can be subdivided into 7 important steps:

1. Acknowledging climate change by the highest management (the Executive Board)
2. Researching the current footprint (creating a baseline)
3. Continuing carbon accounting
4. Appointing a Sustainability Coordination team
5. Creating a vision, ambition and action plan
6. Setting clear goals
7. Allocating financial means

After these 7 steps, a first base is created to become a sustainable organisation. The sustainable transition can then be divided into two major tasks. 1. Become sustainable in operations and 2. Creating a sustainable community. As a technical university, we noticed that the second task is as difficult or maybe harder to establish than the first task. The right governance and technical systems can be put in place but as the community does not act sustainably, TU Delft will not reach its goals. The university tries to establish this by informing the community about its goals and engaging them. A collaboration between the multiple communication departments is set up to create a unified and recognisable flow of information regarding sustainability. In addition, the LSCs followed a Climate Conversation course, which helps them to open up meaningful conversations about climate change.

It can be seen that becoming sustainable is not something that can be achieved within a short time. It is a transition which needs the support and dedication of not only the top management but the whole community. In the past years, TU Delft focussed on the first task. It can be seen that sustainability is something taken on in every faculty and university regarding operations. At least at the management level. The next important step is to get the whole community involved.

7. Acknowledgement

The authors would like to thank TU Delft's Executive Board for recognising this challenge and their immediate action to appoint a Sustainability Coordinator and Project Manager and financially support the plans made by them. Although not everyone always agrees on the steps that need to be taken we are thankful for our community that is willing to listen and have an open dialogue about this important topic.

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Managing net-zero strategies for a complex university estate

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Abstract: Building Estates departments across the country struggle to find an efficient and cost-effective way to meet net-zero targets of reduced operational and embodied carbon emissions. Often in dispute are the methods and the speed of delivery of any solution that reduces energy demand and carbon emissions associated with the building, particularly those requiring upgrading and retrofit. On one hand, buildings are predominantly heated with natural gas technology (gas boilers) with the potential to be replaced with electrical heating systems (heat pumps) in a fast and efficient manner. On the other, there are specific building envelope performance retrofit interventions that reduce energy demand but need to be archetype-specific and may take longer and impact occupants. Although the speed of carbon reduction and the initial upfront costs are deciding points to consider, other options need to be analysed, such as the whole-life carbon of solutions, maintenance, replacement costs and the thermal comfort of users over the occupation periods. This paper discusses the two methods outlining the social and economic impacts and an approach that considers a whole-life carbon balance that is relevant to the retrofit of non-domestic buildings in a university campus setting. The arguments between the two methods are well known, however, there are specific approaches which may lead to adopting more hybrid methods to achieve a "sweet spot" between the two at various stages of the process. Both have the potential to propose innovative advances through technology, new materials and the best use of energy sources, however, choosing only one approach is not the best way forward.

I. Introduction

Buildings account for a fifth of global greenhouse gas (GHG) emissions and in the UK Buildings and the construction industry were responsible for 23% of the total in 2019 (Committee on Climate Change, 2020). 70% of this UK total corresponds to GHG emissions from residential buildings and a further 30% for commercial, and public buildings (BEIS, 2022). These emissions are partly from the operation of buildings split between 17% from direct energy use (space and water heating, pumps & fans, lighting) mostly met (74%) by fossil fuels such as natural gas. The efficiency of the building envelope and the selection of the materials used as well as the heating and ventilation technology define the performance of the building. The direct energy demand and its associated carbon emissions accounted for 87 $MtCO_2$ in 2019 with domestic properties emitting 67 $MtCO_2$ and non-domestic buildings a further 20 $MtCO_2$. However, 31 $MtCO_2$ emissions are associated to indirect sources equivalent to 59% of UK's electricity consumption, (Government Commercial Function, 2022), (Brown et al., 2023) which are often not counted in many net-zero calculations.

The Further and Higher Education (FHE) sector has made significant pledges to become more sustainable by meeting net-zero carbon emission targets and reducing both direct and indirect emissions. Out of a total of 133 UK universities participating in emission reports to the Higher Education Statistics Agency (HESA), approximately 1.4 million MtCO2e were associated with the direct and indirect emissions of the 2021-2022 academic year, contributing 0.5% of the UK total emission of that year (Higher Education Statistics Agency, 2023). This resulted in approximately 7.15 TWh including both direct and indirect energy demand sources, the majority met by natural gas for heating buildings. Such buildings managed by the FHE sector represent a large amount of existing buildings footprint, approximately 15 thousand buildings representing 29.5 million meters squared of gross internal floor area requiring space heating over long heating periods in the UK.

The University of Edinburgh was founded in 1583 and currently occupies more than 550 academic, administrative and residential buildings throughout the city of Edinburgh across five campuses. Out of that total 171 of these buildings have a category A, B and C listed status which poses restrictions to their changes and interventions. Statistics from HESA contemplate data from 460 buildings occupying 930 thousand square meters of gross internal floor area. During the 2021/ 2022 academic year, it consumed 2.82 MWh of direct and indirect energy, or a per square meter of a building of gross internal floor area of 300 kWh/m2 adding a carbon intensity of 70 kgCO2e/ m2 considering the varied building archetypes, ages, uses and locations within the city. This places the University of Edinburgh in the top 20 UK universities for energy consumption and the top 10 for carbon emissions (Higher Education Statistics Agency, 2023). However, the University of Edinburgh occupies the 7th position in the highest number of students (35,375) which impacts directly on the use and needs of their buildings and is significantly higher than many other universities across the UK (HESA, 2023).

As the industry moves towards net-zero performance it is critical to evaluate buildings with a more holistic approach where low-carbon considerations are used at design and construction phases. One method is taking a whole-life carbon approach including operation, embodied, maintenance and eventually disposal and end of life (Stephan and Stephan, 2016). All such stages provide a wider look at the building, and in most cases easier to optimise and improve during the design stages but harder once occupied and in operation. This approach in the UK has been developed by the Royal Institute of Chartered Surveyors (RICS) (Royal Institution of Chartered Engineers., 2017) and outlined as a British Standard BS EN 15978:2011 considering evaluations of buildings with a whole life cycle assessment (British Standard, 2012).

2. Background

Currently, there is real pressure on building Estate managers of complex FHE buildings to meet net-zero levels of performance within institution-wide targets and the wider Scottish and UK targets by 2045 & 2050 respectively. Complex buildings in FHE institutions have a range of issues split into two scenarios 1] The management of new buildings, designed and built using conventional natural gas heating technology and standard level building envelope performance, compliant at the time, but now redundant to meet net-zero carbon performance; and 2] the existing heritage and older buildings within FHE Estates that can range in age and archetype widely with buildings from the 16th C to the early 2000's using a variety of methods of construction, all with different levels of performance. A real concern for many, which is the case of buildings as part of the University of Edinburgh, is that there are many buildings with a variety of methods of construction which have undergone over the years multiple retrofits, adaptations and upgrades, some poorly catalogued and managed using reactive maintenance approaches rather than preventative maintenance methods.

Both problematic building scenarios present high-energy demands and consequently, high levels of operational carbon emissions which are complicated to mitigate given their occupancy rates with students and staff accessing such premises during normal and out-of-hours. Often opportunities to conduct upgrades and retrofits have a very narrow downtime period in the summer holiday periods. Those with a full retrofit programme of work require a full decant over long periods, where relocation of staff and teaching facilities is challenging. Therefore upgrading the building envelope to lower the energy demand of such buildings requires careful planning and elevated costs not just for the capital expenditure but for other more complex needs such as relocation, space sharing and storage of equipment. There are efforts to drive forward an archetype approach for Scottish buildings through the Zero Emission Social Housing Taskforce (ZEST) which identifies common building characteristics within existing domestic and non-domestic buildings in Scotland to then identify measures of retrofit-specific interventions (Smith, 2021).

Applying new heating systems has been the preferred choice to lower carbon emissions and reach some of the imposed net-zero targets. This is the case of the University of Edinburgh which has implemented combined heating and power (CHP) district heating networks servicing buildings in their campuses and student accommodation. However, despite being a currently cheaper solution that controls energy use and generates some income through financial agreements with suppliers, these consume large amounts of fossil fuels from natural gas. Despite the efforts to install solar PV panels and other more efficient technology, the drive to highly efficient electrical heating systems that operate with less energy thus reducing carbon emissions is currently the preferred method.

Both the building envelope improvement and the efficient low-carbon heating solutions have the potential to lower carbon emissions and meet net-zero levels, however, at what price and at what speed are these to be delivered? Equally important, are the repercussions to the environment, thermal occupant comfort, embodied carbon of solutions and overall risk of security of supply, all of which can balance or disbalance the preferred choice for many FHE building Estate managers.

3. Why is it so complex?

Although the “Fabric-First” solution is often the preferred choice, for the control and decrease of energy demand and lowering carbon emissions this can often take longer than anticipated. This slower rate is due to difficulty in applying retrofit fabric solutions as these are not well established or known due to the diverse and complex set of building types with distinctions in method of construction, age, historic conservation solutions, and diverse use of buildings. Required is often a select set of surveys of the condition of the buildings involving measurements and actual performance tests that can be expensive and difficult to accurately capture the extent of the building problems.

Applying efficient technology to lower carbon emissions in heating, ventilation and other needs requires the change to a decarbonised fuel, which at present in Scotland and the UK means switching to electrically powered buildings. Adopting renewable energy is deemed as the preferred solution, however, often not enough to fulfil the buildings needs due to difficulties in location (orientation), unreliable sources (sun/ wind) and inadequate maintenance which can lower efficiencies. The alternative can be hybrid efficient systems such as heat pumps that use electricity and can convert air or water into heated water to provide space and water heating in buildings at a ~200 or ~300% efficiency compared with conventional natural gas boilers at a ~90% efficiency. This high efficiency of heat supply lowers energy use and thus means less carbon emissions using an already low carbon intensity fuel. Applying renewable sources as an abatement of carbon emissions can further lower building total emissions thus being considered the fastest solution by many to reach net-zero carbon targets. Evidence of this can be seen in the work by Reguis et al., (2023).

4. The different solutions

As each business in the UK focuses on reaching net-zero performance based on institutional and country-wide targets, there is pressure to act as quickly as possible to meet sustainability promises, road maps set and a race to be a net-zero leader in the sector. This can be the case for many FHE Estates across the country with complex users, building types, and locations (city or rural settings). Therefore, the pace at which we reach net-zero is key to many Estate teams across the FHE sector. There are two sides to the argument: 1] does the building undergo a series of retrofit solutions such as window replacements, insulation and draftproofing leading to overall lowering energy demand or, 2] does the building replace its heating method by using a mix of renewable energy technology and/ or efficient forms of decarbonised electrical heating methods (heat pumps).

Many professionals in the industry, including FHE Estate managers claim that going for the building retrofit approach is not going to be as impactful and fast enough to meet the pledges and targets set. The argument is that even if the building is retrofitted it is not guaranteed that the building will lower the promised energy and carbon emissions unless very strict and practical interventions are used, often difficult in older heritage buildings where conservation and listed restrictions apply. The cost to retrofit all the buildings in each Estate will also be a barrier to many as government grants are not as available as those in the domestic sector with public country-wide and local government financial help.

Fully changing the heating technology can provide speedy benefits that can cut energy and carbon emissions whilst using decarbonised electricity and operating efficiently. Larger Estates install small district heating solutions, which may have been in place before with other technology such as that of the University of Edinburgh campuses using combined heat and power (CHP) plants that operate with natural gas providing heat to buildings and generating electricity. Replacing these with more efficient heat pumps or having district heating systems can lower emissions at a fast pace with relatively low capital investment.

The retrofit approach, although is more expensive and technically difficult, has its benefits which need to be discussed. Retrofit interventions after conducting building surveying and strict measures of workmanship need to be met by good occupant awareness (energy frugality and air quality consciousness) to lower energy demand and carbon intensity. This lower demand is essential not only to lower operational energy and carbon emissions of the building but also if done consciously using local and natural materials can lower the embodied carbon of the building which is an important component of the net-zero criteria. Equally important is the thermal comfort of building users which is improved drastically by increasing the mean radiant temperatures of the building envelope by making walls, windows and other surfaces warm and comfortable to sit and be around. Additionally, indoor ambient temperatures are increased, balancing internal humidity levels and contributing to improved indoor air quality vis-à-vis improving health in occupants. The building retrofit option, coupled with good ventilation strategies is a user-centred solution, making indoor space comfortable and desirable for students, staff and visitors.

Changing the heating strategy is a quick solution to lower energy demand and carbon emissions. However, it will only do this if installed and sized properly, and often if the demand is high (high heat loss), the system will need to operate much more using more energy to reach the desired indoor temperatures. Most heat pumps operate as a low-temperature heating system which if sized appropriately will operate with smaller heating emitters (radiators), making existing radiators redundant and requiring replacement [10]. If energy demand is already low and temperatures are reached rapidly indoors, systems operate similarly to quoted efficiencies, which is the case in new and properly refurbished existing buildings. Another aspect of heat pumps, despite nowadays being cheaper to purchase and install, many of the components used to manufacture them are of high embodied carbon which negatively outweighs the net-zero carbon evaluation of the buildings. This is also coupled with the need to often replace refrigerants and some of their main components, which can be argued is the case for most technology, particularly if installed individually in buildings with a lack of maintenance. However, installing heat pumps or similar electric heating technology is required, especially as we transition to a decarbonised electrical grid and we can't fully lower the energy demand of specific heritage buildings deemed too complicated and costly to refurbish. Having low-carbon heating strategies is required, however, lowering demand goes hand-in-hand with the system installed. With a lower demand, there is also a higher chance that our energy providers can meet the required capacity for buildings and other energy hungry industries (transport).

Despite the geopolitical insecurities of energy across Europe, generating and taking advantage of green energy sources or using surplus heating sources is essential which paves the way to innovation and alternatives to heat pumps if the building and its location require it.

5. The correct balancing act

Choosing the correct solution for the existing building stock in any FHE Estate requires a balance of methods and decisions.

As a first principle, reducing the energy demand should be a priority. Building heating requirements represent a large amount of energy and carbon emissions, and those occupied in FHE campuses have a higher impact given its use and operation. Existing buildings should undergo a basic benchmarking exercise using regional best and typical practice energy normalised values. This will allow for an Estate evaluation and a building-by-building comparison, highlighting the poorly performing based on their above or below-average performance, considering also the carbon intensity of each heating system and the fuel used. A good example of this is the work by Zero Waste Scotland and the Scottish Energy Officers Network (SEON) producing the Scottish Public Sector Energy Benchmarking Tool (SPSEBT) which obtained actual energy demand from public buildings and generated a Scottish benchmark (Stinson, 2022). Subsequently, through this analysis, identify the best interventions available as suitable retrofits that lower heat loss and improve energy efficiency. With a diverse set of building types comes a diverse set of solutions, however, in most Estates there are common trends and typologies. Estate managers need to get to know their stock and characterise it into archetypes to combine the set solutions to retrofit. Many overlaps will emerge, such as the replacement or upgrade of windows or the use of solid stone insulation methods. This will generate a pattern book and guidance to address these heat loss issues that can also cover remedial work and have a comprehensive account of the method of construction used. Following this, clear guidance will generate archetypal solutions which can be recognised as tried-and-tested interventions considering the original materials and methods of construction linked to historical and conservation practices (if relevant). Variations will emerge within similar archetypes, however, the core basis of the solution will remain, and it is only with bespoke cases that a new solution will arise. Applying this approach will assure Estate managers that the solutions are considerate of the existing building type and can drive down energy and carbon once applying a whole building approach.

With the same archetype approach, buildings can be assessed on their existing heating methods and relevance to using alternative low-carbon solutions and technology. Based on the identified archetype a series of technologies can be assessed to provide the best reduction of carbon emissions through better efficiencies but considering the location, existing ancillary provisions and nearby sources and surplus of energy. For example, sharing heating with nearby community heating systems or using heat from nearby swimming pools and data centres. Nearby buildings, such as university campuses, and small district heating methods should be adopted using low-carbon heating methods with efficient heat pumps or other forms of innovative technology. Identifying the best technology and fuel source is met by using digital tools such as the Scottish Government Heat Map also identifying typical energy demand (The Scottish Government, 2022), considering the energy supplier's security of energy supply.

However, reaching an acceptable energy demand and low-carbon technology on its own is not an acceptable solution. Buildings should be assessed based on their net-zero potential (NZP) where an individual assessment is made of the percentage to which the building can achieve the net-zero target of 0%. Some buildings will meet this level more easily and others will only be able to do so by a fraction less. Once this assessment is made, a sweet spot is identified assessing how much the building envelope can be improved through retrofits and how much a low-carbon efficient solution can be employed, considering the complexities of conducting the work, the cost, the disruption and the time needed. It is only once you assess buildings in this way that a real building potential and net-zero assessment is made. This balanced approach should be done technically but also considering the building's whole life carbon trajectory in which there are considerations not just at the delivery stages but at the end of life considering maintenance over the years, replacements, re-use and recycling and disposal (Lockie and Berebecki, 2012). Buildings with heritage and historical significance in a city centre location will have restrictions in deep retrofit interventions, regardless of their chosen archetype. These buildings will reach their potential by applying limited retrofits and to some extent the application of low-carbon heat, but through collaboration and the decarbonised grid (electricity and then heat), their potential may be met differently. Other more common existing buildings with minimal restrictions may achieve this sweet spot more easily and achieve the net-zero potential by reducing demand and the leftover energy needs met by efficient low-carbon heating methods, fuels and technology.

6. Conclusions

This paper has addressed the complexities experienced by many Estate managers, with a specific focus on those managing FHE Estates across the UK. The discussion refers to the case of the campuses managed by the Estate Department at the University of Edinburgh highlighting the enormous task ahead based on building type solutions that are cost-effective at the start and throughout its lifespan. Applying a no-regrets approach which assures that the adopted solution can last and be cost effective would most likely adopt a balanced approach to find that sweet spot which considers the limitations of the building.

Both solutions discussed have their merits and challenges, however, neither can be done in isolation and the implementation of a net-zero potential (NZP) analysis is required to assess buildings based on the application of a retrofit archetype approach and the use of low-carbon technology. The decisions made now for any FHE Estate will impact the trajectory towards achieving net-zero targets, therefore an informed and balanced approach is needed.

Although the speed of the process has been discussed as being a determining factor, it is a no-regrets approach that is needed where reduced demand is a priority, followed by the best possible low-carbon heating technology. Achieving this will involve the archetype approach to cluster buildings by their method of construction and determining features which can adopt a common pattern book of interventions focusing on envelope energy efficient solutions and the appropriate low-carbon technology for heating, cooling, and ventilation.

Finally, to achieve this it is essential to follow these 5 steps: 1] assess your building stock using benchmarks and the net-zero potential, 2] cluster buildings by archetype and heating type, 3] decide on a common archetype approach which is affordable and can reduce energy demand and carbon emissions, 4] use district heating and/or renewable energy and take advantage of surplus heat where possible, and 5] understand your occupants as they will be in these buildings through this net-zero journey.

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MEASURING THE CARBON FOOTPRINT AT UNIVERSIDAD DE NAVARRA (SPAIN)

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Abstract: The purpose of this study is to gather valuable information that will aid in advancing the sustainability strategy of the campus. By doing so, we aim to establish a sustainable campus that is committed to caring for both people and the environment. The study focuses on the carbon footprint, which measures the greenhouse gases emitted by an entity, including not only CO2 but also other gases like methane (CH4), nitrous oxide (N_2O), and ozone (O3). To simplify this complex concept, an indicator called Ton CO2 equivalent (Ton CO2 eq.) has been developed and will be used throughout this document.

The purpose of this text is twofold: firstly, to explain the methodology used to calculate the carbon footprint of Universidad de Navarra (Spain) during the 2021-22 academic year, and secondly, to present the key findings of this measurement.

This project was initiated in alignment with the University's 2025 Strategy, which aims to prioritize the sustainability of all University Campuses located in Pamplona, San Sebastián, and Madrid. The project comprises 17 different initiatives under 7 areas of action that will be implemented by 2025.

One important measurement for the University is its carbon footprint, which serves as an indicator of the environmental impact of its activities. This essential data enables decision-making, prioritization of current projects, and assessment and planning for future projects.

The University has emitted a total of 10,812 Tons of CO2 eq. The emissions are mainly caused by gas boilers, university-owned vehicles, air conditioning systems, electricity consumption, seasonal student movements (domestic and international), and employee trips and stays for work-related purposes.

Keywords: Measuring; Methodology; Carbon footprint; sustainability; indicator;

1. Introduction

The "2025 Strategy: University and Sustainability" of Universidad de Navarra places a focus on caring for both people and the environment. The five years plans scope is modify and redefined depending on the actual worries. The 2025 strategy outlines twelve strategic projects based on three key elements of the university's mission: transformative education, research with focus and impact, and interdisciplinary university.

As part of this process, the university has defined five guiding principles and an environmental materiality matrix that prioritizes seven areas of action (Navarra, 2020). These priorities are detailed in 17 projects to be completed by 2025.

One of the key projects is the measurement of the university's carbon footprint. This data will help with decision-making, prioritization of projects, and the development of future projects. This report outlines the methodology used for the measurement, the defined scopes, and the results obtained. Finally, the report includes details on the reduced carbon footprint measurement for the Clinica of the Universidad de Navarra, and the annexes provide a detailed explanation of the calculations used.

The Universidad de Navarra has recently performed its first carbon footprint measurement calculation. This was a complex task due to the lack of defined processes and the need to obtain data from various areas of the university. To tackle this challenge, the measurement focused on calculating the activity related to the Teaching Centers of Pamplona, San Sebastián, and Madrid campuses for the 2021-2022 academic year, including the Residence Halls located in the Pamplona Campus. However, the measurement did not include the activity of the Clínica Universidad de Navarra and other centers linked to the University such as IESE. The calculation was performed using the internationally recognized GHG Protocol (GHG, 2022), which outlines the environmental, geographical, temporal, and activity limits considered in this first study.

1. Methodology

This study followed the Greenhouse Gas Protocol (GHG, 2022) as its methodological standard. The GHG Protocol was created by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD) in collaboration with companies, governments, and environmental groups worldwide. It is the most widely used international tool for calculating and communicating emissions inventory. In fact, in 2016, 92% of Fortune 500 companies used the GHG Protocol to report their environmental impact to the Carbon Disclosure Project. The study used the operational control criteria provided by the GHG Protocol to determine what is included and what is not. For cases where the GHG Protocol did not have equivalents for specific consumption, official sources from the Spanish Ministry of Ecological Transition were used. To support the Campus Planning and Design Service, a nuclear work team was created and supported by Sinnple, a sustainability consulting firm. In the first session, the team identified all possible existing impacts identified by the GHG Protocol, the people necessary for data collection, and the most efficient way to collect them.

2. Scope and measurement

Before measuring a carbon footprint, it's essential to define the scope of the measurement. This includes setting three main limits: temporal, geographic, and activity. By defining the scope, we can determine which aspects will be considered and which ones won't be included in the measurement.

2.1. Temporary, geographic, and activity limits

Time limit. The academic year for 2021-2022 has been set as the time limit for measuring the Carbon Footprint of Universidad de Navarra. This is the first time such measurements are being taken and this year will be used as the base year for calculations.

Geographical limit. The campus activities are organized in three different locations: Pamplona, San Sebastián and Madrid. Each center has its own facilities and is managed by the campus. The Universidad de Navarra has other locations, including Barcelona where IESE is located, but these are outside the scope of this study because they are not part of the campus activities.

Activity Limit. This activity centers on university life, encompassing teaching, research, central services, and residential halls. While Residence Halls operate independently, those located within the Pamplona campus are taken into account due to their operational dependency in decisions regarding their facilities and consumption.

Due to its complexity, the information for the excluded subject could not be compiled for this first edition. Additionally, the healthcare activity of Clínica Universidad de Navarra in Pamplona and Madrid has not been included as it is separate from the university's activity. However, some data related to the university's footprint are presented in a partial and disaggregated manner in this report.

2.2. Environmental limits

Once the scope is defined, it is necessary to define environmental limits. Scope 1, 2, and 3 emissions have been considered, as shown in Figure 1.

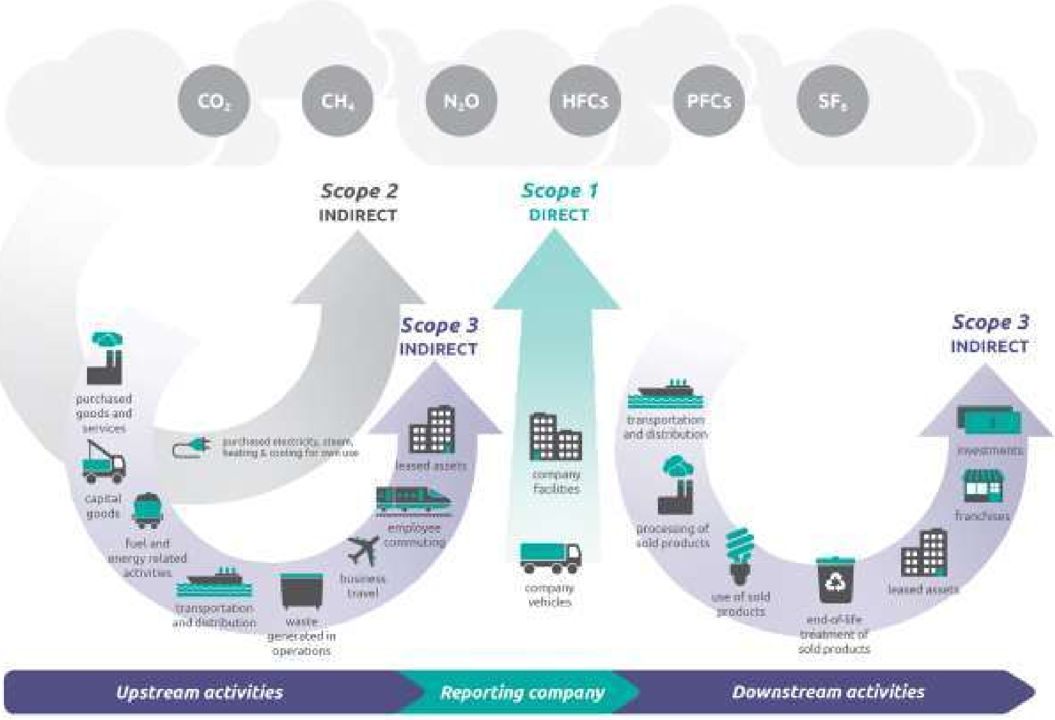


Figure 1: Different origins of emissions. Autor GHG Protocol

To better understand greenhouse gas emissions, they are divided into three scopes based on the level of responsibility for direct or indirect emissions throughout the value chain. Here is a summary of each scope.

Scope 1 emissions, also known as direct emissions, are emitted from the organization by and during its activity. This includes those derived from the use of boilers, own vehicles, refrigerants for air conditioning or refrigeration equipment, fire extinguishing systems, direct emissions during the manufacturing process, etc.

Scope 2 emissions are also known as indirect emissions, derived from energy consumption. This group considers the generation and purchase of electricity, steam, heat, and cold.

Indirect emissions are not emitted from the organization but are related to its activity (posting of workers, import and export of products, etc.). It has 15 different emission sources and represents a calculation challenge for any organization.

2.3. Selected environmental limits:

This research covers all emissions from Scope 1 and Scope 2 that are within the established boundaries mentioned earlier. Moreover, we have chosen to include Scope 3 emissions that have the most significant impact on the carbon footprint and are easier to gather.

Scope 1: All possible emission sources were analyzed. Direct emissions and those that are a focus of emissions within the activity of the university have been identified. In this case, there are emissions from boilers, vehicles, air conditioning, and fire extinguishing systems. As mentioned in the activity limits, the emissions derived from the laboratories were excluded from this study because it was not possible to collect information.

Scope 2: In this case, only electricity consumption is included because the university does not purchase steam, heat, or cold for its activities.

Scope 3: Considering the large number of concepts that can be included within Scope 3 emissions and following the GHG Protocol criteria, the potential impact on the footprint of each of the 15 possible emission sources were evaluated, as well as the ease of obtaining the data.

The project team worked with consultant Sinnple, who specializes in sustainability, to create the matrix shown in Figure 2. This was done to determine the potential impact of each source of emissions on the total carbon footprint.

Figure 2: Priority matrix. Autorship Sinnple for Universidad de Navarra

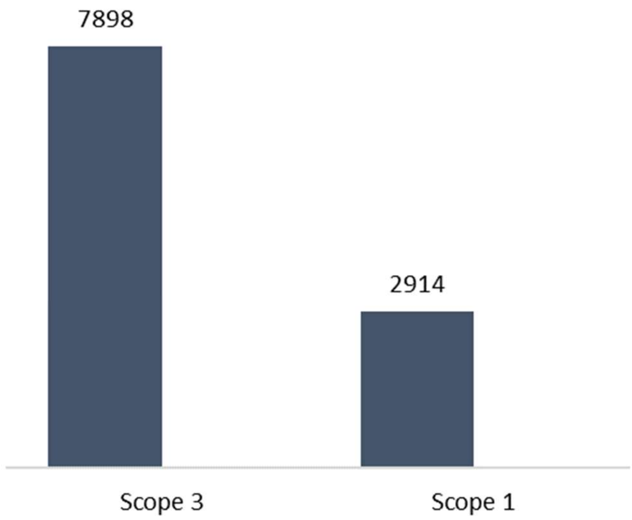
The concepts of carbon footprint and emissions from student and employee trips are highly relevant and can be calculated using current processes (upper right quadrant). These emissions are included in scope 3 of this study. Other environmental impacts that are also highly relevant (lower right quadrant) will be measured in the future as their calculation becomes more feasible. Environmental impacts that are difficult to calculate and of little relevance to the carbon footprint as a whole (lower left quadrant) will not be included in this study. The Universidad de Navarra team faced a challenge conducting this study, which is the first of its kind. The team built data collection instruments and identified data providers, met with various teams, and conducted a search for necessary data. Thanks to the cooperation of people from the management team, Residence Halls, and the Clínica Universidad de Navarra, this task was possible.

3. Measurement results

Based on the previous section's considerations, we converted the obtained data into equivalent tons of CO2. This section presents the detailed results of both gross and net emissions. Additionally, we also provide partial results according to the environmental scope.

3.1. Carbon footprint: gross emissions

The Universidad de Navarra emits a total of 10.8129 tons of CO2 eq.10 as a result of its activity on the Pamplona, San Sebastián, and Madrid campuses, with the limits and considerations described in the previous sections. As can be seen in Graph 1, the highest percentage (73%) is derived from Scope 3 emissions, whereas the rest (27%) is due to Scope 1. As will be seen later, Scope 2 is 0.



Graphic 1: Total emissions of the Campus. Autorship Sinnple for Universidad de Navarra

In order to measure emissions and track progress over time, it's important to calculate emission intensity. This metric accurately reflects changes in an organization's activity and allows for comparisons with other universities, as shown in the "Comparison with other universities" section. At the Universidad de Navarra, the emission intensity factor is calculated by dividing the total emissions by the number of students enrolled in the 2021/2022 academic year, which is 11,824. This yields a result of 0.91 Ton CO2 eq. /student. To put this into perspective, each student in this course produced the same amount of carbon as 91 trees would capture during the same timeframe. It's helpful to break down the intensity factor by Scope 1 and 2 to ensure comparability with other universities since not all universities have calculated Scope 3, and those that have used different criteria.

Table 1 developed breakdown:

	Scope 1+2	**Scope 3**	**Total**
Emissions Ton CO_2 eq	**2.914**	**7.898**	**10.812**[12]
Intensity: Ton emissions CO2 eq. Per student	**0,25**	**0,67**	**0,91**

In the case of Scope 1 and Scope 2 emissions, the intensity of each geographic center is shown in Table 2. In the case of Pamplona, it is higher than the others, mainly because of the greater use of fossil fuels in heating systems. In addition, there were no vehicle emissions or air-conditioning refrigerants in the centers of Madrid or San Sebastián. The latter exhibits the lowest emission intensity:

Table 2: Intensity factor depending on location

	Pamplona	**San Sebastian**	**Madrid**
Intensity: scope 1+2: Ton emissions CO_2 eq. Per student	**0,27**	**0,10**	**0,20**

To help you understand the calculations, we have provided a breakdown for each scope. We recommend consulting the Calculus section of this report for more detailed information.

In Scope 1, a total of 2,914 tons of CO2 in Eq. were produced by 4 direct emission sources. As indicated in Table 3, 92% of these emissions were due to the use of gas to operate boilers, while the remaining 8% were caused by road trips made by university vehicles, gardening vehicle operation hours, and refills of refrigerant gases in air conditioners.

Although fire extinguishing systems are installed on campus, there were no records of any recharges made this year.

Table 3: Emissions Scope 1

	Concept	Amount	Unit	Ton. emissions CO_2 eq.
1	Private vehicles	787517,00	Km/year	217
2	Boiler	16823,00	Mw/h/year	2681
3	Air conditioning	10,50	Kg recharges/year	16
4	Fire extinguisher	0	Kg recharges/year	0

Scope 2 emissions are zero tons because 100% of the electricity consumed is of 100% renewable origin.

Ten years ago, in 2012, the university made a commendable decision that has had a significant impact. By avoiding the emission of 5,039 tons of CO2 eq. every year, the university has reduced its Scope 2 emissions. This means that the total emissions have been kept at 10,812 instead of increasing to 15,851. It is worth noting that Scope 3 emissions make up 73% of the total emissions. The emissions have been categorized into two groups: student trips and employee trips, including Research Staff [PDI] and Administration and Services Staff [PAS].

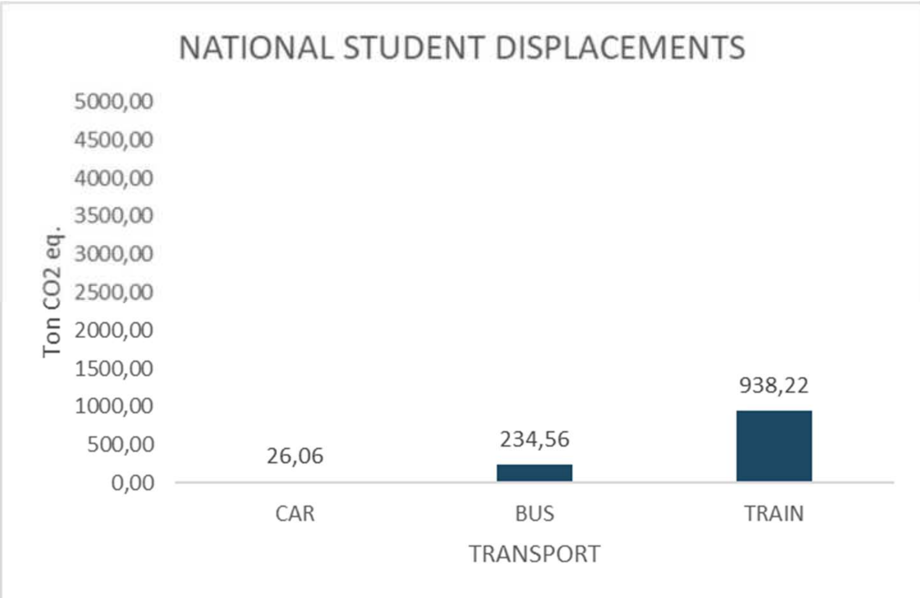
Table 4: Emissions Scope 3

Concept	Amount	Unit	Total Ton CO_2 eq.
Student displacement			
Students from outside of Navarra	61065353	Km	5830
Voluntary exchange	3363268	Km	290
Total	59890878	Km	6120
Employers journeys (PDI + PAS)			
Displacement to the cities	17415969,82	Km	1.485
Stays carried out	6958,00	Overnight stays	294
Total	17422927,82	Km	1.779

Student displacement, 6,120 Tons CO2 eq. They accounted for 77% of the emissions measured in Scope 3 this year (Table 4). Within this group, the following two sources of emissions were recorded, with 95% of the emissions falling on the second of the sources: trips made by students from outside of Navarra. Voluntary exchange. 290 Tons CO2 eq. (5%). During their studies at the Universidad de Navarra, 541 students voluntarily participated in an exchange program in another country. A round trip from Pamplona to the capital of the country of your destination has been accounted for, and depending on the distance, the mode of transport (mainly plane) has been defined. Students from outside Navarra, international and national. 5830 Tons CO2 eq. (95%). A total of 10,366 students came from outside of the oral community. Travel from cities or countries of origin was also included. A round trip from Pamplona to the destination was accounted for, and depending on the distance, the mode of transport was defined according to the following assumptions:

a) International students: It is estimated that they travel by plane. A total of 4,093 international students, except Portugal and Andorra. In the case of students from Portugal (47) and Andorra (14), it was estimated that they traveled by car.

b) Students from the rest of Spain: It has been estimated that 60% of students travel by train, 30% by bus, and the remaining 10% by car. As these are medium distances, it has been estimated that each person travels home three times a year for Christmas, Eastern, and summer holidays. See Graph 4.



Graph 4: National student displacement. Autorship Sinnple for Universidad de Navarra

The majority of emissions resulting from STUDENT TRAVEL come from air travel by students coming from outside of Spain who choose to study at the Universidad de Navarra. These students make up 38% of the group. By traveling by plane from distant locations to attend school, they are responsible for 78% of the emissions in this category.

Finally, as mentioned in the previous sections, this measurement could not include the emissions generated by the two relevant sources:

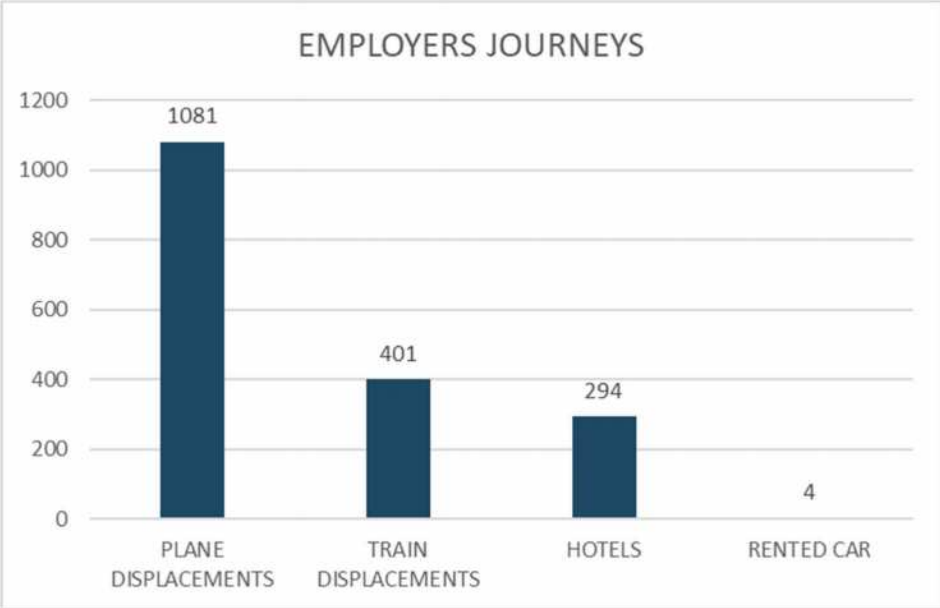
a) Daily trips by students, teachers, and other professionals to attend classes or work

b) Compulsory curricular transfers of undergraduate and master's students.

Both aspects, as will be discussed in the recommendations section, should be considered and included in future carbon footprint calculations.

Employee travel (PDI + PAS): 1,779 Tons CO2 eq. This category includes the trips of employees (PDI+PAS) for work reasons, and two emission sources can be distinguished. Trips to the corresponding cities, accounted for by distance and means of transport (plane, train, and rental cars), using both factors to accurately measure emissions. Stays made in said destinations, calculated based on the number of nights and category of accommodation.

Analyzed by concept or means of transport, it is observed once again that air travel has the greatest impact on the carbon footprint within EMPLOYEE TRAVEL (PDI+PAS), as can be seen in Graph 5.



Graph 5: Emissions of employers during displacements depending on the transport. Autorship Sinnple for Universidad de Navarra

3.2. Carbon footprint: net emissions

To determine net emissions, the Universidad de Navarra subtracts the gross emissions of CO2 eq. emitted during the year. Gross emissions refer to all the emissions emitted by the organization, while net emissions consider emissions mitigated through activities such as compensation or direct tree planting.

The Universidad de Navarra captures CO2 through the flora of the Pamplona Campus, which is mainly derived from the 3,766 trees on the facilities. The university has a specialized team that manages the biodiversity of the campus, with green areas occupying 40% of the surface and containing 149 plant species, 92 tree species, and 57 shrubs. This allows for an average capture of 11 tons of CO2 eq. per year.

Additionally, the university offsets emissions from air travel through programs with airlines. The Universidad de Navarra has offsets of 29.2 tons of CO2 eq. through Air France's CO2 capture program and 2.8 tons of CO2 eq. through Lufthansa's purchase of 921 kg of sustainable aviation fuel on behalf of the university. This results in a total offset of 32 tons of CO2 eq. per year for the Universidad de Navarra. Finally, RICOH, the reprography company contracted by the Universidad de Navarra, compensated for the 37 Ton Co2 eq. generated during the academic year 2021-2022.

4. Discussion

4.1. Towards natural neutrality

In this section, we will share the lessons we learned from the previous results. Our goal is to gradually decrease our organization's carbon footprint and move the Universidad de Navarra closer to climate neutrality. This aligns with the European Union's objectives for 2050. We will also highlight specific insights for the campus sustainability strategy for 2025, which aims to achieve a sustainable campus.

Scope 1: To significantly reduce Scope 1 emissions, it is necessary to influence emissions derived from gas or diesel boilers because they account for 92% of Scope 1 emissions and there are not enough lines of action within the 2025 strategy “Towards a sustainable campus.” To achieve this, one can act on two fronts:

EFFICIENCY: Measures aimed at reducing consumption due to more efficient equipment, a new consumption policy, or elimination of unnecessary consumption.

SUSTAINABILITY: Replacement of boilers by sources with less impact. Mainly biomass or electricity.

Strategy 2025 "University and Sustainability" The strategy includes project P13 "Energy Rehabilitation of Buildings: Ed. Investigation" for the 2024-25 academic year, which would affect EFFICIENCY, reducing the consumption of gas and diesel. In addition, it is recommended that projects P11 "Integration of Renewable Energies,” P5.1 "Energy Plan" and P5.7 "Building Protocol" Building Protocol’ consider the importance of fossil fuels in boilers to incorporate sustainable options. for them, thus drastically reducing the university’s carbon footprint.

In addition, emissions from university-owned road vehicles can be reduced. They are only 7% of the total, but they have a greater visual presence and can graphically reinforce the university's commitment to sustainability.

EFFICIENCY: replacing vehicles with more efficient ones, training in efficient driving, or new vehicle use policies.

SUSTAINABLE VEHICLES: Replacement of certain vehicles with sustainable options. This is a hybrid, plug-in hybrid, or electric vehicle, depending on the need.

SUSTAINABLE FUELS: Use of biofuels with lower emission rates.

No action on air-conditioning equipment or fire extinguishers is considered relevant beyond more efficient solutions when it is time to replace them. This is because they only represent 1% of Scope 1 emissions, and in the case of air conditioners, by running on electricity, the use of fossil fuels is already being avoided.

Scope 2: Emissions are zero; therefore, it is advisable to maintain a renewable energy contracting policy. On the other hand, the generation of renewable energy would not affect Scope 2 gross emissions, but it would make it possible to reduce net emissions because the emissions avoided by the energy produced can be subtracted from the gross emissions generated, in addition to the visual impact that would have reinforced the entity's sustainability strategy.

Scope 3: Reducing Scope 3 emissions is more complex because it does not directly depend on the Universidad de Navarra policy. As can be seen, the greatest emissions come from air travel, which is the most polluting medium.

To reduce emissions, we should explore replacing some plane trips with more eco-friendly options, especially for travel within Spain. It would also be helpful to encourage students to use shared transportation and consider sustainability when choosing their mode of travel.

As for emissions produced, the University could donate money to organizations that plant trees or develop CO2 capture projects. This would offset some of the emissions and help reduce net emissions. We already do this for air travel and should consider doing the same for vehicle emissions.

4.2. IMPROVEMENTS IN THE MEASUREMENT PROCESS

Here, we collected the possible improvements that were identified in the measurement process, applicable in the following years.

• LABORATORIES: This year, it was not possible to measure direct emissions from existing laboratories at the university. We see this point as critical to having a complete Scope 1 and 2 footprint and thus being able to register the footprint in the future in the Carbon Footprint Registry of the Ministry for Ecological Transition and the Demographic Challenge21, opting for the corresponding stamps.

• VEHICLES DESTINED FOR GARDENING WORK: As can be seen in the Annex, the total emissions of these vehicles are based on the fuel consumption standard per hour worked. To achieve the most representative possible results, the most appropriate thing, in this case, would be to ask the manufacturer for this information. An improvement opportunity is to have more specific data on the models of these vehicles to obtain the power of that specific model.

• FIRE EXTINGUISHERS: Different data providers record revisions in different ways. In the case of emissions derived from fire extinguishers, it is interesting to identify recharges. In some cases, this has been an easy task, but in others, the maintenance actions carried out on the equipment installed on different campuses are unknown. Here, it is suggested that, from this measurement, different data providers incorporate the same form of registration to facilitate the capture of data for future carbon footprint measurements.

• DATA CAPTURE: To incorporate GIS, it is pertinent to explore how this platform could serve to improve the data capture templates or replace them directly. Here, it is also suggested to validate for future annuities the best date of the year to measure, so that the teams prepare in advance and know on which dates the information will be required to be able to measure the next annuity.

• INTERNATIONAL BENCHMARKING: Given the global nature of universities and their good position in international rankings, it is recommended to extend the analysis of the carbon footprint of other universities to the international arena. For this, it will be necessary to find universities that measure emissions under an international protocol (GHG Protocol or similar) that report their Scope 1 and 2 emissions separately and divide them by the number of students to compare emission intensities.

• NEW MEASUREMENTS IN SCOPE 3: Regarding Scope 3, it is suggested to incorporate three emission sources that are considered relevant to the scope.

o DAILY DISPLACEMENT OF STUDENTS AND EMPLOYEES: At first, we planned to include the transportation of students and university staff in the Scope 3 category of indirect emissions. Unfortunately, we couldn't do so due to the lack of information necessary to estimate the data accurately. However, given the frequency of these trips, we must develop a system or form to gather this information in the coming years. This will help us determine the overall emissions saved by encouraging more sustainable modes of transportation like cycling, walking, and electric scooters among a significant portion of the student body.

CURRICULAR TRIPS FOR BACHELOR AND MASTER PROGRAMS. Going forward, it's crucial to incorporate these data. To achieve this, it's advisable to collaborate with faculty managers to devise a strategy for gathering and documenting this information for future evaluations. Alternatively, we can explore methods to approximate the emissions generated by these movements.

o WASTE: While the footprint may not be the main focus, it would be beneficial to consider including other sources of Scope 3 emissions, such as those resulting from waste. To achieve this, the Campus Sustainable Development Plan's projects, specifically P7 for daily recycling infrastructure and P16 for food waste recycling, should prioritize actions that measure the generation, collection, separation, and recycling of the waste cost-effectively. Additionally, implementing a consistent and well-defined waste management policy is recommended.

5. Clínica Universitaria: Simplify footprint

Clínica Universitaria de la Universidad de Navarra is a hospital founded in 1962 with over 2,800 professionals offering care in 46 medical and surgical specialties at its locations in Pamplona and Madrid. Due to the nature of the hospital's activity, a simplified calculation of its carbon footprint was conducted. While a more detailed analysis is necessary, data from available sources were used in this study as a starting point for future refinements.

• Gas boilers: The consumption of registered gas boilers supposes emissions of 1,848 Ton CO2 eq.

• Fire extinguishers: The recharges carried out represent emissions of 350 tons of CO2 eq.

• Electricity: As the same contracting policy of 100% electricity from renewable energy is followed, the emissions derived from said consumption are 0 Ton CO2 eq.

• No calculation has been made for Scope 3

This adds up to 2,198 tons of CO2 eq. for all sources of emissions analyzed.

For future years, it is recommended to carry out a detailed calculation following the GHG Protocol standard of at least Scope 1 and 2. To do this, in addition to performing the same calculations again, it is necessary to identify and incorporate the remaining emissions that may be involved. For this, we leave some indications that may be useful: vehicles owned by the Clínica, recharging refrigerating equipment or air conditioners, and emissions derived from the use of chemical elements.

6. Calculus

A detailed explanation of the calculations made to measure the carbon footprint is presented below. In addition, the Campus Planning and Design Service has evidence of all the data obtained. Although it has made the measurement process more complex, it has been vital to have good data quality and to be able to compare the information when necessary. Likewise, this helps a future audit process to verify the footprint of the University and to be able to register it with the Ministry for Ecological Transition and Demographic Challenge.

scope 1

OWN VEHICLES:

Within the vehicles of the University, a general classification has been made, which separates, on the one hand, road vehicles owned by the University and, on the other, vehicles used for gardening work such as tractors, lawnmowers, etc., etc.

• ROAD VEHICLES OWNED BY THE UNIVERSITY: Within this group, there is a great variety of vehicles. In order to obtain the most representative result possible, the mission factor of each of the models in IDAE22 has been consulted. However, due to the lack of exact data on the model in some cases and the absence of said model on the ministry's page in others, the following two exceptions have been made: An attempt has been made to find the most similar model possible and carry out the calculations with this emission factor. In the event that this model or any similar one does not appear in the tool, the calculation has been made based on the data provided by GHG Protocol, assuming that the fuel of the vehicle owned by the University is known. The results have been obtained using the following formula**:**

$$\sum Ton\ COe = \frac{\text{amount of Km with car (Km)x Emission factor (KgCO2e)}}{1000}$$

• VEHICLES INTENDED FOR GARDENING WORK: In this second group of vehicles, vehicles used for gardening activities such as lawnmowers, tractors, etc. have been included. In this case, unlike the first group, the emission factor used to perform the calculations has been the same for all vehicles. One factor for Gasoline vehicles * Data from E5 (2,445 Kg CO2 eq./liter) and another for those that consume Diesel (2,718 Kg CO2 eq./liter). Both data from the table for the year 2021.

• Regarding average consumption, this data is based on a report published by the ministry, where it is estimated that this type of vehicle, on average, consumes 15 liters/hour.

• In this case, based on knowledge of the hours of operation and the power of each of the models, this has been the formula used to obtain the results.

$$\sum Ton\ COeq = \frac{\text{Power (hp)}x media\ consumption\ \left(\frac{l}{h}\right) hours\ (h) x\ emission\ factor\ (\frac{KgCO2e}{l})}{1000}$$

BOILER:

As previously mentioned, 92% of the total direct emissions are derived from the consumption of the Boiler. In this case, in the GHG Protocol, the emissions data is given by mmBTU, so first, it has been essential to convert the consumption from Kw/h to mmBTU (millions of British thermal units). BTU is the amount of heat required to raise the temperature of one pound of water at its maximum density by 1 degree Fahrenheit (approximately 39° F).

1mmBTU=293,071 Kw/h

$$\sum Ton\ COeq = \frac{\text{Total consumption (mmBTU)x emission factor (Kg}\frac{\text{CO2e}}{\text{mmBTU}})}{1000}$$

REFRIGERANTS:

This group includes both air conditioners and firefighting equipment at the University facilities. In the case of refrigerants, only the recharges that have been carried out in the year in which the calculation is being made are counted, since it is assumed that if a recharge has had to be carried out, this means that at some point there has been a gas leak. That is, the calculated emissions are due to leaks that may have occurred during previous years but have not been recorded until the year in which they are recharged. In this case, the formula used is the following:

$$ATU\ emissions - chiller\ (Ton\ CO2\ eq.) = \frac{\text{Kg chiller recharge charg x PCG}}{1000}$$

The PCG of a gas refers to its Global Warming Potential and this data has been obtained from the GHG Protocol tables.

scope 2

The data for annual electricity consumption has been 19,457,370 Kw/h. However, as previously mentioned, by consuming energy from a 100% renewable source, consumption is multiplied by 0 Kg CO2 eq. / kWh.

Scope 3

MOBILITY OF STUDENTS FROM OUTSIDE AND VOLUNTARY EXCHANGES:

In this case, despite having distinguished the students into different groups according to the mode of transport in which they travel, the method and formula to obtain the final result have been the same.

This time, for trips by car, it has not been possible to know the model of car used by each student. Neither was the mode of transport used for each of the trips, so the data has been based on the following estimation:

a) Students who travel outside of Spain do so by plane, except in the case that the destination is Andorra or Portugal. In this case, due to proximity, it is estimated that they travel by car.

b) In the case of students from outside Navarra, within Spain: 60% by train, 30% by bus, and the remaining 10% by car, the formula used has been as follows:

$$\sum Ton\ COeq = \frac{\text{Amount of Km (Km) x Emission factor (KgCO2e)}}{1000}$$

EMPLOYEE TRAVELS (PDI + PAS):

Within the work trips made, the stay in hotels, classified by category, and, on the other hand, the trip to the respective cities, have been considered.
to. STAY IN HOTELS:
These data have been obtained thanks to the reports of El Corte Inglés, who is in charge of providing this service to the University.
The data has been classified into 3 main groups, according to the category of the Hotel (3, 4, or 5 stars). There is a fourth group in the tables provided by El Corte Inglés under the name "others". In this case, the decision has been made to include this group in the 3-star category. Starting from the data of the accommodation category and the number of overnight stays in each of them, the calculator published by CeroCo2 23 has been used, where the results of the stays made in the hotels can be found.
b. DISPLACEMENTS:
As in the calculation of Scope 1 vehicle emissions, in this case also for rental cars, the car model has been taken into account to select the emission factor. However, it should be mentioned that in this case, we do not know the exact model of the vehicle group. Using this data, it has been possible to estimate and find out the average emission factor for said group published by car rental companies.
Regarding air travel, the emission factor extracted from the GHG Protocol has been used. Mileage has been calculated from Loiu Airport as this is currently the closest airport from which many domestic and international flights depart. There are indeed more nearby airports frequented by students, such as the Pamplona airport, but in this case, it does not have international flights, these being the ones that have the greatest impact on the carbon footprint. As for the destination airport, the one located in the capital of each country has been chosen. And in the case of the train, the emission factor has also been extracted from the GHG Protocol, and the distance has been calculated from Pamplona to the capital of the destination.
In all cases, the formula that has been applied is:

$$\sum Ton\ COe = \frac{\text{Amount of Km (Km) x Emission factor (KgCO2e)}}{1000}$$

Net emissions

For the calculation of emissions captured by the trees of the campus, we have taken as a reference the conifers, which are the most represented species among the flora (approximately 25%), and the capture factors available to the Ministry24, details of which can be seen in the document at the bottom of the page.

7. Conclusions

The Universidad de Navarra has conducted a study analyzing the carbon footprint of its Teaching and Research activities and Residence Halls in Pamplona, as a first of its kind. The work team faced challenges while compiling evidence to ensure good practices were incorporated from the outset. The results of the study show that the university has a good starting position in carbon footprint compared to other universities in the area, with a total of 10,812 tons of CO2 equivalent emissions. These emissions are mainly from fossil fuels used in boilers and air travel. The breakdown of emissions is detailed in the results section.

Another significant result of measuring the footprint is that it valued the environmental actions carried out previously. Here, it is worth noting the decision taken in 2012 to exclusively contract and consume electricity of 100% renewable origin, backed by the Guarantees of Origin (GDO), which has prevented the footprint from being 48% higher. In addition to the historical commitment to take care of biodiversity and the protection of large green areas (40% of the Pamplona campus) that capture 11 tons of CO_2 eq. every year.

The goals are to decrease carbon emissions and enhance the measuring procedure.

The starting point for future annual payments included the region of Navarra.

8. References

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Navarra, U. de (2020) *Estrategia 2025*. Available at: https://www.unav.edu/conoce-la-universidad/estrategia-2025#:~:text=La Estrategia 2025 de la,con otras personas e instituciones. (Accessed: 20 June 2022).

Mixed methods approach to understanding occupant acceptance and use of a personal ceiling fan – a field case study

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Abstract: The need for mitigation measures in the face of climate change has focused on using personal environmental control systems (PECS), especially to reduce cooling energy impacts. Though the benefits of PECS are known, in-situ measurements and post-occupancy analysis are scarce. This work aims to investigate the effect of occupants' expectations, information, and knowledge on the use of a personal ceiling fan and their satisfaction with indoor environmental quality (IEQ). Using a mixed-method approach, IEQ and employees' behavior and psychological responses in an office building in Germany were collected. Semi-structured interviews were conducted to investigate employees' expectations of cooling strategies. Results showed that aligning occupants' expectations with PECS features, particularly personal control, increased occupants' thermal comfort and fan interactions. In addition, employees with greater knowledge of how the fan works and awareness of the building design increased their expectations and satisfaction with the device and IEQ, but did not necessarily correlate with their interactions with the fan. This study emphasizes the relevance of providing occupants with personal control possibilities and with information on how such technologies work. To increase the acceptability of PECS in buildings, their implementation should be accompanied by objective building measurements and information on occupant feedback.

Keywords: personal environmental control systems; thermal comfort; monitoring; post-occupancy evaluation; resilient cooling

1. Introduction

Resilient cooling design is an urgent requirement for future and existing buildings. A combination of passive and active cooling design measures and cooling strategies with flexible control have a high adaptive capacity during heat waves (Attia et al., 2022). Personal Environmental Control Systems (PECS) allow thermal comfort at relatively higher ambient temperatures and provide personal control of the occupant's microenvironment. As such, they can improve occupant comfort, health, and productivity, while significantly improving the energy efficiency of the overall heating, ventilation and air-conditioning (HVAC) system (Rawal et al., 2020). Despite the proven benefits, there are currently a very limited number of commercially available PECS, and their applications have not reached the wider market.

A possible reason for this may be the limited number of field studies, as most studies focusing on the evaluation of different types of PECS and the application of personal comfort models for system automation and control have been conducted in climate chambers (André et al., 2020). Although the automation of environmental conditions is an important tool for implementing PECS, providing occupants with a higher degree of personal control can increase their thermal satisfaction (Kwon et al., 2019). However, simply having access to personal controls does not mean that comfort is improved (Zhang et al., 2010) and may even result in increased energy consumption if the user does not operate the system correctly

(Veselý and Zeiler, 2014). Successful information about the building design and control systems can increase occupant satisfaction (Day and Gunderson, 2015) and their expectations of indoor environmental quality (IEQ) (Arpan et al., 2022). However, little is known about the impact of occupant expectations of cooling solutions and building controls on the use and acceptance of PECS in real-world contexts (Rissetto et al., 2022).

This work aims to investigate the effect of occupants' motivations, expectations and level of knowledge on their acceptance and use of PECS, and to relate this to occupants' satisfaction with the indoor environmental quality in non-residential buildings. Specifically, the following research questions will be addressed:

- Do different motivations and expectations for choosing a cooling strategy have an impact on the use and satisfaction with PECS?
- Does having more positive expectations and a higher level of knowledge of PECS and the building design affect the use and evaluation of the device and relate to higher levels of satisfaction with the IEQ?

2. Methods

This study involves a cross-sectional study with a mixed-method approach, including the collection and analysis of quantitative and qualitative data. A pre-registration of the work can be found at Open Science Framework (OSF) with the number 6cg42[1]. The present work is developed within the framework of a district office building renovation in Dillingen an der Donau, Germany, where a personal ceiling fan, as a type of PECS, was installed.

2.1. Building description

The building has 3 floors and office rooms of around 20 m^2 for one or two employees. A refurbishment of the existing building was carried out in 2019, including improving the façade's thermal transmittance, new windows and blinds with an automated system, and a decentralized ventilation unit for each office room (Figure 1, left). The windows can be manually operated and have a control system for night ventilation. To improve the employees' thermal comfort in summer, personal ceiling fans (PCF) were installed individually at each workplace. These fans are integrated into an acoustic panel and have a removable grid to adjust the airflow direction (Figure 1, right). More details are available in Rissetto et al. (2021).

Figure 1: Two-person office room, with new window system and ceiling fans (left). Detail of personal ceiling fan integrated into an acoustic panel with a removable grid (right). Copyright (left image): 2021, Bergische Universität Wuppertal.

The quantitative data consists of 1) indoor environmental quality measurements and occupants' behaviors from a monitoring campaign, and 2) employees' reported behaviors and satisfaction with the building obtained from a longitudinal survey campaign carried out before

[1] https://osf.io/6cg42

and after a building renovation. The qualitative data consists of information obtained from semi-structured interviews with a selected number of employees, focusing on motivations and attitudes towards cooling strategies, the building renovation, and satisfaction within the building.

2.2. Data collection

The data collection was conducted within the framework of a research project, fulfilling data protection and ethics approvals. Participation consent forms were obtained from the interview participants.

2.2.1. Monitoring and survey data

Monitoring data from May 2021 to September 2021 was used for this analysis. In total data from 93 rooms and 130 employees was collected. Table 1 provides an overview of the data.

Table 1: Overview of monitoring data used in the present study: variables, measurement interval and range.

Variable	Interval	Range
Indoor temperature	5-min	0–50°C
Ceiling fan speed	By change	0–100%
Window position-tilted	By change	Opened–closed
Window position-open	By change	Opened–closed

A longitudinal survey campaign was conducted in the building in the years 2018 (before renovation), 2019 (during the renovation phase), 2020 and 2021 (after renovation phase). Table 2 shows the main variables analyzed in the present study.

Table 2: Overview of survey data used in the present study: variables, scale points and labels.

Variable	Scale	Labels
Fan effectiveness	7-point	very bad – very good
Fan experience	7-point	very negative – very positive
Importance of fan characteristics	7-point	very unimportant – very important
Satisfaction with fan characteristics	7-point	very dissatisfied – very satisfied
Satisfaction before/after refurbishment	7-point	very dissatisfied – very satisfied
Thermal comfort	5-point	very uncomfortable – comfortable
Thermal sensation	7-point	hot - cold
Evaluation of indoor air quality	5-point	very bad – very good
Satisfaction with indoor air quality	5-point	very dissatisfied – very satisfied
Perception of air movement	7-point	very strong – very weak
Preference for air movement	7-point	much stronger – much weaker

Before the final implementation of the PCF, a user guideline (information sheet) with detailed information about the fans and other technical devices installed in office rooms (mechanical ventilation, windows, shading devices) was given via email to the building employees.

2.2.2. Interviews

Semi-structured interviews were conducted in September 2021 to understand employees' drivers and motivations for the use/non-use of the personal ceiling fan. The case selection strategy was based on most different cases to capture different user types: 1) employees who have hardly used the ceiling fan, and 2) employees who have used it actively. Therefore, an exploratory analysis of the monitoring data was carried out. The relative frequency of use was calculated, by measuring the total amount of time (minutes) of the activated ceiling fan (fan level values greater than 5% were considered as turned on) divided by the total days of use. The mean was calculated and values that deviate the most from the mean were considered as "extreme" users. Due to time and resource constraints for conducting the interviews, twenty employees who showed extreme patterns of use were invited to participate, from which ten voluntarily agreed on participating.

The interviews were audio-recorded, and field notes were taken by two researchers from the research institute. The interviews took place in an air-conditioned room where no ceiling fan was installed; only two interviews were conducted online. 70% of participants work in two-person offices. All participants work five days a week with varying hours (60% full-time) and have worked in the building for more than three years. Only two participants were permanently in the office during the 2020 lockdown, most were on a rotating basis. 60% of the participants are between 45 and 55 years old, the rest are between 26 and 45 years old. The participants' offices are located on the 1st, 2nd, and 3rd floors.

The guided interview was divided into five thematic blocks, covering demographics, activity/experience at the district office, indoor climate preferences, reported behaviors with the control systems in the room, and feedback on the building retrofit. In block 3, the participants were asked to explain the operation of the ceiling fan and to give feedback on the information sheet they received during the renovation phase. In block 4, a card sorting technique took place, in which users are asked to sort information into logical groups. This technique was used to better understand employees' knowledge and expectations of cooling methods and their behaviors in the office. Participants were given 11 laminated paper cards with different concepts and definitions (Figure 2): *fresh air, airflow, high cooling effect, ease of use, energy savings, cost savings, noise level, fast cooling effect, personal control, do not disturb colleagues, integration in the room*. In addition, there were three blank cards with the possibility to write additional concepts. Participants were asked to think of possible cooling strategies in any office, both active and passive, and the most important decision factors when choosing a cooling method. The task was to sort the cards from important to unimportant (left to right) and describe their thoughts on the choice aloud in the process.

Figure 2: Concepts for the card sorting (in German).

2.3. Data analysis

A mixed-method approach was conducted for the data analysis. The qualitative insights obtained from the interviews were contrasted with the monitoring and survey data. The monitoring and survey data were analyzed with the software environment R Version 4.1.3 (RStudio Team, 2020). Participants were coded with the letter P and a number (e.g., P01 for participant 1), to anonymize the room number of the employees. We analyzed the data using the k-means algorithm to disaggregate the use of ceiling fans and windows into behavior patterns for each employee. As the number of clusters has to be defined before running the algorithm, we looked at the Dunn Index indicator (DI). This index evaluates the goodness of the cluster structure by measuring the optimal inter-cluster (far apart) and intra-cluster distance (small variance). A higher DI value indicates better clustering.

The interview data were analyzed through direct content analysis. The direct content analysis approach can be used to extend conceptually a theoretical framework (Hsieh and Shannon, 2005) and provide predictions about the variables of interest or the relationships among variables. Using existing theory or prior research, researchers begin by identifying key concepts or variables as initial coding categories (Potter and Levine-Donnerstein, 1999). The proposed themes in the present study derive from previous relevant research findings on expectations of the indoor environment (Rissetto et al., 2022; Schweiker et al., 2020) and the effect of information on thermal satisfaction and behaviors (Day and Gunderson, 2015; Schweiker and Shukuya, 2011). For the analysis, we followed the steps described in Cavanagh (1997). Firstly, categories of information were created to "code" the transcripts of the interviews. The categories were based on themes previously defined according to the concepts of card sorting and the research questions. The categorization was applied by coding the first two interviews to assess the reliability and adjust the coding system. The data analysis was done with the software MAXQDA 22.5.0 (VERBI Software, 2021). Adjustments were applied to the coding system and then the coding was done for the whole data by the same researchers who conducted the interviews. Table 3 shows the main codes and the sub-codes. In total 540 segments were coded.

Table 3: List of codes with a selection of the assigned subcodes.

Main codes (themes)	Sub-codes (selection)
Actual thermal perception	-
Personal characteristics	Age, category of use, habits
Temperature type	Body parts, warm/cold sensitive
Work and tasks	Working since, working hours, main tasks, …
Office room	Number of people, satisfaction
Evaluation of room climate	Perception, satisfaction
Personal ceiling fan	Control and use, air movement, knowledge, …
Windows and doors	Night ventilation, use, satisfaction, knowledge, …
Ventilation system	Use, knowledge, satisfaction
Blinds	Use, knowledge, satisfaction
Other cooling strategies	Evaluation
Decision factors (11)	Definition, importance
Knowledge	Information sheet

We grouped the codes thematically and built “sets” of codes so that the content supported or refuted the sample group’s alignment with our research questions. The thematic sets are presented in the form of quotes[2]. The same coding principle used in the quantitative analysis to identify participants was applied to the interview data.

3. Results

This section is divided into three parts: the first part analyzes the ceiling fan usage patterns for the 93 monitored rooms to gather general information on the use of the fan in the building; the second and third parts answer the research questions above mentioned.

3.1. Ceiling fan usage patterns

To better visualize participants' interactions in the building, we clustered all employees who used with the fan according to their probability of turning it on for different temperature bins (Figure 3). The probability of turning on the fan is very low for most participants up to 25°C, but increases between by 15-40% at warmer temperatures, depending on the cluster group. Some employees (namely from cluster 3) have a very low probability of turning on the fan, regardless of the temperature.

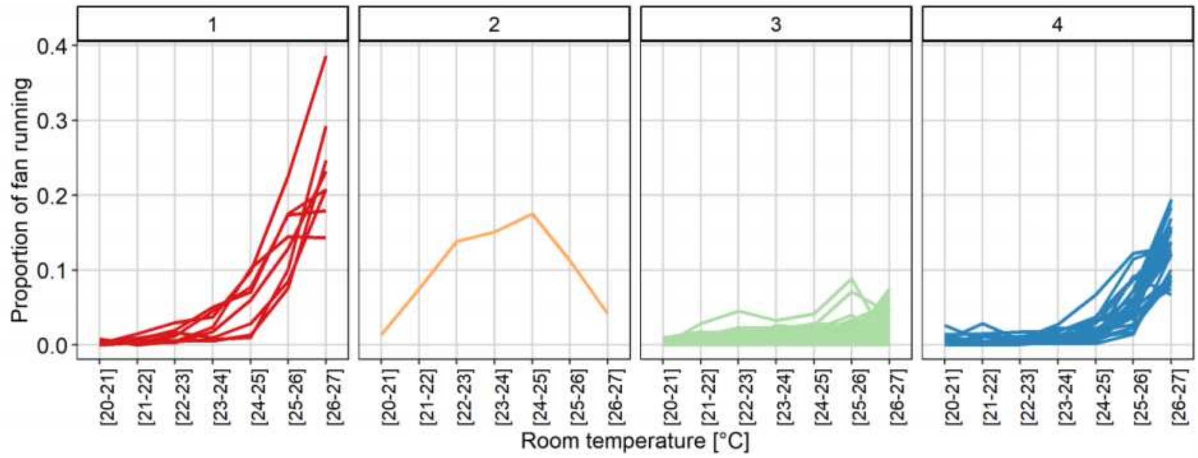

Figure 3: Proportion of ceiling fan running for each temperature bin grouped according to cluster number for all 93 rooms.

3.2. Cooling strategies and decision factors

Figure 4 shows participants’ probability of turning on the fan for different temperature bins only for participants who were interviewed. The DI calculation suggested three clusters, but after a visual inspection of the profiles, a total of two clusters were defined for the analysis. The interview cluster structure resembled closely two of the larger sample clusters (Figure 3). The probability of using the fan increases with higher temperatures for participants in clusters 1 (P04, P06, P01, P08). Participants in cluster 2 (P2, P3, P5, P7, P9 and P10) have a very low probability of using the fan (less than 7%), even at high room temperatures.

[2] Disclosure: The quotes presented here were asked in German and for the purposes of this study have been simply translated into English using DeepL Translator Deepl SE (2020). The translations were checked by one of the researchers who is fluent in both languages.

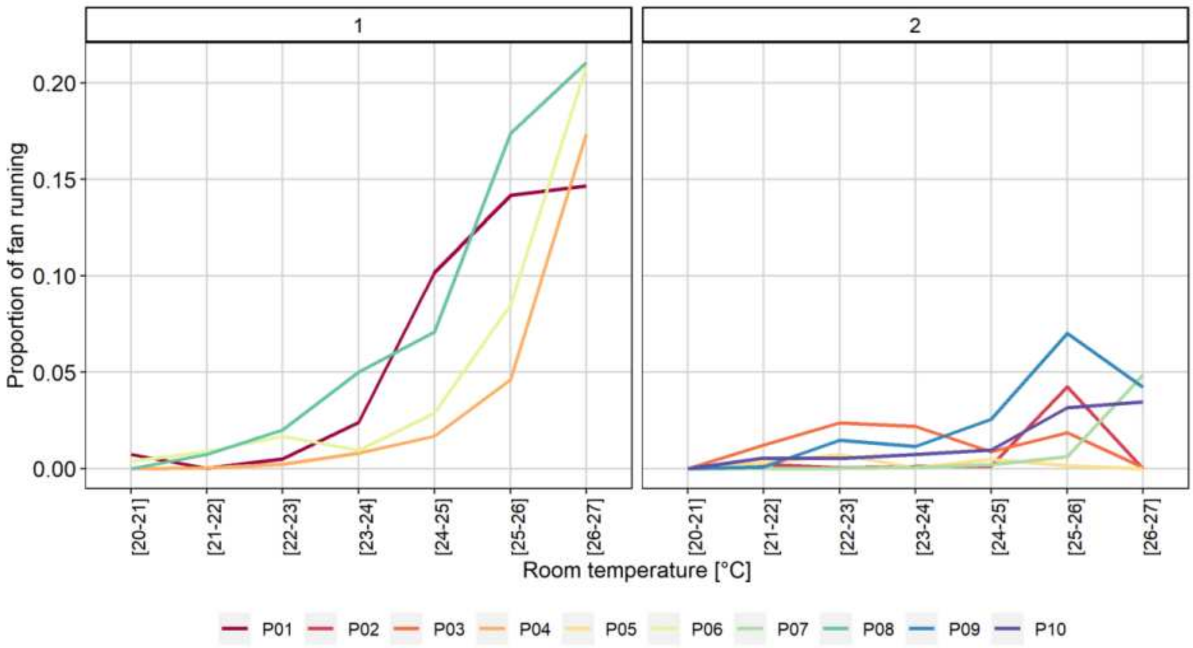

Figure 4: Proportion of ceiling fan running for each temperature bin grouped according to cluster number.

Although most participants reported that the ceiling fans were rarely used in the summer of 2021 (mostly due to the rather acceptable indoor conditions), participants reported that they had to turn on the ceiling fan on very hot days:

P04: "[…] there were **longer warm periods when I used it every day**. And usually from, let's say, **midday until evening**, until I go home."

P01: "Only in summer. **When it's extremely hot** there."

P07: "**Only when it's really, really hot.** So usually, when the heat on the west side is building up in front of the windows, so that it's **getting hotter outside than inside, then I close the windows, lower the blinds, and turn on the fan**. So, the fan is usually on when the windows are closed."

P06: "But um, yes, I'm always the one that wants **just to cool down** or **to stir up the air a bit**, … already used [it], yes."

We clustered participants according to their probability of opening the window according to different temperature bins (Figure 5). In general, the probability of opening the window is higher than the probability of turning on the fan (fan running proportions are lower than 25%). Participants in cluster 1 (P01, P03, P04, P05 and P09) are more likely to open the window as the temperature increases, but the proportions rarely exceed 10%. Participants in cluster 3 (P06, P07, P08) also show a likelihood at higher temperatures up to 26°C and a decreasing likelihood at temperatures above 26°C. The two participants in cluster 2 (P02, P10) show the highest increasing probability (30%) and increase up to a room temperature of 27°C.

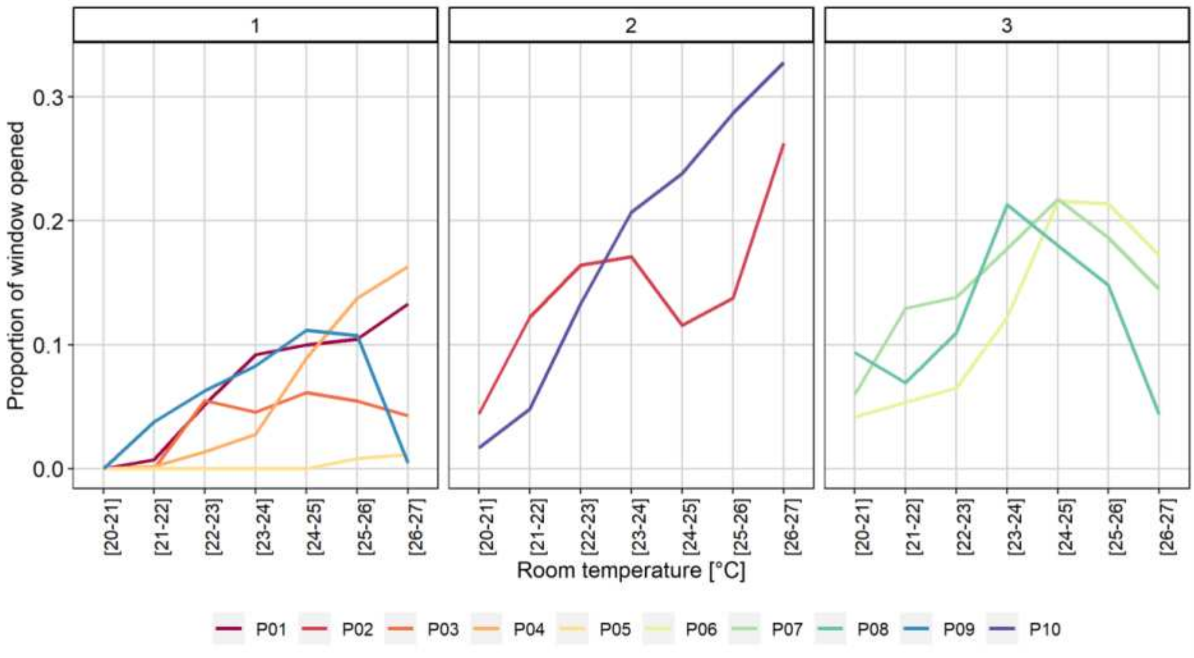

Figure 5: Proportion of window opened for each temperature bin grouped according to cluster number.

To better understand participants' motivations for using the fan and windows, the card sorting results were analyzed. Figure 6 shows the order on the importance scale (1 - very important to 11 - very unimportant) that participants assigned to each factor related to cooling strategies. There is a tendency for *fast* and *high cooling effects, personal control,* and *fresh air* to be considered the most important factors when choosing a cooling strategy. However, *personal control* and *fresh air* show a narrower range, i.e., they were generally more important to most respondents. In contrast, *cost savings* and *energy savings* were ranked last by all respondents with a few exceptions, and *integration into the space* was also considered unimportant.

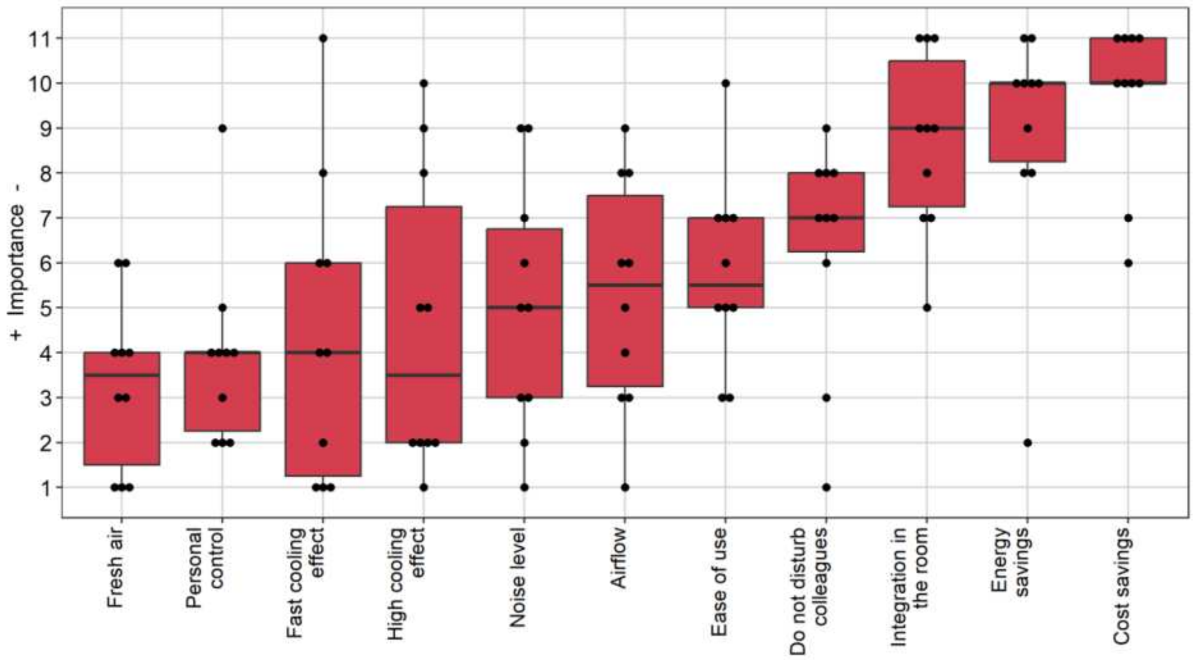

Figure 6: Boxplot of decision factors by importance. Black dots represent the individual voices.

People who rate *fresh air* as an important aspect of a cooling strategy prefer to open the windows rather than turn on the decentralized ventilation or the ceiling fan:

P03: "My office **used to be stuffy**. [...] in the summer, if you have the window open, then it **[the ventilation] is off anyway**. In the morning you open the window and try to bring in a bit of freshness or simply exchange the air, so as I said, I come in in the morning, now turn on the light, turn on the printer that's on the way, and then open the window. [...] I **just like better**, the window open **than somehow a fan on**."

P06: "[...] my first thought, I'll say **because of the air**, too, because I still think that's the most important thing, **even if it's warm**, to **open the window first**."

P08: "And I just **always opened the window, if I want to ventilate a bit**, I mean now because of Corona, you have to have it open anyway, but I also find that if there is fresh air in the room and it is then just circulated, it is **more pleasant**. And with **the ventilation system**, if you open the windows, then **it goes out**."

As can be seen in Figure 4 and Figure 5, participants 3, 6 and 8 were less likely to turn on the fan than to open the window, but at temperatures above 26°C, participants 6 and 8 preferred to use the fan than to open the window.

Respondents for whom *personal control* is an important aspect of a cooling strategy associate it with controlling the ceiling fan and opening the windows, when they were asked to explain it:

P01: "Hm, it is always the same with the.... the air conditioner, I always find it constant. Now with the fan, I **can regulate for a short time**, **make it stronger** for a short time, [...] and then I want to turn that back and just run it so lightly."

P08: "Yes because I can **determine that for myself**. So, these fans, I think **that's okay**, that they can be controlled that way, I think that's great, but I **also like to be able to open the windows myself**. So that's also important to me."

In Figure 4 we can see that participants 1 and 8 have a similar fan usage profile, with the highest probability of switching on the fan for a temperature range between 23°C and 26°C. In addition, when analyzing the results of the longitudinal surveys, both participants expressed satisfaction with the personal control of the ceiling fan.

High or fast cooling effect were chosen as the next most important factor. Those who considered these factors important were thinking of active cooling strategies, such as air conditioning:

P04: "Well, when you say it so extreme, I **would immediately think of the air conditioner**. Because then it's the **only chance to cool down at all**."

P07: "When you say cooling strategy, I **think of air conditioning**."

These participants were asked about their thermal sensation and comfort in the room, and they found the thermal conditions "neutral" and rated them as either "slightly uncomfortable" (participant 4) or "uncomfortable" (participant 7). However, they showed very different patterns of fan and window use: Participant 4 tended to use the fan and windows as the temperature increased, while Participant 7 rarely used the fan but increased the likelihood of opening the windows at temperatures between 23-26°C.

The three participants who chose *airflow* as an important factor associated it with fresh air, usually coming in through windows or doors, and a feeling of coolness:

P01: "Simply the **air circulating, that I feel** this airflow [...] that I first notice that I am **being cooled down**. [...] It's more comfortable for me now when there's a little bit of a light draft. In fact, if the **window is open**, then the air comes like that, so **somehow that's a bit**, yes right, **more natural,** yes."

P04: "So airflow is also important for me. I know now quasi the situation that you only have to **open windows and doors**, where you then also have to watch out **when you sweat** [...] that it is also pleasant for you, and now not only has the effect that you **just sit in the flow**."

P06: "So airflow is for me also… because of the background with the air freshness, because **if I have flow, then the air is not standing in the room**, but moves and **is exchanged**, so airflow is actually **the same as air freshness**."

The same participants were asked to rate the airflow coming from the fan. They all perceived it as "strong" ("very strong" for Participant 1; "strong" for Participant 4; "slightly strong" for participant 6), which may explain their preference for opening the window for fresh air. In addition, they were all satisfied with the air quality in the room after the building renovation, suggesting possible satisfaction with the effectiveness of the windows. Although these participants shared the same motivations and preferences for cooling strategies, their interactions can be very different. When analyzing their observed behavior (Figure 5), the participants fell into different clusters, i.e., they showed very different patterns of window opening.

3.3. Information, knowledge and expectations

Employee involvement and communication about the refurbishment plan played an important role in participants' satisfaction with the building. The higher the level of awareness, i.e., the employees who knew that ceiling fans and other technical equipment would be installed, the more positive their expectations of the building renovation:

Interviewer: "You also worked in this office before the building retrofit. I would like to ask you if you knew what was going to be done with the refurbishment."

P05: "**Yes, so roughly**. I knew then already, from the realities, and that, with the new windows and this facade, **a lot has really been done**."

P02: "I already had the **hope that it would bring something**. And that has also **come true**."

P09: "I have a bit of a special position [...], I was actively involved in the planning of the renovation and **was very positively surprised and was also pleased that they have participated** in this experimental project here."

In addition, participants who had more positive expectations of the energy-related refurbishment expressed a greater perceived control, which led to greater satisfaction with the indoor climate and the control systems in the room:

Interviewer: "Can you say that your expectations of the building refurbishment have been met?"

P05: "Yes, because that has been an insane investment with the employees, that **now we have possibilities, so more is not possible**."

P06: "**Sure, of course**, [...] so **from the basic feeling** it is clear, well, what does clear mean, it is already more pleasant, [...] last summer, there was now **no day, where one said, now it does not go at all,** in that sense... you've **always have ways to kind of deal with it**."

P07: "**Operation has become easier.** In the past, there were **these blinds** that you had to crank and turn, it's much easier now. [...] The **high cooling effect** I would say is either the same or has gotten better now **due to the ceiling fan**, where you have additional cooling **when it is hot outside**. [...] We used to have these **huge windows**, and when I opened them, there was air very quickly, so you could say that it has become worse, but **not so important anymore,** because in the summer **now these little flaps are open at night**."

P08: " I think that **it has brought quite a lot** [...] the **climate in the office is much better**. I think that's probably **everything together, these fans and this window ventilation**, also, this **ventilation system**, that in the morning these little parts are open, and it is already ventilated when we come in."

Successfully communicating the features of the personal ceiling fan, could increase occupant satisfaction with the device. Some participants expressed satisfaction with the potential to improve the room acoustics, the minimal noise level, or the possibility to direct the airflow:

P09: "What I find very good, is that with these fans, or maybe also just because of **these insulation panels** that came in, which also have a very **pleasant effect on the room acoustics**."

P10: " I would say it is successful, because, yes, the **fans are not loud**."

P05: „Head and hair, a bit. [...] So **from the side and the front**. That's **kind of a breeze**. But that's because I **asked to set it up that way**. I realized that was too much for me."

On the contrary, participants who complained about a lack of information were less satisfied with the PCF. For example, one participant was concerned about the operation control and the possible accumulation of dust in the acoustic panel:

P01: "And um **a bit technical** [...]. I didn't know that we had that [information sheet], but if we have that, then..."

Interviewer: "And controlling the speed?"

P01: "Yes **that's a problem**. [...] if there were levels there, from 1 to 10 or from 1 to 5, let's say so, [...] so the setting is a bit, **needing to get used to**."

P10: "If I don't turn the thing on that often, I assume that, um, quite a **lot of dust will collect on top**. And then somewhere there is the feeling that when I turn it on, the dust whirls around and I don't want that now."

P01: "I was wondering that if it doesn't work for a long time, all the **dust is already on top** and then you switch the parts and then [unclear] **the whole room at some point**."

In addition, there is a tendency for participants who understand the operating principle of ceiling fans (cooling effect on the skin) and correctly understand the purpose of the other technical devices in the room to express satisfaction with the personal ceiling fans. For example, participant 8 rated the effectiveness of the fan as "good" and had a positive experience with it:

P09: "But you have to consider that the fan, it doesn't do anything else than **this chill effect on the whole**. And we don't have any active cooling here, which that is, **no subcooling of the air**, but rather this chill effect, and that also **ensures that you then feel somehow comfortable**."

P09: "So in **early summer it's mostly cool** because we still **have these flaps on the windows that open automatically**. In the morning you don't need the fan. Then mostly, when the **temperatures outside rise**, when the temperatures in the office also rise so slowly and through **the human heat or all the devices**, so at noon, in the afternoon you already like to turn on the [ceiling fan]. And then it runs until the evening."

P08: "So I use that almost every day. [...] I always thought then the **warm air rises** and that is blown down, that [the air] just circulates a bit in the room."

Not fully understanding how the airflow from the ceiling fan affects skin temperature and not the room temperature could lead to a lower degree of satisfaction with the unit:

P01: "I always feel it's not enough, even if the fans **bring the cooling, or the one that cools down the heat or just cools down the air**, the window has to be open too."

P03: "If I feel, yes now **the temperature is okay**, then **I turn back a little bit**."

Participants 1 and 3 think that the room's indoor climate, i.e., the temperature, can be changed by using the ceiling fan. These same participants rated the effectiveness of the fan lower than the other participants ("slightly bad" and "neutral", respectively). However, their dissatisfaction with the fan does not necessarily reflect their interaction with it, as they showed very different patterns of use (Figure 4). Similarly, participants 8 and 9 show very different fan use profiles, even though they were both informed about how the fan works.

4. Discussion

The first research question aims to investigate how different triggers and motivations when choosing a cooling strategy may impact the acceptance and use of the PCF. The results showed that personal control and indoor air quality are important aspects for occupants when it comes to choosing a cooling strategy in the office building. It has been studied that perceived control affects occupants' thermal perception and consequently their satisfaction in the building (Luo et al., 2016; Yun, 2018). Kwon et al. (2019) concluded that higher controllability leads to higher thermal satisfaction, especially when personal control of ventilation is provided. In this study, the personal ceiling fan (PCF) combined with the decentralized ventilation provided personal control for occupants and ensured good indoor air quality in the building.

However, it seems equally important to provide the occupants with different opportunities to adapt to the indoor environment (Baker and Standeven, 1996). Occupants can act not only in response to the indoor environment, such as turning on the fan instead of opening the windows when outside temperatures are high but also according to their preferences and expectations of what a cooling strategy should be like. For example, in this study, personal control was associated with both the ceiling fan and the manual operation of the windows. Hellwig (2015) proposed a model to describe perceived control, which relates to the locus of control of the indoor environment, the person's self-efficacy and individual expectations. Participants for whom personal control and fresh air were important showed similar profiles of fan use, which may indicate that their expectations of the PCF and windows in terms of providing acceptable indoor air quality and operation were met, and a correlation between the qualitative (motivations) and quantitative (behaviors) analyses was observed.

High and fast cooling effects were relevant aspects of cooling strategies, but not the most important factor chosen by participants in this study. A possible explanation could be due to the employees' previous experiences and expectations of the existing building. Kim and Dear (2012) found that occupants of naturally ventilated buildings have relatively modest expectations of their thermal environment compared to those in air-conditioned buildings and tend to attribute thermal discomfort to their actions rather than the thermal environment provided by the building. Thus, those participants who prioritized a high/fast cooling effect had probably higher expectations of the IEQ and control opportunities, leading to lower thermal comfort. However, the same participants showed different behavioral patterns to restore comfort, even though they were both satisfied with the PCF and the adaptive opportunities in the room. The subjective information provided by the surveys did not necessarily correlate with their adaptive actions, suggesting that failure to meet expectations of cooling strategies may directly affect IEQ satisfaction, but may not be related to occupants' interactions with the PCF.

The second research question focused on the impact of knowledge and information on the acceptance and use of the PCF driven by occupant expectations. Hellwig (2015) studied that having a few but successfully assigned controls and strengthening occupants' knowledge may lead to more satisfaction than providing a wide variety of controls, which could potentially lead to more confusion for occupants. The results of the interviews in this study showed that participants' knowledge of how to operate the personal ceiling fan, and a better understanding of how the fan works, could increase occupant satisfaction with the indoor environment. As studied by Day and Gunderson (2015), occupants in high-performance buildings who understood how to change their conditions were more satisfied with their environment than those who did not understand how to change it. Similarly, the results showed that communication about building refurbishment and the design objectives increased occupants' expectations, which in turn increased their satisfaction with the indoor environment. As studied by Leaman and Bordass (2007), occupants were more tolerant of conditions when they received more and better information about the building design and management.

Although successful communication of building adaptive opportunities can increase occupant satisfaction with the building, this does not necessarily correlate with occupant behaviors and interaction with the control systems (Steinberg et al., 2009). For example, the survey and interview results from this study showed that not all participants chose the PCF as their first cooling strategy or were necessarily satisfied with the device, even though the monitoring results showed that the PCF was most often turned on by these participants at high indoor temperatures. This apparent discrepancy between quantitative and qualitative data may have implications for the evaluation and implementation of PECS. Post-occupancy evaluation (POE) data should be accompanied by objective observations of physical conditions and occupant behavior to understand the actual performance of the buildings. To develop guidance on how to design with PECS, future studies should focus on the effective communication of PECS characteristics in the context of the building design and their interaction with the HVAC systems, particularly in building refurbishment. Understanding and aligning occupant expectations with building design, and providing personal control of different adaptive strategies, could increase the acceptability of PECS in non-residential buildings.

5. Conclusion

This study aims to investigate the impact of occupant knowledge, building design information and cooling expectations on the use and satisfaction with personal environmental control systems (PECS) and indoor environmental quality (IEQ) in non-residential buildings. Using a mixed-methods approach, including building monitoring, survey, and interview data, we investigated the use and acceptance of a personal ceiling fan in a building retrofit. The study found that aligning occupants' cooling expectations with PECS features, particularly personal control, increased occupants' thermal comfort and their interactions with the personal fan. In addition, employees with greater knowledge of how the fan works and awareness of the building design increased occupants' expectations and their satisfaction with the device and the IEQ, but did not necessarily correlate with their interactions with the fan. Overall, this study highlights the relevance of providing occupants with personal control possibilities and with information on how such technologies work. To increase the acceptability of PECS in buildings, their implementation should be accompanied by objective measurements and subjective post-occupancy evaluations of occupant feedback.

Acknowledgments

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Reducing operational carbon while maintaining thermal comfort through evaporative cooling

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Abstract:

Evaporative cooling systems have garnered attention for their energy-efficient cooling capabilities, particularly in hot and dry regions. This literature review delves into the advantages of these systems, including mist cooling technologies, water spray systems, and outdoor cooling applications. However, a research gap exists as there are limited studies on evaporative cooling in tropical climates and the integration of direct and indirect cooling approaches to enhance thermal comfort.
To address this gap, the research assesses cooling performance on different scales, spanning from the overall environment to individual occupants, while also considering the energy consumption required to achieve net-zero energy targets.
The research methodology involves conducting computational fluid dynamics (CFD) experiments, administering thermal comfort surveys, and testing direct evaporative cooling and water drip systems. The results showcase that passive wind walls significantly augment natural ventilation in the classroom, and the direct evaporative cooling system attains a substantial reduction in dry bulb temperature along with increased relative humidity.
Furthermore, the water drip system proves effective in lowering ambient temperature and displays potential synergy with direct evaporative cooling. Additionally, the study explores the viability of specialized paints, with White 2.0 paint emerging as the most efficient in reducing surface temperatures.
Overall, this research sheds light on the potential of hybrid cooling systems in tropical climates and offers valuable insights into designing efficient cooling solutions. Future investigations will explore the practicality of using cooled water for indirect cooling and further optimize paint applications to enhance cooling performance.

Keywords: Evaporative cooling; thermal comfort; low energy; tropics

1. Introduction

1.1. Literature Review

Evaporative Cooling Systems:

Several papers highlighted the benefits of using evaporative cooling systems in buildings, particularly in hot and arid climates. The study by Cuce & Riffat (2016) emphasizes that evaporative cooling systems have a great potential to save energy and are more cost-effective compared to traditional air-conditioning applications. Naticchia et al. (2010) present a new technology called "water-evaporative walls" that can reduce overall summer energy load in buildings by absorbing summer cooling loads through the latent heat of water evaporation.

Desert et al. (2020) conducted an experimental study to explore the impact of mist cooling technologies on outdoor comfort in a hot and humid climate. The study found that mist cooling led to a significant reduction in air temperature, mean radiant temperature, and the universal thermal climate index without significant increases in ambient humidity. The occupants consistently reported a cooling effect after spending time within the mist.

Montazeri et al. (2015) investigated the cooling performance of a water spray system with a hollow-cone nozzle configuration. The study investigated the impact of several physical parameters on the evaporative cooling provided by the system. The study found that increasing the temperature difference between the inlet air and the inlet water droplets improved the sensible cooling capacity of the system. Injecting water droplets with a temperature higher than the dry-bulb temperature of the air can still provide cooling, although the amount of cooling reduces considerably compared to the case with water at lower temperatures. The study also shows that reducing the mean droplet size and increasing the width of the droplet size distribution can enhance the cooling performance of the system.

Ulpiani (2019) conducted a systematic review of mist spraying systems used for outdoor cooling in different climatic contexts. The study highlighted the potential of water spraying against local overheating and the heterogeneity in investigation techniques and performance metrics. Water spraying is a cost-effective, versatile, and high-impact blue mitigator.

Cooling Technologies in Outdoor Spaces:

Yang et al. (2013) present a study on thermal comfort in outdoor urban spaces, while Farnham et al. (2015) discuss the use of an evaporative spray cooling system to provide thermal relief on hot days in outdoor spaces. The results from Yang et al.'s study showed that solar radiation has the most significant influence on human thermal sensation in outdoor spaces. Meanwhile, Farnham et al. found that the mist and fan combination was highly efficient in providing thermal relief to pedestrians in subtropical climates. Vanos et al. (2020) studied the use of outdoor misters in restaurants in a hot, dry climate to improve thermal comfort for customers. The study found that outdoor misters were effective in reducing the thermal stress experienced by customers. However, the study also highlights the potential risks associated with the use of misters, such as increased humidity and the risk of Legionella bacteria growth.

Optimization of Dry Mist Systems:

Two papers focus on the optimization of dry mist systems for thermal comfort in a controlled environment. The study by Parametric study on the cooling effects from dry mists in a controlled environment analyzed different values for wet bulb depression, pressure, and water temperature. The results showed that wet bulb depression is a good indicator for determining operating conditions of the dry mist system, while the pressure can be varied to achieve optimal cooling at various heights on a fixed distance downstream. The study by Experimental investigation on the performance of a water spray cooling system examined various factors that influence the system's performance, including nozzle atomization effect, spray height, heat flux, inlet pressure, and gravity angle. The study found that the spray mass flow rate is the main influencing factor, and the heat transfer performance improves with an increase in mass flow rate.

Zheng et al. (2019) studied the use of air-assisted "Dry Mist" systems for cooling in hot and humid tropical countries like Singapore. Suitable operation conditions were found to be during hot afternoons where Relative Humidity is lower, between 50–65%. Wind velocities above 0.58 m/s and Solar Irradiances above 571 W/m2 are the limits for operation. The study also found that the majority of the participants felt colder from the system, and there was an increase in wet feeling pleasantness.

Models for Water Droplet Evaporation:

Two papers proposed models for water droplet evaporation. Belarbi et al. (2006) proposed a cellular approach to estimate the time needed for water droplet evaporation in shower towers and passive downdraft evaporative cooling. The approach considers the spray as a pile of rigid spheres of equal size, each containing a drop in its center. Meanwhile, Dombrovsky et al. (2011) present a model for calculating the amount of direct and scattered solar radiation that can pass through a mist layer of water droplets in the atmosphere. The model takes into account the water content and droplet size of the mist layer, and can be used to study the potential of water misting systems as a protection from harmful UV radiation.

Application of Mist Systems in Urban Areas:

Giuseppe et al. (2020) present a study on the use of dry mist systems as a water-based mitigation strategy against urban overheating. The study uses a 3D microclimatic model in ENVI-met to simulate a misting system installed in Rome, Italy, and performs parameterizations on the water mist system to determine the impact of key design variables on the cooling capacity. The results show that the cooling capacity increases with the total water flow rate and in the presence of calm air.

Passive cooling methods have been found to be effective in improving thermal comfort in hot and humid climates. Oropeza-Perez & Østergaard's (2018) study identified building color, shading systems, night ventilation, controlled ventilation, roof coating, and eco-evaporative cooling as the most suitable passive methods for extensive use in the Mexican housing sector. A decision-making program was developed to determine the most suitable cooling method for a dwelling based on the climate, status (new or existing), and affordability.

Salas et al. (2021) focused on designing the best opaque double skin facade with an evaporative cooling system. The study used numerical simulations to find the optimal air cavity width and spray water characteristics, such as droplet size and nozzle separation. The best arrangement for hot-arid conditions is an air cavity of 0.4 m, a droplet size of 25 μm, and a separation of 0.6 m between each nozzle. The method can be used to design and evaluate double skin facades with evaporative cooling strategies.

1.2. Research Gap

Most of the papers reviewed indicate the success of evaporative cooling systems for thermal comfort in non-tropical climates where there are larger wet bulb depressions. However, there is a lack of similar studies in the tropical climates. Furthermore, these studies typically adopt direct evaporative cooling methods like misting. There are few studies that consider indirect systems, and even fewer that look at integrating both systems for thermal comfort.

1.3. Research Objectives

This study seeks to accomplish the following objectives:

- To design, fabricate, and optimize, an indirect-direct evaporative cooling system that is suitable for thermal comfort in the tropics
- To analyze the degree of cooling that can be provided in both the environment-scale and the human-scale
- To measure and calculate the operational energy required for such systems, in the context of an entire building, for pushing towards net-zero energy

2. Research Methodology

2.1. Site context

This study was conducted in a secondary school based in Singapore, a country in the tropics, with hot and humid climates throughout the year. The school campus is located in the central west region of Singapore and there are only mid-rise residential apartments in the immediate proximity of the campus, as shown in Fig 1. The campus is well ventilated due to the low urban density in that area and unblocked access to the prevailing wind coming from the south and south-west.

Figure 1 Site context of the school campus (circled in red)

A specific classroom on campus was chosen for the study. The dimensions of the classroom measure 7.5 width by 8.5m length by 2.7m height and has sufficient capacity for 40 students. The east-facing wall has a window-wall ratio of 0.8 and is made of glass and metal façade. Roller blinds are installed along the perimeter of the east-wall to provide shading from the sun during hot mornings. Two doors are located on the opposite west-facing wall, allowing cross ventilation through. Due to the class size, the room is considerably densely packed. There are also seven ceiling and wall fans, so the interior space is very drafty even without natural ventilation.

There are several key challenges for this classroom. Firstly, due to the average high humidity, evaporative cooling is not typically considered a good solution. However, a horizon scan across humidity levels in the hot afternoons suggest that evaporative cooling can be a viable and sustainable alternative to providing thermal comfort. This is illustrated in Figure 4 below. Secondly, the classrooms are poorly oriented towards the sun, and gets full blown sun in the morning when classes are ongoing. The radiant temperatures get significantly high due to the direct solar exposure through the glass facades. While shading devices are installed outside the window, the widths are too short to provide effective shading. The school has installed roller blinds to circumvent this issue, but the roller blinds are mostly non-porous and thus also block natural ventilation into the room.

2.2. Climatic Conditions

Singapore is located near the equator and has hot and humid climatic conditions throughout the year. Figures 2 & 3 show the Dry Bulb Temperature (DBT) and Relative Humidity (RH) values for Singapore's climate. Being situated near the equator, Singapore does not experience any seasonal changes, and the climate is rather consistent throughout the year. Daytime temperatures are around 29-34^{o}C, while night-time temperatures are 23-28^{o}C. Daytime RH is around 50-80%, while night-time RH is around 80-95%.

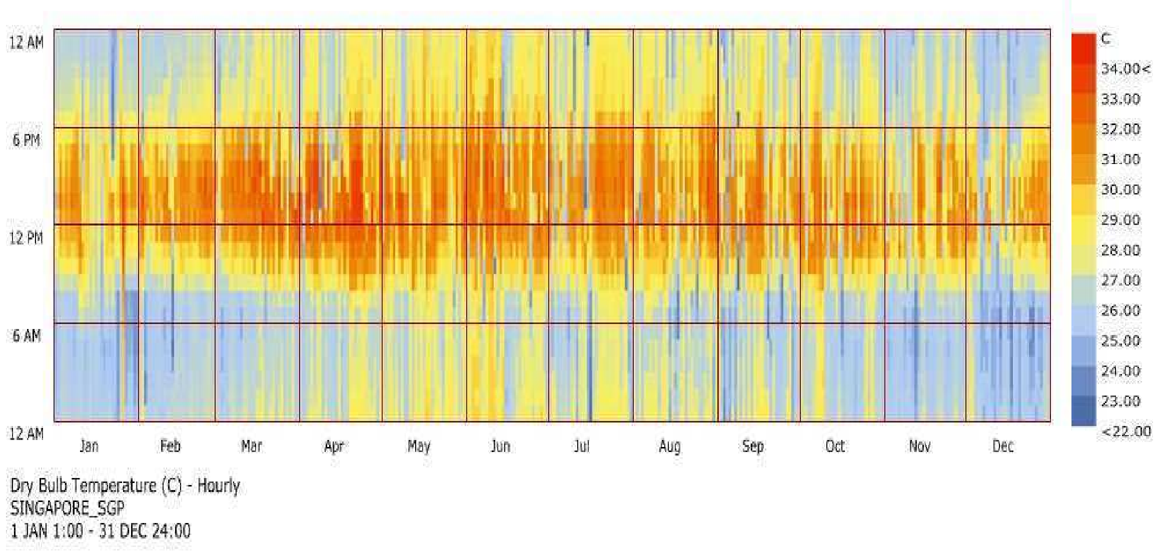

Figure 2 Dry bulb temperature climatic values for Singapore

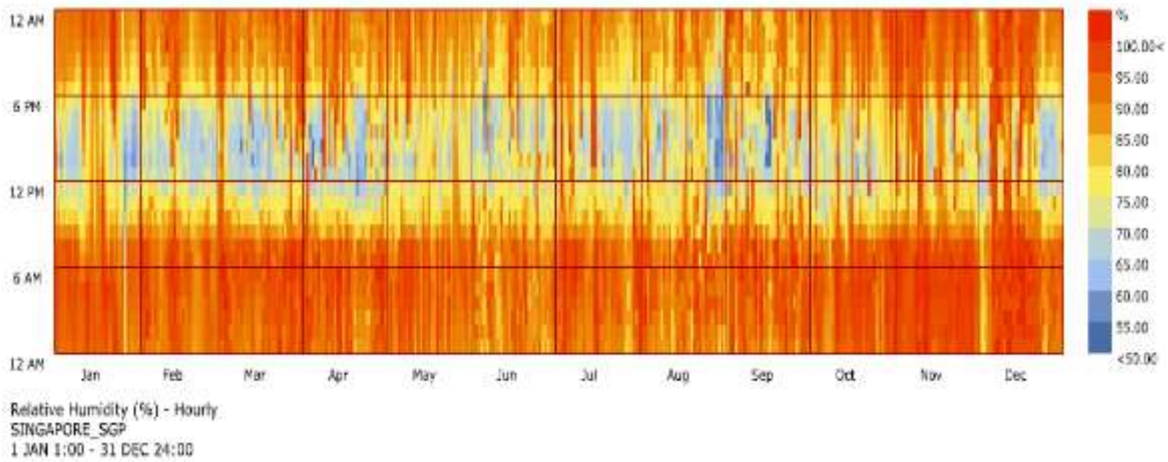

Figure 3 Relative Humidity climatic values for Singapore

The climatic conditions for Singapore can be extracted from the Energy Plus Weather (EPW) file and imported into a Psychrometric chart for better visual representation. The daytime conditions, from 9am to 5pm, are shown in Figure 4 and the number of hours for those conditions are represented by blue shaded boxes. The amount of shading shows the number of hours, with the darker boxes representing more hours. It can be seen that the darkest regions are when RH values are between 60-80%.

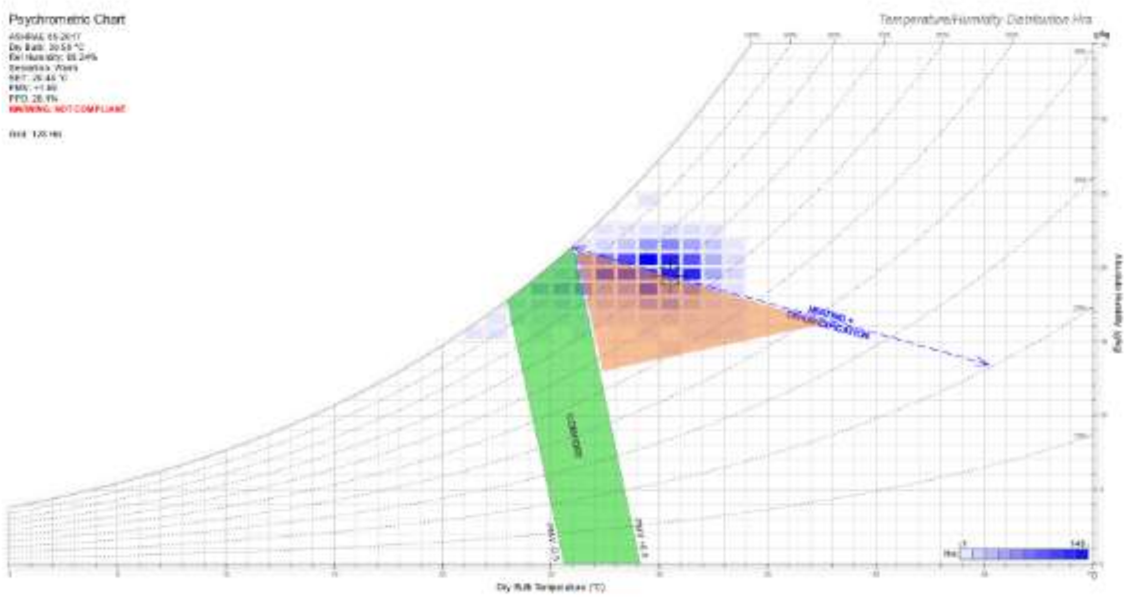

Figure 4 Psychrometric Chart showing Singapore EPW values

A thermal comfort band, based on ASHRAE 55 standard for Thermal Comfort, can be plotted into the Psychrometric chart, represented by the green region where Predicted Mean Vote (PMV) is between -0.5 and +0.5. The comfort band is based on 0.6 m/s wind velocities, 0.7

Clo value, and radiant temperatures equal to DBT. The wind velocity is chosen based on average values measured in the classroom, and the Clo value is based on the students' uniforms.

The potential for evaporative cooling can then be represented on the chart, shown by the dotted blue line. Evaporative cooling is an adiabatic humidification process, where there is no change in enthalpy. The limit of evaporative cooling is represented by the wet bulb depression, which is the difference between the dry bulb and wet bulb temperatures. With the EPW data, comfort band, and evaporative cooling line, the orange shaded region shown means that at least half of the hours outside the comfort band can be moved within the band through evaporative cooling.

2.3. Evaporative Cooling Solutions

This study tested three different methods for Direct Evaporative Cooling (DEC). For all solutions, the total energy consumption is measured with an energy meter in terms of Watt-hour (Wh). The water consumption rate is also measured physically in terms of litres per hour (l/h)

The first system tested is the Ultrasonic misting system. This system uses ultrasonic nodes to vibrate water at ultra-high frequencies and force the evaporation of water. The equipment used here is submersible and includes ten ultrasonic nodes. The schematic for the system is shown in Figure 6. It is placed in a tank of water, with a fan placed on top of the tank to direct the mist further into the classroom, represented by Figure 5. This works based on the negative pressure generated from the back of the fan, providing suction for the mist to be redirected.

Ultrasonic Mister:

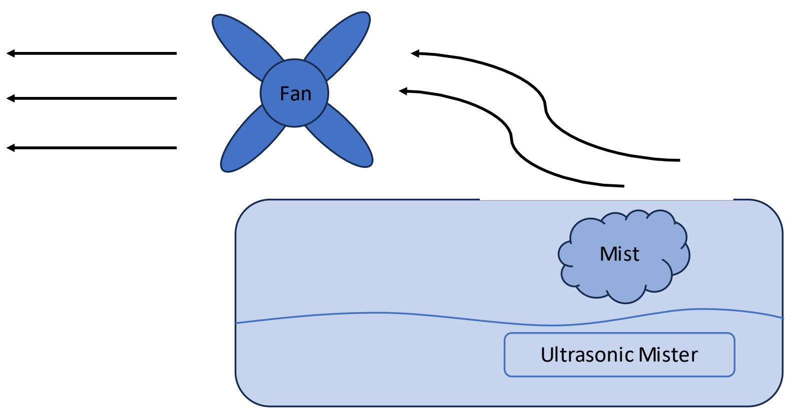

Figure 5 Ultrasonic misting system set-up

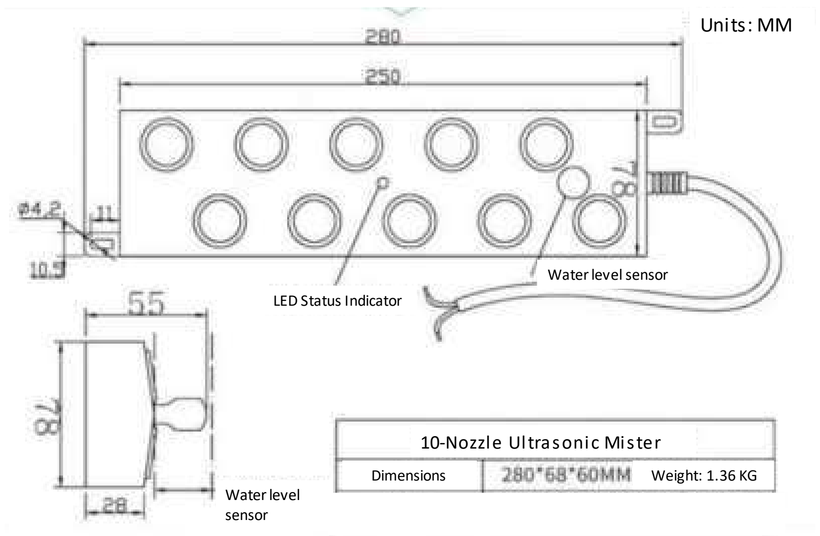

Figure 6 Schematic for 10-nozzle ultrasonic mister

The energy consumption rate is measured to be 63Wh for one system, including the mister and the floor fan. Two of such systems are placed in the classroom to provide evaporative cooling. The water consumption rate works out to be 0.5l/hr per system.

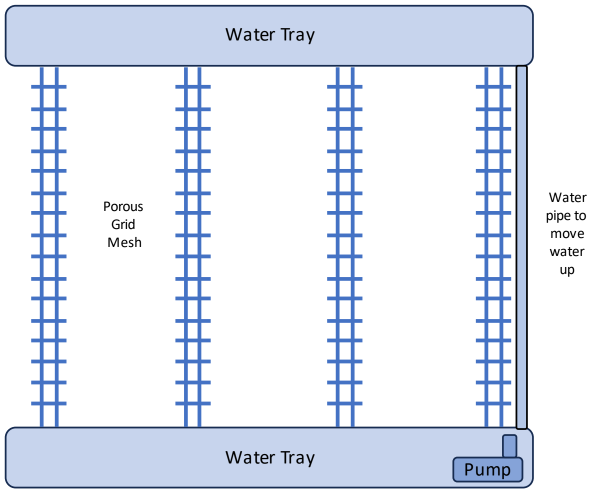

Figure 7 Sectional view of water drip system

The second system tested is the water drip window system. The system consists of water trays at the top and bottom, with strips of porous media in between, and an optional water pump to move water up. This is represented by the schematic shown in Figure 7. The strips of porous media are meant to be wetted, like water wicks, as water drips downward, and the porosity allows natural ventilation to flow through. This leads to direct evaporative cooling and uses very little energy since it taps on natural ventilation. The porous media is made of nylon, and water from the bottom tank can travel up the material through capillary action. Water from the top tank can likewise travel up the material, before moving downwards through gravity. Due to the combined forces of capillary action and gravity, the water wicks remain wetted throughout the day even without the need for water pumps. The energy consumption is 0 Wh, and the water consumption rate is 50ml/hr.

2.4. CFD Experiment

A Computational Fluid Dynamics (CFD) study was also conducted to evaluate the wind flow into the classroom. The goal is to use less energy for mechanical ventilation and tap more on natural ventilation. The CFD software used is ANSYS Fluent 2022 version and meshing is done using ANSYS Mesher with the following settings:

- Domain has 1.58 mil cells for both simulations.
- Mesh quality is checked to ensure there are no skewed cells with skewness > 0.9.
- Realizable K-Epsilon turbulence model with scalable wall functions is adopted for the wind flow simulations.

2.5. Thermal Comfort Survey

Thermal comfort surveys were conducted to evaluate the subjective comfort of the building occupants. The respondents for the thermal comfort survey were all girls aged 13, since the experiment was conducted at classrooms allocated for secondary-1 schoolgirls. The girls are dressed the same during the experiments, in blouses and covered shoes, having a Clo value of 0.7.

Several environmental measurements were taken simultaneously with the survey. Temperature and Relative Humidity data loggers, research-grade HOBO MX2301A, are spaced out around the classroom, and data is measured across 5 different locations. A weather station is also placed on the roof of the same building, to measure ambient air temperature and relative humidity data.

In a chosen day, the survey is conducted for the same students three times at different times of the day. The first survey is conducted before the cooling systems are turned on (thus termed 'baseline'). The second survey is conducted 1hr after the cooling systems are turned on, so that the classroom can reach an equilibrium state. The third survey is conducted 1hr after the cooling systems are turned off, to test the thermal adaption of the students.

2.6. Paint Tests

Tests were also conducted for three selected paints. The goal is two-fold. Firstly, if effective, these paints can be used on the building façade to reduce solar heat gain into the building. Secondly, the water temperature decreases during the operation of the evaporative cooling system. This lowered water temperature can possibly lead to greater cooling if used in indirect evaporative coolers. However, the water temperature also gets raised as it gets exposed to ambient air. Thus, the goal is to keep the water as cool as possible for further applications.

The set-up is shown in Fig 8. The three paints used are namely a normal ceiling white paint, Nippon SolaReflect paint, and White 2.0 paint. The SolaReflect paint employs a cooling technology to supposedly reduce solar heat gain by reflecting solar radiation. The White 2.0 paint is the paint with the whitest pigment available commercially and claims to reflect more UV light than other white paints. A control, an unpainted 3mm thick acrylic, is also used. Type-K thermocouple wires are taped with silver reflective tape at the back of the acrylic sheets, to measure surface temperatures.

Figure 8 Paint tests conducted on clear acrylic sheets

3. Research Results

3.1. CFD Experiment

A CFD simulation was run for the existing classroom, considering average 2.8m/s natural ventilation. This is based on technical guidelines from Singapore's Building and Construction Authority (BCA). All windows and doors are assumed to be open. Area averaged wind velocities are taken at 1m height from ground, as shown in Figure 9. This height represents the average height where the students feel cooling effect when seated down. As seen in Figure 9, there is good wind flow only along the lines of cross ventilation between windows and doors, represented by green and red contours. The area weighted averaged wind velocities in the classroom is calculated to be 0.57 m/s, which is a good gentle breeze. However, ventilation around the tables and chairs can be improved. The current layout makes it too dense and hard for wind to flow, leading to many stagnant zones represented by blue contours.

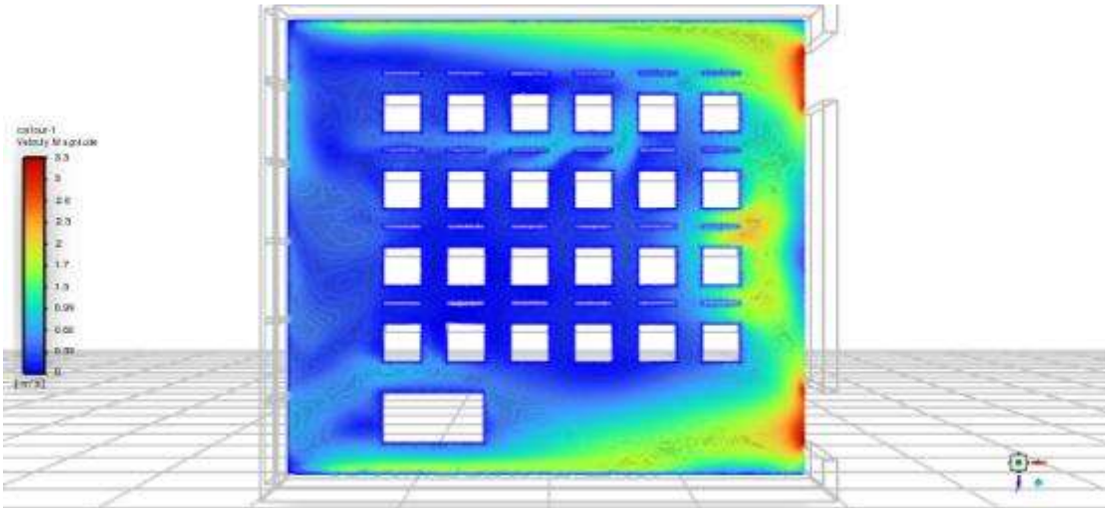

Figure 9 Wind velocity contours at 1m height

Wind velocity contours are also taken across the front and back sections of the classroom, as shown in Fig 10. Due to the design of the windows where there is a parapet wall at the lowest elevation, wind flow is mostly directed to the higher elevations of the classroom. Air at the table height is thus stagnant, shown by the blue contours around the table regions. The same results are found in the middle of the classroom.

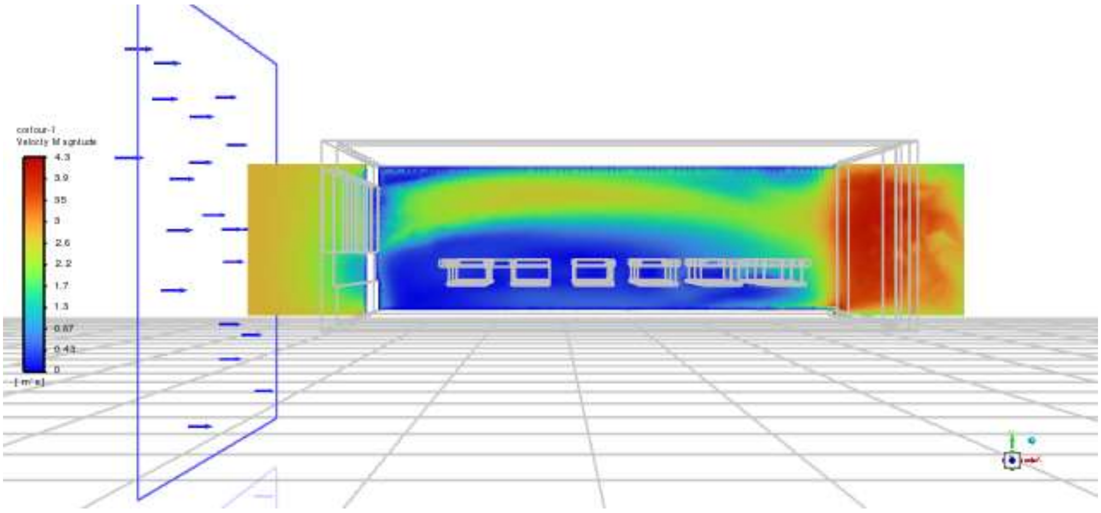

Figure 10 Wind velocity contours at the back of the classroom

To improve the natural ventilation in the classroom, an intervention was introduced in the form of angled wind walls. To direct the wind flow into the lower elevations, wind walls are installed on the window railings. These walls are only 1cm thin, extends 20cm out from the window, non-porous, and angled at 30 degrees toward the ground plane. Two layers of these walls are installed, at the mid-height of the window, and at 90% of the window. These walls are installed only in the middle of the room, shown in Fig 11, where there is no true cross ventilation since wind flow is already good in those areas.

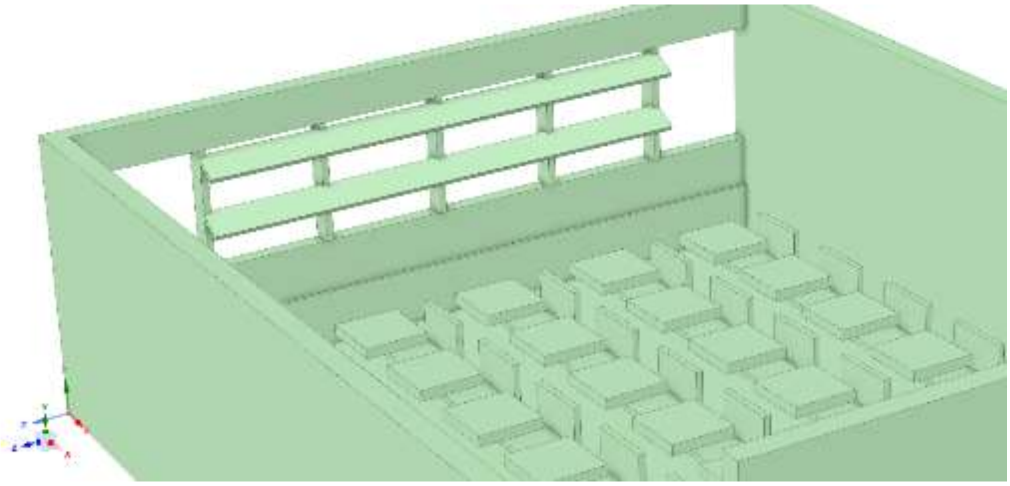

Figure 11 Angled wind walls on the window railings

The resultant wind flow both at the horizontal and vertical plane are much improved. Fig 12 shows the wind flow at 1m elevation, and wind flow through the tables and chairs is very good and starts to slow down further downstream from the windows. But even then, there is good wind flow more than 1m/s.

The value of installing these wind walls is clearly seen in Fig 13. Where the wind was originally directed towards the ceiling like in Fig 10, the wind is now directed towards where the students are seated. Some of the wind is also directed towards the feet from the redirection from the tables.

The area weighted average wind velocity is now 0.96 m/s, compared to 0.56 m/s without the intervention. This represents much better thermal comfort, with just a passive system, with no energy consumption, installed.

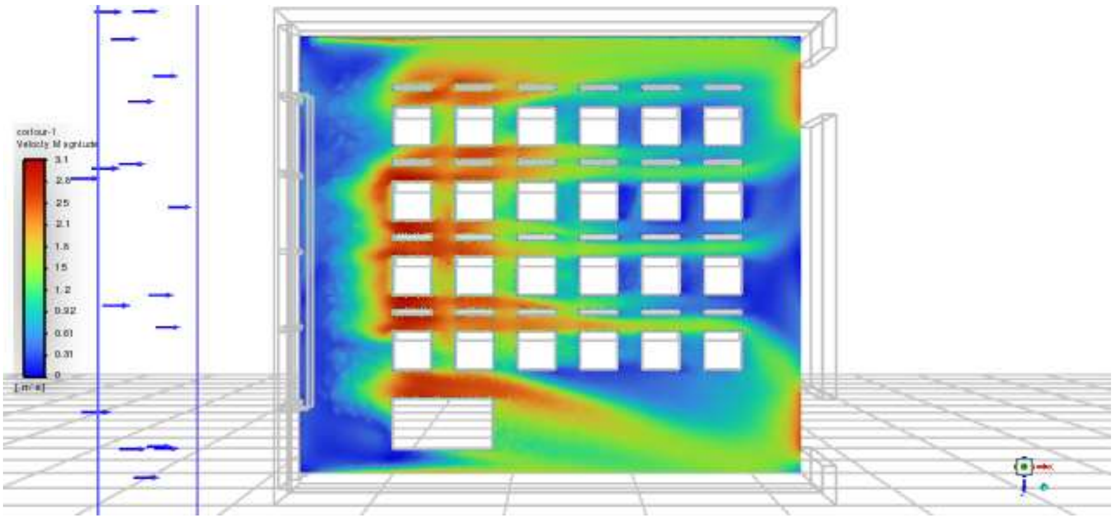

Figure 12 Wind velocity contours at 1m elevation

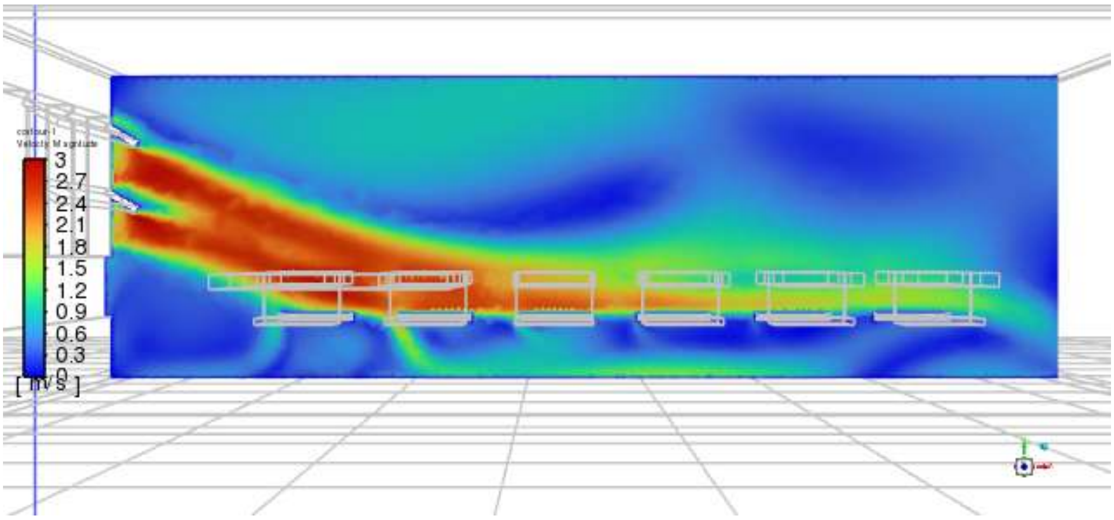

Figure 13 Sectional wind flow contour in the middle of the room

3.2. Direct Evaporative Cooling System

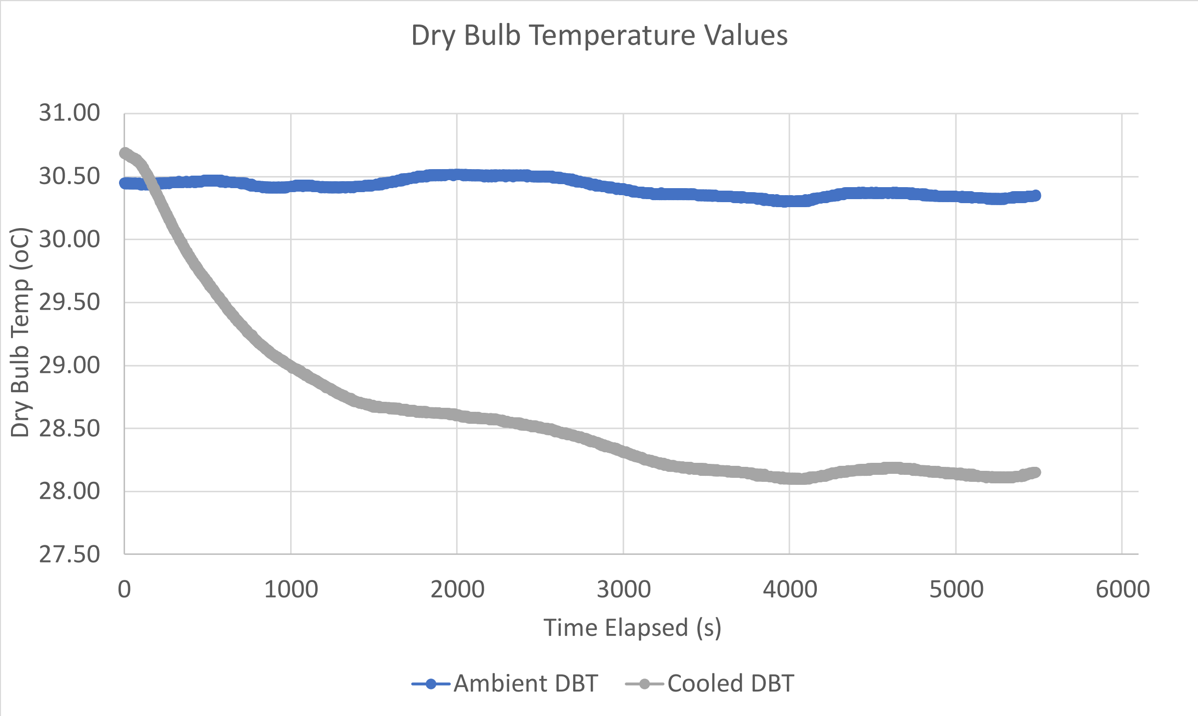

Figure 14 Air temperature values comparing ambient and cooled air

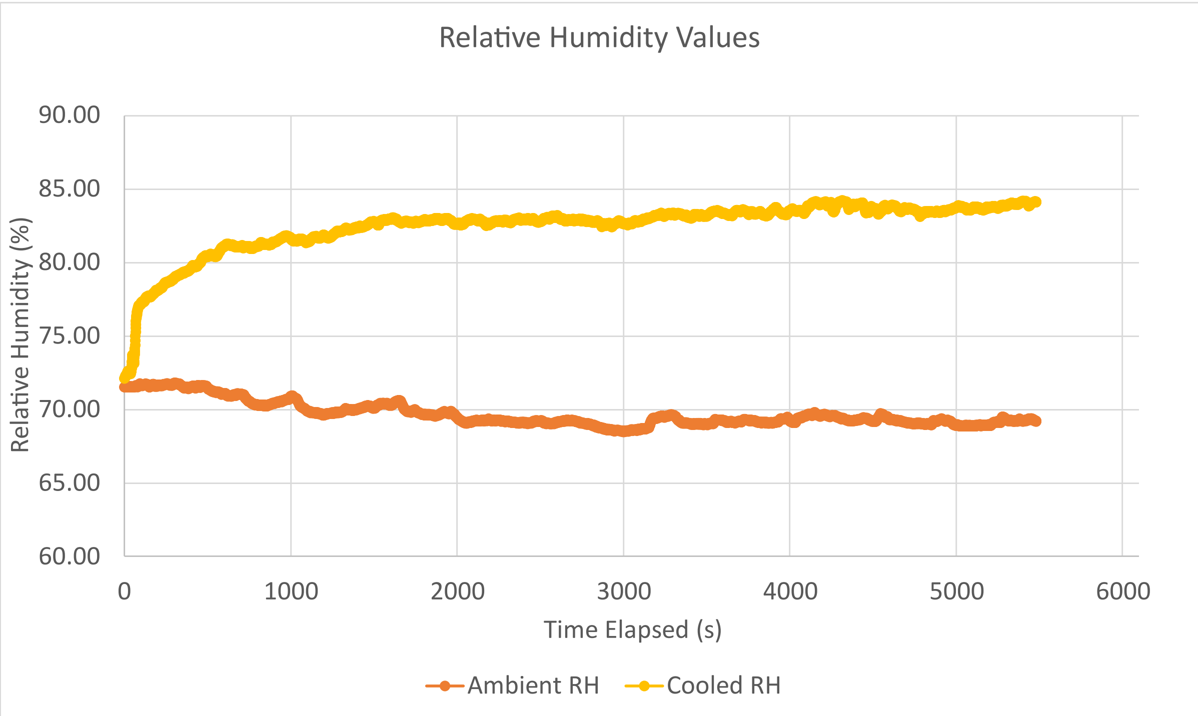

Figure 15 Relative humidity values comparing ambient and cooled air

The DEC system was run for about 90 mins and the dry bulb temperature (DBT) and relative humidity (RH) was recorded through the data logger. They are shown in Figures 14 and 15. Several observations can be made. Firstly, after reaching an equilibrium state and the data points have stabilised, it was observed there was a 2.2°C drop in DBT, with a premium gain of

15% RH. This was expected and is roughly along the line of adiabatic humidification like shown in Figure 4. Next, it can be observed that from the start point of operation, it took almost 1 hour for the DBT data points to reach equilibrium. On the other hand, it took only about 10-15 minutes for the RH values to stabilise. This can be attributed to the fact that as evaporative cooling occurs, the water that flows back into the water tank also decreases in water temperature. This process repeats until the water temperature does not change any further. This also represents the potential for the cooled water to be further reused for indirect evaporative cooling using a heat exchanger.

3.3. Window Drip System

The results from the window drip system are shown in Figures 16 & 17. In the first hour of measurement, the weather was hot and sunny, before it turned cloudy for the next hour. This explains the general variations in values across time. However, comparing the ambient and cooled air, the temperature drops ranged from 0.5 to 1^{o}C, together with a premium in RH of about 2-3%.

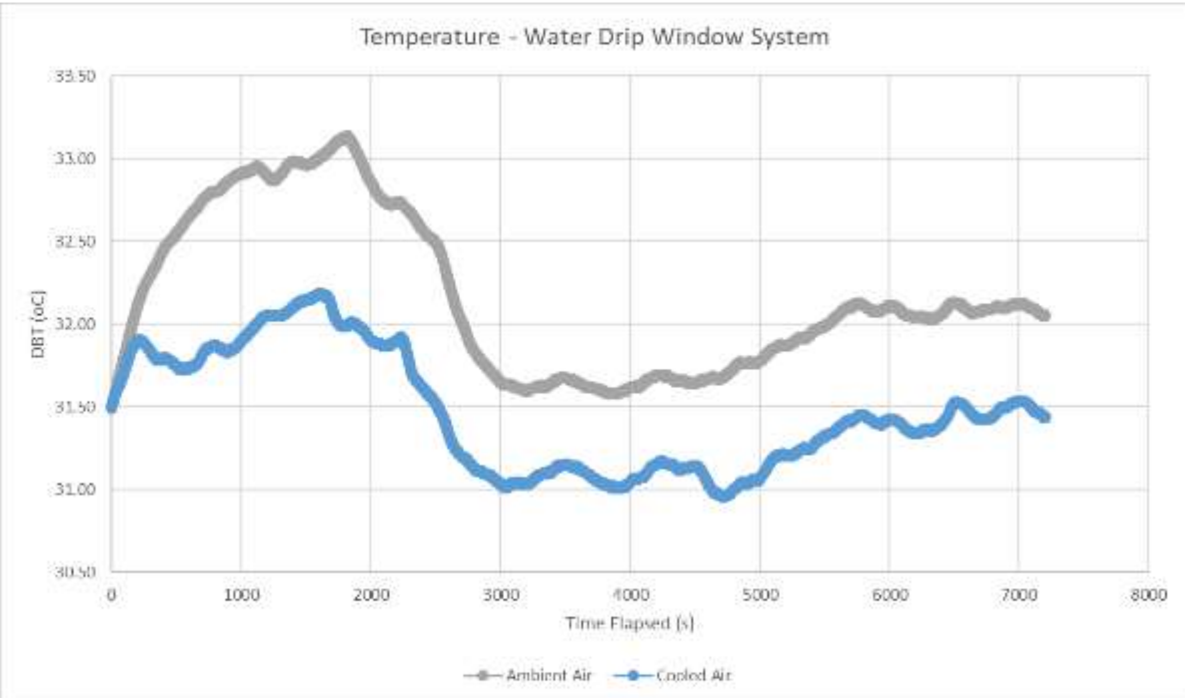

Figure 16 Temperature differences in the water drip window system

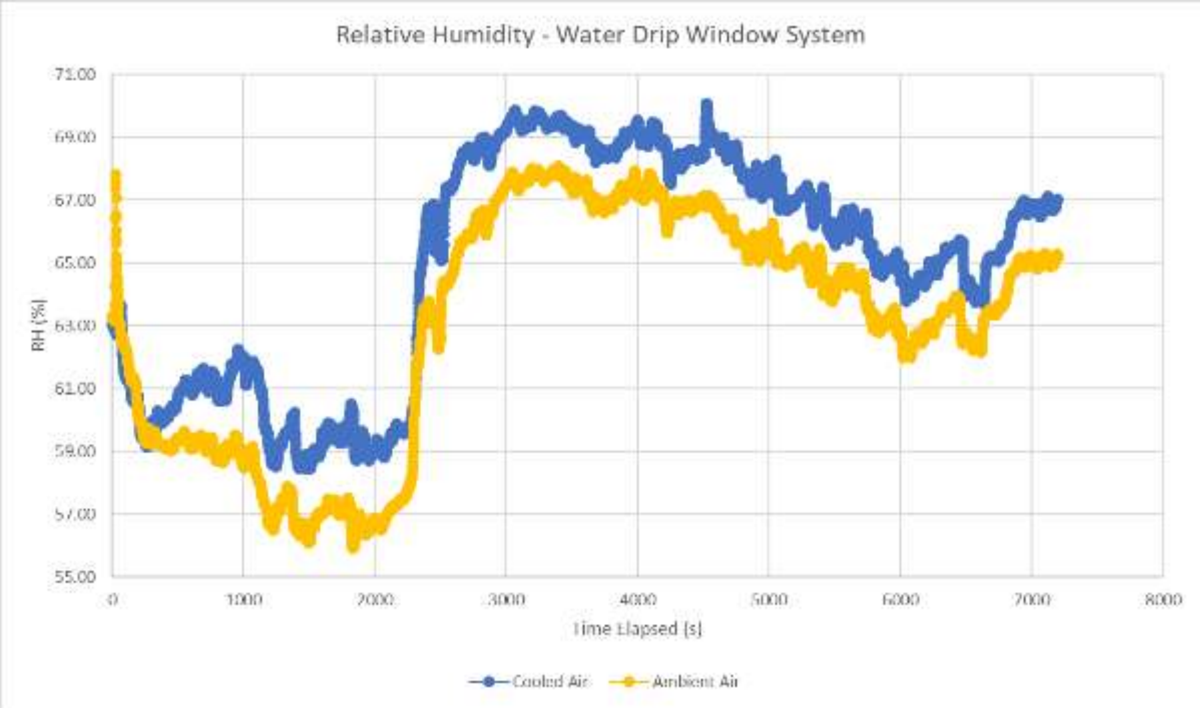

Figure 17 Relative Humidity value differences in water drip window system

3.4. Paints Test

Figure 18 shows the results from the paints test. The ambient air temperature was also measured, and the temperatures showed gradual increase as the day went by, represented by the yellow line. The control, 3mm thick acrylic with no paint, expectedly showed the highest increase in surface temperatures. For most of the duration, the surface temperature was 10^{o}C higher than the ambient air temperature. This peaked as high as a 15^{o}C difference. The control is represented by the light blue line. The other three selected paints displayed results that were similar, averaging about 3-6^{o}C higher than ambient air temperature. The normal white paint and the SolaReflect paint showed the most similarity. The White 2.0 showed the best results, averaging about 1-1.5^{o}C lower than the other two paints.

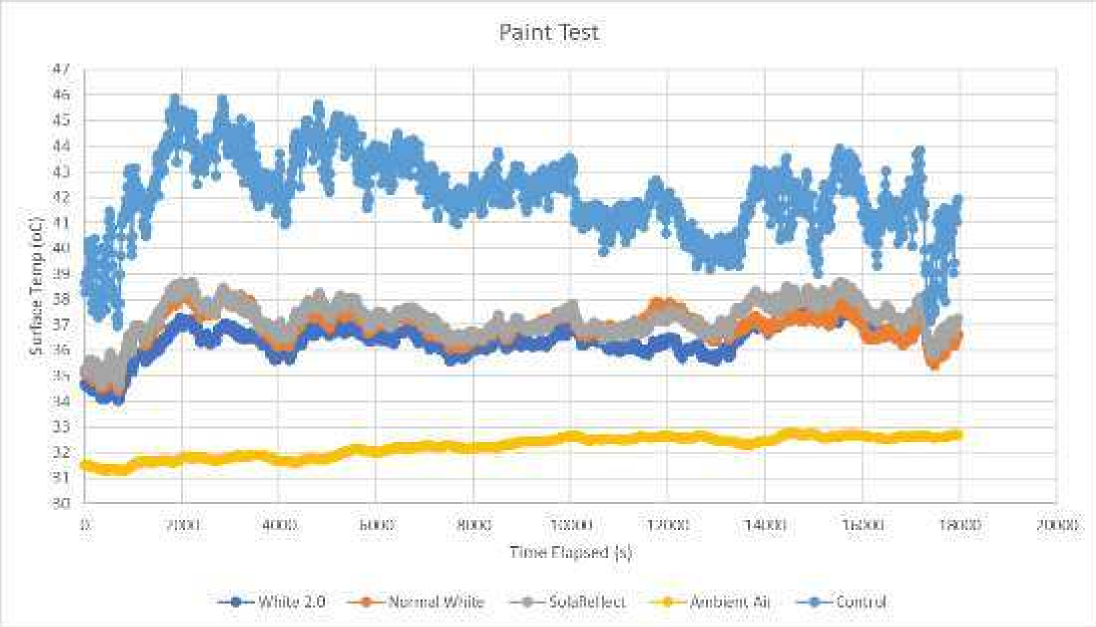

Figure 18 Paints test for surface temperatures

After determining that the White 2.0 paint is the most effective, retroreflective beads were added to the White 2.0 paint. In order that the beads do not fall off when exposed to the elements, the beads were scattered on two coats of paint first, then covered with another coat of paint. Expectedly, this meant that the beads are unable to fully reflect sunlight back towards the source. Such results can be seen in Fig 19. Overall, the surface temperature results are worse than purely using White 2.0 paint. This may be explained by the thermal mass of the beads having a higher thermal conductivity. However, the greatest difference is that the surface temperatures fluctuate at much wider margins where they heat up very quickly, but also cool very quickly when the sun is covered by clouds. This can be seen from the widely fluctuating line compared to the gradual changes from the paints' line. This represents an opportunity, since we can get surface temperatures that are much closer to ambient air temperatures, if not directly exposed to the sun. As seen in Fig 16 in the best-case scenario, the surface temperature was only 1^{o}C above the ambient.

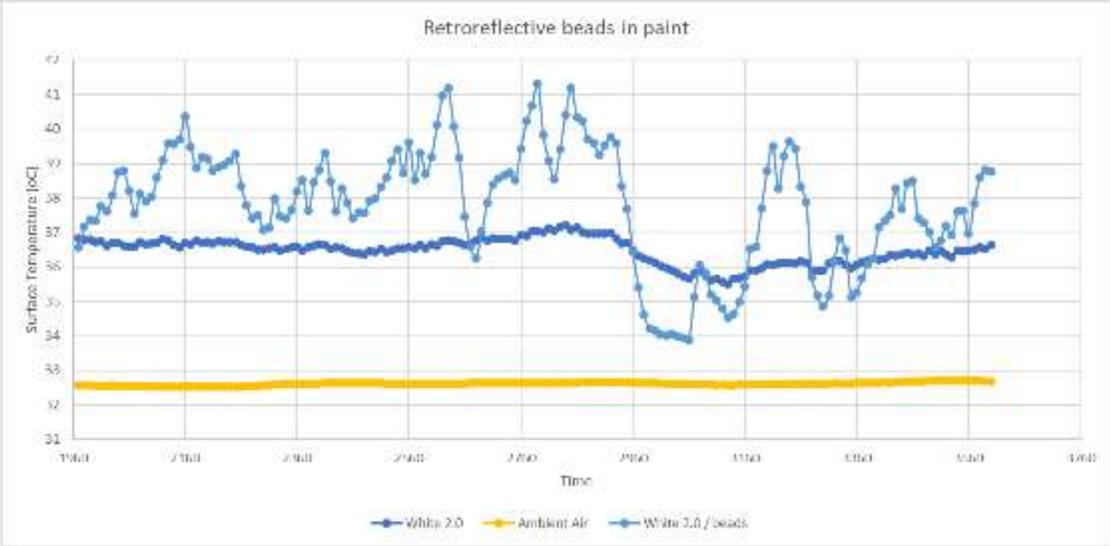

Figure 19 Retroreflective beads with White 2.0 paint for surface temperature

4. Results Analysis

4.1. CFD Experiment

Looking at the baseline study, although the area weighted average wind velocities indicate comfortable values, the wind flow around where the occupants are seated is very stagnant. This can be attributed to the densely packed seating arrangement, the design of the window openings at a higher elevation, and the lack of true cross ventilation in the room, except for the front and back of the room where the doors are located. Because of the stuffiness, the school has installed 7ceiling and wall fans in the classroom, thus increasing energy consumption at roughly 300Wh per hour. Of the possible reasons, designing windows at lower elevations of a room is not possible due to safety concerns, while creating openings at the eastern side of the room is also not possible as it leads to a corridor and there are concerns for noise.

However, this study has shown that by installing a passive and low-cost wind wall, wind flow can be redirected towards important areas of the room where occupants spend the most time. In fact, the wind velocity may even be a bit too drafty for some occupants. Furthermore, the large wind flow volume into the classroom also means larger volumes of warm ambient air in the room. This conflicts with the evaporative cooling system since the goal is to retain the cooled air within the room as long as possible. Given that the air change rate is much higher than necessary for fresh air requirements, future studies will look at reducing the overall air change rate by reducing the window opening size, while still ensuring sufficient wind flow, and thus also allow the evaporatively cooled air to remain longer in the room

4.2. Direct Evaporative Cooling System

The results from the DEC are plotted on a psychrometric chart and shown in Fig 20. As shown above, the green band represents the zone that is thermally comfortable, and the blue shaded boxes represents the number of hours Singapore experiences those conditions. The average change from the DEC is shown by the red circles and line. There is a clear movement closer towards the band of thermal comfort, but it still falls short by about 1.5°C. Should the amount of evaporation from the DEC increase, it seems likely to achieve the thermal comfort band. However, that would likely come at the expense of fully saturated air. It is of the authors' opinion that that is not ideal, and thus highlights the shortfall of using purely DECs.

To achieve the 1.5°C further reduction, solutions that either only increases humidity by a little, or do not increase the humidity further should be adopted. Further research will investigate using the cooled water and redirecting them to be used in indirect evaporative coolers. The results, combined with the results from the water drip window system, also show great potential at bringing the ambient conditions very close to the thermal comfort zone.

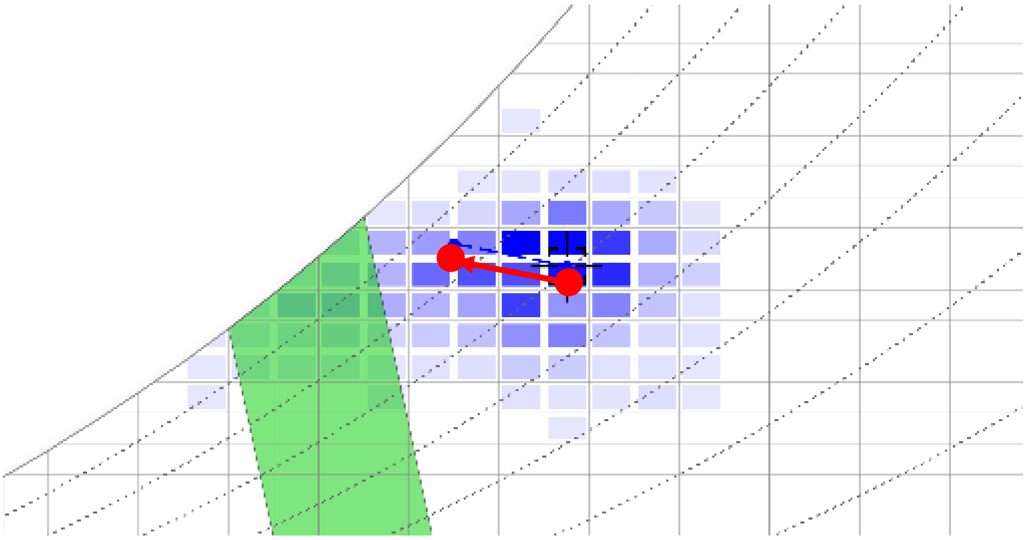

Figure 20 Psychrometric chart showing change in air conditions from evaporative cooler

4.3. Water Drip Window System

The decrease in DBT is not significant, only at 1°C at the maximum. This is expected, considering that this system uses net zero energy, and the water consumption rate is also low. However, in the cooling of a space, the DBT is not the only important metric, and one must also consider the volume of air (in terms of CFM) in those conditions. Since the system is retrofitted unto existing windows, the CFM is significantly high from the size of the window openings. Compared to the DEC system which provides spot cooling, the water drip system provides an overall decrease in temperature across the room, thus highlighting the value of such a system. The increase in RH of about 2-3% is relatively insignificant and unlikely to further contribute to uncomfortable wet sensations for the occupants. The system thus shows good synergy with the DEC system, since the air is pre-cooled as it enters through the window openings, before it is further cooled via spot cooling from the DEC. The only potential energy consumption comes from the water pump, which was about 5Wh. This may be used when the evaporation rate is higher than the capillary action of the water wicks.

4.4. Paints test

It was shown that the chosen white paints all showed similar results in surface temperatures, but White 2.0 showed the best results. Given the cost premium for the White 2.0 compared to normal white paints, it seems to suggest it may be more economical to use normal white paints. Regardless, the use of white reflective paints is undoubtedly useful for reducing solar heat gain. Further studies will look at adopting this paint on the water tanks that hold the evaporatively cooled water and test if the water can be kept sub-ambient to be used for indirect evaporative coolers.

The results from the use of retroreflective beads are more mixed. The heat transfer rate, or thermal conductivity, increased when the beads are used with the White 2.0 paint. This meant that the surface heated up faster, but also lost heat more quickly. This could be useful under shaded conditions, or if it is undesirable for heat to be stored in the thermal mass. Further tests will be conducted to determine the effectiveness of the beads without painting over them

5. Conclusion

This study looked at improving thermal comfort through the domains of wind velocity, air temperature, and relative humidity, by adopting low-energy consumption solutions. The wind walls significantly improved the wind velocities within the classroom. The water drip system and DECs also improved the air temperatures in the classroom, bring thermal comfort significantly closer to the comfort band.

However, the solutions proposed still did not manage to improve hot afternoon conditions to within the thermal comfort band. Further solutions that do not significantly increase the air humidity must be considered. One such approach is the use of indirect evaporative coolers, and this will be tested in a further study.

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Designing Local Radiant Heating Devices for Different Body Parts: Effects on Skin Temperature

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Abstract:
Local radiant heating systems are a promising alternative to traditional heating systems, as they can provide targeted warmth to specific body parts without heating the air around them. This can lead to significant energy savings, as well as improved thermal comfort. This paper presents the design, development and testing of radiant heating devices for specific body parts to study how skin temperature changes. These results will be used to enhance an existing thermal sensation and comfort model which correlates with skin temperatures, because the model was developed based on air convection heating, which could be different from the radiation heating. To achieve this goal, localized radiant heating devices for different body parts were designed to ensure minimal asymmetric radiation from surrounding surfaces and maximize the potential for increasing mean skin temperature. For this study, the human body was divided into 18 different segments. Devices were designed for specific body parts such as the head, face, neck, chest, arms, leg, hand, foot, back, and pelvis. The localized body-part radiant heating devices were designed, built, and tested in a climate chamber under controlled conditions where the mean air temperature was 19.5±0.5°C. A total of 10 participants tested the device on 18 different body parts. The results of our study indicated that the use of local radiant heating devices at ambient temperature of 19.5°C led to an increase in skin temperature and the subjects' local skin temperature reached to the neutral skin temperature which was achieved in an ambient temperature of 26°C. Consequently, this temperature increment helps individuals maintain better thermal conditions even in cooler environments.

Keywords: Localized heating, Local radiant heating, Radiant heating device, Skin temperature, Low-energy

1. Introduction

Local radiant heating systems unlike traditional heating systems, which heat the whole indoor environment, provide targeted heating to specific body parts. Local radiant heating methods have benefits, such as quiet operation (Hao et al, 2007), minimal air movement and dust circulation (Olesen, 2002), and reduced temperature fluctuations (Lin et al, 2016). In addition, radiant heating minimizes heat loss since the air is not directly heated, as opposed to traditional air heating systems that cause a higher rate of heat loss (Taumoefolau et al, 2004).

Due to the reasons mentioned above, along with many others, radiant heating devices/systems are becoming more and more popular (Rhee, 2015). This is evident by the fact that 30-50% of new residential buildings in Denmark, Germany and Austria are equipped with floor heating systems (Olesen, 2002).

The major scientific challenge in evaluating radiant heating systems is the analysis of body-part-related thermal sensation/comfort in asymmetric thermal environments. There are various numerical models, e.g., Dynamic Thermal Sensation (DTS) by (Fiala, 1998) and Thermal Sensation (TS) by (Zhang, 2003) which take into account the heat exchange between humans and their surroundings, but in detail only for convection processes. The Equivalent Homogeneous Temperature model obtained by thermal manikin tests (Nilsson, 2007, Wyon et al, 1989) focuses on the comfort of different body parts – however, it does not include the physiological parameters of the body and does not account for the level of comfort. Fanger's Predicted Mean Vote model (PMV) (Fanger, 1970) responses to the steady-state conditions of the whole body, however it cannot be used to assesse comfort in transient and asymmetrical conditions. Gagge presents the New Standard Effective Temperature (SET*) model (Gagge et al, 1986) to deal with non-uniform conditions, but, the model is also a whole-body model, and it does not apply in asymmetrical conditions. It includes the effect of air speed, but the air flow direction is disregarded. Kingma's research explores the human thermoneutral zone (TNZ) (Kingma et al, 2014) by including the internal and external heat balances together. However, it has limited use for asymmetrical conditions.

In addition to the general thermal comfort studies and models described above, (Miyanaga et al, 2001, Atmaca et al, 2007, Schellen et al, 2013, Sakoi et al, 2007, Ghali et al, 2020) discussed the local thermal comfort for radiant phenomena. (Guan et al, 2003, Wang and Peterson, 1992) focused on whole-body thermal comfort/sensation in transient environments. The study of Hui Zhang addressed the change of thermal sensation/comfort by the effect of convection (Zhang, 2003, Zhang et al, 2010). This model is suited to include additional parameters, i.e., a new coefficient for radiation effects can be involved. This coefficient could be derived from experiments with an adequate experimental setting.

To improve Berkeley Comfort Model, local radiant heating experiments are needed. To conduct these experiments local radiant heating devices, have to be developed. Also, effects of these devices on thermal sensation and comfort in previous studies should be reviewed to reach a better understanding for the experimental design. Researchers have previously investigated personalized/local radiant heating of different body parts comparing different heaters and thermal sensation and comfort. These local heating systems often require low energy and maintain a small temperature difference between the environment and the heated panel, resulting in a stable thermal condition within the occupied zone (Kim and Olesen, 2015). Madsen and Saxhof (1977) and Nelson and Langness (1992) found that using radiant heating panels resulted in a 3°C decrease in ambient temperature while maintain same level of thermal comfort. There are some experiments that used local radiant heating and could achieve acceptable thermal condition for part of the subjects in low ambient temperature such as 17°C (Sørlie, 1993) and 14°C (Melikov et al, 1998). There are different designs for these heaters. They could be mounted on the chair (Madsen and Saxhof, 1977, Limpens-Neilen et al, Oi et al.), under the table (Nelson and Langness, 1992, Sørlie, 1993), both chair and table at the same time (Melikov et al, 1998), and on the floor around the sitting area (Foda and Sir´en, Yu et al).

Also, some researchers design special heating devices for specific body parts, such as , leg (Wang et al, 2022), hand (Vissers, 2012, Vasely et al, 2013), foot (Oi et al, 2011) or a combination of them (Zhang et al, 2015). They used these devices to investigate the importance of that body part on whole body thermal comfort and sensation. They reported that subjects had same level of whole body thermal sensation while decreasing the operative temperature. A review of local radiant heating systems and their effects on thermal comfort and sensation was done by (Hooshmand et al, 2023).

The results of these studies demonstrate the relation between local skin temperature and mean skin temperature. Additionally, the significance of local sensible heat loss was emphasized as it influences whole-body thermal sensation. But the results were not elaborated, and the researchers did not link the results to a thermal sensation model. Also, local radiant heating is an effective method to improve thermal condition of occupants in indoor environments. But most of the studies used it to heat a few body parts and did not investigate its effect on all body parts or the whole-body. Looking at the increasing trend of radiant heating systems and devices and the effect that these systems have on the skin temperature, this paper aims to introduce the design, development and testing of radiant heating devices for specific body parts, that reduce asymmetric radiation from other surfaces, to study the skin temperature change. These results will be used in the future to improve an existing thermal sensation and comfort model – in particular the four different but connected partial models (local sensation, local comfort, overall (whole-body) thermal sensation, overall thermal comfort) of the Berkeley Comfort Model – by including an elaborated sub-model for radiant heat exchange between the human body parts and their thermal environment.

2. Methods

In this section, the design and construction of the heating devices and their testing procedure are explained.

2.1. Design & Construction of Local Radiant Heating Devices

To heat different body parts, different devices are designed. Each device is designed and constructed based on the body part that needs to be applied to. For the hand, foot, leg and arm heating devices, wooden frames are designed, so that the radiation of the heating fabric will be as unobstructed as possible. The wooden frames include rings that are made of plywood and the connecting rods are wooden as well. For example, a spherical device is used for the head, and cylindrical devices are constructed for the arm and leg. Figure 1 indicates the schematic of the arm heating device. For the foot and hand, the design was rectangular. Three rectangular wooden parts were connected by wooden rods. By using a wooden structure, conduction heat transfer is minimized. Heating fabrics have the advantage of wrapping around body parts. The pelvis and back received the radiation by a heating fabric that is fixated to a wooden chair and table.

To heat the face and chest, no wooden structure is used. For the chest part, the fabric is insulated from one side and the other side was in front of the participant chest. The area around the fabrics is covered with insulation to avoid affecting other body parts. For the face, a new approach was needed to heat the face without blocking participants' vision. Two curved shapes are designed for each side of the face. In each one, a piece of radiant fabric is installed and insulated. They are connected and tested to provide even radiant heating in each side of the face without vision blockage.

After the construction of the local heating devices, the main objective was to get the internal Globe temperature of the devices around 35°C in an ambient temperature of 19.5°C. To achieve this, a globe thermometer was placed within the heating devices, making sure that it doesn't touch the heating fabric. Also, it was made sure that the globe was placed in the middle of the heating device with no physical contact with any surface of the heating device.

Different voltages were applied to the heating mats based on the size of the heating mats and the size of the heating devices. Furthermore, using the trial and error method, the required voltages were found to reach the desired radiant temperature for individual heating parts. The variable voltage power supply allowed for precise control over the process of heating and ensuring that the temperature in the device is consistent across the interior surface of the devices.

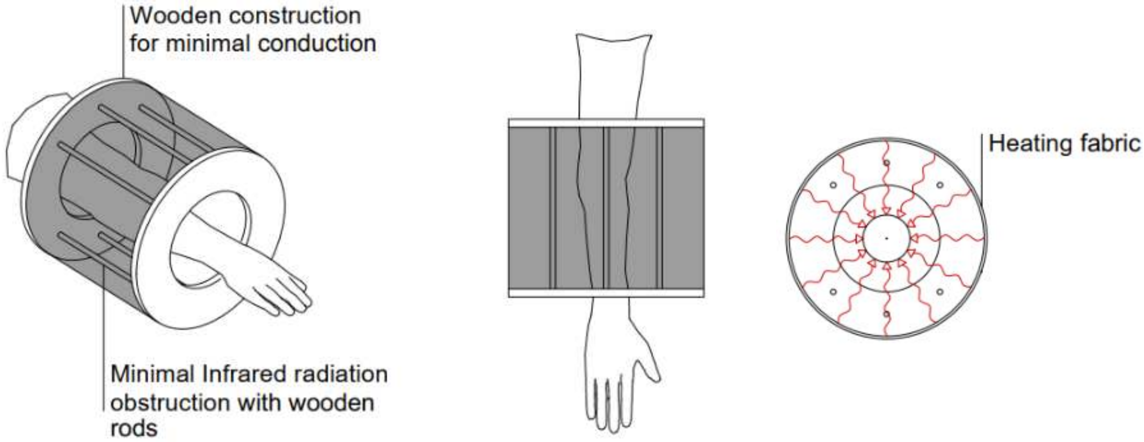

Figure 1. Schematic of the arm heating device

2.2. Experimental design

2.2.1. Subjects' characteristics

For testing heating devices, we recruited a total of 10 subjects, consisted of 5 males and 5 females. Subjects selected based on their body mass index and age. Their body mass index is in the healthy range and in the age range of 18 to 35 years old. The mean and standard deviation of their data are shown in Table 1.

Table 1. Mean and standard deviation of participants' data

	Male	**Female**	**All**
Age (years)	26.0 (±4.2)	27.2 (±5.3)	26.6 (±4.5)
Height (m)	181.6 (±3.0)	170.4 (±5.0)	176.0 (±7.1)
Weight (kg)	78.7 (±7.3)	68.0 (±10.2)	73.3 (±10.1)
BMI	23.9 (±2.9)	23.3 (±2.3)	23.6 (±2.5)

2.2.2. Climate chamber

Experiments were conducted at the Karlsruhe Institute of Technology's Laboratory for Occupant Behavior, Satisfaction, Thermal Comfort, and Environmental Research (LOBSTER) indoor climate test facility. (Wagner et al. 2018) describe the test facility in detail. LOBSTER is composed of two test rooms measuring 4 × 6 × 3 m^3 each. The facility also has a small preparation room for acclimation. Using hydronic capillary tubes, the surfaces of the rooms can be cooled or heated at different temperatures, acting as heat sinks and heat sources. The facade was rotated to face north to minimize the impact of solar radiation on participants and the window temperature.

2.2.3. Experimental procedure

To improve the Berkeley model, a sub-model for radiant heat exchange by correlating subjective (responses from humans) and objective data (physiological measurements), collected from experiments in a climate chamber under steady/uniform, steady/asymmetric, and transient/asymmetric thermal conditions, using the newly developed devices for measuring radiant heat exchange with single body parts, is needed.

In this experimental study, the local skin temperature was monitored under a defined range of the radiant heat flux for each of the mentioned 18 body parts. The skin temperature of each part was recorded every 2 seconds. The tests were held under steady/uniform, transient/asymmetric and steady/asymmetric conditions at an operative temperature of 19.5 °C. To prevent situations that could block radiation, such as air gaps in the subjects' clothing, a uniform clothing design was employed. Skin temperatures were monitored using iButtons, one at the middle location of each body part. The iButton is taped on the body parts under the clothing to avoid radiation on the iButton from the surrounding radiant environment. As indicated in figure 2, in each experiment three different body parts were heated individually. The application duration is 20 min, and the recovery duration is 30 min. There are 60 min from the beginning allowing body to be acclimated to the test ambient conditions. The entire tests continue for 4 hours. This procedure was designed to observe the effects of local radiant heating devices on skin temperature. Each subject participated six times and 18 different body parts were heated and a total of 60 experiments conducted. The experiments were conducted in March and April of 2023 in morning and afternoon sessions.

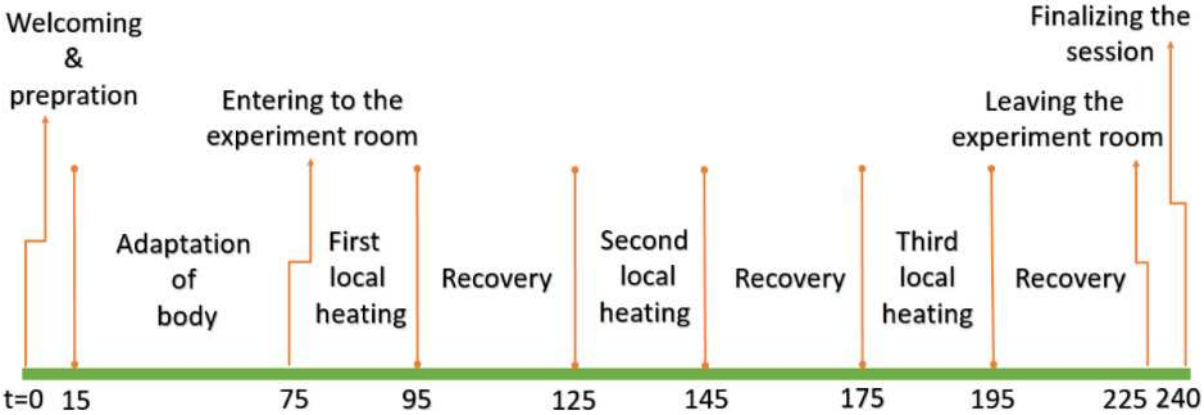

Figure 2. The sequence of the experimental study

3. Results

3.1. Local Radiant Heating Devices

Figures 3 shows the heating device wooden frame for the hand and arm. The local radiant heating devices that were designed and built for different body parts are shown in figure 4. Nine different local heating devices were built for 18 different body parts. Some devices could be used for different body parts on left and right side of the body. The experiments were repeated for the left and right extremities.

In comparison with other types of local radiant heaters, a wooden structure leads to lower building costs. In order to test the devices and observe the skin temperature changes caused by them, these devices are tested in the experimental chamber.

A B

Figure 3. Wooden structure for A) Arm and B) Hand

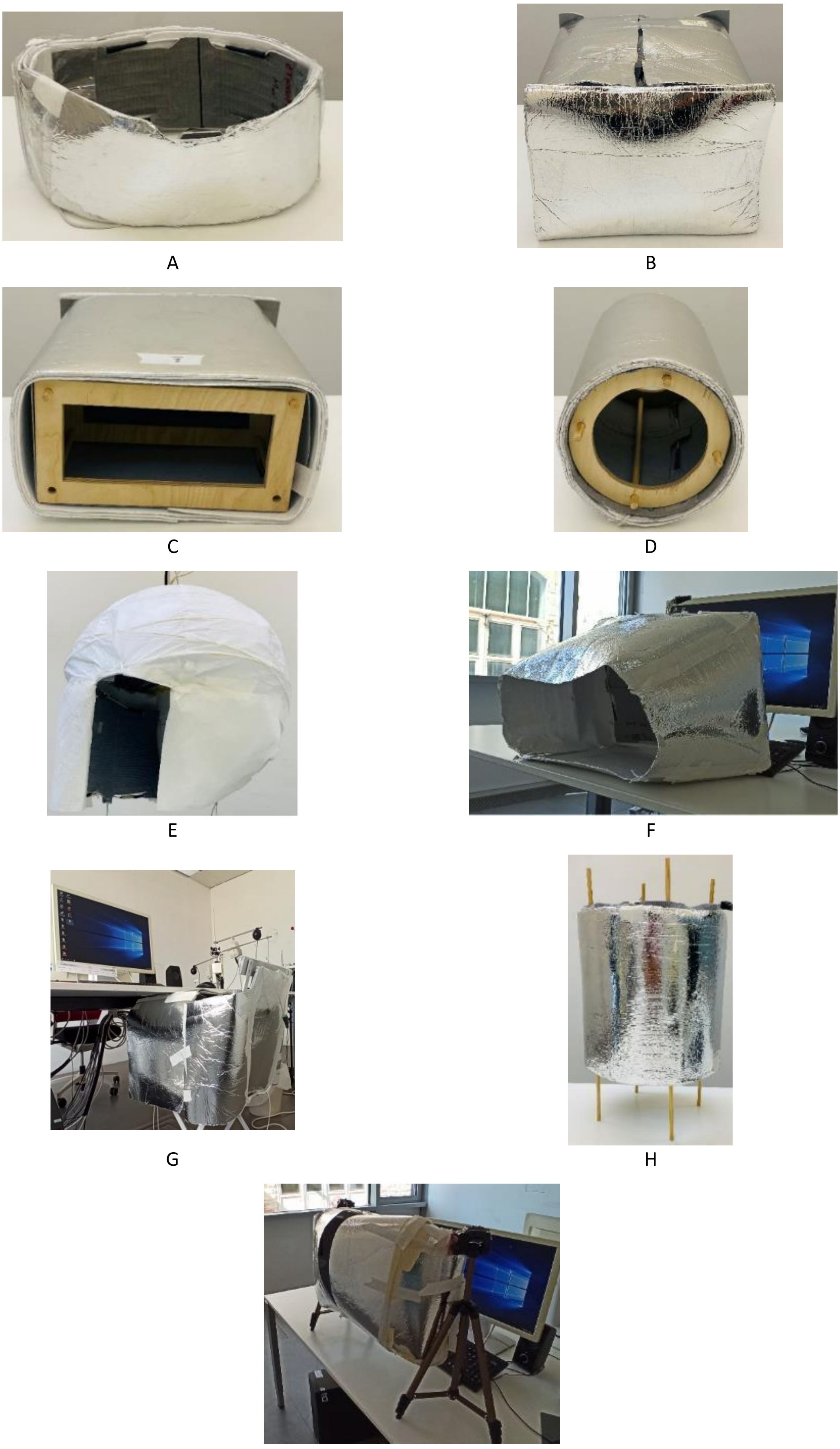

Figure 4. Local radiant heating devices for A) Neck, B) Right and left foot, C) Right and left hand, D) Right and left upper and lower arm, E) Head, F) Chest, G) Pelvis and Back (using the fabric at the back of chair), H) Right and left upper and lower leg and I) Face

3.2. Testing the effect of the local heating devices on the skin temperature

In each local heating period skin temperature increased and reached to a maximum temperature and decreased after removing local radiant heating device. In Figure 5 the mean of subjects' maximum skin temperature at the end of the 20 min heating application and its standard deviation after applying local radiant heating for six different body parts (neck, chest, left lower arm, right hand, left lower leg and right foot) are presented. Each body part has a different temperature in a neutral condition. Using local heating increases the skin temperature. The skin temperature increment in a cool thermal environment improves thermal sensation and satisfaction. In this experiment low temperature radiant heating was used in a cold environment to increase the skin temperature. (Zhang 2003) reported the local skin temperatures in a neutral stable condition with an ambient temperature around of 26°C. The temperature for the neck, chest, lower arm, hand, lower leg and foot were 35.8, 35.1, 34.6, 34.4, 32.9 and 33.3°C respectively. Based on (Olesen and Fanger, 1973) study neutral temperatures for chest, lower arm, hand, lower leg and foot are 34.5, 32.7, 33.5, 32.6 and 32.2°C. The thermoregulation system of the body tries to stabilize the core temperature of body. There is a higher concentration of blood vessels in the chest, which is closer to the heart and vital organs. The skin temperature of the chest is higher than hand or foot skin temperatures because of the proximity to the core and increased blood flow (Nardin et al, 2010).

Skin temperature decreases in cool thermal conditions (Zhang 2003). Figure 5 shows that low temperature radiant devices can increase the skin temperature in a cool condition (19.5°C) and help that body part to reach a temperature close to the neutral condition.

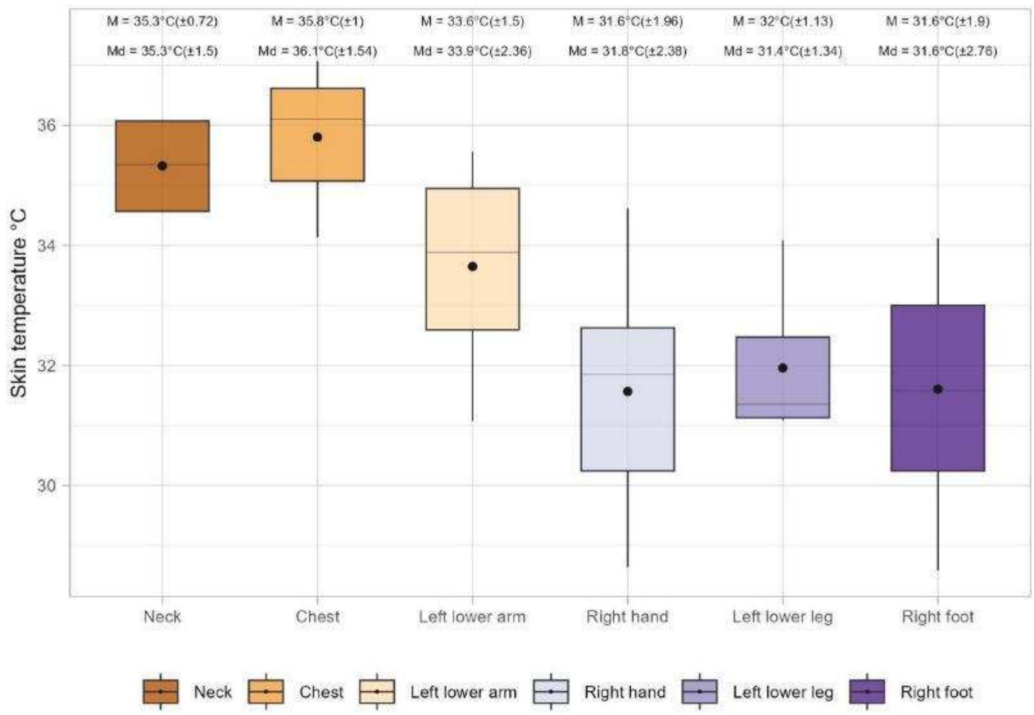

Figure 5. Mean skin temperature and its standard deviation after applying local radiant heating for 20 minutes

Table 2 shows mean and median temperatures of each mentioned body parts for male and female subjects. A Welch Two-Samples T-Test showed that the difference between male and female subjects' mean maximum skin temperature was not statistically significant (p-value > 0.05, df = 8). Figure 6 shows the mean of maximum skin temperature and its standard deviation after applying local radiant heating for male and female subjects. Based on this figure the mean temperature of male and female subjects is close to each other for the body parts that are in the middle part of body like chest, neck and upper arm. In body parts like lower leg, hand and foot mean temperature of male subjects is higher than female. (Fanger, 1970) indicated that the difference between two genders in their satisfaction is insignificant, however most of the studies were based on uniform indoor environments (Zhao et al, 2023). But the number of subjects is limited in the current human subject tests and conducting this experiment with a higher number of subjects to reach a better understanding is needed.

Table 2. Mean, standard deviation, median and inter quartile range of participants' skin tmperature

Body Part	Male		Female		P-value
	Median ± iqr	Mean ± sd	Median ± iqr	Mean ± sd	
Neck	35.6±1.5	35.4±0.8	35.1±1.5	35.3±0.8	0.857
Chest	36.6±1.6	36.0±1.1	36.1±1.1	35.6±1.0	0.545
Left lower arm	33.6±1.9	33.7±1.1	34.1±3.1	33.6±2.0	0.922
Right hand	32.6±1.0	32.7±1.7	30.6±2.0	30.4±1.6	0.058
Left lower leg	32.1±2.5	32.4±1.4	31.1±0.5	31.5±0.7	0.227
Right foot	32.1±1.5	32.0±1.5	30.6±3.6	31.2±2.3	0.545

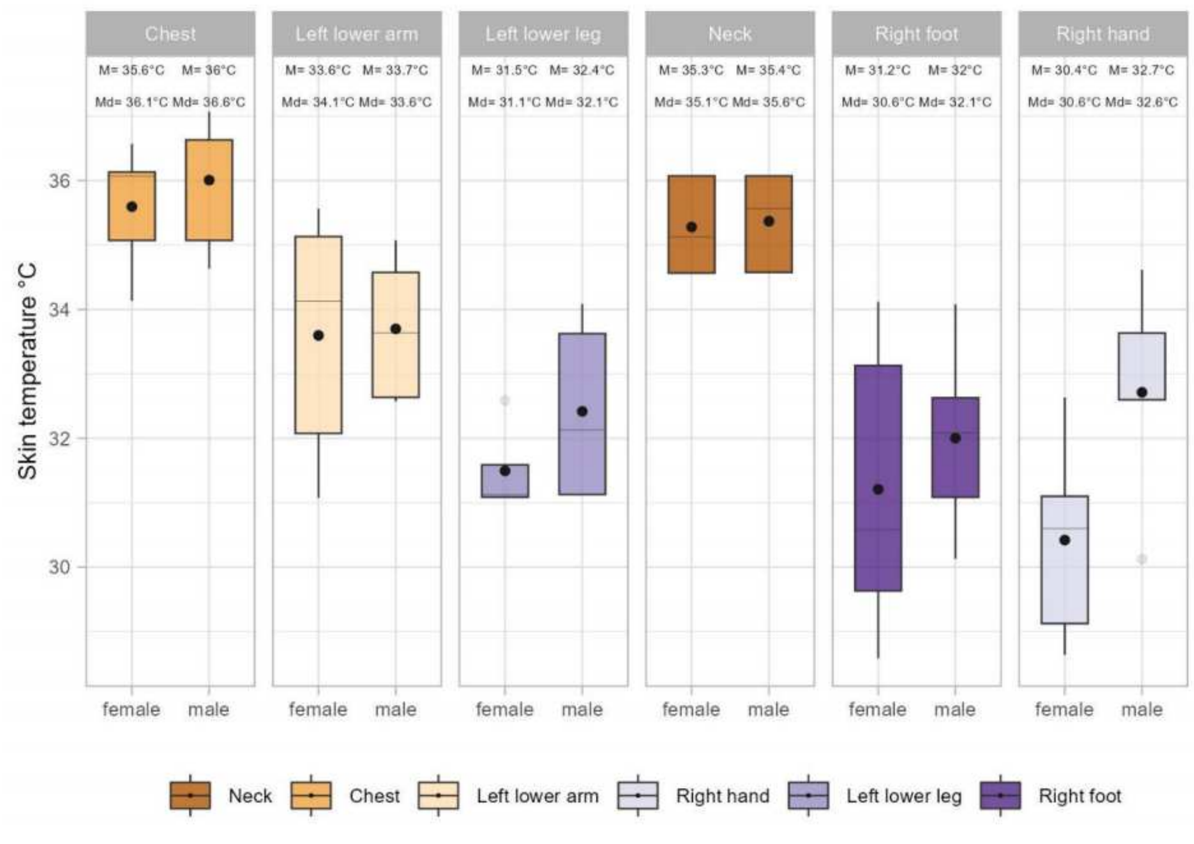

Figure 6. Mean skin temperature and its standard deviation after applying local radiant heating for 20 minutes

4. Discussion

Based on the results, using radiant heating fabrics for building a local heating device provides a proper heating condition. These devices offer proper heating in a cool environment. Increasing skin temperature in a cool indoor environment led to higher thermal sensation and improved thermal comfort (Tan et al, 2022). Based on the results by using local radiant heating devices, different body parts can achieve skin temperatures close to the neutral condition but in an environment around 6.5°C cooler compared to the neutral environmental condition. The mean chest skin temperature after heating is 35.8 °C which is higher than its temperature (35.1 °C) under neutral sensation condition (26 °C). In the obtained results there was a difference between male and female skin temperatures, but it is not statistically significant. Results indicate the capability of local radiant heating devices to increase skin temperature for different body parts.

5. Conclusions

Due to the fact that local radiant heating devices heat only their surfaces, not the entire interior environment, they have high heating efficiency. So, in this paper different local radiant heating devices for 18 body part are proposed.

These systems have a quick response and can heat body parts in a short amount of time. They use low voltage and because they provide occupants' comfort in a low temperature condition, the energy use is low.

These devices show potential for researching localized or personalized heating specially in office type locations and activities. Further investigation regarding their operation under different conditions is needed.

To investigate the difference between genders, conducting experiments with more subjects recommended. The final step is to correlate subjective sensation and comfort votes with skin temperatures using radiant heating devices, to develop an elaborated a comfort predictive sub-model for radiant heating.

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Balancing aesthetics, operational energy and embodied carbon emissions: critique analysis and guidance

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Abstract: This paper aims to analyse the embodied and operational carbon emissions associated with a municipal building established in 2015 in Ireland. The building was designed and promoted to achieve high environmental sustainability standards yet used very carbon-intensive materials. Furthermore, according to an energy audit, the building performs poorly in terms of energy efficiency. This study aims to analyse and establish the reason for these inefficiencies. A whole-life carbon analysis was undertaken to forensically analyse the building's embodied carbon. A thermal modelling study evaluated and identified weak points, establishing the reasons for the performance gap between the designed standard and actual real operation.
The findings of this paper showed that the embodied carbon and whole-life carbon of the case study building are both higher than other benchmark buildings. The difference was especially striking when the worst-case scenario was analysed. The thermal modelling showed that significant energy savings can be achieved when the windows align with the thermal barrier.

Keywords: embodied carbon, thermal analysis, whole life carbon assessment, building envelope, environment

1. Introduction

When considering the environmental effects of buildings, energy efficiency and operational carbon emissions linked to heating, cooling, ventilation, and lighting have been the main topics of attention in recent research and in government policy. These studies do not consider embodied emissions; most building regulations promote reducing operating energy loads. As buildings become more efficient operational energy consumption declines, combined with the planned decarbonisation of the electricity grid ("Climate Action Plan 2023," 2022), embodied energy use—the energy used in the building process—becomes a larger share of the carbon emissions of a building's life cycle. There is currently no law in Ireland to control the amount of carbon that is embodied during the construction of a building. In this paper, embodied energy, or cradle-to-gate energy, refers to the energy needed to obtain and transform raw ingredients into a completed product.

37% of all GHG emissions in Ireland are ascribed to the built environment, with a third of these emissions coming from the manufacturing of raw materials, the transportation of resources, and the building and demolition of structures. (O'Hegarty and Kinnane, 2022)

1.1. Case study and problem statement – LexIcon Library – Dun Laoghaire - Ireland

The case study building of this paper is a library built in 2014, located in Dun Laoghaire, Ireland. The structure was constructed from contemporary materials, exhibits modern building management systems and is an example of high-end architecture in the area.


Figure 1: LexIcon Library ("Library in Dublin / Carr Cotter & Naessens," 2014)

The building won several national and international awards. The building also won a sustainability award (Irish Architectural Foundation, 2015). The library is of interest because of the construction's considerable use of concrete and steel. These materials are known to have high embodied carbon content. Furthermore, according to an energy audit conducted in 2020 (Powertherm, 2020), the building performs poorer than expected. Some windows are offset from the thermal barrier to suit aesthetic needs, suggesting potential heat loss in those areas. This paper analyses these potential defects and points out the shortcomings in building regulations that allow these issues to be present.

The case study building has a reinforced concrete shell with granite cladding on the north, east and west facades and brick cladding to the south with granite stripes between floors. The windows are bronze-clad.

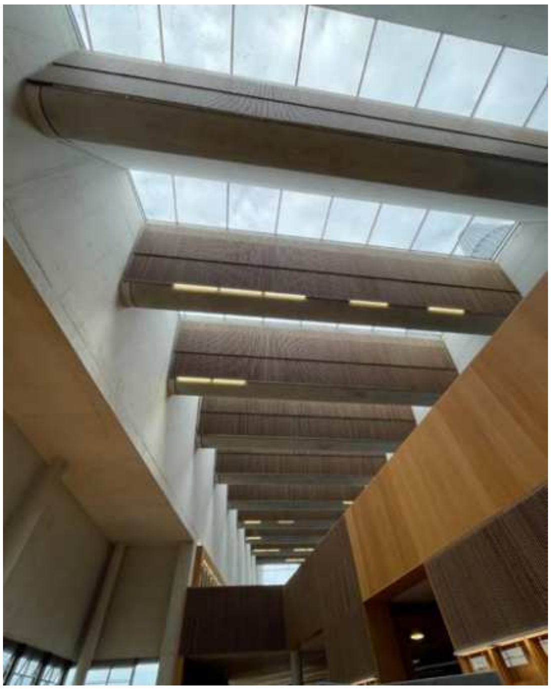
Figure 2: Precast concrete beams (Photo by BC)


Figure 3: Window on external face of wall (Photo by BC)

Figure 4: Window on internal face of wall (Photo by BC)

1.1.1. Hypothesis

It is hypothesised that during the design process, the embodied carbon of materials was not taken into account. It is also suspected that certain aesthetic choices compromised energy efficiency, resulting in increased operational carbon.

1.1.2. Embodied carbon

The author conducted an initial study as part of a Master's degree thesis. These original findings are aimed to be validated in this study. As per these findings, the case study building has a higher embodied carbon overall than other buildings of similar scale and use. It was also shown that the pre-cast beams in the roof structure have a significant role in that. (Császár, 2022)

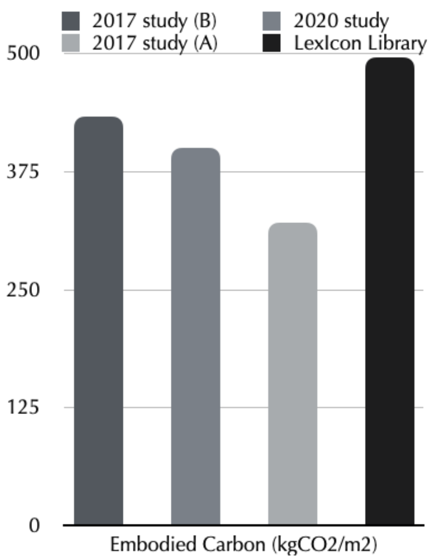

Figure 5: Embodied carbon of buildings based initial analysis

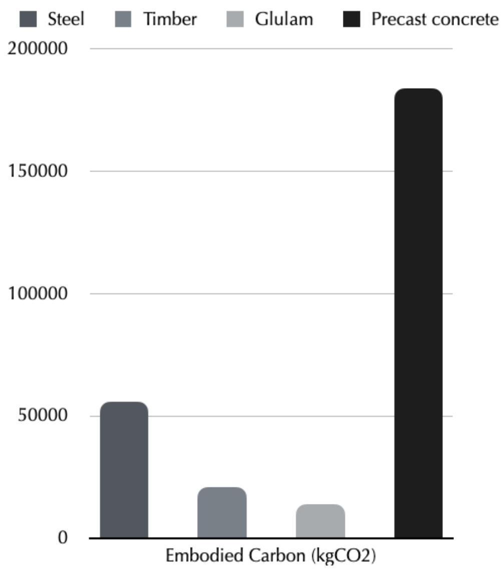

Figure 6: Embodied carbon of studied materials for roof structure

The results above are part of an initial analysis where the embodied carbon content of materials was estimated based on a 2008 publication. (Jones and Hammond, 2008)

This paper is intended to use a more comprehensive method to calculate the whole-life carbon of the materials in this particular building.

1.1.3. Operational carbon

Strategies to increase energy performance

High sustainability standards and considerations were a big part of the design process. As per the sustainability consultants of the project, passive solar gain is completely utilised, and a system of internal shafts organised along the spine of the building produces natural ventilation and heat recovery at their point of discharge. This building was specifically built to satisfy high standards of environmental sustainability. While the building's principal energy comes from renewable sources, the heating is provided by gas- and biomass-fired boilers. A passive ventilation system that leverages the stack effect and the wind to circulate fresh air into and out of each room in the building is provided by nine wind cowls. It was designed to harness natural wind currents to create air pressure sufficient to deliver an abundant and healthy supply of fresh air without using any energy. It also includes heat recovery. ("dlr LexIcon Dun Laoghaire - Arup," n.d.)

There is conflicting information as to how the building is ventilated. According to the Irish Building Magazine, the building is largely naturally ventilated, and according to Arup, it is a mixture of both. According to the energy audit done in 2020, the building is primarily mechanically ventilated.

The large V-shaped beams on the roof level are hypothesised to have been designed with solar shading in mind, but this has not been confirmed.
The glazing included bronze-clad windows, for which a customised design analysis and extensive sample fabrication were performed to maintain high standards. ("DLR Lexicon – Building an Icon | Irish Building Magazine.ie | Ireland's Leading Construction News & Information Portal," n.d.)
However, as mentioned above, the windows do not align with the thermal barrier, causing thermal bridges and potential heat loss.

Energy consumption

The Library's electricity consumption averages out to 869,254 kWh in the years 2017, 2018 and 2019, or 104 – 107 kWh/m^2/year. Gas and wood chip consumption for the same period averages 288,704 kWh and 124,132 kWh, respectively. As per CIBSE benchmarks, the amount of electricity used is significantly higher (worse) than at comparable facilities. When total energy consumption is taken into account, the LexIcon slightly outperforms both CIBSE Good Practice for Art Galleries and Libraries. This might be disappointing, considering that it was supposed to be a low-energy design. However, because it has mechanical ventilation and cooling, its power consumption will unavoidably be higher than that of a structure with natural ventilation and cooling. The report also noted that the Library was not built with LED lighting fixtures. The current lighting accounts for close to 285,900 kWh, or around 34% of the total electricity used. (Powertherm, 2020)

Thermal bridging

A basic thermal bridge modelling was conducted to show the impact of the windows not being in line with the thermal barrier. The findings showed thermal bridges in these instances. This study aims to quantify these initial results and calculate the heat loss that resulted from these design decisions.

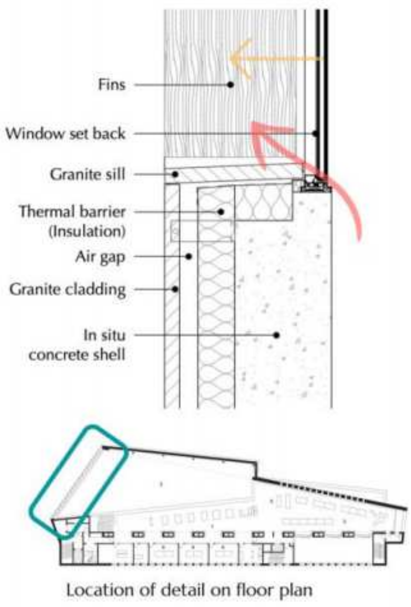

Figure 7: 2D detail drawing of wall build-up at granite cladding with window on internal face and location of detail on floor plan.

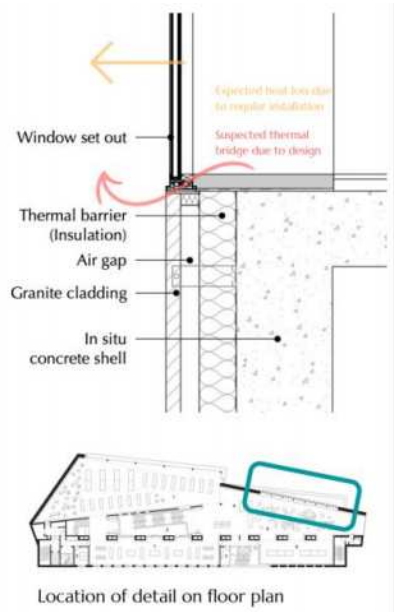

Figure 8 : 2D detail drawing of wall build-up at granite cladding with window on external face and location of detail on floor plan.

2. Literature review

This literature review focuses on issues relating to the case study building. It was designed and promoted to meet high environmental standards, but the main building materials are concrete and steel. Furthermore, it was designed for low operational carbon but performs poorer than expected.

2.1. Operational and embodied energy consumption

Embodied energy consumption is a critical issue to address, as in Ireland, the only focus of the regulations in terms of building's impact on the environment is the operational energy use, hence the rules to keep u-values (thermal transmittance) as low as possible. According to a recent study, however, 13% of all Irish emissions are due to embodied carbon relating to the built environment. Out of that, nearly half is due to cement production. (O'Hegarty and Kinnane, 2022)

New buildings use less operational energy, operational energy is decarbonising, and we need emission reduction in the short term. Promoting the development and use of low embodied carbon building materials and services, energy efficiency of construction machines, and renewable energy use are the three crucial opportunities to reduce the construction sector's carbon emissions. (Huang et al., 2018)

These changes have to happen at the government level, and some countries are already leading the way with policies that demand the reduction of embodied carbon emissions. Just last year Toronto, Canada introduced a law that requires Whole Building Life Cycle Assessment for proposed buildings. The regulation includes a cap at $350kgCO_2e/m^2$ of embodied carbon for the production stage (A1-A5) of any mid-rise non-residential building. (Toronto, 2022)

2.2. Environmental impact of materials

Cement is the world's most mass-produced industrial product. It produces cement-based goods (e.g., concrete) when mixed with water and mineral aggregates. It is the world's second most utilised material after water. Because of that, cement manufacturing accounted for around 7% of the world's carbon dioxide emissions in 2018. (Scrivener et al., 2018) The steel industry is also responsible for an additional 7% of all emissions. (Hassan and Johansson, 2018) Cement and steel (and reinforced concrete) occupy a sizeable portion of the built environment due to their affordability, durability, workability and strength. They may be moulded into any desired shape and have exceptional fire and sound resistance. The cement industry's greenhouse gas (GHG) emissions have been researched and analysed. (Barcelo et al., 2014) (Cruz Juarez and Finnegan, 2021)

Clinker, the base component of cement, is a solid substance made up of limestone, clay and other materials cooked in kilns at temperatures up to 1450 °C. This process accounts for 40% of the carbon emissions in cement production. In comparison, the chemical process that creates the calcium and magnesium oxides that form the clinker produces 50%. While approximately half of the carbon emissions from cement production cannot be avoided, fuel utilisation and kiln efficiency significantly influence carbon emissions.

In the case of steel, recycled content is also very important. Virgin steel has a carbon footprint that’s five times more than steel with high recycled material content. The type of furnace can also play a role; on average, electric arc furnaces (EAF) use 93% recycled steel, whereas blast furnaces use 25% recycled steel. EAFs may also be powered by renewable energy sources, minimising steel's environmental impact. (Hassan and Johansson, 2018) While steel and cement can be replaced in certain scenarios, such as in the superstructure of a building, the substructure often has to be reinforced concrete due to the limited choices of materials available for this use. In the case of both cement and steel, therefore, it is very important to use materials created with the best-practice available.

When we take a whole-life carbon approach, the other important aspect to consider is the end-of-life and recyclability of these materials. Steel is widely recycled; concrete, on the other hand, mostly ends up in landfill due to regulations of recyclability. As per the EPA in Ireland, recycling concrete can not adversely affect the environment and human health, amongst other easier achievable targets, such as market value, technical requirements and usage for specific purposes. Concrete can induce high pH discharge into groundwater due to its alkaline composition. It may have a significant metal content because of the binders used to make the cement. It may also contain fly ash from coal-fired power plants. As a result, sulfate or chloride salty water drainage may occur. Currently, only one company is licenced to recycle concrete into aggregates. (“Concrete recycling in Dublin,” n.d.)

2.2.1. Recycled content impact on embodied carbon

Research suggests that recycled aggregate concrete can be used as an alternative to conventional concrete for attaining global sustainability criteria in construction. Concrete with high recycled content is responsible for less greenhouse gas emissions than conventional concrete while still having strength qualities that represent structural elements. (Sabău et al., 2021)

Ground Granulated Blast furnace Slag (GGBS), a by-product or co-product of the steelmaking process, can be ground up and used as a substitute for cement. This was used in the case study building, with up to 50% GGBS content in the reinforced in-situ cast concrete. The embodied energy decrease GGBS gives was previously calculated and showed a significant reduction in embodied carbon. (Kinnane et al., 2019)

2.3. Building fabric of new construction

The building fabric must meet particular requirements as stated in Part L of the Irish Building Regulations. ("Technical Guidance Document L - Conservation of Fuel and Energy - Buildings other than Dwellings," n.d.) Additionally, there are requirements for the thermal transmittance (u-value) that each building component must meet.

This u-value quantifies the amount of heat lost through a specified material. The requirements state that steps should be taken to minimise excessive heat losses and local condensation problems by reducing local thermal bridging, for instance, at window, door, and other wall openings, connections between elements, and other places. Thermal bridging should not increase the likelihood of surface or interstitial condensation. The average u-value should be changed to reflect any excessively increased heat loss brought on by the thermal bridge. Less than 16% of the predicted total heat loss through the plane's structural components should come through thermal bridges.

The current regulations only focus on the building structure's individual elements. The guidelines regarding these elements' connection are vague and allow for personal design choices. Therefore certain aspects are often overlooked, such as keeping the openings in line with the thermal barrier to avoid further thermal bridging.

3. Methodology

3.1. Lifecycle embodied carbon calculation methods

Embodied carbon calculates the amounts of GHGs emitted into the atmosphere throughout the production of building materials and during construction, the replacement of materials, and end-of-life management.

This paper only includes the environmental impacts of material production, transportation, repair, refurbishment, and replacement. The whole-building embodied carbon covers the cradle-to-grave processes, except for construction (A5), as construction is a negligible contributor to total embodied carbon. (Moncaster and Symons, 2013) (Vukotic et al., 2010) (Davies et al., 2015)

Demolition and end-of-life carbon comprise emissions occurring during demolition and waste material transportation. This study does not include it since it accounts for just 0.2-0.3% of total lifetime primary energy consumption. (Meneghelli, 2018)

The method used in this paper to calculate the case study building's embodied carbon emissions was described in a paper by Meneghelli. (Meneghelli, 2018)
The paper breaks down the embodied carbon of materials into three categories: (i) Production stage (A1-A3), (ii) Transportation stage (A4), (iii) Repair, refurbishment and replacement stage (B3-B5).

This method was chosen because it focuses on a sensitivity analysis of the building materials considering their recycled content as well. The research was conducted on a library of a similar scale, which was also an important factor.

3.1.1. Building components and materials

Construction drawings, specification papers, Building Information Modeling (BIM) models, and site visits were used in this study to gather information on the building's components.

The library's final fit-out and furnishing were left out, and the analysis concentrated on crucial components in the building envelope and load-bearing internal walls. As a result, the following key elements were included: foundations, steel, concrete, brickwork, insulation and roofing. The DEFRA criteria were followed to calculate carbon emissions at the transportation stage. ("Department for Environment, Food & Rural Affairs," 2023) Precast roof beams are calculated independently from the rest of the structure since they are believed to have a significant role in the building's possibly high embodied carbon. (Császár, 2022)

Table 1. Materials used in the LexIcon Library and their quantities.

Material	Mass in model (t)	Density (kg/m³)	Approx. Embodied carbon (kgCO_2/kg)
Reinforced concrete	15244	2300	0.101-0.202
Precast concrete	1046	2100	0.194
EPDM	4	70	1.200
EPS	9	12	3.290
Masonry	140	1873	0.227
Granite	377	2600	0.640
Zinc	21	7135	2.880

3.1.2. Production stage (A1-A3)

The production stage represents embodied carbon emissions during material extraction, transportation, and manufacturing, as known as cradle-to-gate.

Each structural component may be defined in terms of attributes like material density and the Embodied Carbon Coefficient (ECC), which considers the GHGs connected to the material's energy source. The CO_2 equivalent unit (CO_2e), which is based on the warming potential of six distinct GHGs as mentioned in the Kyoto Protocol ("Kyoto Protocol - Targets for the first commitment period | UNFCCC," n.d.), is used to measure the environmental effect in terms of global warming potential.
It is calculated by the equation below.

$$EC_{A1-A3} = \sum_{i=1}^{n} \mathrm{EC}prod = \sum_{i=1}^{n} V\ x\ \rho\ x\ ECC$$

EC*prod* = embodied carbon of building component
V = Volume (m^3)
ρ = Density (kg/m^3)
ECC= Embodied carbon coefficient ($kgCO_2e/kg_{material}$)

The University of Bath produced a database of building material ECCs used in this study. Despite the Inventory of Carbon and Energy (ICE)'s ("Embodied Carbon - The Inventory of Carbon and Energy (ICE)," n.d.) limitations, which include that the data is primarily UK-specific and has not been updated since 2011, it continues to be the best and most complete source of ECCs, especially when it comes to recycled material content.

3.1.3. Transportation stage (A4)

The transportation stage includes the environmental effects of moving goods and materials from the factory gate to the construction site. In this analysis, both the amount of materials carried and the transit distance are taken into consideration using the functional unit $kgCO_2e/t$ km.
It is calculated by the equation below.

$$EC_{A4} = \sum_{i=1}^{n} \mathrm{EC}transp = \sum_{i=1}^{n} M\ x\ d\ x\ \mathrm{ECC}transp$$

EC*transp* = embodied carbon in transportation of building component
M = Mass (t)
d = distance travelled (km)
ECC*transp*= Embodied carbon coefficient for transportation ($kgCO_2e/t$ x kg)

Material Wastage (A5w)

While Construction (A5) is a negligible contributor to total embodied carbon. (Moncaster and Symons, 2013) (Vukotic et al., 2010) (Davies et al., 2015), it is important to mention construction waste. (A5w)

Manufacturing, fabrication, and assembly are examples of instances when extra material is consumed. This must not be overlooked in embodied energy and carbon analysis. Additional waste materials are generated during the construction of a structure, for example, due to over-ordering of materials or goods or as a result of breakages or off-cuts. In the case of this study (Orr et al., 2020) guidance was used.

The material wastage (A5w) emissions factor accounts for carbon emissions produced during waste generation, transportation, and disposal. The factor itself represents a percentage estimate of how much of the material supplied to site is lost (through a waste factor, WF), allowing the A5w factor to be multiplied by the same material amount used for the A1-A3 calculations. It is calculated as follows. (Orr et al., 2020)

$$EC_{A5w} = WF\ x\ (EC_{A1-A3} + EC_{A4} + EC_{C2} + EC_{C3-C4})$$

WF = waste factor, based on expected % waste rate
EC $_{A1\text{-}A3}$ = Embodied carbon emissions for production of the wasted material
EC $_{A4}$ = Embodied carbon emissions for transporting the wasted material to site
*EC $_{C2}$ = Embodied carbon emissions for transporting the wasted material away from site
**EC $_{C3\text{-}C4}$ = Embodied carbon emissions for processing and disposal of waste material

*As per guidelines assumed 50 km by road to the nearest reuse/ recycling location = 0.005 kgCO2e/kg
** As per guidelines 0.013 kgCO2e/kg was assumed. ("RICS Guidance on calculating Embodied carbon," n.d.) (RICS, 20176 , Section 3.5.3.4)

3.1.4. Repair, refurbishment and replacement (B3-B5)

These stages show the environmental implications of building material replacement or maintenance over a structure's lifespan.

It is calculated by the equation below.

$$EC_{B3-B5} = \sum_{i=1}^{n} \text{EC}ren_1 + \text{EC}ren_2 =$$

$$\sum_{i=1}^{n} \left\{ M\ x\ \left[ECCprod_{(\%Recycled\ content)}\ x\ \left(\frac{Desing\ life}{Expected\ life} \right) + d\ x\ ECCtransp \right] \right\}$$

M: Mass (t)
ECC*(%Recycled content)*: Embodied Carbon Coefficient based on recycled content ($kgCO_2e/kg_{material}$)
Design life: 60 years
Expected life: Expected building component life before replacement
d: Distance travelled (km)
ECC*transp*= Embodied carbon coefficient for transportation ($kgCO_2e/t$ x kg)

The calculation formula is based on that proposed in RICS's Methodology for Calculating Embodied Carbon. ("Whole Life Carbon Assessment for the Built Environment," n.d.)

3.2. Operational energy

3.2.1. COMSOL Multiphysics modelling – heat flux analysis

A 2D detailed sketch of the connections where thermal bridging was suspected was obtained from the contractor's public website and analysed. ("DLR Lexicon," n.d.)

Using heat flux monitoring, the experimental investigation in this research explores the thermal bridging influence in three details that were observed in the case study building.

According to ISO 14683 (ISO 14683, 2017) the accuracy of the finite element technique is ±5%, but the simpler methods of thermal bridging computation have a typical accuracy of ±20%.

The components' heat flow and surface temperature were tracked using Finite Element Modeling software.

COMSOL Multiphysics software generated 2D heat transfer models to simulate temperature changes in structural components under real temperature profiles.
It was utilised to generate thermal pictures and heat flux results to examine the energy-saving effects of insulation.
Trisco 2D software was used to generate heat flow data per ISO 10211 to validate the results. (ISO 10211, 2017).

3.2.2. Boundary conditions and material properties

The external temperature was set to -5 °C, and the internal temperature was set to 20 °C. During the investigation, the heat flux was measured on the external face of the building. This made it possible to express the energy efficiency of the walls in simple terms.
All the properties of the materials used are presented in Table 2.

Table 2. Material properties

Material	**Density (kg/m^3)**	**Thickness (d) (m)**	**Heat Capacity (Cp) J/(Kg·K)**	**Thermal conductivity (k) (W/(m·K)**	**R-value (m2K/W)**	**u-value (W/m2·K)**
LexIcon Library granite walls						
Reinforced concrete 1% steels	2300	0.2	880	1.8	0.11	
EPDM	70	0.015	1.71	0.29	0.05	
Expanded Polystyrene board (EPS)	11.5	0.16	1450	0.038	4.21	
Air cavity	1.276	0.08	1006	0.025	3.20	
Granite	2600	0.04	850	2.9	0.01	
					7.59	**0.13**
LexIcon Library masonry walls						
Reinforced concrete 1% steels	2300	0.2	880	1.8	0.11	
EPDM	70	0.015	1.71	0.29	0.05	
Expanded Polystyrene board (EPS)	11.5	0.16	1450	0.038	4.21	
Air Cavity	1.276	0.08	1006	0.025	3.20	
Brickwork	1873	0.102	800	0.5	0.20	
					7.78	**0.13**
Additonal materials						

Silicone (filling)	1.5 [g/cm³]	n/a	0.71 [J/g*K]	0.02
Steel (Fixing)	7850	n/a	475	44.5
Wood (Fixing)	532	n/a	2700	0.15

4. Calculation and results

4.1. Embodied Carbon assessment

4.1.1. Production stage (A1-A3)

The embodied carbon for the production stage was calculated in the table below. It uses Embodied Carbon Coefficients based on the ICE database. ("Embodied Carbon - The Inventory of Carbon and Energy (ICE)," n.d.)

Table 3. Materials, their quantities and embodied carbon calculation

Material	Type	Volume (m^3)	Density (kg/m^3)	Mass (t)	Total Mass (t)	Embodied carbon coefficient (ECC) ($kgCO_2/kg$)	Production A1-A3 (tCO_2)
Reinforced concrete	External walls	1663	2300	3825	**15244.4**	0.202	3079
Reinforced concrete	Internal walls (LB)	580		1334			
Reinforced concrete	Slabs	2900		6670			
Reinforced concrete	Foundation	1485		3416			
Precast concrete	Stairs	44	2100	92	**1046**	0.194	203
Precast concrete	Columns	21		44			
Precast concrete	Precast beams	433		909			
Granite	External walls	145	2600	377	**377**	0.64	241
Masonry	External walls	75	1873	140	**140.475**	0.227	32
EPDM	External walls	63	70	4	**4.41**	1.2	5
EPS(walls)	External walls	674	11.5	8	**12.0635**	3.29	40
EPS (roof)	Roof	375		4			
Zinc	Roof	3	7135	21	**21**	2.88	60
Total tonnes of embodied carbon associated with production							**3661**
Total kg of embodied carbon associated with production/m²							**572**

Recycled content in cement

According to an article by Engineers Ireland ("Dun Laoghaire's new Central Library – the DLR Lexicon," n.d.), the concrete used had up to 50% recycled content. We can present a best- and worst-case scenario of the embodied carbon content of concrete.

With the best-case scenario of 50% recycled content using Ground Granulated Blast furnace Slag (GGBS) as the additive, the embodied carbon coefficient of concrete could be reduced significantly, making the reinforced concrete's ECC to be 0.101 $kgCO_2/kg$ assuming 1% steel. (Kinnane et al., 2019). If the whole building used 50% recycled content concrete, that would potentially reduce the embodied carbon per m^2 for production to **330kgCO$_2$/kg**. The source states "up to 50%"; therefore, the actual amount will be between the best and worst-case scenarios.

4.1.2. Transportation stage (A4)

Table 4. Materials, their quantities and embodied carbon calculation regarding transportation stage

Material	Volume (m^3)	Mass (t)	Tonne per journey[1]	m^3 per journey [2]	Amount of journeys[3]	Distance (km)[4]	Full ($kgCO_2$/km)[5]	Empty ($kgCO_2$/km)[6]	Total kg CO_2
Precast concrete	498	1046	17	◯	62	157	0.864	0.672	14838
Reinforced concrete	6628	15244	◯	8	829	28.3	1.111	0.667	41688
EPDM	63	4	◯	82	1	26	0.864	0.672	31
EPS	1049	12	◯	82	13	82.8	0.864	0.672	1627
Brick	75	140	17	◯	8	24.5	0.864	0.672	311
Granite	145	377	17	◯	22	85	0.864	0.672	2895
Zinc	3	143	17	◯	8	25	0.864	0.672	323
Total $kgCO_2$ associated with transportation									**61713**

[1] Based on 17-tonne HVG freight truck weight capacity. (Department for Environment, 2008)
[2] Based on 17-tonne HVG freight truck volume capacity. (Department for Environment, 2008)
[3] Amount of journeys needed between site and distributor one way.
[4] Google Maps calculated the distance travelled based on the suppliers' factory location. While most materials were supplied locally, the granite was shipped from Spain. The road distance travelled includes an estimation of the distance between the mine to port, port to factory and factory to site. Shipping milage was excluded, as it was insignificant.
[5] $kgCO_2$ per vehicle km. One-way journey with 100% load based on DEFRA's GHG Conversion factors (Department for Environment, 2008) Annex 7, Table 13a. (Department for Environment, 2008)
[6] $kgCO_2$ per vehicle km. One-way journey with 0% load based on DEFRA's GHG Conversion factors (Department for Environment, 2008) Annex 7, Table 13a. (Department for Environment, 2008)

Table 5. Waste calculation table

	Waste rate	Waste factor	A1-A3	A4	$C2_1$	$C3\text{-}C4_2$	Total
Reinforced concrete	5%	0.05	3049	41688	0.005	0.013	163806
Precast concrete	1%	0.01	203	14383	0.005	0.013	2174
EPDM	1%	0.01	5	31			50
EPS	20%	0.25	40	1627	0.005	0.013	10407

Masonry	20%	0.25	32	311	0.005	0.013	8078
Granite	20%	0.25	241	2895	0.005	0.013	60974
Zinc	1%	0.01	60	323	0.005	0.013	603
Total kgCO$_2$ associated with B3-B5							**246092**

[1] As per guidelines assumed 50 km by road to the nearest reuse/ recycling location = 0.005 kgCO2e/kg
[2] As per guidelines 0.013 kgCO2e/kg was assumed. ("RICS Guidance on calculating Embodied carbon," n.d.) (RICS, 20176 , Section 3.5.3.4)

4.1.3. Repair, refurbishment and replacement

The building envelope has a 30-year life expectancy; all other components are believed to require no minor or substantial renovations over the structure's 60-year service lifespan. (*Life Expectancy of Building Components*, 2006) The carbon footprints of repair, refurbishment, and replacement are determined by the ECCs and transportation input discussed in previous sections. Variations at this step are caused by changes in the material ECC, assumed transportation distance, and the transportation carbon emission factor.

Table 6. Repair, refurbishment and replacement calculation table

	A1-A3 (t)	A4 (kg)	Design life	Expected life	Total
Reinforced concrete	3049	41688	60	50	618138
Precast concrete	203	14383	60	50	43477
EPDM	5	31	60	50	1006
EPS	40	1627	60	30	41627
Masonry	32	311	60	30	32311
Granite	241	2895	60	50	48779
Zinc	60	323	60	30	60323
Total kgCO$_2$ associated with B3-B5					**845660**

4.1.4. Results

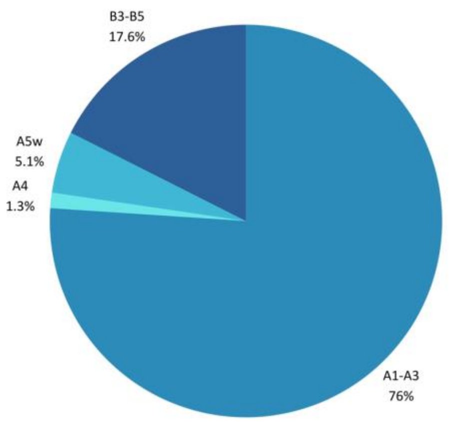

Figure 9: The Production stages (A1-A3) provide 76% of the embodied carbon in the case study, whereas the Repair, Refurbishment, and Replacement phases (B3-B5) contribute 17.6%. Waste (A5w) was responsible for 5.1% and transportation (A4) only accounted for 1.3%. As a result, A1-A3 and B3-B5 stages substantially influence the environmental impact of the construction and are very sensitive to the tested assumptions.

A comparison analysis was conducted using two significant studies to establish whether the embodied carbon of the case study building is low or high.
In a 2017 study, a typical building classified as "other" has an embodied carbon of 321 $kgCO_2/m^2$, whereas a building classified as a "public assembly" has an embodied carbon of 433 $kgCO_2/m^2$. The calculations considered both figures since the Library may fall into any of those groups, and the embodied carbon difference is substantial. In this study only the production stage (A1-A3) was considered. (Simonen et al., 2017)
Another study done in 2020 in China suggests that a conventional commercial building would have an average of approximately 400 $kgCO_2/m^2$. (Zhu et al., 2020) In this study all stages were considered.

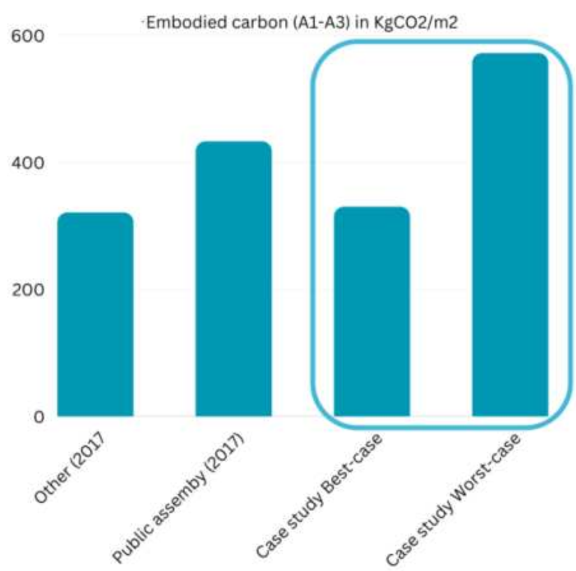

Figure 10: Embodied carbon (A1-A3) in kgCO2/m2.

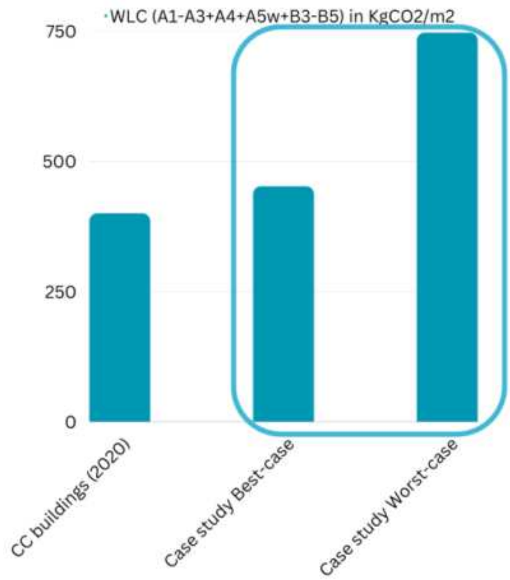

Figure 11: Whole life carbon in kgCO2/m2.

4.2. Thermal assessment

4.2.1. COMSOL Multiphysics Software – heat flux analysis

Three details were analysed to establish the heat flux changes measured on the external face of the wall and the cill.

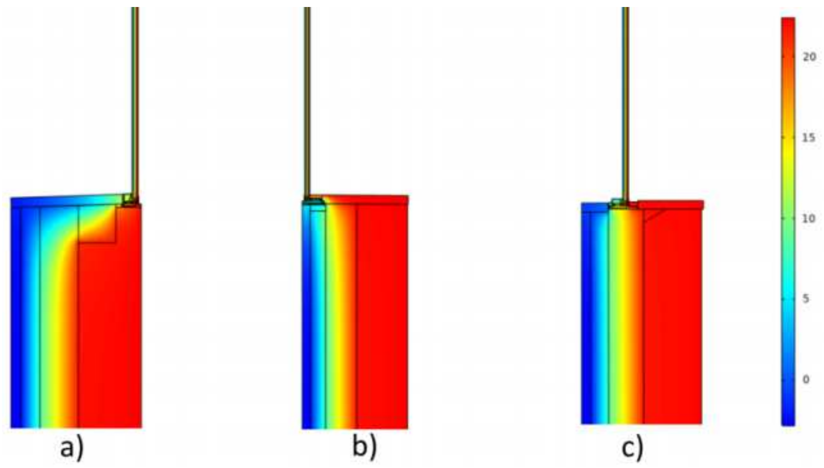

Figure 12: Thermal images of analysed details modelled in COMSOL Multiphysics.

a) Window installed on internal face of wall
b) Window installed on external face of wall
c) Window installed in line with thermal barrier

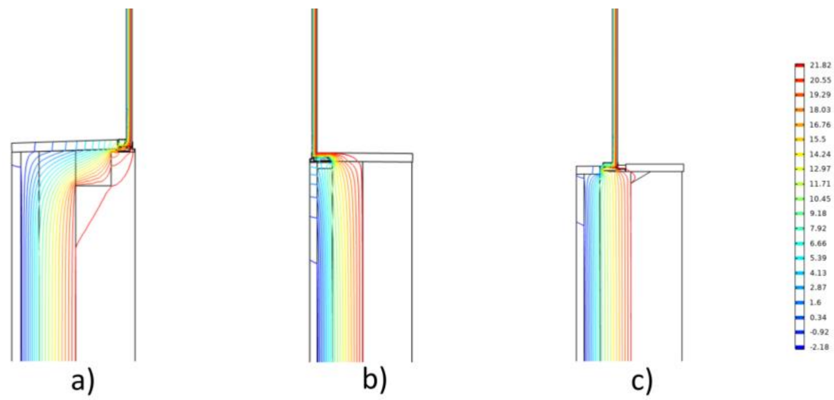

Figure 13: Isothermal contour images of analysed details modelled in COMSOL Multiphysics.

a) Window installed on internal face of wall
b) Window installed on external face of wall
c) Window installed in line with thermal barrier

4.2.2. Trisco 2D software

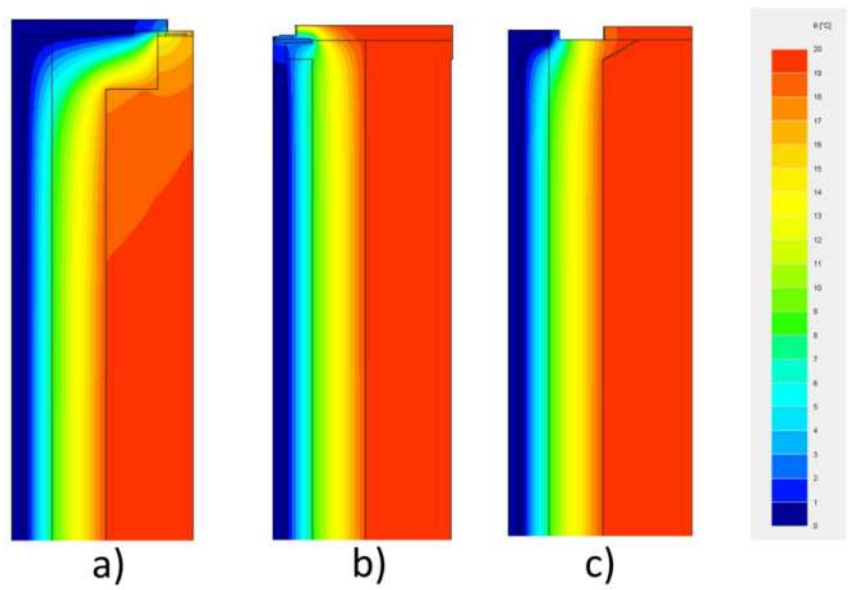

Figure 14: Thermal images of analysed details modelled in Trisco2D.

a) Window installed on internal face of wall
b) Window installed on external face of wall
c) Window installed in line with thermal barrier

4.2.3. Results

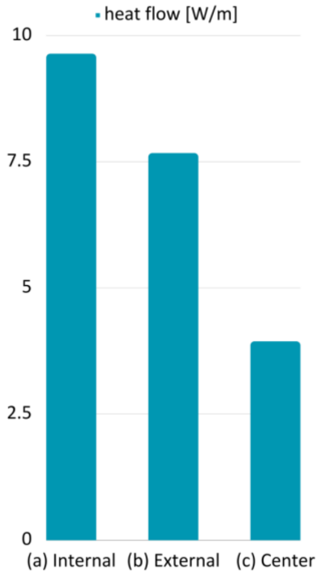

Figure 15: Heat flow results of analysed details modelled in Trisco2D.

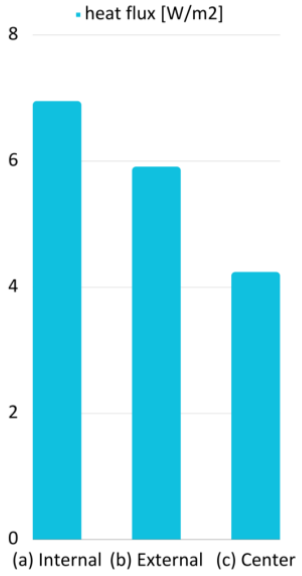

Figure 16: Heat flux results of analysed details modelled in COMSOL.

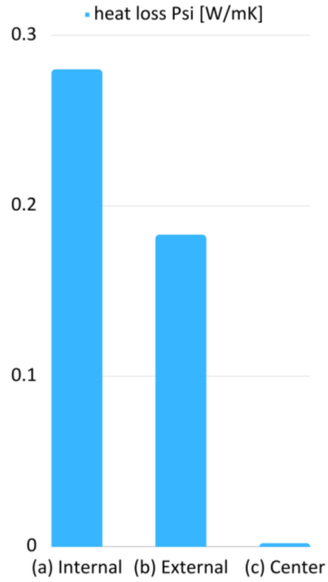

Figure 17: Heat loss results of analysed details modelled in Trisco2D.

The above results show that the heat flux and heat flow can be reduced by choosing to place the windows in line with the insulation. According to these findings, the reduction is significant. A 60% reduction was observed in heat flow when placing the window in line with the thermal barrier compared to installing the window on the internal face and 49% compared to placing them on the external face. A 40% reduction was observed in heat flux when placing the window in line with the thermal barrier compared to installing the window on the internal face and 30% compared to placing them on the external face.

The heat flow analysis also suggests a significant reduction by installing the windows in line with the thermal barrier.

5. Conclusion

5.1. Embodied carbon analysis

The Production stages (A1-A3) provide 76% of the embodied carbon in the case study, whereas the Repair, Refurbishment, and Replacement phases (B3-B5) contribute 17.6%. As a result, these stages substantially influence the environmental impact of the construction and are very sensitive to the tested assumptions.

5.2. Thermal assessment

The further the insulation from the thermal barrier, the more heat loss was observed. These findings show the importance of placing openings aligned with the thermal barrier to achieve the highest possible energy efficiency.

6. Discussion

There is a culture in architecture of praising buildings that conform to some ideas of aesthetic beauty, and environmental concerns fall behind these preconceptions. Considering the climate emergency we are all facing, it is important to point out these issues.

Whole-life carbon analysis can help identify the cause of high embodied carbon content. Therefore, legislation should be implemented at the government level to encourage designers and developers to make more environmentally conscious decisions. This can be achieved by demanding the reduction of embodied carbon related to material choices and operation carbon emissions associated with aesthetic value-based design choices.

7. Limitations and further research

Operational carbon associated with post-occupancy behaviour can greatly impact operational energy and is not considered in this study. Further research is needed to regulate occupant behaviour and its consequences.

This study does not consider interior features, flooring, paint and non-loadbearing walls. The choices relating to these can also impact the overall environmental footprint of the building. In the case study building, a library, interior features are especially important considering the amount of shelving required and decorations involved. If these features are sourced through questionable ways, the whole-life carbon content of the building can rise further. According to an article, ("DLR Lexicon – Building an Icon | Irish Building Magazine.ie | Ireland's Leading Construction News & Information Portal," n.d.) the joinery was sourced in Denmark, and the solid timber for shelving was sourced in Italy. The selected trees grew in Germany and Croatia. Quantifying the amount of carbon dioxide involved in travelling to these places and transporting these goods is difficult. Arguably, timber could be sourced locally, limiting the CO_2 emissions associated with the above.

This leads us back to the question of whether aesthetics should override the importance of the climate crisis.

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Toward passive survivability: barriers and opportunities to optimize the built environment for greater thermal safety

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Abstract

The concept of "passive survivability" can be defined as the ability of a building to maintain habitable conditions during an extended power outage or loss of heating fuel. There have been ongoing efforts in the United States to address this issue since Hurricane Katrina struck New Orleans, Louisiana, in 2005. Since then, passive survivability has taken on global recognition and relevance in the face of a quickly changing climate. The building design and construction industry has identified the need for resilient design that ensures thermal safety and, as such, has adopted performance metrics to assess passive survivability in indoor environments. However, recent data from the U.S. Department of Energy suggests that a staggering proportion of existing and new homes fail to meet the performance thresholds to achieve passive survivability – including homes designed to meet the latest ICC model energy codes and Passive House standards. Passive survivability has eluded even the most well-insulated and airtight high-performance homes.

Despite our collective failure to realize housing that ensures passive survivability, many of the metrics, barriers to uptake, and opportunities to unlock the potential of passive survivability align closely with those of net-zero energy and net-zero carbon building. This paper addresses three specific industry needs that will unlock the potential of passive survivability as a market standard that better ensures community resilience and zero-carbon outcomes:

a. Public access to consistently produced downscaled climate projection data.

b. Consensus on how passive survivability is measured and assessed.

c. "HVAC/off" functionality and advanced passive solar heating and cooling simulation in easily accessed early-stage design and analysis platforms using validated building energy modeling software.

Keywords:

Passive survivability; resilience; passive heating; passive cooling; climate data; building energy modeling

1. Introduction

Defining passive survivability

Passive survivability refers to the idea that certain buildings, especially houses and multifamily structures, should be designed and built to maintain habitable temperatures in the event of an extended power outage or interruption in heating fuel (Wilson 2019). The concept of passive survivability emerged following Hurricane Katrina in the Gulf Coast of the United States in the Fall of 2005 when several chapters of the U.S. Green Building Council (USGBC) organized and led a series of design charrettes in an effort to guide the reconstruction that would occur following the storm's destruction to enhance sustainability.

Over the past two decades, the building design and construction industry has defined methodologies and performance metrics to assess the passive survivability of indoor environments. However, the majority of existing U.S. residential building stock fails to provide thermal safety by meeting passive survivability; moreover, a large segment of houses designed to the latest energy codes and even Passive House Institute US (PHIUS) standards fail to meet passive survivability.

The imperative to achieve passive survivability requires the international building design and construction sector to address three shortcomings in the current marketplace:

1. Downscaled climate projection data must be methodically developed, regularly updated, publicly available, and compatible with validated, highly utilized building energy modeling programs.

2. The capability to access and leverage standardized passive survivability metrics must be made available to building design teams within early-stage building energy modeling with "HVAC/off" functionality.

3. Data shows that we cannot insulate our way to passive survivability. The industry must expand the current capabilities and offerings provided by easily accessible early-stage building energy modeling tools in order to allow building design teams with basic competencies to incorporate, compare, and optimize passive solar heating and cooling strategies in order to help projects achieve passive survivability.

2. The climate projection data “unlock”

Imperative for climate-adaptive architecture

The Intergovernmental Panel on Climate Change (IPCC) finalized the Synthesis Report for the *Sixth Assessment Report* during the Panel's 58th Session held in Interlaken, Switzerland in March 2023. The report (IPCC 2022) concludes that “human activities, principally through emissions of greenhouse gases, have unequivocally caused global warming, with global surface temperature reaching 2.0°F (1.1°C) above 1850–1900 in 2011–2020. Global greenhouse gas emissions have continued to increase, with unequal historical and ongoing contributions arising from unsustainable energy use, land use and land-use change, lifestyles and patterns of consumption and production across regions, between and within countries, and among individuals (high confidence).”

Widespread and rapid changes in the atmosphere, ocean, cryosphere, and biosphere have occurred. Human-caused climate change is already affecting many weather and climate extremes in every region across the globe. Adaptation planning and implementation has progressed across all sectors and regions, with documented benefits and varying effectiveness. Continued greenhouse gas emissions will lead to increasing global warming (IPCC 2023).

In response, the building design and construction industry is increasingly focused on resilient design strategies that seek to better ensure the thermal safety of building occupants. The term *climate-adaptive architecture* has emerged to refer to buildings that respond “to a new or changing environment that exploits beneficial opportunities or moderates negative effects (IPCC 2022). To successfully adapt to future climate conditions, an innate consideration of climate-adaptive architecture are climate projections over a building’s service life.

In pursuit of downscaled climate projection data

Climate projections are not a new concept. The climate has already changed in a way that is measurable and definable (Owen 2021; Crawley & Lawrie 2021). Moreover, the climate is changing faster than the scientific community had anticipated (Wuebbles et al. 2017a; Loeb et al. 2021). Using measured data averaged from the three most recent decades has been generally considered a sufficient representation of a climate (Owen 2021) and approximately the ideal duration of measured data to establish ‘climate normals’.

Using climate normal, various “typical” or reference year weather files are publicly available for locations throughout the world. These files have become the primary resource for building design teams to analyze a building design’s operational characteristics. In the U.S., the various iterations of Typical Meteorological Year (TMY) dataset produced by the National Renewable Energy Laboratory (NREL) serves this purpose.

However, in a time of rapid change, these historical data poorly characterize the diversity of weather conditions that a building will experience in a changing climate during its lifetime (Rastogi & Khan 2022). This is likely to result in buildings that will fail to realize their lifecycle goals for greenhouse gas (GHG) emissions from operations due to changes in the nature of dominant peak and average load types (Yang et al. 2021). These buildings may also fail to maintain indoor comfort and air quality, especially those that use natural ventilation, mixed-mode ventilation, and passive systems. Building and HVAC (heating, ventilation, and air-conditioning) systems that are already over-designed may not suffer the same issues, but might instead incur higher operational costs, use more energy, and emit more GHGs due to higher utilization. Other changes such as those to ambient air temperature and relative humidity may shift a structure’s actual heating and/or cooling loads beyond the design loads of its HVAC system. This could lead not only to considerable HVAC performance issues, but also to unintended changes which may threaten the longevity of the structural system (Owen 2021).

One major limitation of using a historical record of finite length is that while the probability of covering plausible values increases with the length of record, a changing climate can make such characterizations much less useful. This is clearly exemplified by cross-referencing the global average temperature compared to the middle of the twentieth century to the time periods in which various iterations of TMY data were recorded (i.e., TMY, TMY2, TMY3) (Figure 1). It is worth noting that researchers at Climate.OneBuilding publish TMYx files derived from hourly weather data through 2021 (Lawrie & Crawley 2022).

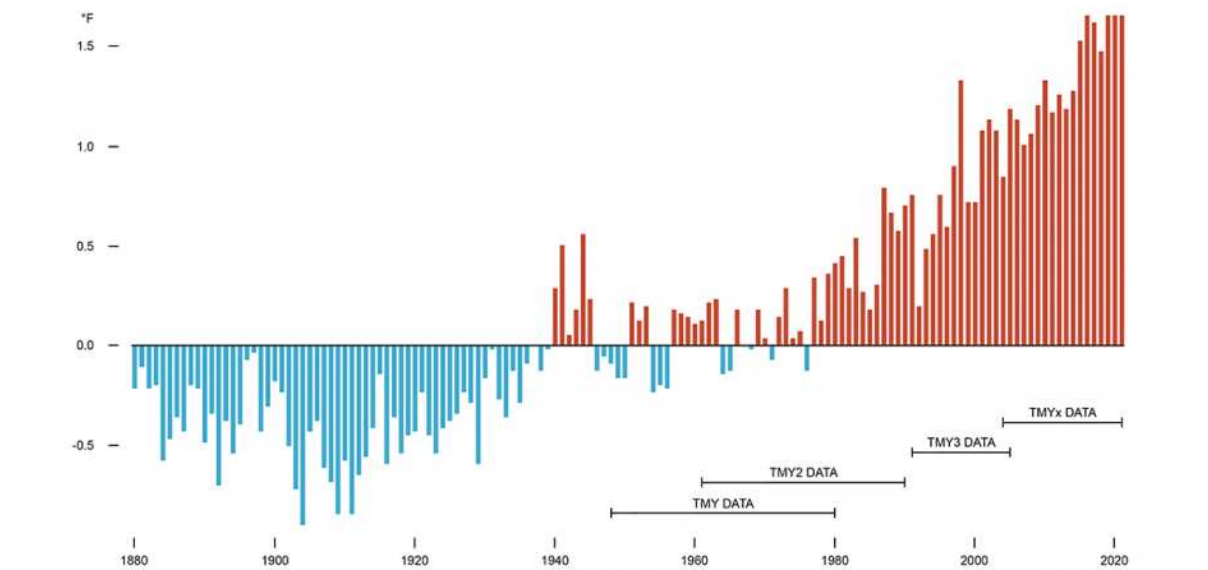

Figure 1: Global Average Temperature Compared to the Middle of the 20th Century. Data source: NOAA National Center for Environmental Information, Climate at a Glance: Global Time Series, published August 2022, retrieved on August 16, 2022 from https://www.ncei.noaa.gove/cag/ Figure by Daniel Overbey.

A rapidly changing climate means that successful climate-adaptive architecture must utilize climate projections.

Multiple studies have extended the concept of a year of typical historical data to establish typical data for future decades (Owen 2021). The most popular techniques involve *morphing* (Belcher et al. 2005; Crawley 2008; Eames 2016) or *stochastic generation* (Rastogi 2016; Grantham et al. 2018). These techniques to create projected estimates based on typical historical data and can be utilized to generate possible future climate trajectories (Rastogi et al. 2022).

To produce climate projection data at a finer spatial resolution (e.g., regional, state, county, or city scale), global climate models must be downscaled using either dynamic or statistical modeling techniques (McSweeney & Hausfather, 2018). The term *downscale* refers to the methodical extrapolation of the effects of large-scale climate processes to regional or local scales of interest (Dixon et al. 2023). These finer spatial resolution models tend to provide more accurate simulations of local physics and dynamics influencing the climate in a specific geographic location (Rastogi et al. 2022).

Barrier to adoption

If downscaled climate projection data are available, why are building design professionals not using them?

Four primary technical and policy barriers to broad adoption of climate data projections have been identified and built upon by the building design and construction community (Rastogi et al. 2022; Laxo et al. 2023):

Lack of consensus on the methodology for creating climate projection data for buildings. A variety of climate models estimate the extent and impacts of future climate change, which are summarized in publications such as the *ASHRAE Handbook—Fundamentals* (Owen 2021) and the *National Climate Assessment* (Wuebbles et al. 2017b). These models can vary widely in their projections. A range of representative scenarios based on different magnitudes of equivalent GHG emissions, the so-called "representative concentration pathways" (RCPs) (van Vuuren et al. 2011), offer a foundation for projecting climate change plausibly. However, building design teams cannot be expected to be conversant with the nuanced interpretation of varying projections. Moreover, the lack of consensus regarding an acceptable method for systematically projecting climate data using specific pathways will undermine trust in the climate projection data (Laxo et al. 2023).

Lack of a publicly available platform for providing climate projections in a resolution, scale, and format suitable for building analysis. Historical climate data is publicly available from meteorological agencies such as the National Oceanic and Atmospheric Administration (NOAA) and the UK Met Office, in file formats that can be used as input for building energy modeling software. High-resolution climate projection data has been freely available from U.S. government websites and international collaborations for years, e.g., CORDEX (cordex.org), Cal-Adapt (cal-adapt.org), and CMIP5 projections (gdo-dcp.ucllnl.org). However, the outputs of climate models are not formatted to a resolution, scale, or format usable in architectural or engineering design and analysis tools. Considering the uncertainties of forecasting, a standardized methodology must be established, and suitable projected data must be managed by a trusted organizational body. Curated projected time series, such as WeatherShift, Indra, and Meteonorm, have not been widely adopted – these resources are not publicly available, have not been regularly or systematically updated by a professional body, and they have not been systematically compared (Rastogi et al. 2022).

Lack of consensus on a standardized framework for communicating the results of simulation with long-term climate data projections. The concept of a single "future typical" file may create a false impression of certainly about future climate trends. Adding a "climate safety factor" may result in building systems that are even more oversized than common current practice and increasing upfront capital investment. A consensus-based, standardized framework may be leveraged to facilitate a common understanding of climate risk would foster a suitable risk-based design approach.

Liability concerns with using projection data. Without a consistent methodology for creating climate projection data, lacking a professional or governmental curator and standard-bearer for climate projections, and devoid of a consensus-based standard for utilizing climate projection data, professional liability concerns abound. A standard or model code could alleviate this concern. Codification and regulation would shift risk away from design professionals.

Building project teams need publicly accessible climate project data

For building project teams to design and adapt our building stock to become more resilient from the standpoint of thermal safety, climate projection data must be leveraged with the following caveats:

a. It must be publicly available through a professional or governmental institution.

b. It must be provided in a resolution, scale, and format suitable for building analysis.

c. Its use must adhere to a consensus-based standardized framework.

d. Its use must be codified and regulated.

3. Passive survivability re-SET

Hurricane Katrina and the New Orleans Principles

Hurricane Katrina made landfall off the coast of New Orleans, Louisiana, on August 29, 2005. It hit land as a Category 3 storm with wind speeds as high as 120 miles per hour. An estimated 1,833 people died as a direct result of the storm, which caused an estimated $108 billion in property damage. It is considered one of the deadliest storms in U.S. history (Gibbens 2019).

The hurricane exposed a series of deep-rooted vulnerabilities, including controversies over the federal government's response and difficulties in search-and-rescue efforts. However, the lack of preparedness for the storm – particularly regarding the city's infrastructure and building stock – resulted in a devastating loss of human life and personal property. Rescue efforts included evacuating approximately 16,000 residents to the Superdome arena in downtown New Orleans – only to be evacuated from the facility within two days after the living conditions disintegrated. The arena was not able to maintain safe conditions without power, resulting in severe thermal safety concerns as ambient dry bulb temperatures rose over 90ºF (32.2ºC) – compounding struggles with hunger, thirst, and human effluents (Gold 2005). It was notable that many of the older homes – many built in the traditional 'shotgun' vernacular style with wrap-around porches – that shaded windows from direct solar gain and facilitated natural ventilation fared better in terms of thermal safety than the more recent air-conditioning-dependent homes built post-World War II (Wilson et al. 2023).

In the wake of the storm's destruction, four Gulf Coast reconstruction charrettes convened in November 2005, bringing together over 160 building design and construction professionals from the New Orleans region and throughout North America to address rebuilding the city. With sponsorship from the U.S. Green Building Council (USGBC), the charrettes were organized by Bill Browning, Hon. AIA; Mary Ann Lazarus, FAIA, and Bill Odell, AIA; Ralph Bicknese, AIA; and Martha Jane Murray, AIA. They addressed four issues: New Orleans planning, green communities, affordable housing (with Habitat for Humanity International), and sustainable schools. (Wilson 2006). One of the primary products of the charrettes was *The New Orleans Principles*, a report that outlines ten key principles to guide the planning and reconstruction efforts following Hurricane Katrina in a manner that embraces environmental, social, and economic priorities (Wilson 2005b).

Among those ten principles is the recommendation to "provide for passive survivability": that homes, schools, public buildings, and neighborhoods should be designed and built (or rebuilt) to serve as livable refuges in the event of crisis or breakdown of energy, water, and sewer infrastructure. The concept of *passive survivability* holds that a building should maintain critical life-support conditions for its occupants if public services such as power, heating fuel, or water are lost for an extended period (Wilson 2005a). In a predominantly hot and humid climate such as New Orleans, a considerable challenge to maintain thermal safety will be managing the wet bulb globe temperature (WGBT), which can regularly surpass 80ºF (26.7ºC) when the ambient outdoor air temperature is over 90ºF (32.2ºC).

Emergence of the de facto passive survivability performance standard

Shortly after founding the Resilient Design Institute (RDI) in 2012, Alex Wilson proposed to USGBC the development of a suite of pilot credits for the LEED Rating System focusing on resilient design. With encouragement from USGBC, a pilot credit committee was assembled in 2013 and work commenced on developing the pilot credits. Co-chaired by Alex Wilson and Mary Ann Lazarus, FAIA, the committee spent nearly two years developing three pilot credits focused on resilience: the first to assess vulnerabilities for a particular location; the second to use best practices to mitigate the most relevant vulnerabilities to the particular location; and the third to ensure that a building maintain at least limited functionality in the event of extended lost power (Wilson 2020).

The pilot credits were adopted by USGBC in the Fall of 2015; however, all three were removed a year later as Green Business Certification Inc. (GBCI), which manages third-party certifications for LEED and several other rating systems in the building sector, adopted of the RELi Rating System in 2017. Developed by the Institute for Market Transformation to Sustainability (MTS) and its Capital Markets Partnership (CMP) coalition in 2012, the RELi standard facilitates an integrative process, hazard preparation and adaptation along with chronic risk mitigation at the building and neighborhood scales (Keane, 2017). The methods and targets of the LEED pilot credits were not consistent with the RELi standard. In late 2018, the revised pilot credits were relaunched. However, in 2022, GBCI ceded ownership of RELi and chose to no longer certify RELi projects (Melton 2021). Today, the revised LEED pilot credits endure as the United States' de facto standards for resilient design at the building scale – including passive survivability via Innovative Process pilot credit 100 (IPpc100), *Passive Survivability and Back-up Power During Disruptions* (USGBC 2022).

Metrics for assessing passive survivability

In accordance with IPpc100, passive survivability in a building may be defined as achieving at least one of three paths:

Path 1: psychrometry
Using a psychrometric chart, a project team shall demonstrate that indoor conditions (dry-bulb air temperature and humidity) never breach the specified overheating and under-heating thresholds, which include Heat Index and / or wet-bulb globe temperature during the peak cooling season (summer) and heating season (winter) seven-day analysis periods. This compliance path was added to bring IPpc100 into better alignment with the RELi rating system.

The University of California, Berkeley's Center for the Built Environment (CBE) Comfort Tool's psychrometric chart serves as a publicly-available tool to assess the following passive survivability metric: https://cbe.berkeley.edu/research/cbe-thermal-comfort-tool/

Heat Index

Heat Index (HI) is a basic and limited assessment metric to gauge thermal safety. During hot-season periods of utility-grid power outages or heating fuel interruptions, a building shall allow natural ventilation via operable windows and/or non-powered natural ventilation and passive cooling to maintain indoor temperatures at or below HI calibrated temperatures (U.S. NOAA and OSHA Heat Advisory Levels) as follows (Figure 2):

a. Commercial buildings (except for essential service providers):

    i. During the cooling season, maintain indoor temperatures at or below 103*F heat index in hot seasons;

    ii. During the heating season, maintain interior building temperature at or above 50*F.

    iii. Manage other space to prevent freezing of water.

b. Residential buildings, facilities and areas: During the cooling season, maintain a maximum 90°F (32.2°C) degree (i.e., the "Extreme Caution" threshold).

Heat index, sometimes referred to as the *apparent temperature*, may be used to communicate what the ambient air temperature is considered to feel like to the human body when relative humidity is taken into consideration. HI is a reference temperature that considers both the sensible and latent heat of the air. It also typically presumes strenuous activity by the individual (NWS 2023).

As such, heat index offers a gauge of heat stress when relative humidity is taken into effect. When the body overheats, it perspires to cool itself off. If the perspiration is not able to evaporate because the air has too much moisture in it, the body cannot regulate its temperature. Therefore, when humidity is high, the rate of evaporation diminishes and heat stress increases.

HI is widely used in the United States. However, HI comes with a few caveats when it comes to its application in assessing heat stress:

a. HI assumes the person is in a shaded area.

b. HI does not take into consideration mean radiant temperature (MRT).

c. HI does not take air velocity into consideration (i.e., it assumes a dead air space).

Heat index has limitations as a passive survivability metric. As such, although the U.S. federal government's Occupational Safety and Health Administration (OSHA) uses HI as an indicator to assess heat stress; the organization is quick to point out that HI may not measure worksite heat as accurately as wet bulb globe temperature due to the additional factors that it considers (OHSA 2023).

Temperature (Fahrenheit)

Relative Humidity	80 °F	82 °F	84 °F	86 °F	88 °F	90 °F	92 °F	94 °F	96 °F	98 °F	100 °F	102 °F	104 °F	106 °F	108 °F	110 °F
40%	80 °F	81 °F	83 °F	85 °F	88 °F	91 °F	94 °F	97 °F	101 °F	105 °F	109 °F	114 °F	119 °F	124 °F	130 °F	136 °F
45%	80 °F	82 °F	84 °F	87 °F	89 °F	93 °F	96 °F	100 °F	104 °F	109 °F	114 °F	119 °F	124 °F	130 °F	137 °F	
50%	81 °F	83 °F	85 °F	88 °F	91 °F	95 °F	99 °F	103 °F	108 °F	113 °F	118 °F	124 °F	131 °F	137 °F		
55%	81 °F	84 °F	86 °F	89 °F	93 °F	97 °F	101 °F	106 °F	112 °F	117 °F	124 °F	130 °F	137 °F			
60%	82 °F	84 °F	88 °F	91 °F	95 °F	100 °F	105 °F	110 °F	116 °F	123 °F	129 °F	137 °F				
65%	82 °F	85 °F	89 °F	93 °F	98 °F	103 °F	108 °F	114 °F	121 °F	128 °F	136 °F					
70%	83 °F	86 °F	90 °F	95 °F	100 °F	105 °F	112 °F	119 °F	126 °F	134 °F						
75%	84 °F	88 °F	92 °F	97 °F	103 °F	109 °F	116 °F	124 °F	132 °F							
80%	84 °F	89 °F	94 °F	100 °F	106 °F	113 °F	121 °F	129 °F								
85%	85 °F	90 °F	96 °F	102 °F	110 °F	117 °F	126 °F	135 °F								
90%	86 °F	91 °F	98 °F	105 °F	113 °F	122 °F	131 °F									
95%	86 °F	93 °F	100 °F	108 °F	117 °F	127 °F										
100%	87 °F	95 °F	103 °F	112 °F	121 °F	132 °F										

Heat Index in Fahrenheit	Heat Index Level
Less than 80 °F	**Safe:** No risk of heat hazard
80 – 90 °F	**Caution:** Fatigue is possible with prolonged exposure and activity. Continuing activity could result in heat cramps.
90 – 103 °F	**Extreme Caution:** Heat cramps and heat exhaustion are possible. Continuing activity could result in heat stroke.
103 – 125 °F	**Danger:** Heat cramps and heat exhaustion are likely; heat stroke is probable with continued activity.
Over 125 °F	**Extreme Danger:** Heat stroke is imminent.

Figure 2: National Weather Service (NWS) Heat Index. Information source: U.S. National Oceanic and Atmospheric Administration (NOAA). Figure adapted by Daniel Overbey.

Wet-bulb globe temperature

Wet-bulb globe temperature (WBGT) is a metric used to assess the sensible and latent heat stress on the human body. It is commonly referenced in occupational health and safety determinations, for sport activities, and in military settings to evaluate the risk of heat-related ailments.

Compared to the heat index, WBGT may be considered a more appropriate metric to assess passive survivability because it considers four major environmental heat factors: dry-bulb temperature, relative humidity, mean radiant temperature, and wind velocity.

Leveraged as a passive survivability metric for IPpc100, a building's indoor conditions in occupied spaces shall never breach the following overheating and underheating WBGT (Figure 3):

a. Commercial buildings without overnight occupancy (except for essential service providers): No hours during the cooling season analysis period permitted to exceed above the 88°F (31°C) WBGT overheating threshold.

b. Residential buildings with overnight occupancy: No hours during the cooling season analysis period permitted to exceed above the 82.5°F (28°C) WBGT overheating.

c. Both building types during the heating season: No hours during the wintertime analysis period permitted to fall below 50°F (10°C) dry-bulb air temperature.

Although WBGT may be appropriate to assess outdoor environments, a major limitation of using WBGT to assess the passive survivability conditions in a building's interior is that WBGT measures heat stress in direct sunlight.

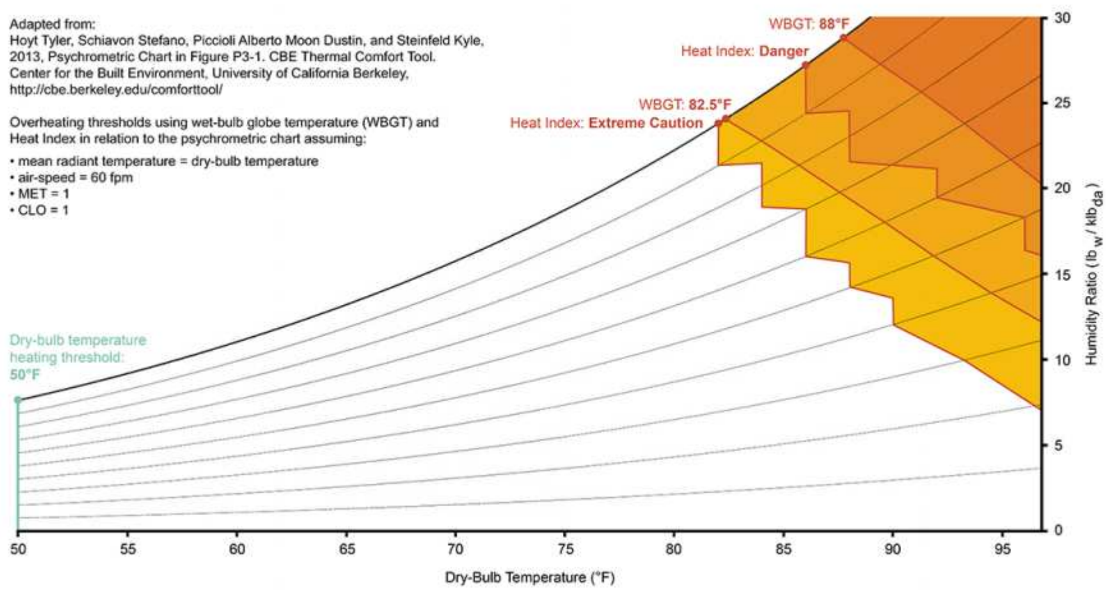

Figure 3: Psychrometric chart with wet-bulb globe temperature (WBGT) thresholds. Adapted from: Hoyt Tyler, Schiavon Stefano, Piccioli Alberto Moon Dustin, and Steinfeld Kyle, 2013, Psychrometric Chart in Figure P3-1. CBE Thermal Comfort Tool. Center for the Built Environment, University of California Berkeley, http://cbe.berkeley.edu/comforttool/
Figure adapted by Daniel Overbey.

Path 2: Standard Effective Temperature

IPpc100 also allows compliance by limiting the deviations from defined livable Standard Effective Temperature (SET) thresholds within a building's interior to a specified number of degree-days (degree-hours) during the peak summer and winter analysis periods.

Developed by A.P. Gagge and accepted by ASHRAE in 1986, ASHRAE Standard 55 defines *Standard Effective Temperature* (SET) as follows (Gagge et al. 1986; ANSI/ASHRAE 2020):

> *The temperature of an imaginary environment at 50% relative humidity, less than 20 feet per minute (fpm) average air speed, and mean radiant temperature equals average air temperature, in which the total heat loss from the skin of an imaginary occupant with an activity level of 1.0 met and a clothing level of 0.6 clo is the same as that from a person in the actual environment with actual clothing and activity level.*

Basically, SET is a comfort indicator that considers indoor dry-bulb temperature, relative humidity, mean surface radiant temperature, and air velocity, as well as the activity level and clothing of occupants in the space. Unlike heat index and wet-bulb globe temperature, SET was conceived as a metric to assess *interior conditions*. It is a comprehensive comfort index based on heat-balance equations that incorporate personal factors of clothing and metabolic rate.

By utilizing SET, project teams can leverage building energy modeling software to demonstrate that a building can maintain passive survivability during an extreme temperature event by maintaining livable (not necessarily comfortable) conditions indoors if the building loses all mechanical functionality for a week. In accordance with the de facto industry standard set by IPpc100, the SET range that constitutes "livable conditions" varies between the 54°F (12.2°C) and 86 °F (30°C) thresholds. To demonstrate passive survivability, project teams would need to demonstrate that the number of SET degree-hours outside of this range do not exceed the following during a 7-day extreme temperature event (USGBC 2022):

- Cooling (extreme hot week) (Figure 4):
  Residential: 216 °F SET-hours
  Non-residential: 432 °F SET-hours

- Heating (extreme cold week) (Figure 5):
  All buildings: 216 °F SET-hours

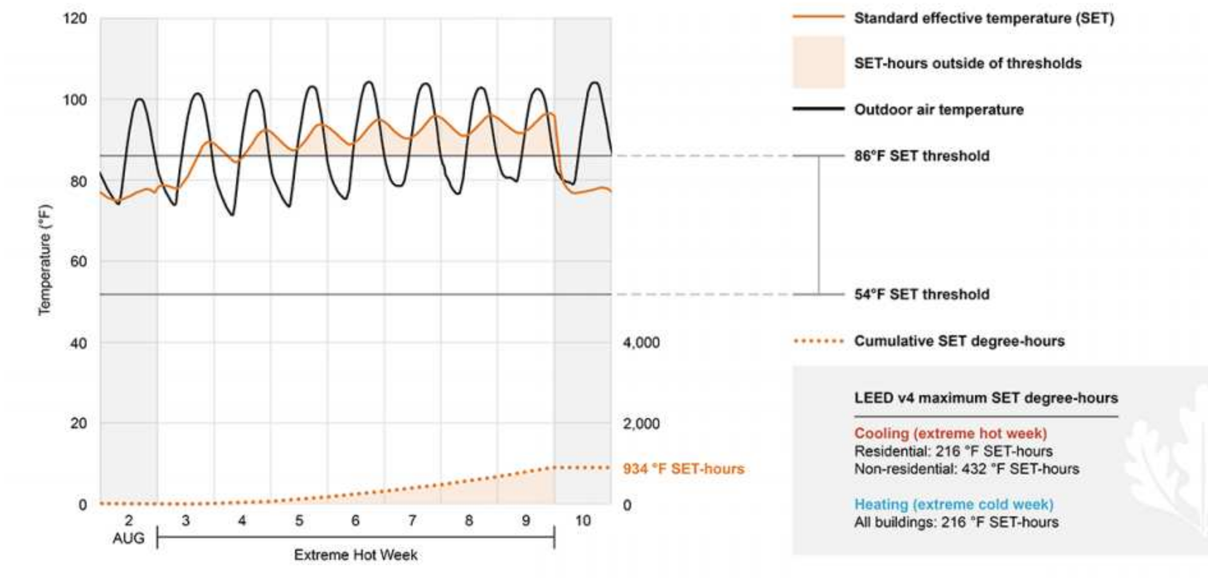

Figure 4: Assessing an extreme hot week (hot-humid location example) using standard effective temperature (SET). Figure by Daniel Overbey.

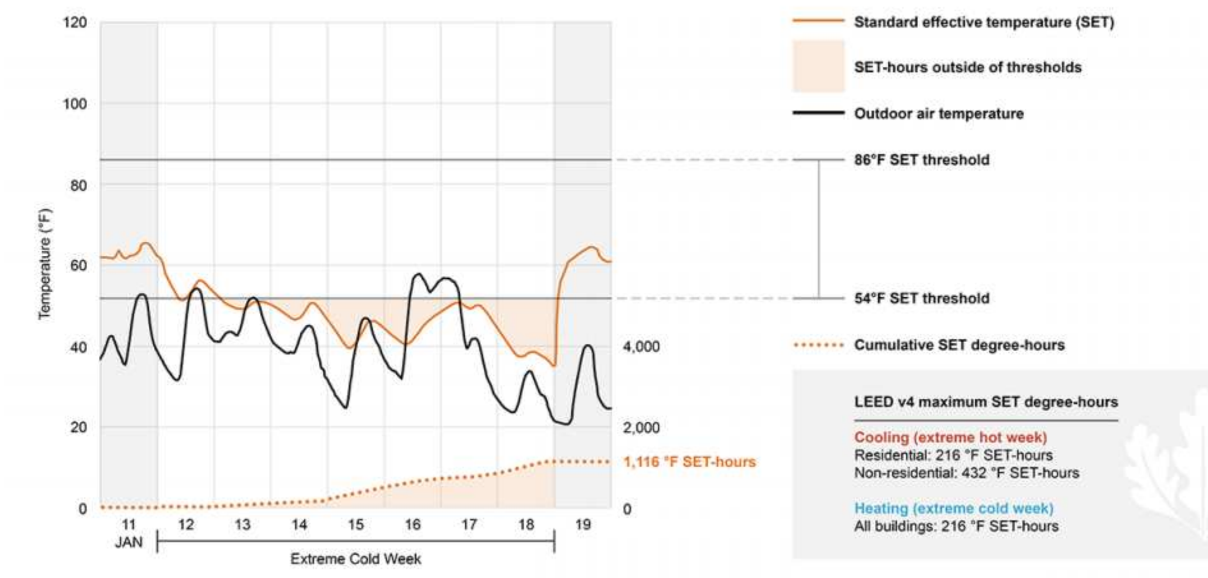

Figure 5: Assessing an extreme cold week (hot-humid location example) using standard effective temperature (SET). Figure by Daniel Overbey.

Path 3: Passive House certification

The third and final way to meet passive survivability in accordance with IPpc100 is to achieve Passive House certification using either Passive House Institute U.S. (PHIUS) or Passive House Institute standards and methodologies. Additionally, projects must include operable windows or other means of natural ventilation to meet specific credit requirements.

Compliance via Path 3 presupposes that Passive House certification generally ensures that the structure will meet the performance parameters to ensure thermal safety. However, recent data suggests that simply meeting Passive House may not ensure passive survivability in a majority of instances when considered across a range of climate zones.

The DOE report demonstrates that the U.S. housing stock largely fails to provide passive survivability – including structures meeting PHIUS

In July 2023, the U.S. Department of Energy's (DOE) Building Technology Office (BTO) released a report outlining a standardized methodology and resulting analysis demonstrating the impact of code and above-code measures toward hazard resilience. The study applied the aforementioned SET thresholds and corresponding SET degree-hours over an extreme seven-day heating and cooling event to ascertain the passive survivability of an average existing residential building, a similar new house built to the latest energy standard adopted by the local jurisdiction, a similar house built in accordance with the 2021 edition of the International Energy Conservation Code (IECC 2021; the latest model energy code from the International Code Council at the time of the study), and a similar house built to PHIUS. The work assessed six representative cities in the contiguous U.S.: Atlanta (Georgia), Houston (Texas), Los Angeles (California), Portland (Oregon), Minneapolis (Minnesota), and Detroit (Michigan). As such, BTO study found that approximately 50% of the analyzed housing conditions failed to meet the SET passive survivability degree-hour limits (Williams et al. 2023).

Building energy modeling software needs to allow "HVAC/off" modes and provide early-stage passive survivability modules

For building project teams to design and adapt our building stock to become more resilient from the standpoint of thermal safety, passive survivability metrics must be leveraged with the following caveats:

a. Assessment of the SET thresholds must be accessible through validated, industry-recognized building energy modeling platforms capable of providing "HVAC/off" functionality.

b. The metrics must be easily accessible through graphic user interfaces that facilitate quick, iterative design analyses during early design stages by building design teams with basic competencies.

4. We Cannot Insulate Our Way to Passive Survivability

It is 1984 all over again

According to the U.S. Department of Energy's Building Technology Office (BTO) study, approximately 42% of all PHIUS-compliant new construction conditions failed to meet the SET passive survivability degree-hour limits across the six cities examined (Williams et al. 2023). Simply, we cannot insulate our way to passive survivability. Supplemental heating and cooling will be required to achieve passive survivability in extreme climates.

In a week-long blackout condition, the options for backup heating and cooling for all electric homes are limited and obvious. One common solution is a *back-up energy system* – such as a generator or battery storage – which would need to be capable of providing electrical energy for critical heating/cooling systems. A drawback to this option is that it depends on converting finite energy resources for a specified period – typically less than a continuous week. Moreover, the technology – and the thermal safety it provides – is solely reliant on the reliable functionality of a myriad intermittently used technical components.

A second backup option is *auxiliary on-site combustion* – via as a stove, fireplace, or similar – which provides heating only. Regardless of the biofuel source (e.g., wood, corn, etc.), innate to such processes is a release of biogenic carbon, degraded indoor air quality, and direct life-safety concerns from fire or burning.

A third option is *passive solar heating and cooling*. By harvesting the natural energy flows of a site and utilizing the building design itself to reliably collect, store, convert, and transfer thermal energy (i.e., heat), passive heating and cooling offers a safer, more stable, and more reliable backup system for heating and cooling that does not rely on converting non-renewable and/or combustible biofuel energy resources.

Only one of the aforementioned options for heating and cooling is truly passive – and therefore markedly more reliable. Yet, passive heating and cooling systems have remained underutilized for decades due to a Western predisposition toward mechanical systems for heating, cooling, and ventilation, which has been perpetuated by the engineering community through a combination of building energy modeling tools that presume the presence of mechanical HVAC systems and codified standards for indoor environments developed around the utilization of such systems (Nicol et al. 2022).

Passive systems work – and if properly designed, they can work exceptionally well

Passive heating and cooling systems have been thoroughly researched and shown to work effectively.

Passive systems utilize the innate design features of a building structure and enclosure to collect, store, and distribute thermal energy (e.g., heat from converted solar radiation) by radiation, conduction, and/or convection.

Predicting the thermal performance of passive solar heating

The standard procedure used to analyze buildings that feature passive solar heating strategies is the *load collector ratio* (LCR) method. This procedure was developed by the Los Alamos National Laboratory between 1977 and 1984. As a result of the LCR method, a project team may ascertain the *solar savings fraction* (SSF) of a passive solar heating system used in a building. The SSF is the most widely accepted metric for evaluating the effectiveness of passive solar heated buildings. The SSF may be defined as the extent to which a building's passive solar feature(s) reduces a building's auxiliary heat requirement relative to a comparable building devoid of passive solar feature(s) (Balcomb et al. 1984).

More recent work through the Ball State University and University of Nevada, Las Vegas (UNLV) have validated the LCR method of predicting the SSF from the passive solar heating strategies of several thermal storage wall systems – direct gain, Trombé wall, water wall, and a sunspace – in a severe winter climate with predominantly cloudy sky conditions (Overbey 2008); however, there is limited recent work that otherwise explores or validates the LCR method of passive solar heating analysis.

Predicting passive heating and cooling via roofpond systems

A thermal storage roof is similar to the thermal storage wall with one obvious difference: the thermal storage mass is located on the building's roof, which liberates the structure from a dependency on solar orientation (Balcomb et al. 1984). In the case of thermal storage roof systems, the thermal mass typically consists of plastic bags filled with water. Historically, water has been utilized as a thermal mass in such instances because of its superior specific heat versus that of any other common building material (Moore 1993). Over time this indirect gain system came to be commonly referred to as the *roofpond*.

The roofpond system was developed by Harold R. Hay and endures as a highly under-utilized passive system that is capable of providing both heating and cooling in severe summer and winter locations. For example:

The Phoenix Prototype (Phoenix, Arizona) monitored thermal performance for a year without the use of supplementary heating or cooling. The system maintained an indoor air temperature between 70 to 80°F (21.1 to 26.7°C) during approximately 91% of the year under "normal" weather conditions (as defined by Phoenix weather data). At all times, the interior temperature was maintained in a range between 68 and 82°F (20°C and 27.8°C) (Marlatt et al. 1984) (Figure 6).

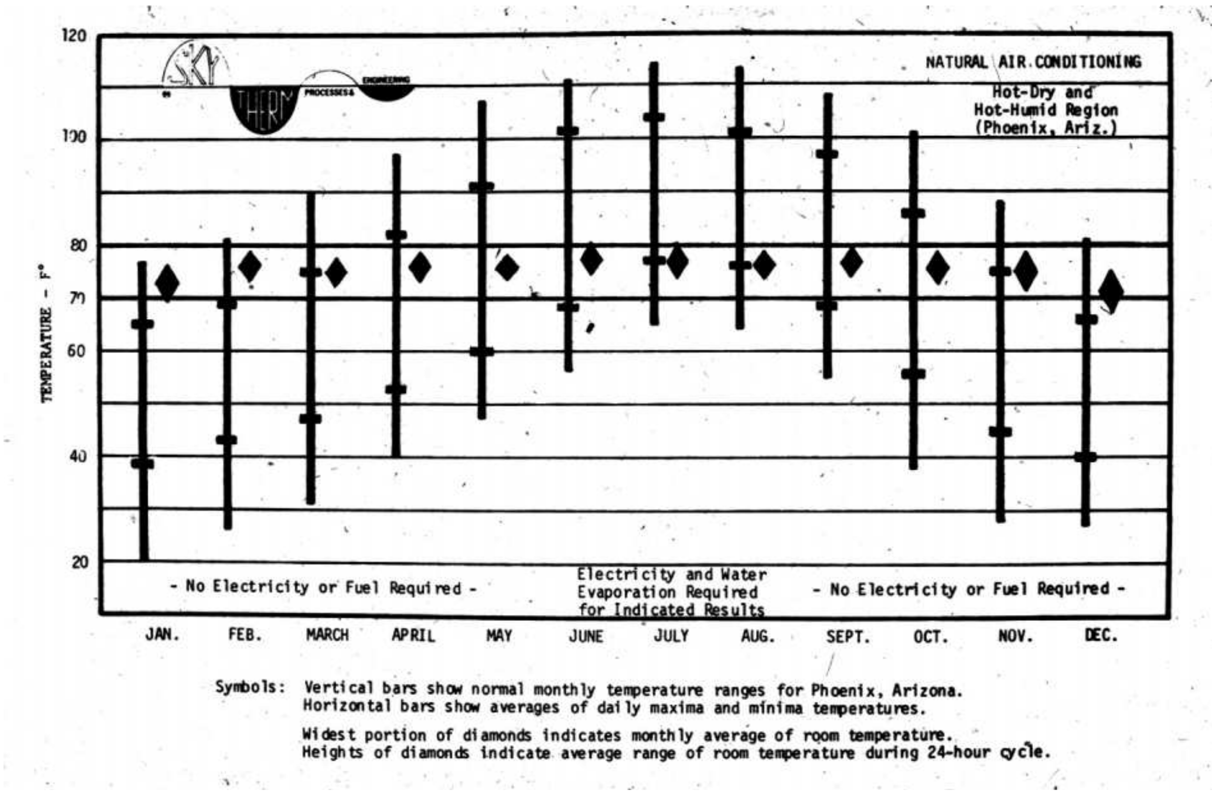

Figure 6: Performance data from the Phoenix Prototype. Courtesy of the Natural Energy Advanced Technologies (NEAT) Laboratory at the University of Nevada, Las Vegas.

The Atascadero House (near San Luis Obispo, California) monitored data for one summer and determined that no electricity was required to maintain an average indoor temperature of approximately 72°F (22.2°C). The average winter temperatures were between 66 and 74°F (18.9 and 23.3°C) without the use of any supplemental space heating (Marlatt et al. 1984).

Skytherm North (Minneapolis, Minnesota) utilized a roofpond in an attic with south-facing skylights. The performance of the system and the backup heating requirements were monitored in this severe winter location. Backup heat pumps kept interior temperatures at a minimum of 62°F (16.7°C) during the winter. The direct gain through south-facing windows contributed 6 to 8°F to the temperature of the inside space during winter operation. When the roof pond reached 90°F (32.2°C), the house temperature was 70°F (21.1°C) in the upstairs living area. During summer operation, exterior overhangs prevent direct solar gain through the windows, and the insulating panels were set to close to help prevent overheating (Marlatt et al. 1984).

In 1984, the Energy Technology Engineering Center operated the most comprehensive assessment of roofponds ever conducted. The report was developed for the U.S Department of Energy and determined that "well-designed [roofpond] systems can provide, without backup HVAC systems, relatively even indoor temperatures at approximately 60 to 80°F (15.6 to 26.7°C) year-round in climates with an outdoor temperature that ranged between 32 and 115°F (0 and 46.1°C)) (Marlatt et al. 1984). This was well within the thresholds of passive survivability.

In more recent years, extensive work at Ball State University and the UNLV have also validated methodologies for predicting the performance of roofponds in terms of SFF (Fernández-González 2004).

In all instances, in predominantly hot and cold climates, the roofpond maintained indoor temperatures well within the range of passive survivability.

The need for accessible, early-stage passive system design analysis

It has been four decades since these landmark publications from federally funded laboratories operating for the U.S. Department of Energy issues methodologies, metrics, and validation that passive systems can be leveraged for effective thermal safety.

Considering the advantages of passive heating and cooling systems, one may ponder why such systems are not employed at a large scale to ensure passive survivability? Similar to downscaled climate projection data and accessible passive survivability metrics in building energy modeling platforms, there is a great “unlock” potential for passive solar heating and cooling if the building design and construction industry demonstrates a collective will to invest in tools to effectively assist teams at the earliest stages of design process.

The most common building energy modeling software in the U.S. – namely, EnergyPlus, which is an open-source platform that serves as the “engine” behind a number of public and private-sector tools and services, including popular modeling and analysis programs such as OpenStudio, DesignBuilder, Sefaira, and cove.tool – were originally designed to assume buildings have mechanical cooling and heating systems to meet the building’s indoor thermal comfort and occupant indoor air quality needs (DOE 2014). Today, EnergyPlus does exhibit the capability model a building in free-floating “HVAC/off” mode without space cooling or heating. It exhibits sophisticated features to model windows and their shading and control system, thermal mass, and solar income. It is still limited in the sense that it is not capable of simulating highly granular thermal fluid dynamics; however, EnergyPlus enables co-simulation with other software tools which can be specialized in certain systems or features. Despite all of these advancements, the most critical shortcoming remains: access. Architectural designers cannot be expected to be conversant building energy modeler with advanced knowledge into simulation analysis. The building design and construction industry offers a range of commercially available early-stage building energy modeling programs (often using EnergyPlus) that integrate into design workflows; however, these accessible platforms do not exhibit modules capable of simulating the complex thermal energy exchanges offered by specific passive solar heating and cooling systems in a “HVAC/off” mode. As a result, it is not possible for project teams to ascertaining the SSF provided by integrated passive systems nor is it possible to quickly simulate design strategies in such programs using an “HVAC/off” functionality and assess building interiors for passive survivability using the standard SET thresholds.

It is important to note that there are products in the marketplace that allow for varying levels of passive solar heating and cooling analysis. The APACHE engine used in IES’ Virtual Environment (IESVE) software offers passive capabilities. Advanced multiphysics computational fluid dynamics (CFD) simulation software such as Simcenter STAR-CCM+ is capable of advance thermal energy transfer; however, such commercially developed products are difficult to access by novice design professionals and the products are cost-prohibitive to all but the largest architecture firms in any given market.

In the interest of promulgating passive survivability, the building design and construction industry needs accessible, validated energy modeling tools capable of early-stage passive system simulation using an “HVAC/off” functionality and SET threshold assessment.

5. Conclusion

Passive survivability is achievable if high-performance enclosures are coupled with optimized passive heating and cooling systems. For building project teams to both design new structures and adapt our existing building stock to achieve greater resilience from the standpoint of thermal safety, the industry must address three critical needs in the current marketplace:

1. Downscaled climate projection data must be methodically developed, regularly updated, publicly available, and compatible with validated, highly utilized building energy modeling programs.

2. The capability to access and leverage standardized passive survivability metrics must be made available to building design teams within early-stage building energy modeling with “HVAC/off” functionality.

3. The industry must expand the current capabilities and offerings provided by early-stage building energy modeling tools to allow project teams to incorporate, compare, and optimize passive solar heating and cooling strategies.

Meeting these needs that will unlock the potential of passive survivability as a market standard in the building design and construction industry and better ensure community resilience and zero-carbon performance outcomes.

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More is Good, High Thermal Mass Buildings for Climate Change Adaptation and Mitigation Strategies in France

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Abstract: Heat stress poses a growing public health concern in France. Current sustainable building standards favoring lightweight, highly insulated envelopes can lead to overheating risks and often prompt the use of mechanical cooling. However, reliance on mechanical cooling presents drawbacks such as increased emissions, exacerbated urban heat island effects, social inequities, and potential unreliability during extreme heat events, raising sustainability and equity concerns. To address these challenges, research on passive cooling measures is vital. Quantitative geospatial analysis of macro-level performance in future climates is necessary to determine prioritized measures, their ability to meet temperature demand, and associated energy and carbon benefits. Yet, quantitative evaluations are currently constrained to dynamic thermal simulations at the building scale, primarily subjected to historical climate conditions. In contrast, macro analyses remain predominantly qualitative. To bridge this gap, this study incorporates established methods for assessing the temperature-demand saving potential of a dominant passive cooling approach (high thermal mass and nocturnal convective cooling) through meteorological variables directly within high-resolution climate projections from the recent EURO-CORDEX ensemble, under two representative concentration pathways Results demonstrate passive cooling's effectiveness, consistently meeting over 99% of comfort temperature demand and entirely satisfying safety demand across scenarios and periods. Correlated energy and carbon gains are also discussed.

Keywords: Thermal mass, passive cooling, heat stress, climate adaptation, climate mitigation.

1. Introduction

The French housing construction industry must undergo adaptation to address the emerging challenges it encounters, some of which directly affect the material composition of buildings.

First, a new public health challenge: the necessity of passively ensuring safe indoor temperatures. Within the gradual transition away from heating- to cooling-dominated climates (Daguenet et al., 2021), and in the face of escalating heatwaves (the temperatures of the 2003 heatwave that killed 15,000 people in France are becoming increasingly common (Ballester et al., 2023; IPCC, 2021; MdS, 2003; Ouzeau et al., 2016)), the reliance on mechanical cooling has proved increasingly unreliable, counter-productive, and socially unfair, with regard to the following factors;

- High economic disparities (Garbinti et al., 2018), coupled with high mechanical equipment prices and increasingly volatile electricity prices (CRE, 2022), resulting in social imbalances in both the access and utilization of the equipment (e.g., 37% of upper-income households own an air-conditioning (AC) system, twice as many as among unemployed households (ADEME, 2021b));

- An escalating contribution to climate change (IEA, 2020), both from embodied emissions (i.e., manufacturing emissions) and operational emissions (i.e., indirect emissions from electricity production, and refrigerant leakage (IEA, 2020));
- An exacerbation of urban heat island effects –stemming from the use of exterior air as a heat sink, coupled with the warming effect of refrigerant leakage), up to several additional degrees for a city like Paris (De Munck et al., 2013; Tremeac et al., 2012);
- Potential non-operability during periods of peak demand (ASN, 2022; RTE, 2019), when utilization is most crucial, as heatwaves are frequently associated with drought and high-pressure compound events (Marx et al., 2021; Zhang et al., 2022), leading to reduced water flow rates in heated river systems and limited wind availability, thereby posing constraints on nuclear power production (thermal discharges and cooling circuit limitations), wind power production (very low wind load factor), and hydro-electric production (depleted reservoirs).

Second, the necessity to establish long-lasting habitats to reduce future construction demands and ensure housing for forthcoming generations, considering the anticipated decrease in the renewal capacity of the building stock. Construction activities on the European market, as evidenced by the construction production index (Eurostat, 2023), closely correlate with the EU petrol supply, which peaked in 2007 and is projected to decline by a factor of 2 to 10 by 2050 (TSP, 2021). This downward trajectory directly contributes to a diminishing climate adaptation capacity. As such, the required permanence of the built environment encompasses:

- The necessity for slowly deteriorating buildings (i.e., a move away from ephemeral and *flimsy* structures to more permanent and massive building typologies);
- The necessity for high social value buildings (i.e., the building's ability to fit into and support the local socio-cultural ecosystem, a determining factor in the local population's inclination to preserve it);
- The necessity to sustain maintenance capacities over time (i.e. the building's ability to rely on a network of local know-how, and locally sourced materials).

Lastly, the necessity to minimize the embodied carbon impacts of construction as part of the transition away from building lifecycle impacts mainly driven by operational emissions (such as fuel-heated existing building stock (IFPEB, 2022)) toward lifecycle impacts primarily influenced by the embodied emissions of construction materials (electricity-heated future building stock (RE2020; Röck et al., 2020)). This necessitates the careful selection of materials based on their low environmental impact and their capacity to serve multiple functions, thereby reducing the material inventory.

With regard to these three imperatives (resilience, durability, and climate mitigation), the implementation of conventional efficient lightweight building envelopes (characterized by layered synthetic product assemblies derived from heating-dominated building performance doctrines and technology-focused comfort concepts (Shove, 2018)) provides limited or no support, as they tend to exhibit the following drawbacks:

- They contribute to the risk of summer overheating (Baniassadi et al., 2018; FAP, 2023; Gustin et al., 2018).
- They have a relatively short lifespan, typically below 50 years (INIES, 2022), with limited social value in terms of both placemaking (urban design and architecture) and construction (procurement and labor) processes.
- They are carbon-intensive (Galimshina et al., 2021; Sadowski, 2023) and heavily reliant on global petrochemical supply chains (Moe, 2014).

In contrast, high-mass buildings constructed using natural geo-sourced materials, such as cut-stone, have consistently demonstrated superior capabilities in addressing these challenges, yielding substantial advantages in the following aspects:

- Thermal resilience through passive cooling by high thermal and hydric inertias, which regulate interior temperature and humidity (Pestre, 2021).
- Enhanced durability and added social value, characterized by slow deterioration, cost-effective maintenance, reliance on longstanding and reliable expertise, dignified aging processes, and the preservation of historical and visual continuity within the European context (Mequignon et al., 2013).
- Reduced embodied emissions in comparison to synthetic products, as natural materials entail minimal manufacturing emissions. Additionally, the amalgamation of structural, thermal, hydric, acoustic, and visual functions enables a streamlined component inventory (de Toldi & Pestre, 2023).

Notwithstanding their merits, high-inertia assemblies remain underutilized and insufficiently explored within the sustainable building industry. Furthermore, their performance, encompassing both climate resilience (in addressing cooling demand for comfort and safety during summer periods and heatwaves) and climate mitigation (in reducing operational emissions through decreased electricity demand for cooling) in future climates, largely remains uncharted and necessitates further investigation.

To that end, this study makes novel use of data outputs from the European Regional Climate Model (RCM) provided through the Coordinated Regional Climate Downscaling Experiment (CORDEX) to bridge gaps between climate and building science. It assesses the capacity of high thermal mass in conjunction with nocturnal ventilation to fulfill domestic cooling demand within the French context, quantified as a reduction in cooling degree days, under historical and future climates for two Representative Concentration Pathways scenarios: RCP4.5 and RCP8.5 (projecting mean global temperature increases of 1.8 °C and 3.7 °C by the end of the century, respectively). The evaluation encompasses safety during extreme compound temperature and humidity events, as well as adaptive comfort during hotter months (see section 4.1). Furthermore, operational energy savings are derived based on their correlation to cooling degree days and analyzed in terms of their associated emission factors (see section 4.2). Overall, the study underscores the relevance of high-mass building typologies within the context of France's warming climate.

2. Background

2.1. Heat stress and the built environment: a new public health challenge

The climate crisis puts growing pressure on buildings to provide thermally viable interior environments for populations increasingly exposed to high temperatures. Depending on the context and the moment, cooling may be required either for comfort (ANSI/ASHRAE, 2017) or for safety (Khan, 2019; Mora et al., 2017; Sherwood & Huber, 2010). The heat released by the body and exchanged with our surroundings for thermoregulation enables us to maintain a body temperature and skin temperature of 37 °C and 34 °C, respectively (Sherwood & Huber, 2010). When the outside temperature rises above 34 °C, heat exchange is no longer sufficient to cool a body, which must resort to perspiration and evaporation (i.e., evaporating cooling), requiring the surrounding air to be below its saturation level (i.e., relative humidity of 100%), otherwise resulting in life-threatening hyperthermia (Sherwood & Huber, 2010). While the concept of "thermal comfort" refers to the ability of a building to maintain indoor temperatures below unpleasant temperatures (e.g., the French environmental regulation, or RE2020, sets the threshold to 28 °C during the day and 26 °C at night), the concept of "thermal safety" refers to the ability to maintain temperature and relative humidity levels below unsafe thresholds (e.g., temperature and relative humidity couplings provided by exposure metrics such as the Heat-Index, borrowed from the field of Environmental Health Research (Steadman, 1979a, 1979b)). It should be emphasized that an uncomfortable environment does not necessarily imply an unsafe condition.

Within the French context (exhaustively covered by the recent Abbé Pierre Foundation Report on summer precarity (FAP, 2023)), thermal comfort is insufficiently regulated (partially included and discarded from new construction and retrofitting regulations, respectively), while thermal safety is absent from the regulation. The new-construction regulations approach summer comfort indicators using cumulative scales, specifically yearly degree-cooling-hours (DCHs) above a defined threshold (as specified in the RE2020). These regulations do not establish a fixed maximum temperature, thus neglecting extreme events. Additionally, there is a tolerance of up to 1250 DCHs beyond the defined threshold, which means that dwellings can be compliant with RE2020 while still being uncomfortable in terms of summer comfort. Additionally, the regulation does not preclude the use of counterproductive features increasing summer overheating risks (e.g., coupling of high insulation and low thermal inertia (Adekunle & Nikolopoulou, 2016)). As for retrofitting regulations, the requirements pertaining to summer comfort are limited to indicative assessments, without imposing any legal responsibility or liability. Consequently, the evaluation of summer performance is disregarded in the calculation method for the 3CL-2021 (DPE, 2021) score, thereby lacking incentives for renovation efforts aimed at enhancing summer comfort. Furthermore, equipment associated with achieving summer comfort is ineligible for renovation grants. Similarly, counterproductive measures are not excluded from public subsidies in this context as well.

Whether for comfort, or safety, biophysical vulnerability due to heat stress is consistently observed to mirror social vulnerability, with factors such as income levels, social isolation, residence location, and building typology increasing the likelihood of heat exposure (Preston et al., 2007; Vescovi et al., 2005). Apartment units within collective housing buildings exhibit 1.54 times higher susceptibility compared to individual houses (FAP, 2023), while the lowest income quintile is four times more prone than the highest income quintile to experiencing difficulties in maintaining adequate cooling in their homes during the summer (Eurostat, 2012). Vulnerabilities are shown to be exacerbated within urban centers (doubling of excess mortality during heatwaves (INSERM, 2004)), due to the accumulation of risk factors (urban heat island effect (UHIs) –up to 10 °C in France (MdS, 2003); high population densities; low ratios of green and open spaces per inhabitant; rising prices and tight market conditions driving the occupation of living areas particularly exposed to overheating risks like attics; etc.), in direct opposition to pavilion suburban typologies, proven to provide living conditions more resilient to heat stress (APUR, 2023; Cazi, 2023). Poorest neighborhoods within urban centers (subject to overcrowding risks; lack of vegetation; increased risks of inadequate ventilation; absence of mechanical cooling equipment; etc.) are shown to be most affected, resulting in residents of *Priority Urban Neighborhoods* (QPV) having 1.29 times more difficulty finding somewhere to cool off during hot spells, compared to the average (ANRU, 2022).

Within this unequal framework, passive and sustainable alternatives to air conditioning will play an increasingly crucial role. Of these alternatives, the primary recommendation emphasized in the recent and comprehensive report on summer insecurity in France is "increasing the thermal inertia of residential buildings" (FAP, 2023). Yet, a systemic method for quantitatively evaluating the applicability and performance of thermal mass in current and future climates is currently lacking.

2.2. Applicability of passive cooling measures

Over the past decades, the field of bioclimatic design has witnessed the development of psychometric charts aimed at identifying the specific climatic conditions conducive to passive cooling techniques (Givoni, 1992), resulting in numerous regional studies focusing on assessments of the feasibility of these measures based on local climate parameters (Guan et al., 2014; Lam et al., 2006; Mahmoud, 2011; Rakoto-Joseph & et al., 2009). While these studies offer qualitative insights into geographical areas where specific passive cooling methods seem promising, they lack quantitative assessments regarding the extent to which passive cooling methods can meet comfort and safety standards. A passive cooling method may be well-suited for a particular climate and capable of delivering *some* of the required cooling, yet it may not fulfill *all* of the required cooling.

Within this context, the quantitative analyses are delegated to Dynamic Thermal Simulations (DTSs). However, this approach exhibits several deficiencies. DTSs necessitate intensive modeling and computational processes, generally restricting their applicability to the individual building scale. Conversely, policymakers require systemic evaluations conducted at the national scale. DTSs have also demonstrated limited reliability when assessing the thermal behavior of structures with high thermal mass (de Wit & Augenbroe, 2002; Mantesi et al., 2018), stemming from inherent modeling and numerical uncertainties (Wetter & Wright, 2004), which arise due to simplifications, assumptions related to intricate physical processes, and errors introduced during simulation modeling (e.g., discrepancies between finite element and lumped mass models). Furthermore, DTSs heavily depend on historical weather data due to their need for high-resolution hourly information. However, the available outputs from General Circulation Models and Regional Climate Models (GCM and RCM, respectively), used to comprehend climate behavior and forecast future changes, do not provide the required level of temporal and spatial resolution, often making it unfeasible to directly apply them in building simulations (Yassaghi & Hoque, 2019). Finally, in exceptional instances where GCM and RCM data outputs are transformed into future weather files at an adequate resolution (Hosseini et al., 2021; Machard et al., 2020) and used in DTSs, the adopted workflow hinders the direct utilization of the key advantages provided by GCMs and RCMs, which generate simulation outputs in gridded data format for numerous locations, but are herein reduced to single coordinates.

2.3. Aim and scope

In this particular context, this study aims to perform quantitative assessments to determine the expected efficacy of high thermal mass as a passive cooling strategy in the future climates of France, considering a comprehensive national scale. The study's systemic evaluation framework is designed to offer strategic forecasts rather than absolute predictions, in response to the European Union's request for sustainable cooling data to inform policy design and evaluation (EEA, 2022). Its objective is to provide policymakers with insights into the significance of thermal mass as a strategy for climate mitigation and adaptation. In that regard, the study aims to provide results that can effectively serve as reliable indicators of median performances, without the necessity of predefining precise building design configurations.

3. Methodology

The methodology that follows is structured into five sections. Section 3.1 details the climate model data (RCM outputs) selected for the study. Section 3.2 presents the thermal mass interior temperature damping model adopted and its integration with RCM outputs. Section 3.3 investigates the correlation between the model and its performance in meeting thermal comfort standards. Section 3.4 explores the model's implications for ensuring thermal safety. Additionally, the adopted format for the presentation of the results is outlined in section 3.5.

3.1. Climate model

Historical and future climate data is extracted from RCM simulations from the Coordinated Regional Climate Downscaling Experiment (CORDEX, 2019). RCM simulations function by dynamically downscaling the data from GCMs, which are utilized as boundary conditions, specifically over selected regions. This downscaled approach enhances both the resolution and accuracy of the simulations. Dynamic downscaling simulations of CNRM-CERFACS-CM5 GCM data (i.e., boundary layer) by the CNRM-ALADIN53 French RCM were considered. The GCM was jointly developed and validated by CNRM-GAME and CERFACS (Mignot & Bony, 2013) for the 5th Phase of the Coupled Model Intercomparison Project (CMIP5), while the RCM's validation confirmed its ability to accurately represent mean climate characteristics and extreme temperatures (Bador et al., 2017; Daniel et al., 2019; Lemonsu et al., 2023).

The study encompassed three distinct twenty-year periods (time period typically assumed for evaluating average residential sector space cooling potential (Jakubcionis & Carlsson, 2017)). The first period, from 1980 to 2000, served as the reference historical scenario. The subsequent periods, spanning from 2040 to 2060 and 2080 to 2100, were selected to represent mid and end-century turning points, respectively. These periods were examined under two different Representative Concentration Pathways (RCPs), namely RCP4.5 and RCP8.5.

For each period, three climate parameters are extracted from the datasets at a daily temporal resolution and a spatial resolution of 0.11 x 0.11° (≈ 11.5 x 11.5 km); (i) the average daily temperature (Te_{mean}, in °C), (ii) the maximum daily temperature (Te_{max}) (see graphical representation in Fig. **1**, wherein the "Daily Climate Variables" are visually depicted as black markers), and (iii) the daily mean relative humidity level (rh_{mean}, in %). Harmonic diurnal temperature cycles are assumed, with periodic variations expressed as a function of time (t, in radians), as follows:

$$T_e(t) = Te_{mean} + \Delta T_e \cos(\omega t) \tag{1}$$

where ΔT_e is the exterior temperature increment above the mean ($\Delta T_e = Te_{max} - Te_{mean}$), and ω is the angular frequency ($\omega = 2\pi/86400$). As such, the daily minimum exterior temperature (Te_{min}, later required) is derived as follows:

$$Te_{min} = Te_{mean} - \Delta T \tag{2}$$

3.2. Thermal mass model

To conduct the study effectively, the selection of an optimal thermal mass model necessitates the following criteria to be met:

- The model must possess adequate accuracy to ensure dependable strategic forecasts.
- The computational demands of the model should be sufficiently low, thereby restricting the computing resources needed for reproducing the study with alternative climate models' output datasets. Intensive computational requirements often hinder the reappropriation of such studies.
- The model should exclusively rely on climate variables to approximate the thermal mass performance. This condition is a prerequisite to avoid predefining specific design configurations and to strictly rely on climate models' outputs to project performance.

The dominant study by Balaras (1996) –conducted as part of a European Commission-financed research project on passive cooling strategies—provides an exhaustive review of existing empirically derived models for projecting cooling loads and indoor air temperatures of high thermal mass buildings, classifying them in terms of their inputs, outputs, restrictions, and levels of accuracy. The model proposed by Givoni (1992) for evaluating the effectiveness of coupling thermal mass with nocturnal convective cooling –built upon his previous fieldwork and research (Givoni, 1969; Givoni, 1987)– is adopted in this study. The selection of this model is based on the following criteria:

- Minimal input variables needed, specifically daily and monthly outdoor temperature data;
- Proven accuracy of the model, validated as representative of thermal mass behaviours across various climates (Givoni, 1998)
- Suitable applicability, designed to represent buildings with sufficient thermal mass and resistance, along with effective measures to prevent excessive solar radiation absorption and penetration (thus maintaining lower daytime temperatures compared to outdoor conditions), all considered acceptable design constraints; and

- The undeniable significance of Givoni's work, which serves as a benchmark in the exploration of passive practices within the building industry (cited numerous times in scientific literature (SCOPUS, 2023)). Givoni's pioneering contributions to psychometric charts for bioclimatic design strategies (Milne & Givoni, 1979) continue to be the industry's leading reference today.

In the model's configuration, the thermal inertia of the interior mass –i.e., well-insulated thermal mass exposed to the interior environment– dampens interior temperature fluctuations and effectively absorbs interior heat gains during the day, subsequently releasing it at night as the mass undergoes cooling through convection with nocturnal ventilation. The subsequent section provides a comprehensive overview of the model's characteristics and components.

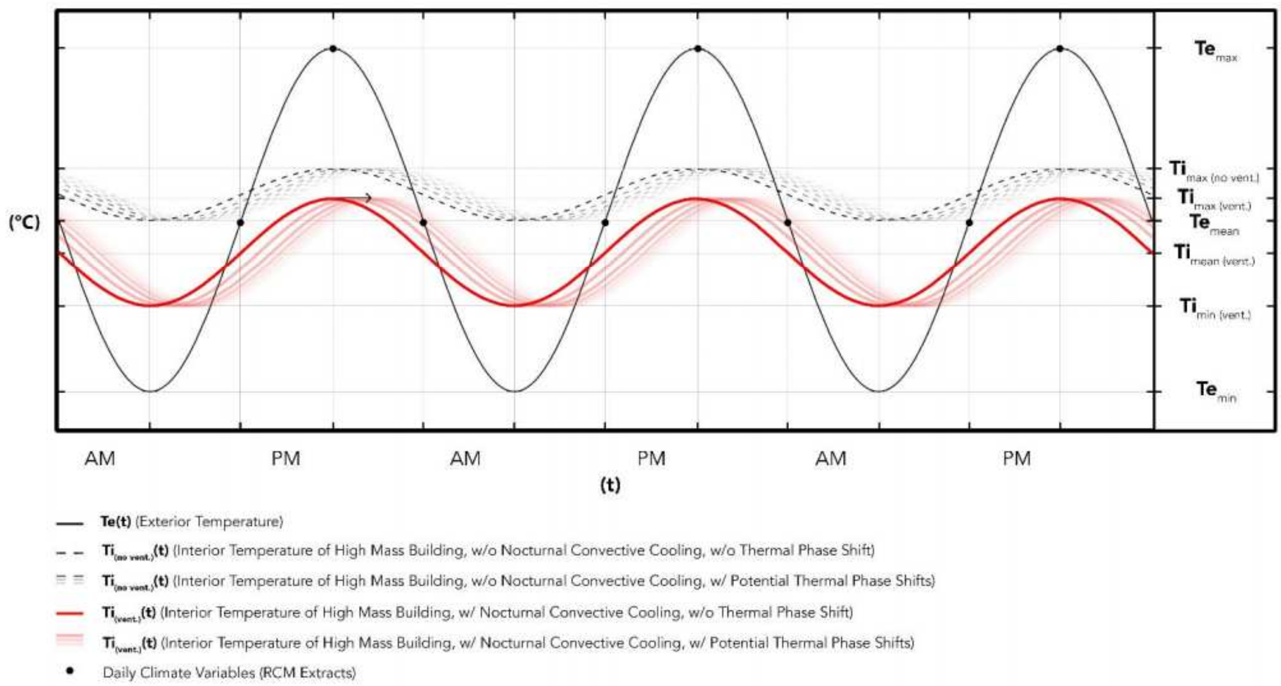
Due to solar radiation absorption and internal heat generation, the indoor average temperature of the building without nocturnal convective cooling ($Ti_{\text{mean}\,(no\ vent.)}$) is assumed to be 1-2 °C above the outdoor daily mean (see dotted line in Fig. **1** for interior temperature swings of a high mass building without nocturnal convective cooling):

$$Ti_{\text{mean}\,(no\ vent.)} = 1.5 + Te_{\text{mean}} \quad (3)$$

Nocturnal convective cooling is assumed to lower the minimum indoor temperature of the high-mass building ($Ti_{\text{min}\,(vent.)}$) by about one-half of the difference between the minimum temperature of the unventilated building and the outdoor minimum (Te_{min}) –see the red line in Fig. **1**:

$$Ti_{\text{min}\,(vent.)} = Ti_{\text{mean}\,(no\ vent.)} - 0.5 * \left(Ti_{\text{mean}\,(no\ vent.)} - Te_{min} \right) \quad (4)$$

FIGURE 1
Diurnal Temperature Variations
(Periodic Cycle)



The decrease in the maximum indoor temperature of a nocturnally ventilated building ($Ti_{\max\,(vent.)}$) compared to an unventilated building ($Ti_{\max\,(no\ vent.)}$), is smaller; approximately half of the decrease observed in the minim temperature:

$$Ti_{\max\,(vent.)} = Ti_{\max\,(no\ vent.)} - 0.25 * \left(Ti_{\max\,(no\ vent.)} - Te_{max} \right) \tag{5}$$

During periods characterized by increasing outdoor temperatures, such as an extended heatwave, the rate at which the indoor temperature rises is comparatively lower than that of the outdoor environment. This effect holds true in medium-mass buildings and is particularly pronounced in high-mass buildings. Consequently, the indoor temperatures during heatwave periods tend to be lower than what is predicted by the aforementioned formulas. Conversely, during periods of declining outdoor temperatures, indoor temperatures tend to be higher than the predicted values. As a result, the model assumes average monthly maximum temperatures as suitable inputs for Te_{max} in equation 5. Given that the thermal phase shift of the interior temperature swing (depicted in Fig. **1**) is a design-specific factor that relies on the thermal mass configurations (e.g., mass thickness and thermal properties), this study adopts a conservative standpoint by disregarding the shift. It is worth noting that any potential shift would solely amplify the performance of the thermal mass during the peak hours of the day in practical applications.

Daily interior temperature fluctuations ($T_{i\,(vent)}(t)$) of the naturally ventilated building can thus be expressed as follows:

$$T_{i\,(vent)}(t) = Ti_{mean\,(vent)} + \Delta T_{i\,(vent)} \cos(\omega t) \tag{6}$$

where $\Delta T_{i\,(vent)}$ is the interior temperature increments above the mean, and $Ti_{mean\,(vent)}$ is the interior daily mean temperature, respectively derived as follows:

$$\Delta T_{i\,(vent)} = Ti_{\max\,(vent.)} - Ti_{\text{mean}\,(vent.)} \tag{7}$$

$$Ti_{mean\,(vent)} = 0.5 * (Ti_{\max\,(vent.)} + Ti_{\min(vent.)}) \tag{8}$$

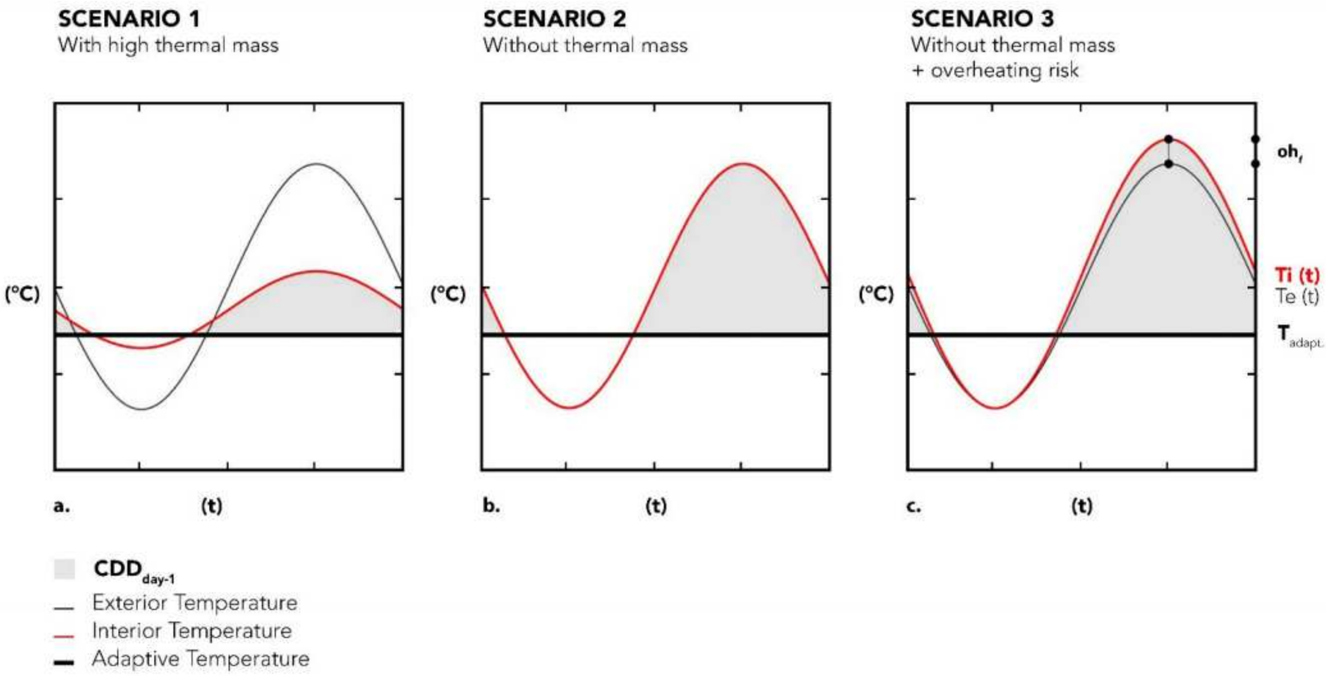
3.3. Thermal comfort model

Research in the field of building sustainability has pioneered the introduction of thermal comfort standards taking into account adaptive behaviours, demonstrating that occupants' perception of comfort varied based on local climates (Brager et al., 2015; Khosla et al., 2021; Nicol, 2006; Nicol et al., 2012). In that regard, this study follows the adaptive comfort model for naturally ventilated buildings (ANSI/ASHRAE, 2017) to define daily target interior temperatures deemed *comfortable* ($T_{adapt.}$, in °C), as outlined below:

$$T_{adapt.} = \max \left\{ \left(17.8 + \left(0.31 * Te_{\text{mean,monthly}} \right) \right), 27.875 \right\} \tag{9}$$

where $Te_{\text{mean,monthly}}$ corresponds to the mean monthly exterior temperature prior to the given day, and 27.875 °C is the upper limit of the adaptive comfort model, aligning with the threshold of 28 °C set by the RE2020 regulation. The cooling degree days per day ($CDD_{day^{-1}}$) are then derived for three scenarios.

FIGURE 2
Diurnal Temperature Variations and CDD_{day-1}
(Periodic Cycle)



A first scenario (see Fig. 2**a**), corresponding to the high-mass building with nocturnal convective cooling, is derived as follows:

$$CDD_{day^{-1}} = \left(\int_0^{86400} \max\left\{\left(T_{i\,(vent)}(t) - T_{adapt.}\right), 0\right\}\right) * \frac{1}{\gamma} \tag{10}$$

where γ is the conversion factor for cooling degree seconds to cooling degree days ($\gamma = 3600 * 24$).

A second and reference scenario (see Fig. **2b**), representative of well ventilated low mass buildings (i.e., no thermal phase shift and no interior temperature damping) in the absence of mechanical cooling, assumes maximum and minimum indoor temperatures equivalent to maximum and minimum outdoor temperatures:

$$CDD_{day^{-1}} = \left(\int_0^{86400} \max\left\{\left(T_e(t) - T_{adapt.}\right), 0\right\}\right) * \frac{1}{\gamma} \tag{11}$$

A third scenario (see Fig. **2c**), representative of a poorly ventilated low-mass building (i.e. no thermal phase shift and no interior temperature damping, with overheating risk) in the absence of mechanical cooling, is derived as follows:

$$CDD_{day^{-1}} = \left(\int_0^{86400} \max\left\{\left(T_{OH}(t) - T_{adapt.}\right), 0\right\}\right) * \frac{1}{\gamma} \tag{12}$$

where $T_{OH}(t)$ corresponds to interior diurnal periodic temperature variations in an overheating scenario, computed as follows:

$$T_{OH}(t) = \left[0.5 * ((Te_{max} + oh_f) + Te_{min})\right] + \Delta T_e \cos(\omega t) \tag{13}$$

where oh_f is the overheating factor, in °C, corresponding to the increase in maximum interior temperature caused by overheating (see oh_f in Fig. **2c**). Note that overheating can come from solar gains and/or internal heat gains from occupants, household appliances, domestic hot water, lighting, etc. While summer overheating risks have been reported to increase interior temperatures of more than 4°C in the French collective housing parc (FAP, 2023), a conservative average of $oh_f = 2\ °C$ is adopted in this study.

For each scenario, the cooling degree days per year ($CDD_{yr^{-1}}$) is then evaluated as shown below:

$$CDD_{yr^{-1}} = \sum_{i=1}^{365} CDD_{day^{-1}\,(i)} \tag{14}$$

Mean $CDD_{yr^{-1}}$ values over the 20-year periods considered are then correlated with useful energy demand for space cooling in each location and for each scenario. The dependency of useful energy demand for space cooling on mean $CDD_{year^{-1}}$ values was recently illustrated through a linear regression analysis ($Q_{cooling}$) found to accurately represent data collected from AC-equipped housing units within 48 US states ($R^2 = 0.87$), and deemed applicable for projecting space cooling demands in French air-conditioned dwellings (Jakubcionis & Carlsson, 2017). The correlation is expressed as follows:

$$Q_{cooling} = \left[(0.051 * CDD_{yr^{-1}}) + 1.483\right] * P_{AC} \tag{15}$$

where $Q_{cooling}$ is the useful cooling demand (in kWh/m^2.year), and P_{AC} (%) is a weighting factor (the percentage of households using AC equipment). As the regression was developed for $CDD_{year^{-1}}$ above 18 °C, equations 10 to 14 are recomputed replacing the target *comfortable* temperature ($T_{adapt.}$) with 18 °C. When forecasting cooling demand, it is imperative to determine the thresholds that trigger households to adopt and operate cooling equipment, which necessitates an understanding of the specific climatic conditions that prompt individuals to install and utilize such equipment. As found by Jakubcionis & Carlsson (2017), the dependency of AC use on climatic conditions is non-linear until approx. 920 $CDD_{yr^{-1}}$, after which a full penetration of AC equipment is typically reached. The interval ranging from 0 to 920 of the function can be generalized by the following logarithmic equation:

$$P_{AC} = 26.33 * \ln\left(CDD_{yr^{-1}}\right) - 81.69 \tag{16}$$

By weighting $Q_{cooling}$ with P_{AC}, the results offer a comprehensive perspective on the anticipated average useful energy demand at a territorial level. While other factors have been demonstrated to influence the penetration of AC in residential spaces and the specific energy demand for space cooling (e.g., personal income (Santamouris & Kolokotsa, 2013)), the exclusive consideration of Cooling Degree Days (CDD) per year as the primary factor is considered acceptable for the following two reasons:

- Firstly, the analysis aims to provide strategic forecasts rather than absolute predictions (see section 2.3), with a focus on relying solely on climate models' output dataset to project the studied variables. Therefore, the methodology was intentionally designed to minimize the reliance on additional datasets, such as Geographic Information System (GIS) data for Gross Domestic Product (GDP) per capita, household size, etc.

- Secondly, while the excluded drivers may have a significant marginal effect on the speed of ongoing mechanical cooling equipment diffusion in response to climate change, it has been observed that AC diffusion is expected to reach saturation as early as 2050 (Andreou et al., 2020). Given that the time periods studied in the analysis pertain to the mid-century and the end of the century, the rate of diffusion between the present and mid-century is considered of secondary importance within the model.

Useful energy demand for space cooling is then converted into operational emissions (g CO_2eq./m^2.year), using a fixed emission factor for French electricity production of 58 g.CO_2 eq./.kWh, projected to exhibit a relatively stable trend across the 2000-2100 period (EUA, 2023; RTE, 2022).

3.4. Thermal safety model

The upper limit for safe temperature and humidity combinations is determined using the Heat Index, an *apparent* temperature scale that provides a representative measure of how the combined effect of relative humidity and air temperature is perceived by the human body (Steadman, 1979a), widely employed to assess the physiological responses associated with various climate conditions (Schlatter, 2005). As the Heat Index does not account for direct solar irradiance and assumes continuous air movement, it is presumed representative of shaded and ventilated interior conditions.

As the dew point temperature is assumed constant during the day (i.e., fixed absolute humidity levels, with diurnal cycles of relative humidity dependent on air temperature), the heat index equation (resulting from multiple regression analysis studies (Anderson et al., 2013; Rothfusz, 1990)) can be used to determine a daily temperature target (T_{safe}, in °F) based on daily mean relative humidity levels (rh_{mean}, in %), by solving for the following quadratic formula:

$$T_{safe} = max\left\{\left(\frac{a - \sqrt{b}}{c}\right), \quad \left(\frac{a + \sqrt{b}}{c}\right)\right\} \tag{15}$$

$$a = -2.04901523 + 0.22475541 * rh_{mean} + 0.00085282 * {rh_{mean}}^2 \tag{16}$$

$$\begin{aligned} b = \; & 2.90957 * 10^{-7} * {rh_{mean}}^4 - 0.00003 * {rh_{mean}}^3 + 0.00231 * {rh_{mean}}^2 \\ & -0.00000796 * HI_{target} * {rh_{mean}}^2 + 0.00491496 * HI_{target} * rh_{mean} \\ & -0.43532 * rh_{mean} + 3.03934 - 0.02735132 * HI_{target} \end{aligned} \tag{17}$$

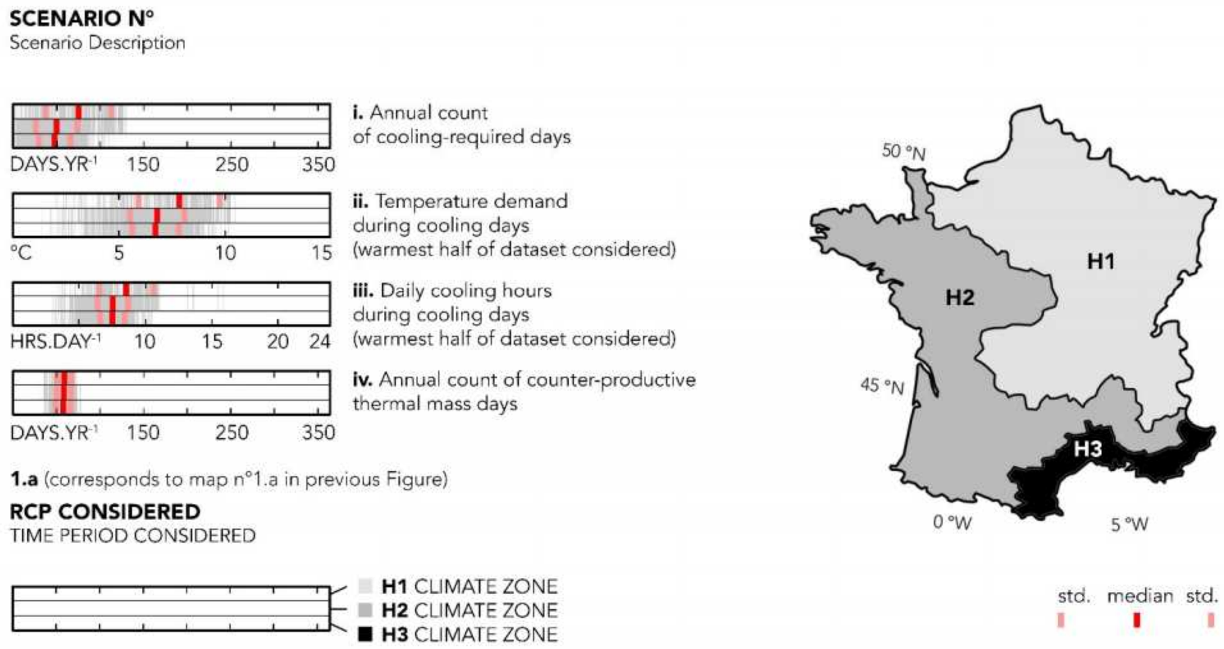
$$c = 2 * (-0.00683783 + 0.00122874 * rh_{mean} - 0.000001999 * {rh_{mean}}^2) \tag{18}$$

where HI_{target} corresponds to the upper limit of apparent temperature considered safe, set at 90 °F (or 32.2 °C). This value corresponds to the threshold for the "extreme caution" classification, with physiological effects described as "*Heat stroke, heat cramps, or heat exhaustion possible with prolonged exposure and/or physical activity*".

Equations 10 through 14 are then recomputed substituting the daily adaptive comfort temperature target ($T_{adapt.}$) with the daily safe temperature target (T_{safe}, converted to °C), to derive the cooling degree days above the safe threshold.

3.5. Restitution format

FIGURE 3
Restitution Format



Each data segment is restituted as a primary climate data map displaying average values for the studied variable (i.e., $CDD_{year^{-1}}$ for comfort, $CDD_{year^{-1}}$ for safety, $Q_{cooling}$, and projected yearly operational emissions) over the considered RCP scenario and time period. Each map is paired with a set of four rug plots in the immediately following figure. The latter depicts further detailed result information (see Fig. **3** for an example of the restitution format), encompassing the annual count of cooling-required days (Fig. **3.i**), the temperature demand during the warmer half of these cooling days (**3.ii**), the average number of daily cooling hours (upper half of the dataset) (**3.iii**), and the annual count of counter-productive thermal mass days (**3.iv**), defined as days where the thermal mass generates more $CDD_{day^{-1}}$ units than it contributes to save. In each rug plot, data is classified according to the regulatory French climatic zones (as defined in the RE2020), defined as H1 (characterized by the coldest temperatures, long winters, frequent rainfall), H2 (milder temperatures, less severe winters), and H3 (exhibiting the warmest temperatures and very mild winters). For each plot, results can thus be interpreted as follows:

> "In the given RCP scenario and time period, this particular climatic zone exhibits x days necessitating cooling (see **i**). Among these cooling-required days, only the warmer half

is considered, disregarding the coldest half where cooling needs may be minimal. Within this selected period, cooling will be necessary for x hours per day (see **iii**), with an average yearly maximum temperature demand reaching x degrees (see **ii**). Although thermal mass can contribute to reducing cooling loads for a substantial portion of the year, the thermal inertia of the mass, such as when it retains higher temperatures than the ambient surroundings after a prolonged heatwave, renders it counterproductive for x days annually (**iv**)."

Rug plots that appear faded indicate the non-applicability of the variable. For instance, "*counterproductive thermal mass days*" are only relevant in the context of high-mass buildings –i.e., scenario 1– and are thus excluded from scenarios 2 and 3.

4. Results and discussion

The result section is organized into two primary sections, respectively discussing the relevance of thermal mass as a passive cooling strategy from a climate adaptation perspective (cooling for comfort –section 4.1.1– and cooling for safety –section 4.1.2), and from a climate mitigation perspective (cooling for energy savings –section 4.2.1– and cooling for carbon savings –section 4.2.2).

4.1. Thermal mass for climate adaptation

4.1.1. Thermal mass for comfort

The obtained results (refer to Fig. **4** to **7**) initially demonstrate, as an important contextual element, a notable upward trend in temperature demand for comfort, as extensively detailed by previous findings (COPERNICUS, 2022; Spinoni et al., 2018). This trend is observed both in the short term and the long term, regardless of the specific RCP scenario under consideration. Mid-century projections indicate a 180% increase in temperature demand for comfort under the RCP4.5 scenario (considering the reference scenario –i.e., scenario 2), while by the end of the century, the demand could surge by up to 451% in the RCP8.5 scenario, compared to a 221% increase in the RCP4.5 scenario. By then, under the RCP4.5 scenario (refer to Fig. **5**, 2c), buildings in climate zone H1 will need to provide cooling for approximately 27 ± 13 days (compared to 47 ± 18 days under RCP8.5, as shown in Fig. **7**, 2c). In zone H2, the corresponding cooling requirement will be approximately 29 ± 19 days (compared to 50 ± 24 days under RCP8.5). Similarly, in zone H3, buildings will require cooling for around 51 ± 33 days (compared to 73 ± 37 days under RCP8.5), with some locations requiring cooling for more than 130 days per year.

In response to this substantial rise in temperature demand, the findings indicate that thermal mass has the potential to effectively address nearly all cooling needs for comfort, both in present and future climates. The combination of high thermal mass and nocturnal convective cooling (scenario 1 in Fig. **4** to **7**) leads to a remarkable decrease in cooling degree days ($CDD_{yr^{-1}}$) across all RCP scenarios and time periods considered, surpassing 99% across all considered RCP scenarios and time periods (i.e., reductions of 99.69% and 99.66% for the

2040-2060 period, and 99.97% and 99.89% for the 2080-2100 period under RCP4.5 and RCP8.5, respectively). Notably, the thermal inertia of high masses seldom becomes counterproductive, with only 7 ± 2 counterproductive thermal mass days observed in the most challenging scenario, namely the 2080-2100 period under RCP8.5, within the H3 climate zone (see Fig. **7**, 1c) –note that the utilized model assumes well-insulated internal thermal mass, and that the counterproductive thermal mass days are specific to this configuration and do not accurately represent the behavior of continuous thermal mass, i.e., thermal mass exposed to both interior and exterior environments. Overall, these findings indicate that despite the exponential increase in maximum daytime temperatures during the analyzed periods, the diurnal temperature ranges remain substantial enough for thermal mass to effectively regulate interior temperatures back to comfortable levels.

While high thermal mass buildings exhibit a consistent capacity to reduce temperature demand for comfort across all scenarios and time periods (reliably fulfilling around 99% of the demand), it is noteworthy that the magnitude of $CDD_{yr^{-1}}$ required to fulfill the remaining 1% of comfort requirements demonstrates an exponential trend, directly correlating with the exponential rise in temperature demand. Yet, even under the most severe scenario (2080-2100 period under RCP8.5), only 11 ± 27 $CDD_{yr^{-1}}$ are found to remain, on average, within the H3 climate zone (i.e., the warmest zone). These $CDD_{yr^{-1}}$ magnitudes (distributed across 12 ± 22 required cooling days, with the warmer half of these days having temperature demands of approximately 3.2 ± 0.3 °C –refer to Fig. **7**, 1c) highlight that even in the most extreme scenarios, the remaining demand after then dampening work of thermal mass is negligible, despite the overall increasing trends.

Conversely, and in the absence of mechanical cooling, low thermal mass buildings are shown to display increasingly uncomfortable interior temperatures, with the upper threshold of acceptable discomfort as fixed by the RE2020 (i.e., 1250 cooling degree hours per year, or 52 $CDD_{yr^{-1}}$) surpassed in different extents across the national territory by the end of the century. Specifically, well-ventilated low thermal mass buildings surpass the upper threshold in 17% to 59% of the national territory under RCP4.5 and RCP8.5, respectively (see scenario 2c in Fig. **4** to **7**). Low thermal mass buildings at risk of overheating (e.g., due to poor ventilation) surpass the threshold in 52.8% to 83.5% of the territory respectively (see scenario 3c in Fig. **4** to **7**).

In this context, the findings indicate both the limited suitability of current new construction practices, specifically lightweight buildings favored by green building standards, and the substantial lack of adaptation among a significant portion of the existing building stock. For instance, around 8.5 million housing units constructed between 1949 and 1974 with low inertia and inadequate ventilation standards (INSEE, 2017), and which already demonstrate a pronounced vulnerability to overheating risks (FAP, 2023), will expose increasingly vulnerable populations to significant challenges in adapting to future climates.

As light thermal inertias demonstrate susceptibility to rising temperature demand for comfort, it becomes crucial to investigate whether the discomfort also poses a safety concern in terms of associated relative humidity levels. This aspect is addressed in the following section.

FIGURE 4
RCP4.5 (1.8 °C Global Warming scenario)
Cooling Degree Days Above Comfort Threshold (CDD.yr⁻¹)
(Adaptive Comfort Scale, 100% Acceptability)

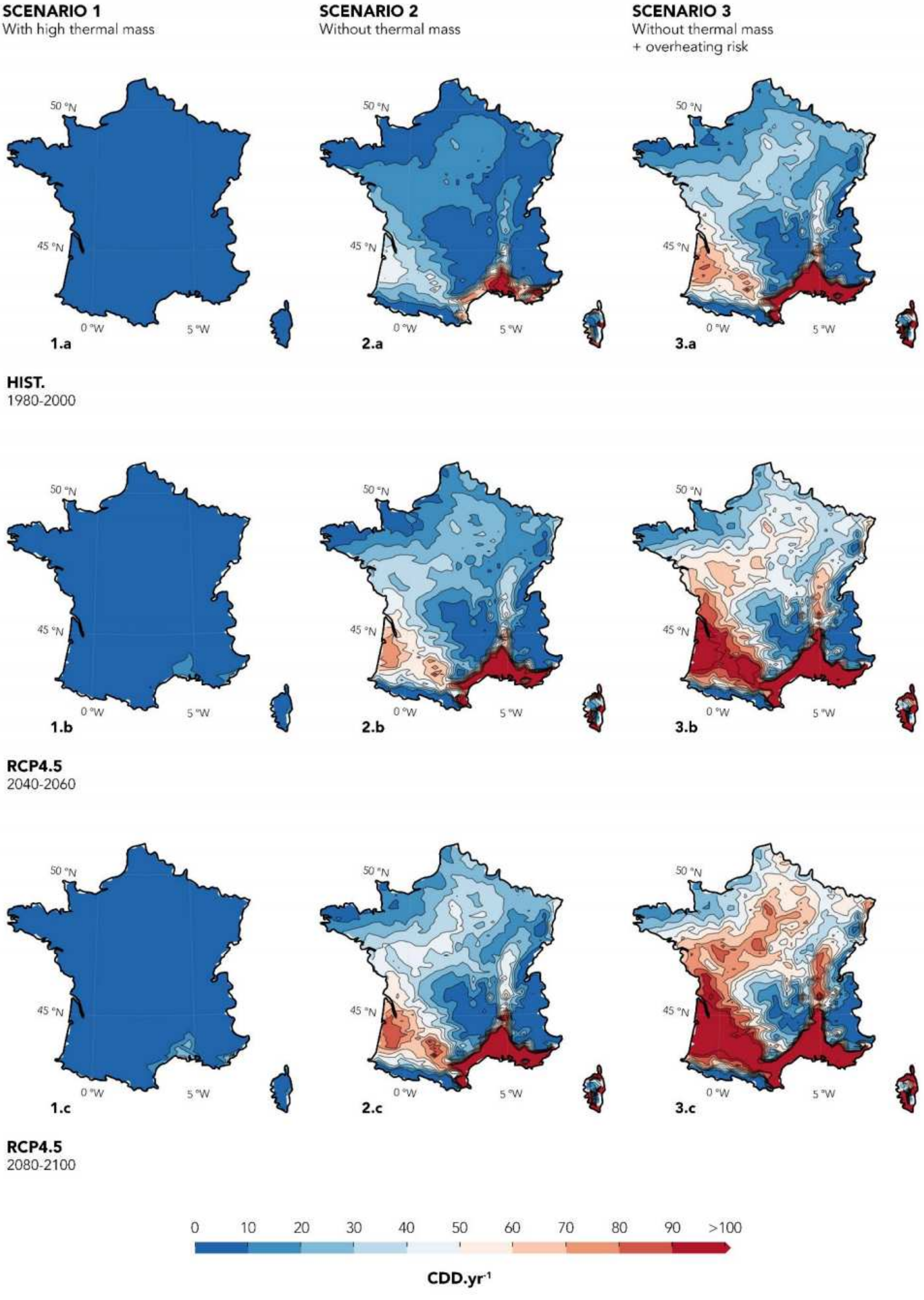


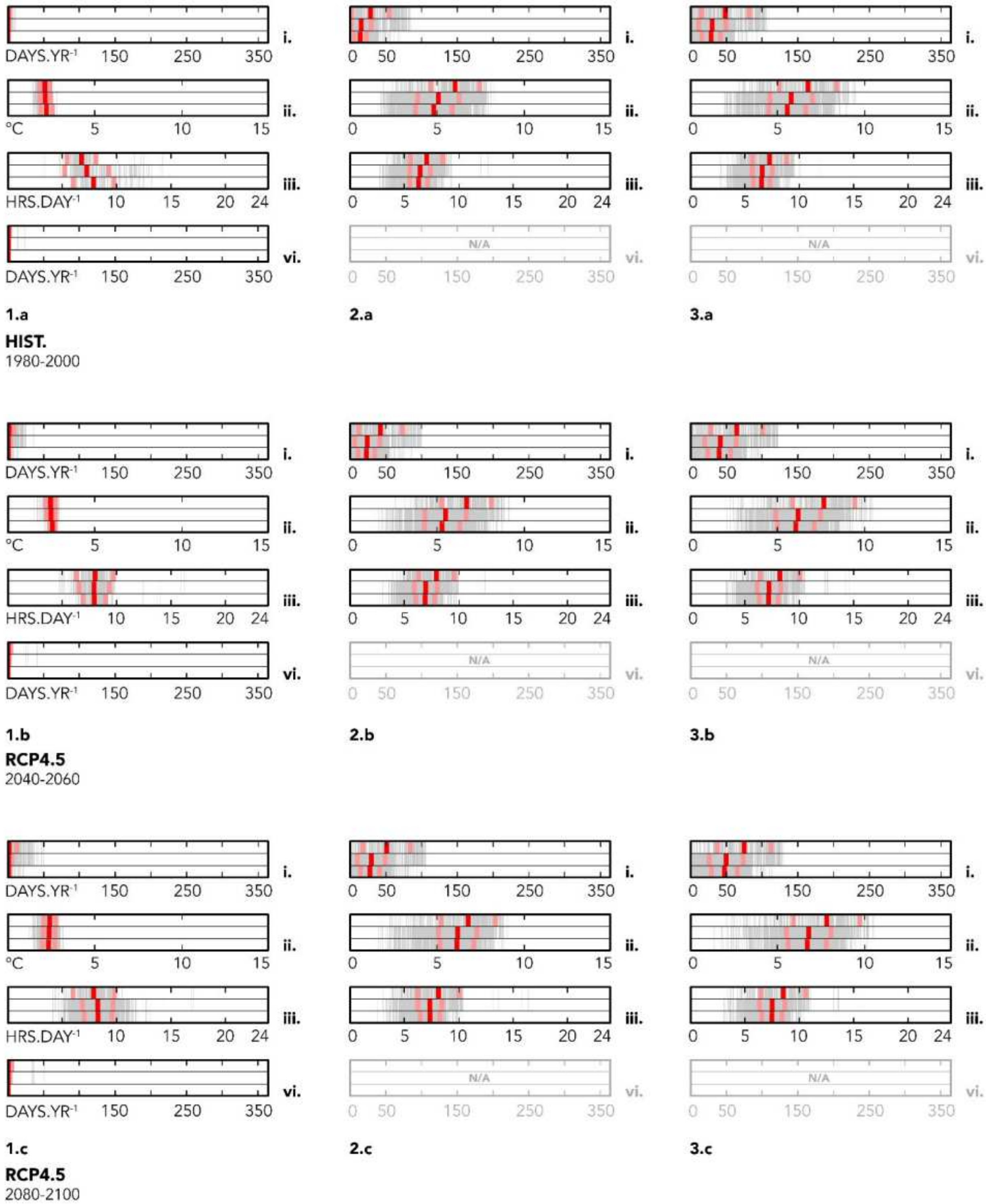
FIGURE 5

RCP4.5 (1.8 °C Global Warming scenario)
Cooling Degree Days Above Comfort Threshold (CDD.yr⁻¹)
(Adaptive Comfort Scale, 100% Acceptability)

SCENARIO 1
With high thermal mass

SCENARIO 2
Without thermal mass

SCENARIO 3
Without thermal mass
+ overheating risk



i. Annual count of cooling-required days **(days/year)**
ii. Temperature demand during cooling days **(°C)**
(warmest half of dataset considered)
iii. Daily cooling hours during cooling days **(hours/day)**
(warmest half of dataset considered)
iv. Annual count of counter-productive thermal mass days **(days/year)**

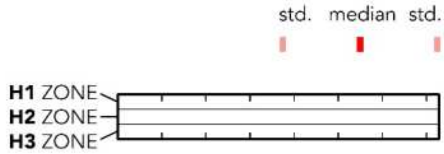


FIGURE 6

RCP8.5 (3.7 °C Global Warming Scenario)
Cooling Degree Days Above Comfort Threshold (CDD.yr⁻¹)
(Adaptive Comfort Scale, 100% Acceptability)

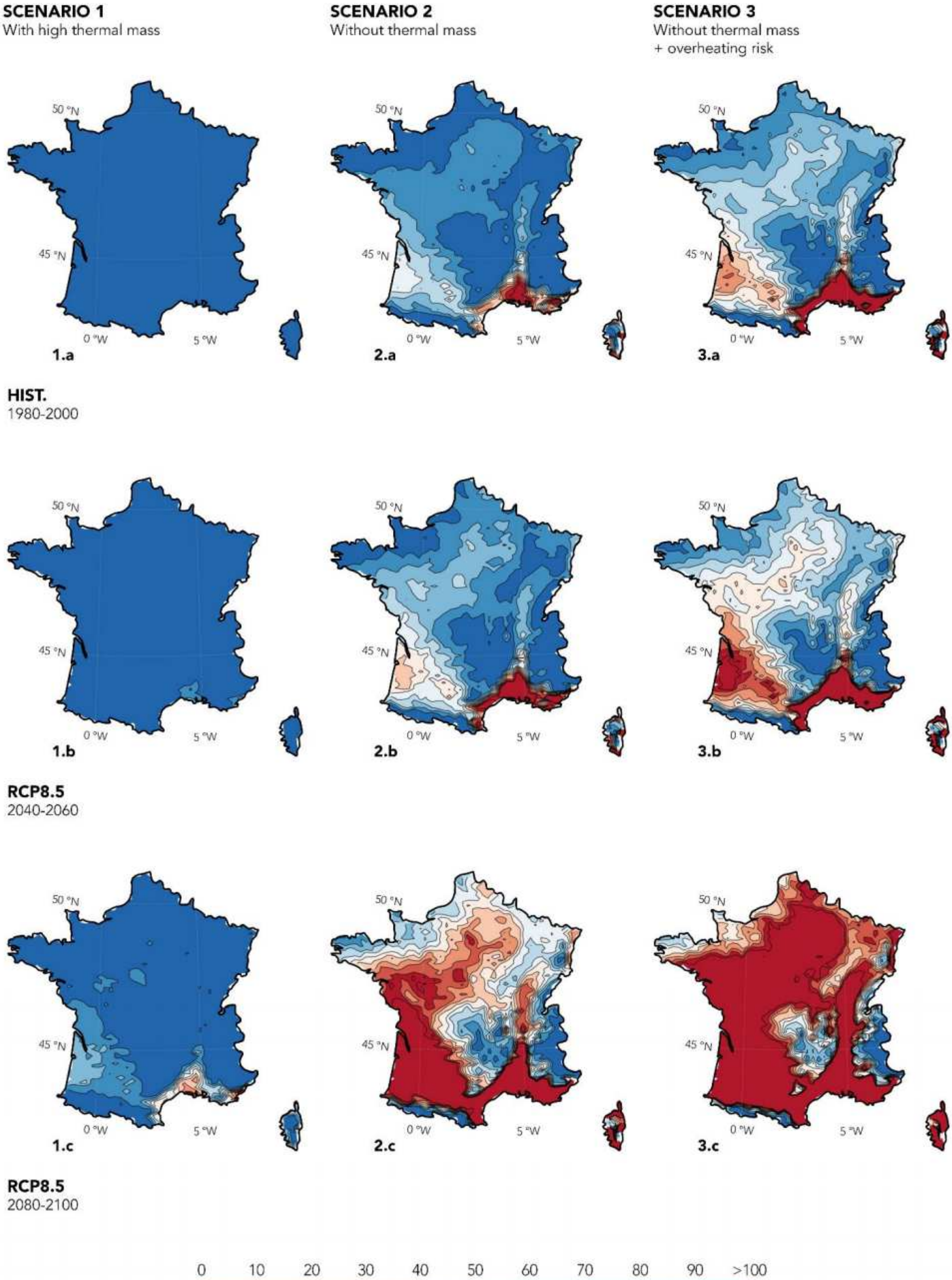
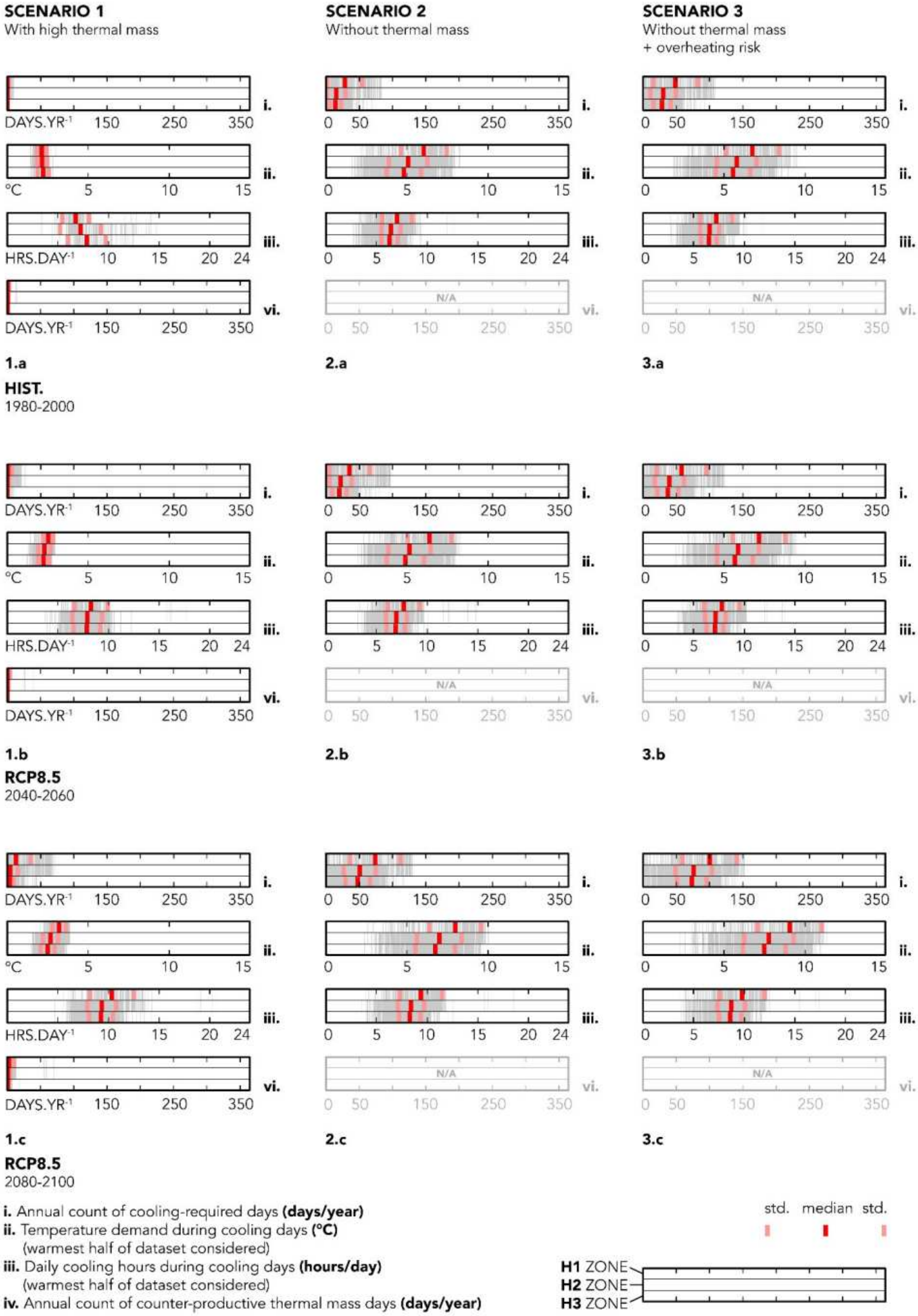


FIGURE 7

RCP8.5 (3.7 °C Global Warming Scenario)
Cooling Degree Days Above Comfort Threshold (CDD.yr⁻¹)
(Adaptive Comfort Scale, 100% Acceptability)



4.1.2. Thermal mass for safety

Considering the threshold corresponding to the *extreme caution* level of the Heat Index (incorporating both dry bulb temperature and relative humidity levels), set at the apparent temperature of 32.2°C, the results suggest that France is not immune to encountering unsafe instances of compound extreme events involving temperature and humidity. Subsequent figures (Fig. **8** to **11**) reveal a notable escalation in the occurrence of such events on an annual basis. By mid-century, the occurrences witness a sharp rise, with a national increase of 258% (2040-2060 under RCP4.5) compared to the historical period of 1980-2000 (refer to Fig. **8** and **9**, scenario 2c). In the H3 climate zone, some locations experience up to 38.23 $CDD_{yr^{-1}}$ for light thermal mass buildings, and 70 for buildings subject to overheating risks, surpassing the previous maximum of 20.7 during the historical period (see Fig. **8** and **9**, scenario 2a, for the considered historical data). By the end of the century, the occurrences could spike further, displaying national increases of 969% under RCP8.5 (see Fig. **9** and **10**, scenario 3c), with certain locations witnessing up to 87 $CDD_{yr^{-1}}$ for light inertia settings (144 $CDD_{yr^{-1}}$ if overheating is considered). It is worth noting that under these scenarios, occurrences would not be confined solely to regions where adaptation has long been deemed necessary, and where it is more probable for adaptation measures to have already been implemented (i.e., predominantly within the H3 zone). Additionally, it is important to note that the "extreme caution" level on the Heat Index scale serves as a warning for potential heat strokes, heat cramps, and heat exhaustion during prolonged exposure. This is particularly noteworthy in relation to the substantial number of hours per day that exceed the threshold in the warmest half of the occurrences, surpassing on average 5 hours daily across all future climate scenarios and periods considered (refer to Fig. **9** and **11**, scenarios 2 and 3).

Furthermore, the exponential heat-stress effect of slight increases in interior dry bulb temperature when compounded with high relative humidity levels (illustrated in common psychometric charts) is here underscored by the significant increase in $CDD_{yr^{-1}}$ resulting from a 2°C overheating factor (compare Fig. **10**, 2c and 3c), with magnitudes of $CDD_{yr^{-1}}$ more than doubling at a national level (+203) and within each climate zone (+209% for H3, +230% for H2, and +210% for H1).

In this context, the findings (scenario 1 in Fig. **8** through **11**) indicate that passive cooling through thermal mass has the potential to fulfill 100% of the temperature demand for safety across present and future climates in all considered RCP scenarios[1]. These results emphasize the significance of such a passive strategy, not only for new constructions but also underscore the need for a more robust framework in the emerging field of thermal mass retrofitting.

[1] It should be noted that high thermal mass natural geo-sourced materials have the potential to combine their ability to dampen interior temperature fluctuations with their capacity (not considered here) to regulate interior relative humidity levels (hygric properties of porous materials). Therefore, when selecting thermal mass materials, a dual evaluation of both their thermal and hygric properties may be warranted.

FIGURE 8

RCP4.5 (1.8 °C Global Warming Scenario)
Cooling Degree Days Above Safety Threshold (CDD.yr⁻¹)
(Heat index «extreme caution» level)

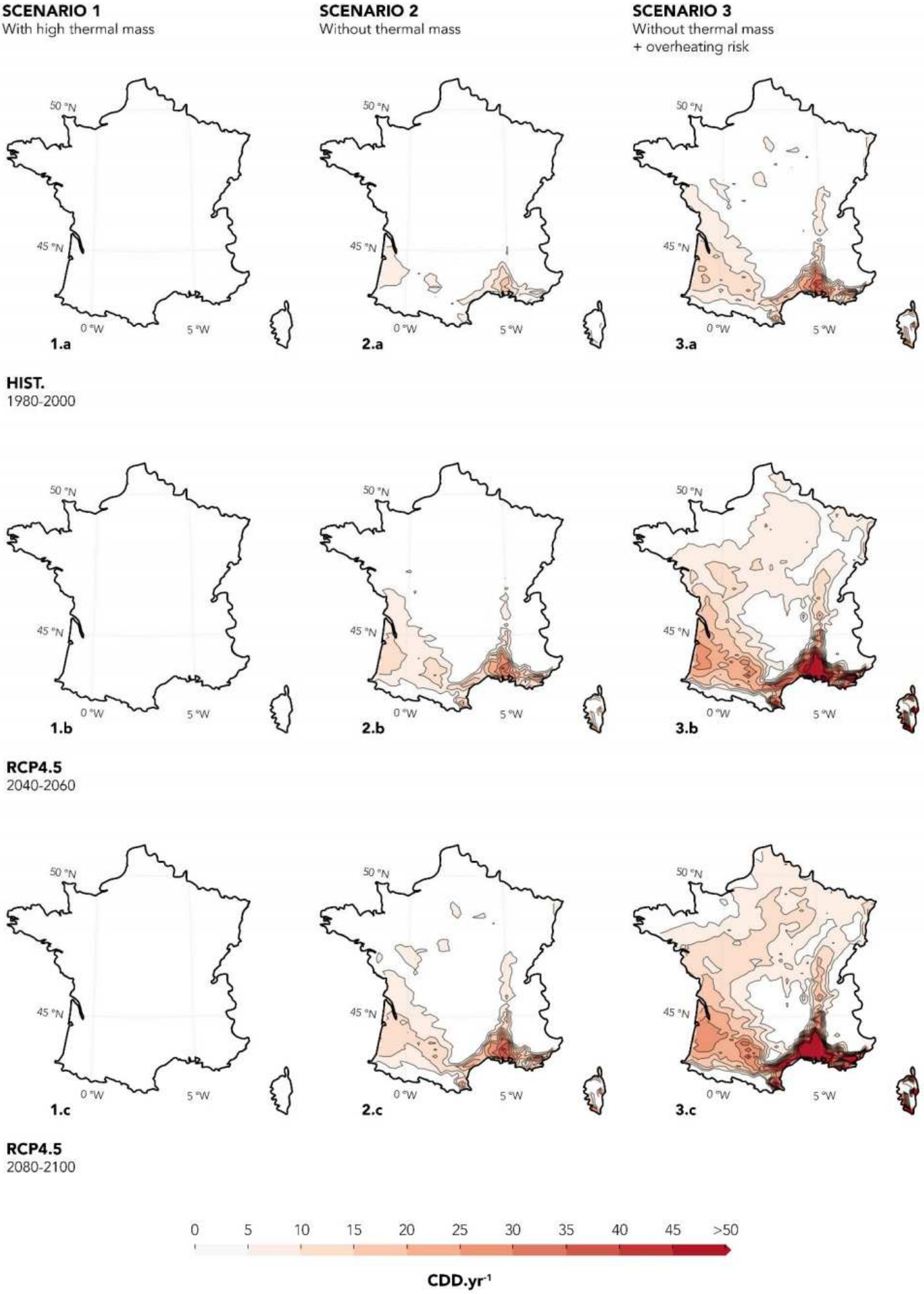
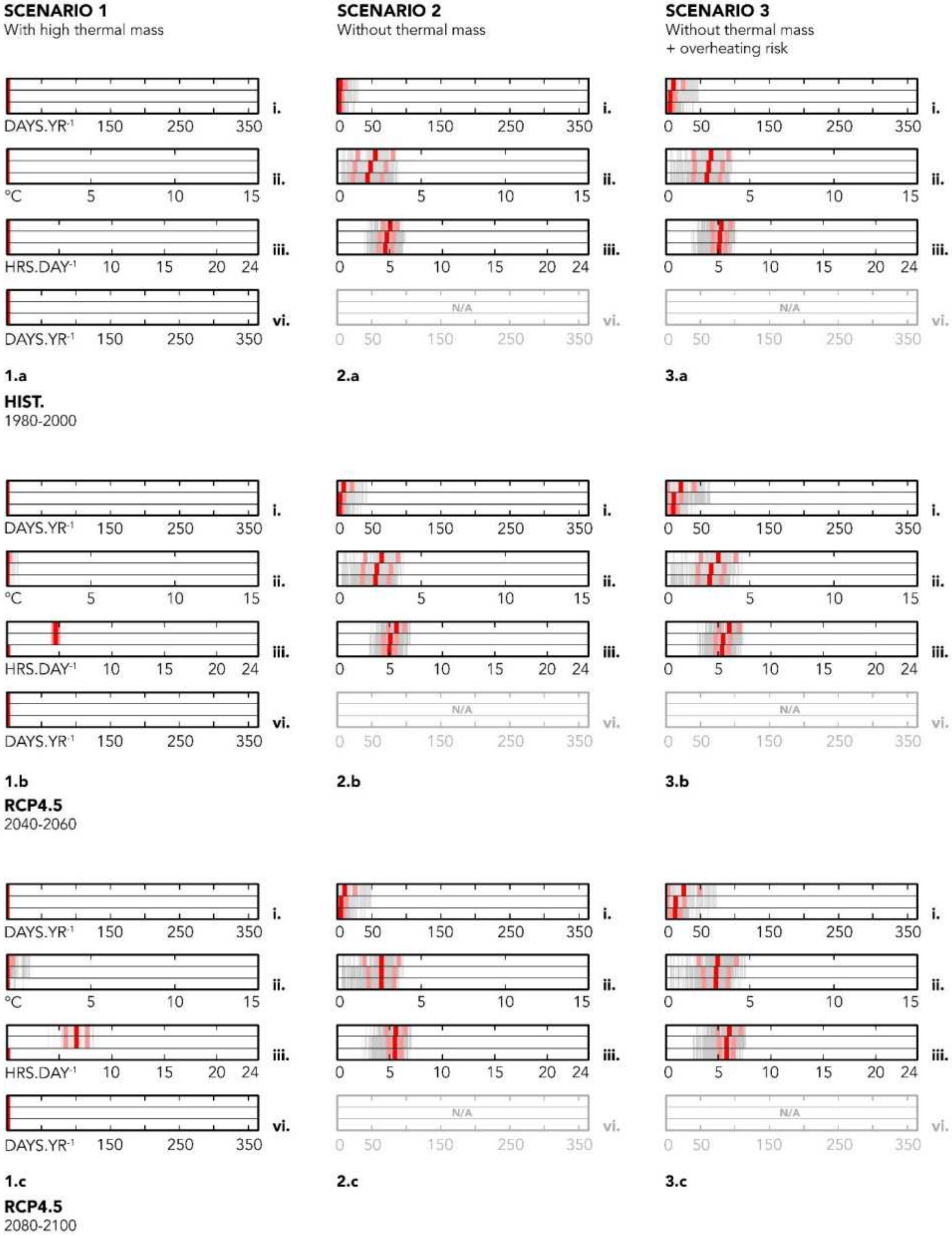


FIGURE 9

RCP4.5 (1.8 °C Global Warming Scenario)
Cooling Degree Days Above Safety Threshold (CDD.yr⁻¹)
(Heat index «extreme caution» level)



i. Annual count of cooling-required days **(days/year)**
ii. Temperature demand during cooling days **(°C)**
(warmest half of dataset considered)
iii. Daily cooling hours during cooling days **(hours/day)**
(warmest half of dataset considered)
iv. Annual count of counter-productive thermal mass days **(days/year)**

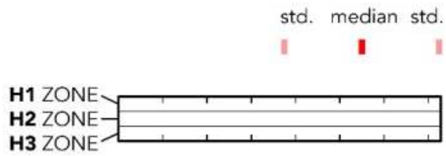


FIGURE 10

RCP8.5 (3.7 °C Global Warming Scenario)
Cooling Degree Days Above Safey Threshold (CDD.yr^{-1})
(Heat index «extreme caution» level)

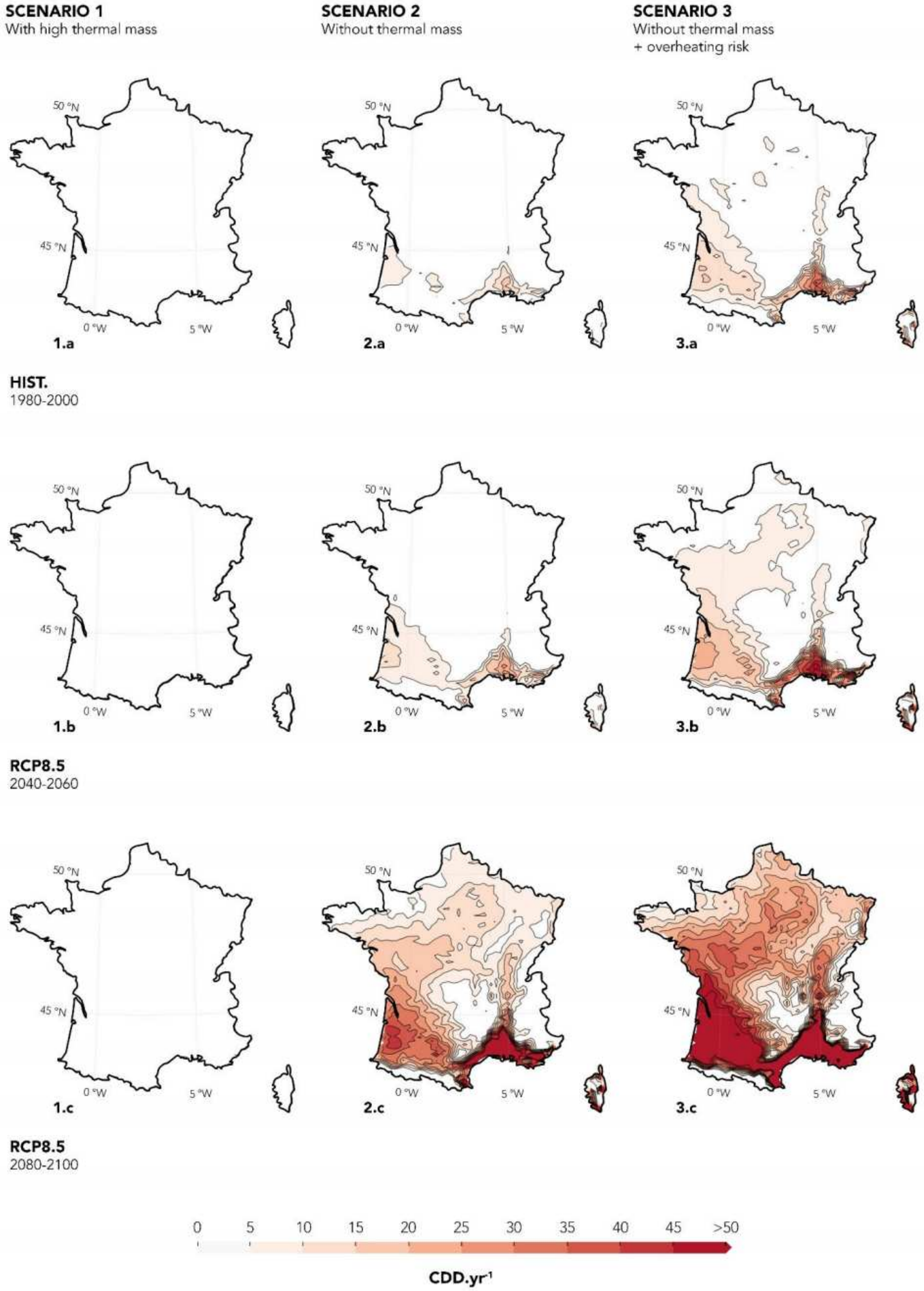
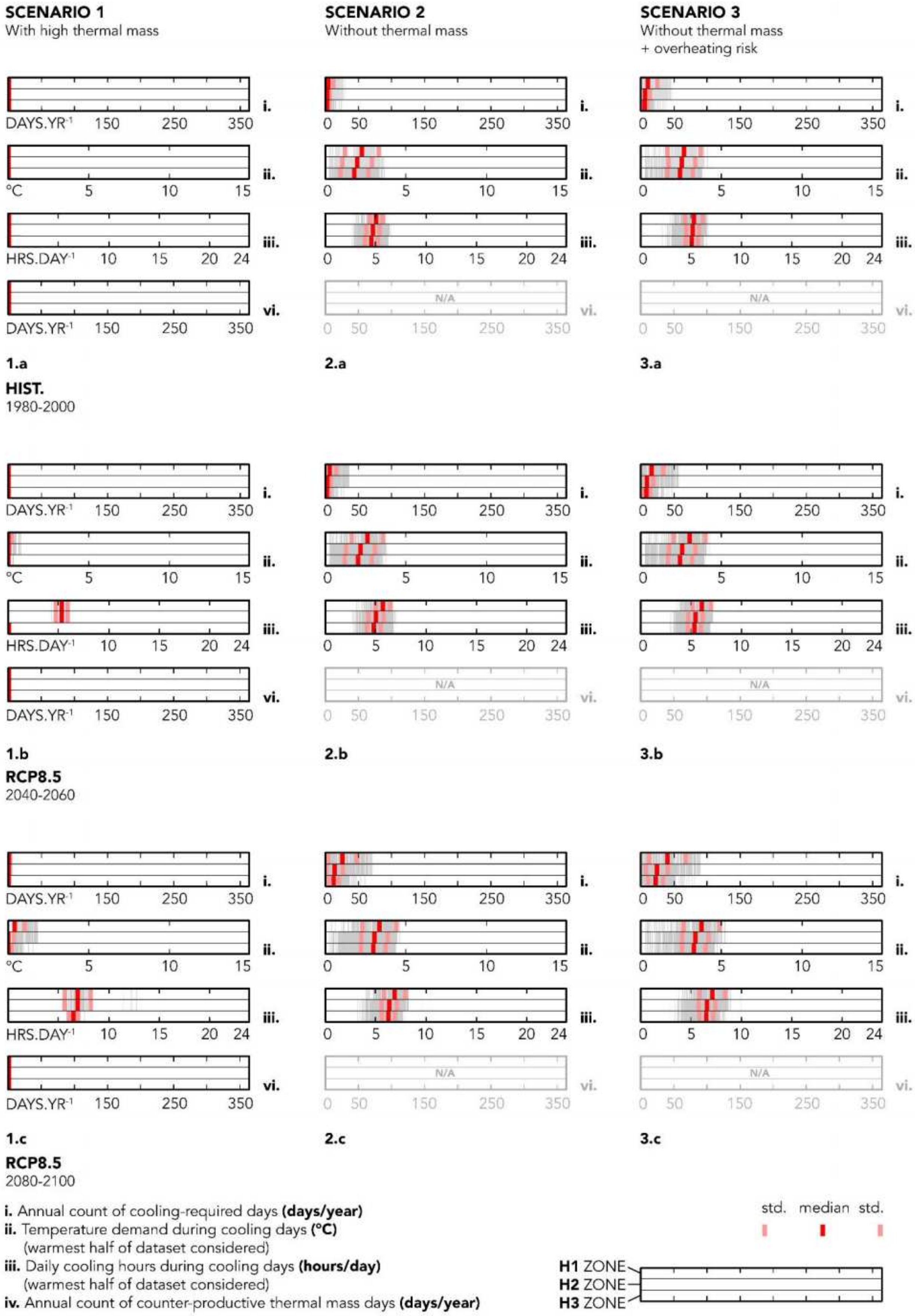


FIGURE 11

RCP8.5 (3.7 °C Global Warming Scenario)
Cooling Degree Days Above Safey Threshold (CDD.yr-1)
(Heat index «extreme caution» level)



4.2. Thermal mass for climate mitigation

If previously presented results suggest that lowering the temperature demand might be required for climate adaptation purposes (i.e., generally for comfort, and occasionally for safety), it is equally imperative to comprehend the potential advantages in terms of climate mitigation (reductions in specific energy consumption and the resulting decrease in operational emissions associated with space cooling in buildings).

4.2.1. Thermal mass for energy savings

The temporal trend of specific energy consumption pertaining to space cooling, as depicted in Fig. **12** to **14**, demonstrates a slower rise than the corresponding escalation in temperature demand for comfort. This behavior can be attributed to the temporal discrepancy between the yearly increase in $CDD_{yr^{-1}}$ and the thresholds at which occupants make investments in AC equipment, as postulated in the employed model (refer to section 3.3). As such, the future climate trends also indicate more pronounced increments in historically cooler zones (e.g., observe the comparison of $Q_{cooling}$ in zone H1 of Fig. **2.a** and **2.b**, revealing a 141% surge, as opposed to a 126% increase in zone H3, despite both zones experiencing equivalent temperature demand elevations of +141% and +142% for zones H1 and H3, respectively), due to a greater number of locations newly surpassing these thresholds over a given period, in contrast to the pre-existing air-conditioned spaces in historically warmer zones.

Within this context, the results illustrate the significant ability of high thermal mass buildings to delay the requirement for AC equipment installation, offering enhanced climate resilience (refer to Scenario 1 in Fig. **12** through **14**, indicating diminished reliance on mechanical cooling for the majority of represented areas). This is exemplified by maintaining over 90% of the studied sites below the 5 kWh/m^2.yr threshold for all scenarios except the 2080-2100 period under RCP8.5 (where it decreases to 38%). The results for the 2080-2100 period under the RCP8.5 scenario (see Fig. **13.1.c'**) suggest that once the threshold necessitating the installation of mechanical cooling equipment is surpassed within high-mass buildings, yearly primary energy consumption will rapidly escalate (resulting in a substantial 237% average increase in specific energy consumption on a national scale between the 2040-2060 and 2080-2100 periods under the RCP8.5 scenario). This phenomenon can be ascribed to the inherent behavior captured in the employed regression model, wherein air conditioning can be employed to cool indoor spaces to temperatures significantly below the adaptive comfort limits illustrated in Fig. **4** through **7**. Indeed, the outcomes presented in this section rely on an *effective* (or *practical*) temperature demand model, which reflects the interior temperature target set by occupants on AC systems after investing in such equipment. This stands in contrast to the theoretical model for temperature demand for comfort utilized in the "thermal mass for climate adaptation" component of the study (i.e., section 4.1.1), which calculates the theoretical temperature drop required to maintain occupants within the adaptive comfort range of interior temperatures. Notably, the adaptive comfort standard used for estimating temperature demand for comfort establishes a discomfort threshold between 25 and 27.87 °C, a range that varies based on the running mean monthly outdoor temperature.

FIGURE 12
RCP4.5 (1.8 °C Global Warming Scenario)
Specific Energy Consumption (kWh/m².yr) **and**
Indirect Emissions (kg CO_2eq./m².yr) **for Space Cooling**

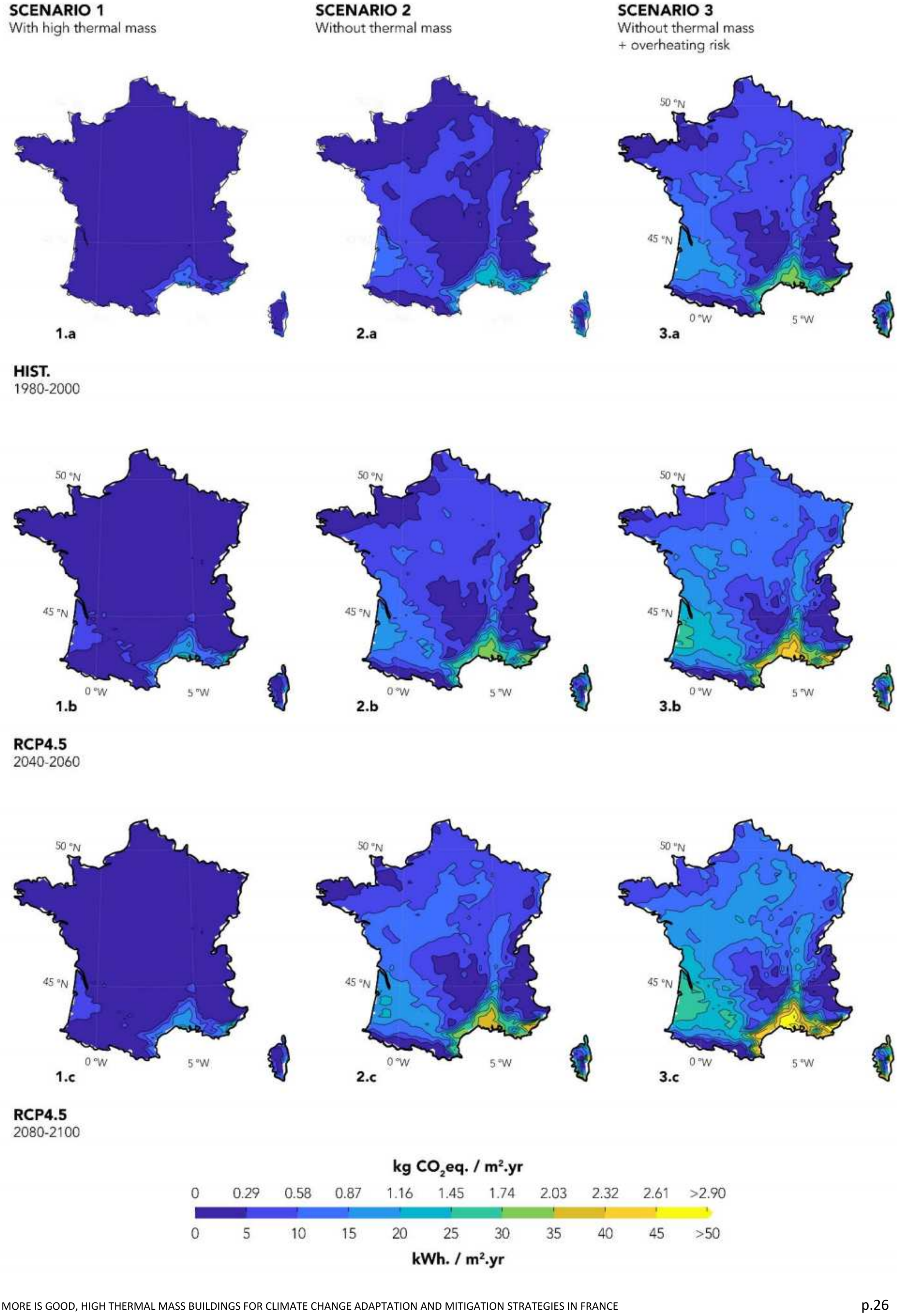


FIGURE 13

RCP8.5 (3.7 °C Global Warming Scenario)
Specific Energy Consumption (kWh/m².yr) **and**
Indirect Emissions (kg CO_2eq./m².yr) **for Space Cooling**

SCENARIO 1
With high thermal mass

SCENARIO 2
Without thermal mass

SCENARIO 3
Without thermal mass
+ overheating risk

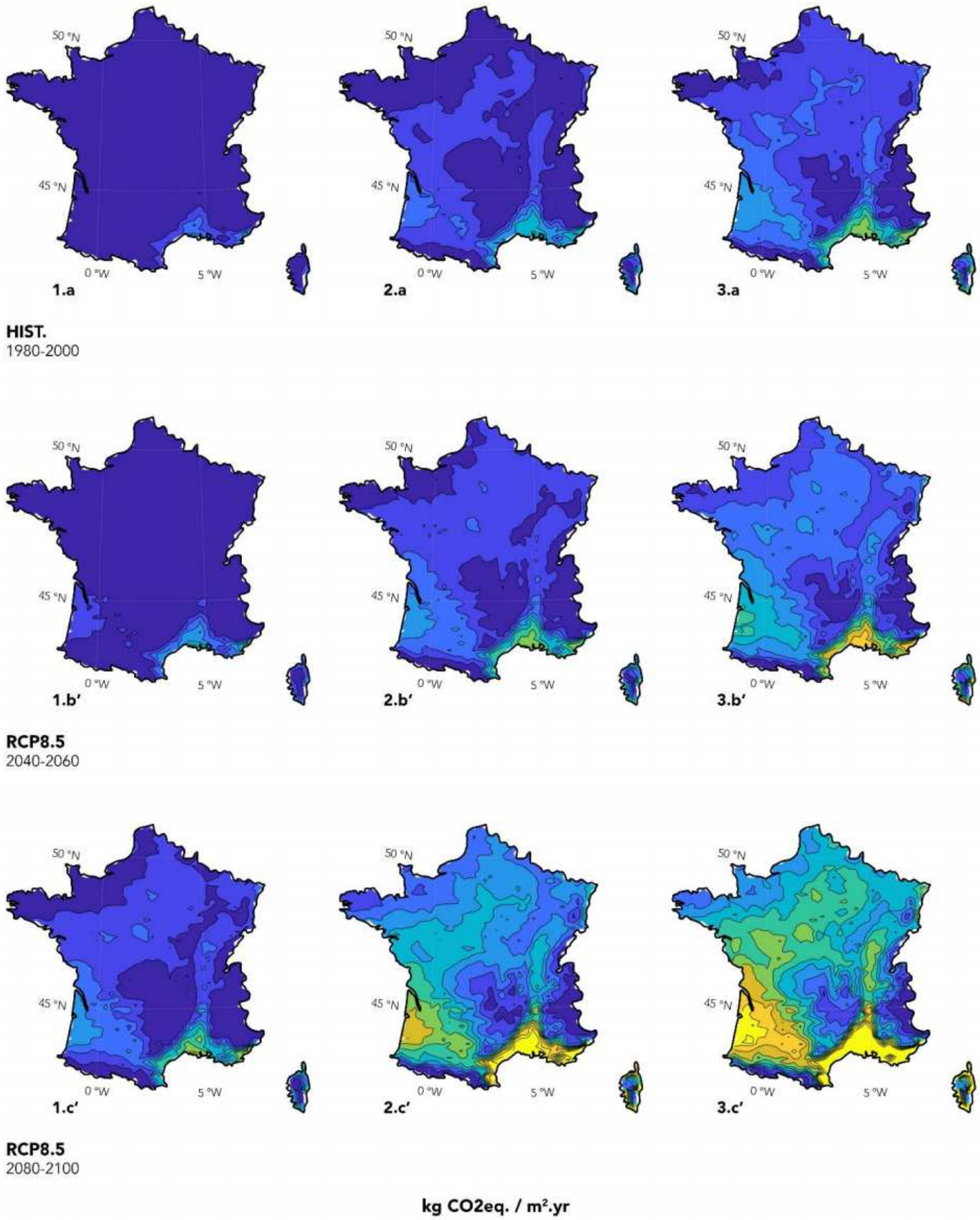
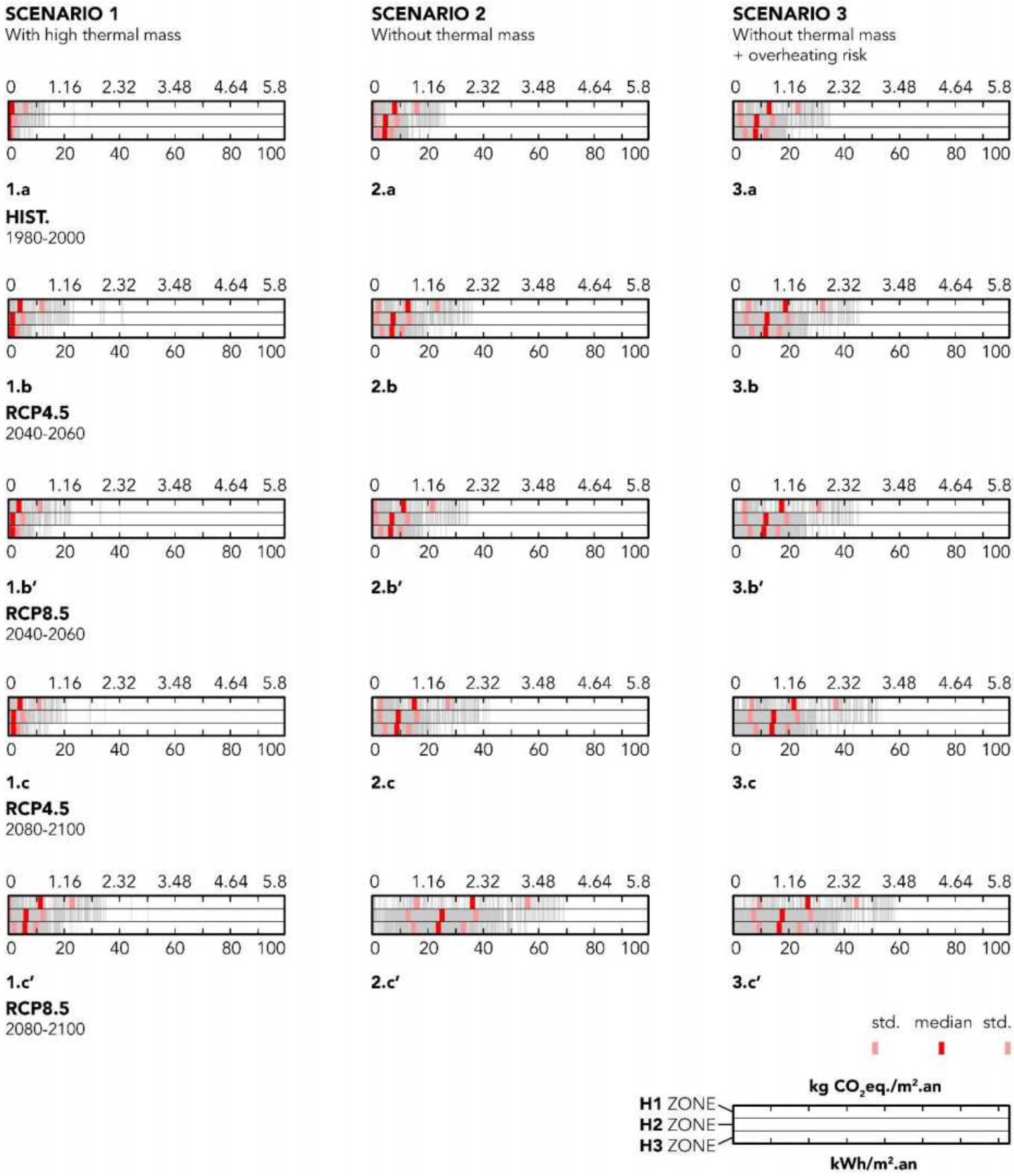


FIGURE 14
Specific Energy Consumption (kWh/m².yr) **and**
Indirect Emissions (kg CO_2eq./m².yr) **for Space Cooling**



In contrast, the specific energy consumption presented in this section is derived from a regression analysis model, assuming air conditioning usage to maintain interior temperatures as low as occupants typically do (even as low as 18°C), a level that may not be attainable solely through passive cooling methods.

Although high thermal mass may not always completely prevent investment in AC equipment, the findings indicate that it consistently and significantly reduces specific energy consumption for space cooling in comparison to light inertia buildings, particularly in situations where there is a heightened risk of overheating.

As portrayed in scenarios 2 and 3 of Fig. **12** through **14**, considerable proportions of the examined locations could potentially face climates that necessitate more than 20 kWh/m^2.yr for buildings exposed to overheating risks to meet mechanical cooling demands. Specifically, this situation would encompass 19% of the national area under RCP4.5 and 70% under RCP8.5. In such instances, thresholds of 50 kWh/m^2.yr would be surpassed over 1.5% and 7.9% of the national area under RCP4.5 and RCP8.5, respectively (depicted in scenario 3c' in Fig. **12** through **14**). In the H3 zone, these thresholds would be surpassed across 10% and 38% of its area under RCP4.5 and RCP8.5, respectively, with peak values as high as 57 and 75 kWh/m2.yr, highlighting the intensified need for high-mass buildings in the southern regions. Given the maximum primary energy consumption thresholds of 70 kWh/m^2.yr established by the new RE2020 regulation (covering all uses), the findings indicate that the mechanical cooling demand could potentially exceed the permitted threshold for numerous buildings if passive cooling strategies are not employed. This underscores the necessity for meticulous planning, in which thermal mass strategies could occupy a strategic role. While these strategies are commonly well-suited for new constructions, the findings indicate once more the need for additional efforts to advance the field of thermal mass retrofits, which currently lacks extensive research (Gjerde, 2014).

Regardless of the RCP scenario and period considered, the findings demonstrate how high thermal mass and nocturnal convective cooling can significantly diminish average projected energy consumption, consistently surpassing 65% reduction compared to light inertia buildings (77% when facing overheating risks).

4.2.2. Thermal mass for carbon savings

Since they exhibit a direct correlation with electricity consumption, the trends in indirect operational emissions for space cooling are consistent with those discussed in the previous section. For further insights, the results should be examined in light of the operational emission thresholds mandated by the RE2020 regulation, which sets a cap of 6.5 kgCO_2/m^2.yr (representing the ultimate threshold for the presently tri-yearly declining caps for collective housing units, and is scheduled for implementation by 2028 –note that beyond this point, there is currently no visibility regarding further updates to French regulations).

As evidenced by the data presented in Fig. **12** through **14**, it can be thus be inferred that by the middle of the century, and with consideration for light inertia buildings (scenario B), approximately 2.2% of the national area (encompassing 15.5% of the H3 zone) will be exposed to climatic conditions that could lead to operational emissions for cooling amounting to one-quarter of the total yearly building operational emissions (equivalent to 1.625 kgCO_2/m^2.yr) under the RCP4.5 scenario. This proportion is projected to increase to 3.5% by the end of the century (accounting for 40.9% of the H3 zone) under RCP4.5 and to 14% of the national area (comprising 47% of the H3 zone) under RCP8.5. In the latter case, certain zones are shown to be exposed to climates prompting operational emissions as high as 3.6 kgCO_2/m^2.yr for light inertia buildings (refer to scenario 2.c’ in Fig. **14**). When considering 2 °C of overheating during peak cooling hours, this value increases to 4.29 kgCO2/m2.yr (see scenario 3.c’ in Fig. **14**).

Having previously demonstrated the significance of high thermal mass in reducing energy consumption for cooling, it follows that this capability extends to decreasing operational emissions. The results indicate that passive cooling through thermal mass could, in the most extreme case (i.e., the 2080-2100 period under RCP 8.5), maintain operational emissions at an average of 0.34 ± 0.23 $kgCO_2/m^2$.yr within the H1 zone, 0.36 ± 0.35 $kgCO_2/m^2$.yr within H2, and 0.67 ± 0.66 $kgCO_2/m^2$.yr within H3, in comparison to 0.96 ± 0.41, 1.02 ± 0.59, and 1.53 ± 1.01 $kgCO_2/m^2$.yr for light inertia buildings, and 1.38 ± 0.52, 1.45 ± 0.70, and 2.09 ± 1.16 $kgCO_2/m^2$.yr for light inertia buildings subject to overheating risks.

5. Limits and future outlooks

As noted in section 2.3, the results presented in this study pertain to strategic forecasts, rather than absolute predictions. In that regard, results are indicative of the overall relevance of thermal mass as a passive cooling strategy, providing necessary insight from both a policy perspective, and for preliminary design phases. However, it should be noted that these results do not replace the need for DTSs at later stages of building design to evaluate specific configurations, as they directly influence the performance of thermal mass. Within the scope of the results, the methodology nevertheless exhibits several inherent limitations:

- The study relies on RCM dynamic downscaling simulations by a single RCM model (CNRM-ALADIN53), driven by boundary conditions from a single GCM (CNRM-CERFACS-CM5). While the equilibrium climate sensitivity (ECS) of the selected GCM – indicative of the sensitivity of the model to increasing atmospheric greenhouse gas concentrations– falls within the mean range for its category (i.e., 3.3 °C, against 3.2 ± 1.3 std for the CMIP5 GCM ensemble), the summer temperature signal from the selected RCM displays relatively high negative biases over France –average bias of -2.5 °C (von Trentini et al., 2019) – when running under CNRM-CERFACS-CM5 boundary layer conditions, suggesting that the results might underestimate the $CDD_{year^{-1}}$ projections overall.
- The RCM simulation presents limited spatial resolution (0.11 x 0.11° ≈ 11.5 x 11.5 km), thereby limiting its capacity to effectively simulate urban heat islands (Lemonsu et al., 2023).
- The climate datasets are derived from models that have displayed inherent limitations in fully encompassing the magnitude of heightened interconnections between systems (Willcock et al., 2023). Should these models be underestimating the true extent of these interconnections, they would be disregarding crucial factors that have the potential to augment stress levels and expedite the occurrence of threshold-dependent change (including underestimations of the frequency and magnitude of heatwaves in future cascading events).

- The model used to derive useful energy demand for space cooling from yearly temperature demand is dependent on statistical analysis conducted using US-based data (Jakubcionis & Carlsson, 2017), which introduces potential disparities in lifestyle dynamics that could hinder the accuracy of the model's projections regarding the European and French contexts (Santamouris, 2016) (see Henderson (2005) for disparities between the model predictions and current AC penetration levels for historical runs).
- The GHG emission savings discussed in the study are limited to the operational impact of air conditioning equipment (i.e., indirect emissions arising from electricity production), and thus discard (i) operational emissions from refrigerant leakage (considered twice as important as emissions from electricity consumption in the French context (ADEME, 2021a)), and (ii) embodied emissions from other LCA phases (e.g., equipment production and installation).
- The Heat Index model employed to evaluate safety thresholds assumes steady air flows, which could misrepresent the interior conditions of inadequately ventilated buildings. This suggests that the cooling demand required for safety within the third scenario (representing overheating interiors due to poor ventilation) might be underestimated.

In that regard, potential future outlooks may involve:

- Applying the methodology to multi-model ensemble climate dataset averages, to achieve a comprehensive understanding of the level of uncertainty associated with the results.
- Employing convection-permitting model simulations (i.e., tenfold increase in spatial resolution) focused on urban centers to enhance the understanding of thermal mass performance within the context of intensifying urban heat islands.
- Conducting an extended GIS analysis to forecast future AC penetration and energy demand for space cooling within passively cooled buildings (Andreou et al., 2020; Santamouris, 2016), specifically incorporating the exhaustive set of drivers of residential space cooling, including household size, gross domestic product per capita, expected efficiency improvements, in addition to the rise in $CDD_{yr^{-1}}$.
- Expand the scope of the climate mitigation study to encompass larger life cycle assessment (LCA) boundaries to provide a more comprehensive understanding of the climate benefits associated with implementing a thermal mass strategy.

Beyond the scope of the paper, future inquiries could involve:

i. Replicate the outlined approach over other countries exhibiting pertinent contexts, specifically those characterized by more frequent and intense heatwaves and higher emission factors associated with electricity production (EEA, 2023).
ii. Integrate quantitative performance evaluation for the coupling of thermal mass with other cumulable passive cooling methods (Zeng & He, 2022).
iii. Utilize the generated heat and energy maps in conjunction with projected new construction and retrofitting rates to assess the potential energy-saving capacity of high thermal mass strategies at the national level.

6. Conclusion

Overall, the study demonstrates the ability of naturally ventilated high-mass buildings to passively meet virtually all the temperature demand for both comfort and safety in France, within current and future climates, regardless of the emission scenario considered. Such passive cooling strategies could offer significant benefits in terms of heat-stress, while also contributing to a substantial reduction in operational energy consumption and carbon emissions. Conversely, the results indicate that in the absence of mechanical cooling, light-inertia buildings could subject occupants to increasingly more uncomfortable and unsafe indoor conditions. This highlights a potential limitation of the prevalent use of lightweight and highly insulated buildings, favored in green standard practices developed for heating-dominated climates, as they may not offer appropriate solutions for regions transitioning towards cooling-dominated climates, where their potential to induce overheating risks raises significant concerns.

The findings provide guidance for both new construction and retrofitting endeavors, shedding light on the significant role that thermal inertia can play in these domains, thereby emphasizing the imperative to identify environmentally conscientious thermal mass materials within the framework of industrial ecology roadmaps aiming to effectively adapt the existing and future building stock to the anticipated climatic changes. While earlier research has established the relevance of such strategies concerning climate mitigation, specifically in terms of embodied carbon (e.g., de Toldi and Pestre (2023)), this current study contributes by demonstrating their pertinence in terms of climate resilience and curbing operational emissions.

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Energy Efficient Retrofit Strategies towards nearly Zero Energy Kindergarten Building in Malaysia

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Abstract: In Malaysia, the building sector is responsible for 14.3% of the total energy consumption. The national energy-related policies and plans emphasize energy savings by non-residential buildings by 11% and achieving a nearly Zero Energy Building scenario by 2040 to meet the climate pledges of the country. However, this falls short of addressing sufficiently the high cooling energy demand of buildings in the tropical climate of Malaysia. Thus, this paper investigates retrofit strategies to achieve nZEB in a preschool at the University of Malaya in Kuala Lumpur as a case study. A set of simulation (IES-VE) measures including air-conditioning, lighting, and plug load electricity consumptions for nine energy-efficient scenarios were implemented to assess the energy consumption and savings. Retrofit strategies are: using solar film, roof insulation, seal air ventilation, daylight harvesting, efficient lighting, small power improvement, heat recovery wheel, and replacing air conditioners with high/highest coefficient of performance. A comparison of simulation results shows a potential reduction of primary electricity consumption up to 59.3% (18477.1 KWH) per year for the building. Plus, acting on the existing building stock implies necessarily understanding the local climate to define the most feasible strategies to meet the target of nZEB.

Keywords: Educational Buildings; Retrofit; nearly Zero Energy Buildings; Energy Consumption; Energy Efficiency

1. Introduction

1.1. Current building sector status

Operational energy demand in buildings (e.g. space heating and cooling, water heating, lighting and cooking) has globally increased by 4% from 2020 and exceeded the previous peak in 2019 (the pre-pandemic) by over 3%, operational CO_2 emissions have also rebounded from 2020 by about 5% to a level of around 10Gt CO_2 and exceeded the pre-pandemic all-time high in 2019 by 2% (IEA, 2022).

The increase reflects the reopening of the global economy as workplaces began to use more energy, alongside households continuing to work in hybrid mode, and growth in economies using gas for heating (UN Environment Programme, 2022).

In Malaysia, the building sector as one of the leading sectors in energy consumption is responsible for 14.3% of the total energy consumption and the commercial and residential sectors contribute to 53% of total electricity consumption (Aldhshan et al., 2021). Malaysia's per capita carbon emissions are rising to about 8 tonnes per capita per year and categorised as being above the upper middle-income countries at 6.6 per capita per year (Zen et al., 2021).

1.2. Decarbonising for Net Zero in 2050 – National Action Plans

Globally, the building sector is currently not on target to achieve net zero by 2050 (UN Environment Programme, 2022). To achieve the needed pathway toward net zero, the

International Energy Agency estimates that energy intensity must improve at a rate of 5% per year by 2030 (IEA, 2022). To do so, alongside decarbonisation of a 6% reduction in emissions every year between 2020 and 2030, the average retrofit rate of the building stock must increase to 2.5% per year (or 10 million dwellings per year) by 2030 (IEA, 2021).

Malaysia is ranked as the second highest emitter of carbon emissions per capita in Southeast Asia after Singapore (Zen et al., 2021). With the full comprehension of the urgency required in addressing the present and future consequences of climate change, the recent and ongoing actions by the government of Malaysia to achieve the mission of carbon-neutral by 2050 are presented in Table 1.

Table 1. Current government plan/actions towards Net Zero in 2050

Plan/Policy	Aim/Objective
12th Malaysia Plan (RMK-12) *(2021-2025)*	• To be carbon neutral as early as 2050; • 45% reduction in GHG emissions intensity to GDP by 2030 (12MP, 2021).
National Energy Policy *(2022-2040)*	• EE savings by non-residential by 11% by 2040 (NEP, 2022).
Kuala Lumpur Climate Action Plan 2050 (KLCAP2050) *(2021-2026)*	• To reduce energy consumption of buildings through technical specifications; • To develop maximum allowable Building Energy Intensities to support increased EE; • To develop a roadmap with strategies across the lifecycle of buildings to reduce GHG emissions have been prioritized (KLCAP2050, 2021).

To meet the ambitious targets set by the Malaysian government in the building sector, the Green Technology Master Plan (2017-2030) emphasizes achieving a nearly Zero Energy Building (nZEB) scenario by 2040. Lee (2019) estimated that just by improving EE in the building and transport sectors, RM 46.9 billion (USD 11.2 billion) in energy spending could be saved between 2016 and 2030.

1.3. nZEB definition in Malaysia

Three fundamental steps to achieve high energy efficiency or nZEB status comprise (1) to optimize building design as passive measures such as envelope insulation, solar heat gain, daylight harvesting, airtight envelope, and natural ventilation; (2) to maximize energy efficiency of building services-systems to minimize the building energy demand as active measures such as HVAC and lighting; and (3) to provide on-site renewable energy generation to supply and counter-balance the residual energy demand of the building to reach the target of nearly zero energy demand (Francesco et al., 2019, Berardi et al., 2014).

Table 2. Japanese definition of ZEB ready, nZEB, ZEB concepts

Phases towards ZEB	Definition
ZEB Ready	Buildings that realize reduction of primary energy consumption by 50% or more from the standard primary consumption
nZEB	Buildings that realize reduction of primary energy consumption by 75% with energy saving (50% or more) and energy creation
ZEB	Buildings that realize reduction of primary energy consumption by 100% with energy saving (50% or more) and energy creation

Based on the climate conditions and country building standards, there are many definitions of zero energy buildings (ZEB) around the world. Crawley et al. (2009) argued that the broad definition of nZEB also leaves room for different interpretations that could be misleading to some stakeholders, such as clients, designers, and contractors; therefore, having a common definition is essential to having consistent design definitions and strategies.

Malaysia adopted the Japanese definition of ZEB (Table 2) with minor changes to suit local standards (Figure 1) (Lojuntin, 2022), it is noteworthy however that building energy efficiency has been practiced in Malaysia since 2002 (Lojuntin, 2017).

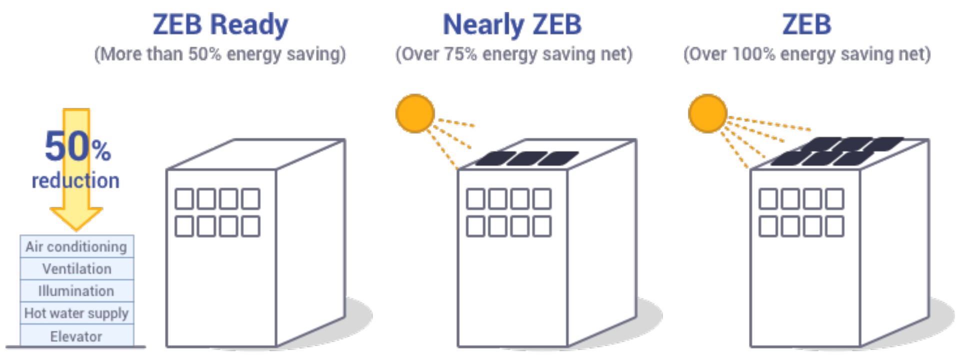


Figure 1. Zero Energy Buildings (ZEB) phases, initiative by SEDA Malaysia, collaboration with JASE-W Japan (Lojuntin, 2022), source: (AGC, 2019)

1.4. nZEB retrofit challenges in Malaysia

Considering the fact that 18 years and older existing buildings consume 1.5 to 2 times more energy than similar new buildings (Fichman, 2010) and the demolition of the existing building stock is a poor solution because of the amount of embodied carbon locked up in these buildings (Historic England, 2019), governments around the world have taken strong measures towards the retrofit of existing buildings (El-Darwish et al., 2017). Correspondingly, the nZEB retrofit concept has been identified and practiced worldwide as a success indicator to reduce energy consumption and mitigate GHG emissions of buildings (Picallo-Perez et al., 2018).

However, the adoption of nZEB principles in the context of hot and humid conditions as a norm has remained an indisputable concern (Ferrante, 2016). The lack of sufficient awareness among the local stakeholders is another impediment to the effective implementation and performance of nZEB retrofit principles in the Malaysian context (BSEEP, 2017).

Although renewable resources (biomass, solar and hydro) to generate electricity are naturally available in Malaysia, the adoption of renewable energy (RE) technology is not commercially viable yet in this country due to the lack of experience and suitable support mechanisms in the market environment (Abd Rahman et al., 2019); limited public awareness in terms of RE technologies; RE social benefit, RE environmental benefits. Hence, EE investment has been regarded as risky and costly in such an environment (Shamsuddin, 2012), particularly by the public and building owners.

To address the gap in this research, an existing preschool building at the campus of Universiti Malaya, constructed before the existence of any national regulations on EE performance, was selected as the case study. The current energy performance and primary electricity consumption of the building are examined using energy audit and monitoring (onsite measurements), complemented by energy simulations of alternative retrofit strategies for transforming it to a nZEB based on the definition presented in subsection 1.3.

It was reported in Quick Facts (2019) that, based on Malaysia's most recent educational statistics, the total number of schools in Malaysia (preschools, primary and secondary schools) amounted to 36,249 schools with 236,267 classes, out of which 25,200 are preschools with 36,249 classes (Mahyuddin et al., 2021). This paper aims to facilitate the widespread adoption of the nZEB retrofit strategy, for existing school buildings in particular, as a norm concept in tropical climate regions to reduce the impact that our buildings have on contributing to climate change.

2. Methodology

The preschool of TADIKUM is an educational building located next to the main campus of Universiti Malaya, in Kuala Lumpur, Malaysia (Figure 2). The latitude and longitude of the site are respectively 3°N and 101°E, and the average elevation of the urban area is 45m (147 ft) above sea level. The data collection, energy assessment, and implementation of EE scenarios for nZEB refurbishment the steps below are taken (Figure 3). Alternative strategies should be characterized as simple, easy to install, working with the budget, and would not influence the daily activities within the preschool building as requested by the management office.

Figure 2. TADIKUM aerial view

2.1. Energy performance audit and monitoring

Through building audit, information on building characteristics such as location, orientation, environmental factors, envelope characteristics, installation systems, and schedules and occupancy are gathered (Güçyeter et al., 2012). The audit provides knowledge of the actual primary energy consumption under real existing conditions.

2.2. Energy performance simulation - EE assessment

Computer-based building-energy simulations are reliable design aid in providing with a comprehensive picture of the building's energy performance and the trade-off alternatives in detail to identify the potential energy savings of the building. The simulation software employed in the study is IES-VE. An energy model in IES-VE software is created and validated based on the input data from the performance audit and monitoring stage. Input calibration parameters include monthly electricity consumption, HVAC data, infiltration and ventilation rates, envelope elements, lighting fixtures, and plug load of appliances.

2.3. Retrofit alternatives implementation and potential energy savings

EE improvement alternatives are explored through 9 scenarios based on the electricity usage under three main categories e.g., air-conditioning, lighting, and plug load of appliances. An onion model approach in implementing EE measures is employed to illustrate the efficacy of each add-up measure progressively until the best-case scenario as the desired optimized nZEB is achieved. Retrofit strategies include using solar film; roof insulation; seal air ventilation;

daylight harvesting; efficient lighting; small power improvement; heat recovery wheel; and replacing air conditioners with high/highest coefficient of performance. Annual electricity usage and saving amounts (kWh) are calculated and compared with the baseline for each scenario.

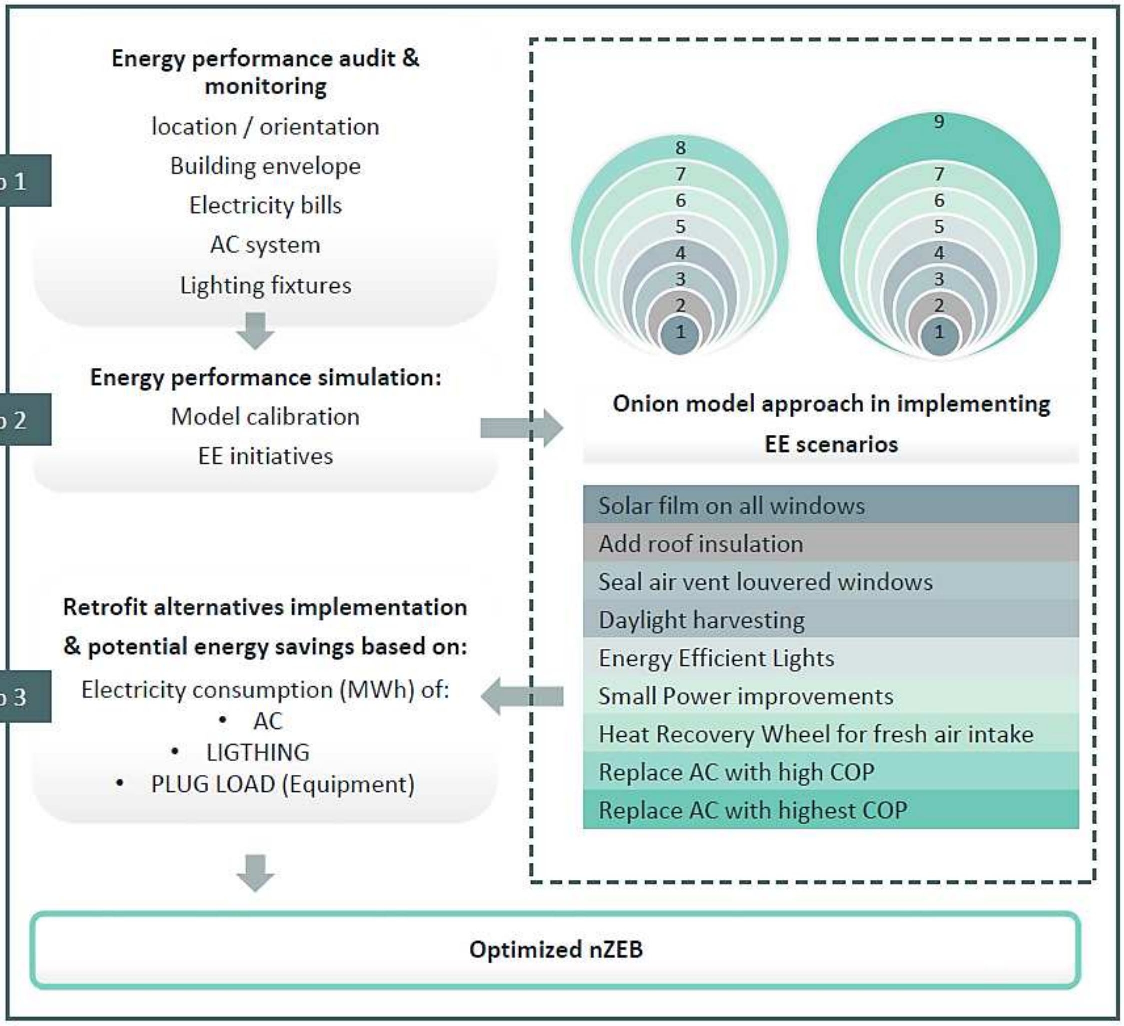


Figure 3. Research methodology diagram

3. Results and discussions

TADIKUM building is a detached double-storey building above ground built in 1984 and previously used as a residential building. A change of use from residential to educational occurred in 2014. It is surrounded by green open space, exposed to a large amount of sun and wind. The building includes a multi-purpose hall, a lobby, 5 classrooms, a kitchen and dining room, an office room, and restrooms for boys and girls. Figure 4 illustrates the layout plans and east-north view of the building. A total number of 88 occupants including staff members and pupils are based in the building. The daily operating hours of classrooms are from 10.00 a.m. to 4.30 p.m.

Figure 4. Floor plan layouts and east-north view of TADIKUM building

3.1. Energy performance audit and monitoring

During the energy audit, all available information regarding the structural elements and electrical equipment and appliances, e.g., location and orientation, architectural drawings, energy performance data (U-values, HVAC system, and installed lighting fixtures), and one-year electricity bills (primary electricity consumption) were obtained, monitored and calculated (Table 3 and Table 4).

Building orientation is an essential aspect of passive design strategy which reduces the primary energy consumption of the building and improves thermal comfort for the occupants. North-South orientation is preferable in tropical climates and the TADIKUM building has oriented opposite in the east-west axis direction. Accordingly, inevitable fenestrations have been built on east and west facades with 13% and 15% WWR respectively. Both improper orientation and WWR on east and west facades resulted in higher heat conductivity through walls and windows and solar heat gain through the windows, plus glare discomfort in classrooms. Poorly sealed horizontal louvre windows on the west façade have caused a high rate of air infiltration and poor thermal efficiency.

The north façade of the main building with an inadequate portion of openings, 12% WWR, has limited daylight penetration into the classrooms and caused full-day dependency on artificial lighting. However, the tropical climate of Malaysia is ideal for daylight exploitation as daylight is invariably and constantly available from the hours of 8 a.m. to 6 p.m. (Tang, 2017b). Thus, educational buildings can benefit from this natural resource to reduce electricity demand.

Large and medium size of windows with 27% and 45% without proper shadings on the south facade have resulted in excessive heat conductivity, solar heat gain, and glare discomfort. A permanent fixed drape has been installed by the users to eliminate these thermal and visual discomforts which brought about full-day dependency on artificial lighting (Mahyuddin et al., 2021).

The glazing type, 6mm clear glass, with a U-Value of 5.82 W/m^{2}K is considered a high U-Value and the major contributor to solar heat gain and heat conductivity through the windows. The main factors the influence the ratio of solar heat gain through windows are shading coefficients of fenestration (SHGC) and window-to-wall ratio (WWR). The higher value of SC and the larger ratio of WWR, both have significant effects on the increase in solar heat gain ratio, cooling load of the building, and electricity consumption consequently. Malaysian standard of MS1525 (2019) for non-residential buildings by emphasizing the fact that the heat gain through the building envelope constitutes a substantial share of cooling load in an air-conditioned building, has required the OTTV factor 50 W/m^2 as the minimum specified requirement for the base building. The OTTV of the TADIKUM building was calculated by the formula provided in MS1525 (2019) as 42.73 W/m^2, which is slightly lower than the minimum requirement.

Table 3. TADIKUM building general information and envelope characteristics

		Main building	The hall building
Location		3°07'10.2"N - latitude 101°38'44.9"E - longitude	
Orientation		North-South	
Surrounding area		An open lot covered by grass and surrounded with congested trees on the west margin of the building lot	
Floor area (m^2)	Ground floor	129.90	59.30
	First floor	78.70	-
Floor to ceiling height (m)		2.85	2.85
Volume (m^3)		594.50	169
Facade surface area (m^2)		296.25	96.90
Roof area (m^2)	Ground floor	64.50	59.30
	First floor	49.50	-
Glazing area (m^2)		48.90	25.44
Wall specification		Brick Wall: 175mm thickness brick wall c/w 6mm thickness cement plaster on both side	
Exterior wall Colour		Light yellow	White
Window Wall Ratio (WWR)	Northern wall	12%	29%
	Southern wall	27%	45%
	Eastern wall	13%	0%
	Western wall	15%	0%
Insulation materials		No extra insulation materials	
Glazing type		Single clear 6 mm thickness glass	
U-Value (W/m^{2}K)	Walls	*2.44*	
	Roof	*2.44*	
	Glazing	5.82	

Table 4 shows the specification and quantity of the air-conditioners and lighting fixtures of the building. All classrooms are equipped with air-conditioners (split units), the COP of the split units is 3.0, the minimum value in compliance with the ASHRAE Standard 90.1. T8 type is the conventional fluorescent lamp used in Malaysia and consumes 36 watts (46 watts including the use of a conventional magnetic ballast) (Li et al., 2016); likewise, the lighting fixture of the TADIKUM preschool comprises 42 T8 – 36W fluorescent lamps without any cover (batten type). All the classrooms have the potential to exploit daylight throughout the normal days but non-climatic building design and user behaviour have resulted in full-day dependency on the use of artificial lighting throughout the year.

Table 4. TADIKUM building air-conditioning and lighting systems

System	Size/Type	Quantity
Air-Conditioning (split unit)	1 HP - 9,500 Btu/h	5
	2.5 HP - 21,000 Btu/h	4
Lighting	Fluorescent T8 - 36W	42

Figure 5 illustrates the electricity usage of the building, collected from the management, in the year 2019. The hottest months recorded for Kuala Lumpur in 2019 are April, May, and June. The school holidays in Kuala Lumpur in 2019 are 23 March – 31 March; 25 May – 9 June; 10 August – 18 August; 23 November – 1 January. Considering these two factors and as the graph shows the trend throughout the year is almost steady with slight spike in February, July, and May with no school holiday. The relatively low electricity needs in June, September, and November are because of the school holidays and rainy season respectively.

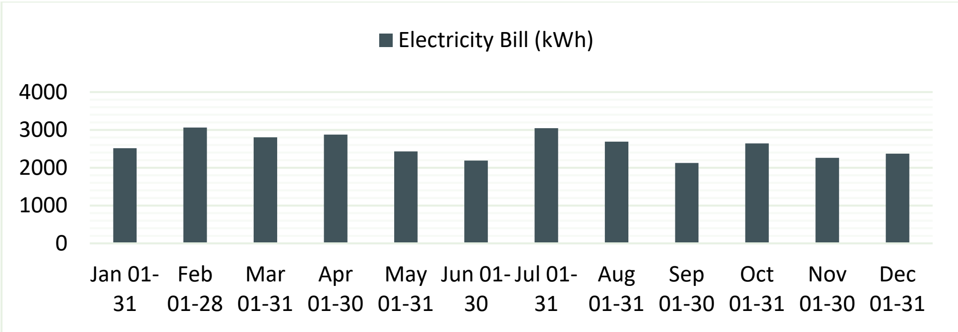


Figure 5. TADIKUM building electricity consumption (2019) – baseline

3.2. Energy performance simulation - EE initiatives

After calculating the existing actual energy performance and primary electricity consumption of the building, and detecting inefficiencies resulting from passive and active designs in this stage the potential energy-saving initiatives will be identified through an energy model in IES-VE software considering the preschool management terms.

The baseline energy model is validated based on the input data from subsection 3.1. The alternatives are conducted in the onion model approach as mentioned in subsection 2.3. To initiate strategies, possible technical solutions based on their effectiveness in EE improvement in tropical climates and easy-to-install factor are implemented and evaluated step by step. The criteria to fulfil these prerequisites are as follows:

SHGC *(1st strategy)* – Solar Heat Gain Coefficient (SHGC) has been proven as the most EE factor to consider in the tropical climate for glazing selection. The lower the value, the better it is because it means that less solar heat is transferred into the building through the glazing. Since the reduction of the glazing area is not possible to decrease the high rate of WWR in TADIKUM, thus reducing SHGC values is implemented. In single glazing, the lowest achievable SHGC is approximately 0.24 (Tang, 2017b).

Roof insulation *(2nd strategy)* – Poor roof insulation is responsible for almost 25% of total building heat losses (Doukas et al., 2017). The cooling savings after insulating the roof are more than 3 times higher than the ones incurred from the placement of insulation on the walls (Serghides et al., 2015). This indicates the high effectiveness of the roof insulation in the reduction of the cooling energy need. On the other hand, forasmuch as insulating the roof does not affect the activities within the building and usable spaces, therefore it is characterized as simple and easy to install and in compliance with the scope of this study.

Sealing fenestrations *(3rd strategy)* – A study of 10 buildings in 2008 by JKR (Malaysian public works department – Ministry of Works) found that the measured total fresh air change rates in buildings were as high as 2.0 ACH, with an average of 1.0 ACH per building (Razad et al., 2010). This indicates that on average and compared to ASHRAE 62.1 requirement of 0.5 ACH in buildings, buildings in Malaysia have an infiltration of an additional 0.5 ACH of fresh air beside the 0.5 ACH fresh air intake by the air-conditioning system (Tang et al., 2017). In the Malaysian climate, infiltration introduces both sensible and latent (moisture) heat into a building. The latent heat presents a larger problem for the building because not only does moisture require a significant amount of energy to be removed by the air-conditioning system, but excessive moisture also leads to a higher risk of mould growth in the building.

Heat recovery systems *(7th strategy)* – An air-tight building would open up further opportunities to improve the EE in the building with the potential use of a heat recovery system to pre-cool and pre-dry the fresh air provided for the building; to reduce exfiltration from the building, thereby increasing the amount of available exhaust air for heat recovery to be implemented. Due to Malaysia’s hot and humid climate, it is most appropriate to implement a heat recovery system that recovers both sensible and latent heat (Tang, 2017a). A heat recovery system is not a feasible energy efficiency option to be implemented in a leaky building because it may cause higher infiltration into the building, and this may lead to condensation and mould growth problems inside the building.

Daylight harvesting *(1st and 4th strategies)* – Harvesting daylight for its health benefits and energy efficiency in this climate is not as simple as providing large window areas on the building envelope. Proper tropical climate daylight harvesting design skills need to be developed to gain the optimum benefits from daylight. Improper daylight harvesting design may cause glare discomfort, excessive heat gain, increased thermal discomfort and high energy consumption in buildings. Due to glare issues, almost all windows in Malaysia are covered with blinds or curtains. For a good quality daylight harvesting system, these design principles are addressed in the simulation scenarios:

- Solar Heat Gain Minimisation (the first scenario covers this point)
- Glare Protection (the first and fourth scenarios covers this point)
- Deep Daylight Penetration ((the fourth scenario covers this point)
- Uniform Daylight Distribution (the first and fourth scenarios covers this point)

LED light *(5th strategy)* – LED lighting is a technology that has seen tremendous improvements over the last few years. LED lights have a longer life span as compared to the normal ones. LED technology is improving very fast and is expected to have improved CRI performance and higher lamp efficacy very soon (Tang, 2017a).

COP (Coefficient of Performance) *(8th and 9th strategies)* – COP as a measurement of the energy efficiency of the air-conditioning unit is calculated as:

COP = Cooling Provided ($kW_{cooling}$) / Electricity Consumed by Chiller (kW_e)

And most of air-conditioners have a COP of 2.3 to 3.5. The building energy index (BEI) is reduced approximately by 10.5 kWh/m^2/year for a COP increase of 1.0. In this study two feasible and available higher COP in the market are assessed in the simulation process for EE improvement.

BEI is a standard measurement mathematical model to evaluate energy consumption in buildings, which is commonly expressed in kWh/m^2/year (Lizana et al., 2018):

BEI = Energy Input (kWh) / Gross Floor Area (m^2). TADIKUM has a BEI of 115.78 kWh/m^2/year and COP of 3 for air-conditioners in the actual baseline scenario.

Following the criteria and climatic considerations discussed above, Table 5 presents the alternative scenarios that are performed accordingly through the building energy simulation.

Table 5. The hierarchy of strategies to conduct in IES-VE for EE improvement to reach nZEB scenario in TADIKUM building

No	Strategies to be implemented	Base	EE Scenario
1	Solar film on all windows (Window SHGC)	0.8	0.25
2	Add roof insulation (50mm Rockwool on 2nd floor ceiling attic)	0	50 mm Rockwool on ceiling of all roof attic
3	Seal air vent louvered windows (infiltration from 1.8 reduced to 0.8), model base AC with max cooling limit (9 kW cooling limit)	1.8 ach	1.0 ach
4	Daylight harvesting - Use of daylight with internal horizontal louvers	1.8 kW	0.9 kW
5	Energy Efficient Lights - LED lights	0.9 kW	0.45 kW
6	Small Power improvements: Use of notebook (laptop) instead of PC, EE refrigerators/printers/TV	1.2 kW	0.8 kW
7	Heat Recovery Wheel for fresh air intake		0.5 ach whichever is lower
8	Replace AC with high COP	3	5.0
9	Replace AC with highest COP		6.0

3.3. Retrofit alternatives implementation and potential energy savings

After simulating the building's energy performance using the IES-VE software, the annual primary electricity consumption was calculated as 31,152.5 kWh for the baseline scenario. In comparison with the actual amount (31,018 kWh), the calculated 0.4% insignificant discrepancy validates the accuracy of the simulation model in this study to perform the EE alternatives accordingly (Figure 6).

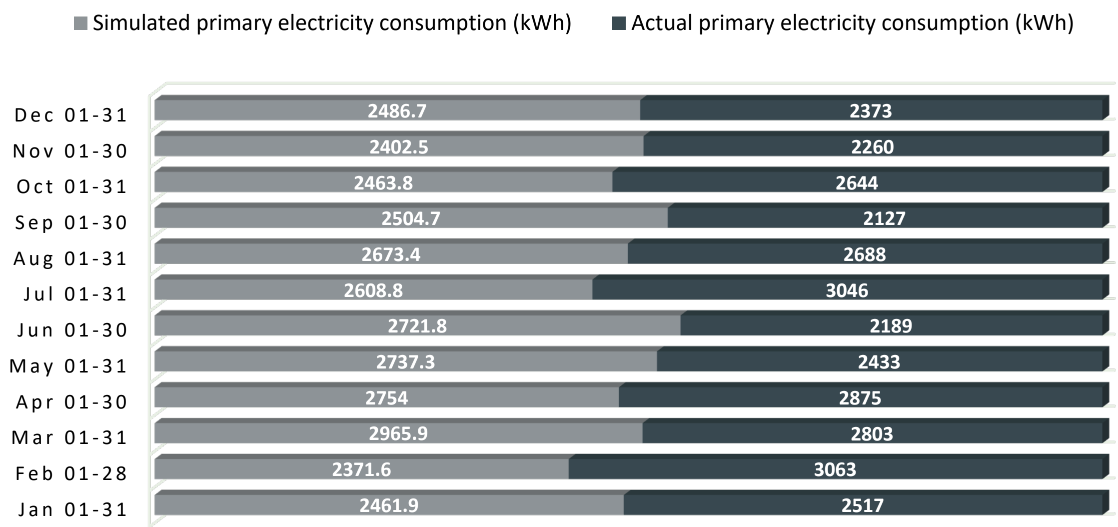
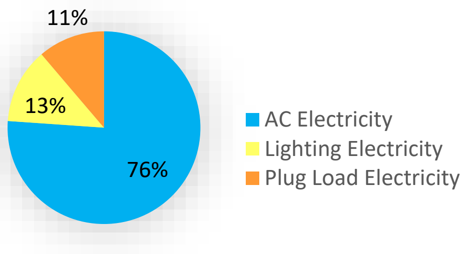


Figure 6. TADIKUM building simulated and actual amounts of monthly primary electricity consumption for the purpose of simulation validation

In the baseline scenario, the major annual electricity consumption is attributed to the high demand for cooling (23,708.5 kWh) followed by the artificial lighting (3,946.3 kWh) demand (Figure 7).



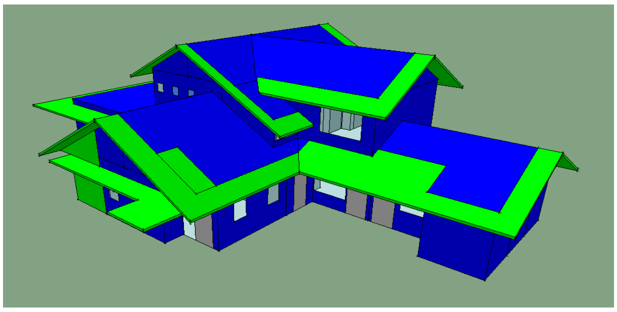
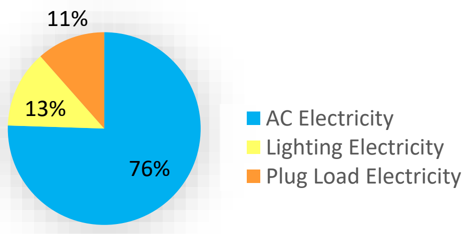
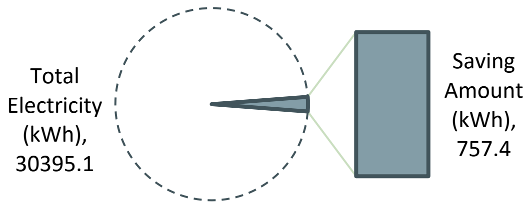


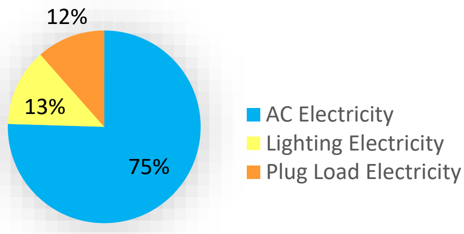
Figure 7. Model setup in IES-VE and calculated baseline annual electricity consumption (31,152.5 kWh)

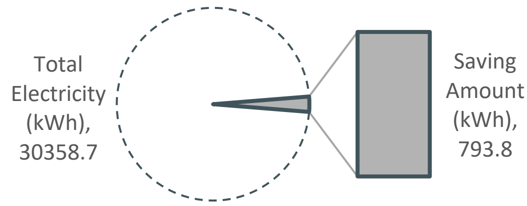
Scenario	Energy saving
Scenario 1: Strategy 1 - Solar Film	**2.4%**



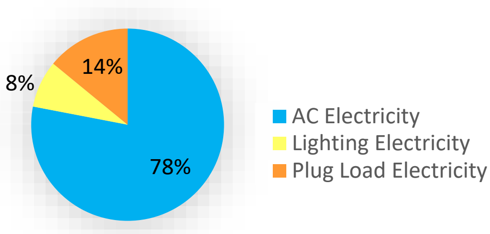


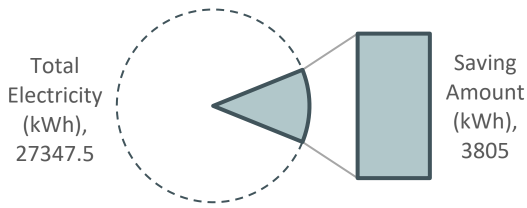
Scenario	Energy saving
Scenario 2: Scenario 1 + Roof Insulation	**2.5%**



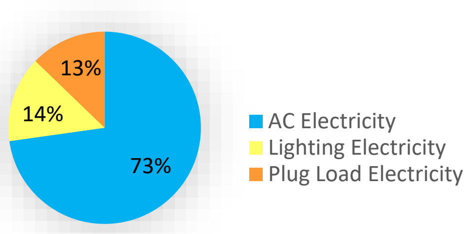


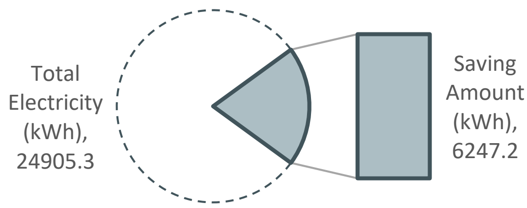
Scenario	Energy saving
Scenario 3: Scenario 2 + Seal Air Vent Louvered Windows	**12.2%**



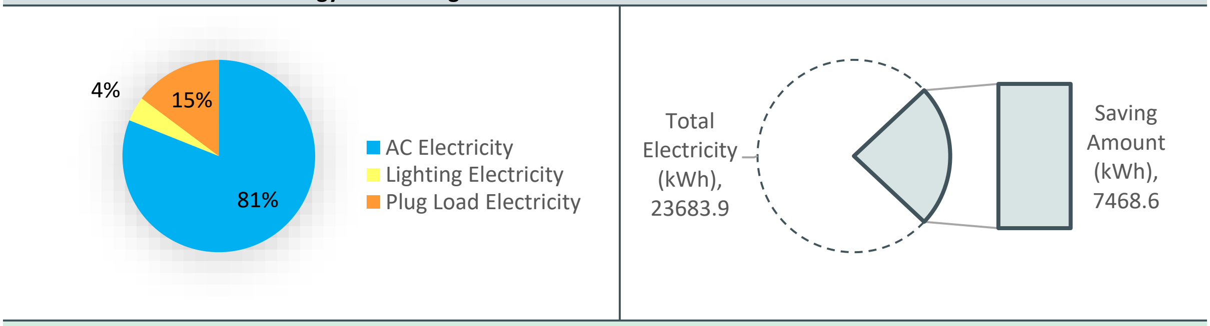


Scenario	Energy saving
Scenario 4: Scenario 3 + Daylight Harvesting	**20.1%**

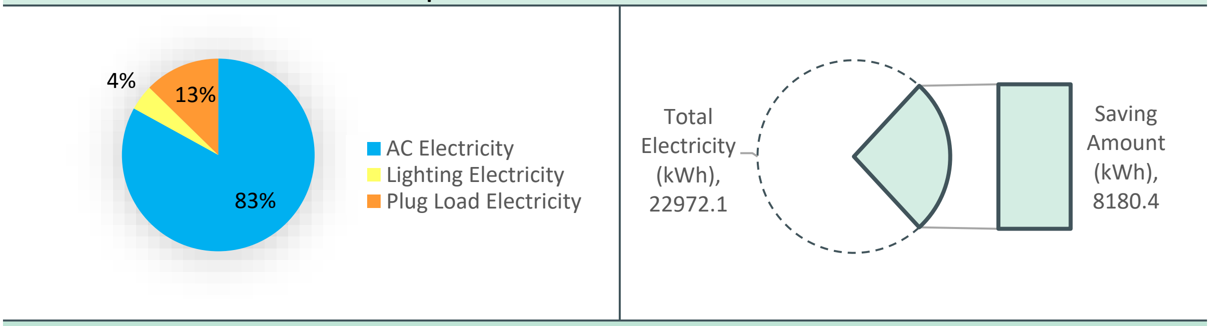




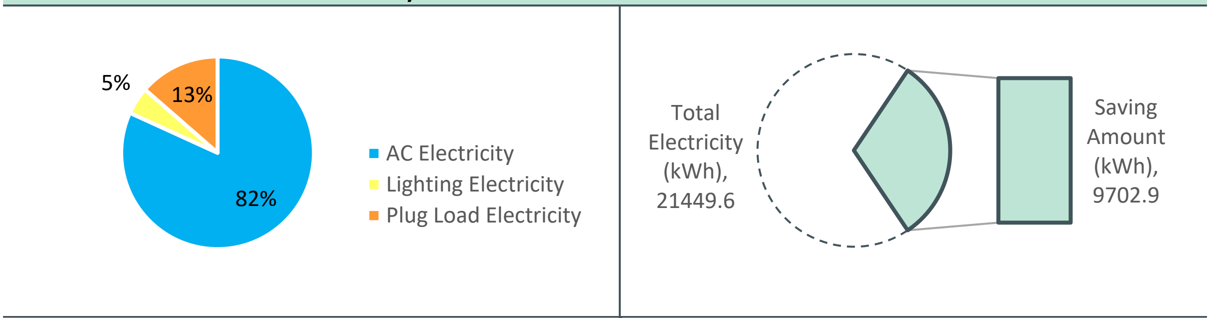
Scenario	Energy saving
Scenario 5: Scenario 4 + Energy Efficient Lights	24%



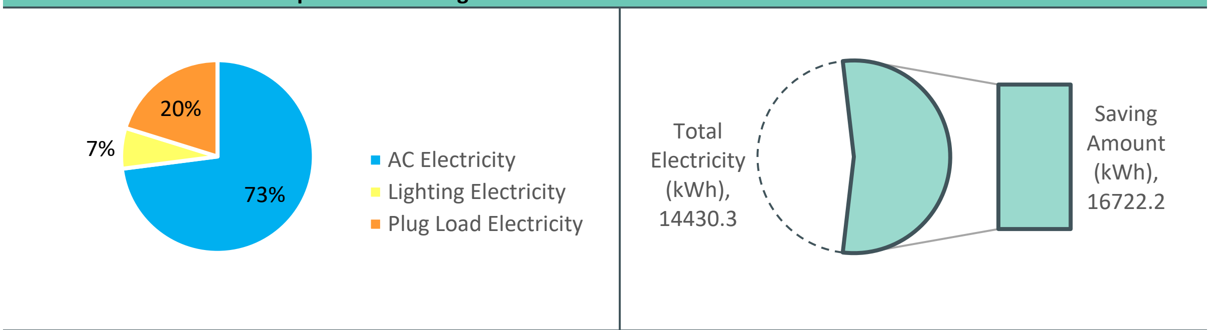
Scenario	Energy saving
Scenario 6: Scenario 5 + Small Power improvements	26.3%



Scenario	Energy saving
Scenario 7: Scenario 6 + Heat Recovery Wheel	31.1%



Scenario	Energy saving
Scenario 8: Scenario 7 + Replace AC with high COP	53.7%



Scenario	Energy saving
Scenario 9: Scenario 7 + Replace AC with highest COP	59.3%

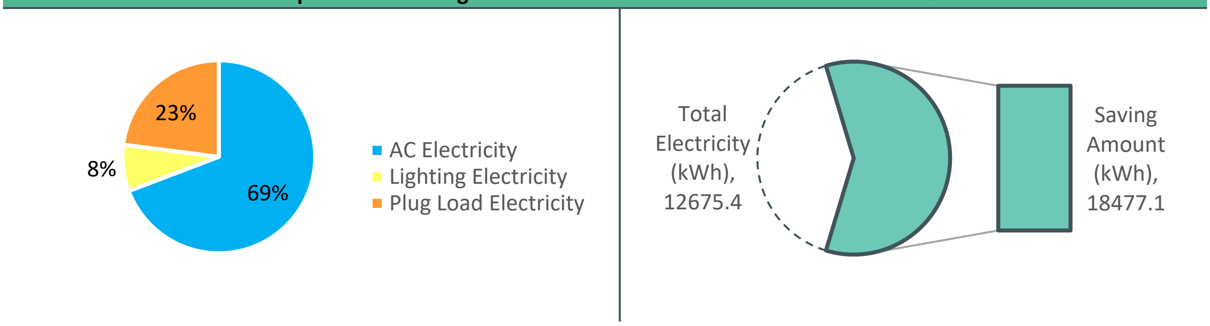


Figure 8. The results of the strategies conducted in IES-VE in onion model approach to reach 50% or more reduction from EE improvement to reach nZEB scenario in TADIKUM building

EE improvement strategies were explored through 9 scenarios in IES-VE. For each scenario, the annual electricity consumption for air-conditioning, lighting, and plug load of appliances were calculated separately to examine the efficacy of each add-up measure. Then the total electricity consumption in each scenario was compared with the primary electricity consumption in the baseline to realize the potential corresponding energy saving. Figure 8 illustrates the results of simulated EE improvement strategies that were conducted through 9 progressive scenarios in IES-VE. Annual electricity usage and saving amounts (kWh) declare that scenarios 8 and 9 reduce the primary electricity consumption by 53.7% and 59.3% respectively (>50%). It means that based on the nZEB definition adopted by the Malaysian authorities (subsection 1.3), scenarios 8 and 9 could reach the ZEB-ready phase by implementing climate-responsive, most effective, and easy-to-install EE strategies yet with the least impact on the activities within the building and the usable spaces before applying the renewable energy to generate the 25% residual energy demand to meet the 75% energy reduction in total. It was understood that the TADIKUM building roof under the current condition with no extra extension can generate about 900 kWh/month of electricity (~ 10,000 kWh/year) by the installation of solar panels to easily and straightforwardly fulfil the nZEB energy saving and energy criteria.

4. EE simulation points to consider

The negligible discrepancy of 0.4% in the model calibration, derived from this research scope, can lead to increased confidence in the performance, reliability, and impact of extensively used IES-VE software on EE retrofit strategies and its suitability for application in different climates when utilizing purely data-driven approach and the default international standards' inputs are not the underlying attitude during the EE simulation. It should be pointed out that the feasibility and accuracy of EE strategies through the simulation modelling strongly depend on the quality of actual input data; local climate considerations; modeller's knowledge and competence on the applied methods in the simulation engine, simplification of complex technologies; local achievable values of different materials; appropriate implementation of local responsive systems; and local by-law requirements and building standards that might differ slightly but effectively from the international standards.

Although this study is confined to the Malaysia building sector and climate, the approach and considerations to use IES-VE for EE simulation initiatives for nZEB retrofit should provide valuable insights and lessons learned for tropical climates' construction professionals to attempt to employ proper EE tools and methods for their practice for decision-making in retrofit solution selection.

5. Conclusion

This paper reviewed the current contribution status of existing buildings in energy consumption and CO_2 emissions in Malaysia. The ongoing EE improvement initiatives and action plans by the government for non-residential buildings towards decarbonising for Net Zero in 2050 and also the main challenges during this transition were briefly explained.

This study observed and proved how implementing passive design strategies and active design technologies in an old non-climate responsive building in hot and humid weather could improve its energy efficiency by almost 60% reduction in primary electricity consumption. The strategies employed the least structural changes on the characteristics of the building envelope due to health considerations of pupils and operation conditions of the TADIKUM preschool.

The aim and approach were to propose a combination of practical and feasible retrofitting measures to improve the EE and investigate the impact of each new strategy on the process as a whole and air-conditioning and lighting systems separately as the most contributors to electricity consumption in the buildings in this region.

Reduction of the building's heat loss and infiltration through fenestrations was realized to be the most effective measure followed by the higher COP implementation. It is important to note that high airtightness strategies should be accompanied by proper air ventilation to not only significantly reduce the cooling load but also prevent excessive moisture, condensation, and mould growth risks in the building. In simulation scenario 7, the heat recovery system was modelled to prevent such a situation plus the EE improvements as discussed in subsection 3.2.

The BEI of the building in actual baseline status was 115.78 kWh/m^2/year, whereas the corresponding reductions after the simulations conducted for scenarios 8 and 9 are 53.86 kWh/m^2/year and 47.36 kWh/m^2/year respectively, achieving more than 50% saving energy in primary energy consumption and enabling the preschool to reach nZEB by using solar panels to create about 15% residual energy demand.

Results declared that acting on the existing building stock implies necessarily understanding the local climate to define the most feasible and effective strategies, passive and active, to meet the target of nZEB with the least structural refurbishment. Designers and stakeholders in the field of EE improvement of existing buildings are also recommended to update their resources about the most recent active technologies in the market such as requesting the latest COP ratings from chiller manufacturers.

In this paper, energy-efficient retrofit strategies towards nZEB for TADIKUM preschool were investigated. The life cycle cost and payback period analyses for each implemented scenario will be presented in a future paper.

6. Acknowledgment

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When means and ends meet: examining strategies and carbon accounting fit for Our Global Future

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Abstract:
Global efforts to accelerate the transition towards whole-life carbon (WLC) neutral buildings are key to ensuring humanity's survival in a world beaten by climate change. WLC design is expected to optimize embodied and operational GHG emissions, and corresponding estimates imply that both types are explicitly accounted for. As varied carbon accounting approaches have been used, this paper overviews two promising strategies for carbon removal - biobased materials and mineral carbonation - and discusses the implications of the main calculation approaches applied to them. Crushed concrete carbonation and CO_2 curing can uptake almost 10% of the original emissions each, at low additional cost. Still, both assume continued use of concrete, which has high embodied emissions. Well-established in temperate climates, biobased construction materials are not mainstream and durability challenges in certain exposure conditions prevent their unrestricted contribution as carbon sinks. As to calculation rules, assigning emissions and uptake to the life cycle stage in which they occur can be tricky when recycling, reuse and waste management activities are inherently involved. By design-reduction and compensation measures must be sought for and - if we are to reach Our Global Future - partnerships and resources urgently directed to all nations to play their part in the collective decarbonization.

Keywords: Carbon removal strategies, Carbon Accounting Rules, Whole-life carbon buildings

1. Introduction

The operational energy demand of buildings has decreased steadily as more stringent regulation gradually came into effect. For example, 'nearly zero-energy' buildings are required in the European Union since 2021. Climate change urgency put forward the Paris Agreement, which requires that the anthropogenic greenhouse gas (GHG) emissions released into the atmosphere are balanced by their removal from it by GHG sinks by 2050. Fulfilling such goal thus relies on 'climate-neutral' buildings, for which the emissions generated throughout their lifecycle are (absolute) zero or (balanced or offset) net-zero. Yet, currently reaching absolute zero GHG emissions from operations (including the supply chain) alone, and offsetting emissions embodied in the building itself, in water supply and in wastewater treatment are goals hard to accomplish today. Hence, in the short- and medium-terms, "net zero" emission is a pragmatic goal, for which offsets play a key role (LÜTZKENDORF; BALOUKTSI, 2023).

If only direct GHG emissions (Scope 1) are considered, buildings with absolute zero operational emissions (i.e. completely decarbonised) can be produced in many climates and typologies, without needing offsets (LÜTZKENDORF; BALOUKTSI, 2023), by combining high energy efficiency and exclusive use of distributed generation (onsite) of renewable energy sources. Even so, GHG are still emitted in the upstream and downstream supply chains

(LÜTZKENDORF; FRISCHKNECHT, 2020). Another background pressure refers to the massive demand boost for minerals and metals (in developed countries) and mining (in developing ones) to support the global transition towards a net-zero future, based on renewable energy generation and storage technologies needed to mitigate GHG emissions and deliver SDGs 7 and 13 (THE WORLD BANK, 2020).

A current shift in the net zero debate tends to allow offsetting of unavoidable residual emissions (Scope 3 plus Scope 1 emissions from refrigerant leaks) while the whole economy decarbonises. Offsets for Scope 1 and Scope 2 emissions from operational energy use would be excluded though (LETI & CIBSE, 2022). This way, building design and construction should minimize GHG emissions before seeking to offset residual emissions and balance them down to net zero (LÜTZKENDORF; BALOUKTSI, 2023) or to use technologies that sequester CO_2 and aspire for carbon negative construction. In fact negative emission technologies (NET) are required by all scenarios in the latest IPCC (2021) report.

Indeed, this concept applies to any building project, climate and market. However, for many parts of the world a net zero lifecycle carbon perspective seems very distant. Poorer regions started further behind in the net zero race and find it harder to catch up than others. Narrow net zero visions are sometimes translated into standards that promote 'superefficient HVAC' solutions, while what is needed is buildings that run for as much of the year as possible on local natural energy (solar in winter and natural ventilation in most seasons). High energy efficiency, based on active equipment, comes at a high cost, not affordable to everyone, everywhere.

Benefiting from a greener-than-global-average electricity mix, like in Brazil (where electricity is about 16% carbon intensive), indeed facilitates to decarbonise building operation. Gomes et al (2018) confirmed that for a demonstration building. Even so, neutralizing its life cycle emissions would only be accomplished if the whole building plus a considerable surface next to it were wrapped in PV arrays. But such conduct is currently unlikely for regular buildings and off the table for social housing due to cost restrictions. Gomes and Pulgrossi (2021) estimated that removal of each hour of heat-related discomfort in units in three regions and climates in Brazil would require between 10 and 13kg CO_{2eq} and that the active solution (fans) responded by 1,5 to 3 times the sum of annualised embodied emissions of all passive measures considered. With little or no fat to shred, even simple passive improvements are unaffordable, and emissions offset or carbon removal are unthinkable in situations of daily energy poverty. A net neutral whole-life carbon goal seems unrealistic.

This paper examines the literature on trends regarding emissions offset or removal, and discusses how calculation rules and local or building segment limitations influence their applicability and might rerank contribution/climate potential of technological options.

2. Method

Given the above-mentioned challenge, we look at CO_2 removal strategies that store carbon in the built environment, compensating for the residual emissions – which will be adamant to allow reaching a net zero status. An exploratory literature review to identify the most promising/feasible options is followed by a discussion on how different (i) carbon accounting rules applied to identified options interfere with the interpretation of their Global Warming Potential (GWP) and environmental attractiveness and (ii) geographic/climate/construction contexts could limit applicability and challenge the net zero target achievement.

3. What seems promising to reach net zero carbon goals?

Most approaches for storing and/or sequestering carbon within the built environment do so during building use, but mineralization/carbonation also uptake carbon during EOL (KUITTINEN et al., 2023). But the low hanging fruit approaches – biobased building materials and biochar in soils - uptake carbon offsite before building use (and during, if biochar is applied) and stored it on site, during use. Climate potential of options for capturing and storing carbon onsite is lower, despite high applicability of carbonation in concrete and of natural photosynthesis/carbon uptake into soils in urban landscaping. Onsite carbon capture and offsite storage options rely on emerging (e.g. HVAC systems with direct air capture (DAC), artificial or enhanced photosynthesis and on marginal (e.g. living structures, building skins) technological solutions, with low or too variable maturity level, and still strongly restricted by their costs and maintenance requirements.

Kuittinen et al. (2023) ranked the approaches according to their climate potential and current applicability to construction. Three families of solutions stood out: biobased construction (wood, bamboo and straw, plus biochar for landscaping) and composites; carbonation of concrete/cement-based items; and urban landscaping (natural photosynthesis; accumulation in soils). CO_2-cured concrete, and air conditioning with DAC *in offices* would complete the medium to high combinations in both axes.

In their systematic literature review, Maierhofer et al. (2023) found that only materials assigned to the Eurostat categories 'biomass' or 'non-metallic minerals' had CO_2 storage potential and, based on their findings, proposed a new categorization: 'biomass - fast growing', 'biomass - slow growing', 'non-metallic mineral - natural' and 'non-metallic mineral - industrial'. The first category consisted of straw, hemp and bamboo but also miscanthus, sheep wool, herbaceous plants, moso bamboo, palm leaves and seaweed. The second category, 'biomass - slow growing', contained materials like wood or timber but also cellulose fibre, cork, cardboard and construction paper. The category 'non-metallic minerals - industrial' included the large group of industrial alkali wastes such as blast furnace slags, coal fly ashes and municipal solid waste incineration ash, among others, while the category 'non-metallic mineral - natural' included magnesium silicate-based rocks like serpentine and olivine, and also akermanite, pyroxene, tremolite, enstatite, wollastonite, nesquehonite and others (MAIERHOFER et al. 2023). Materials in the categories 'biomass - fast growing' and 'biomass - slow growing' have the highest CO_2 storage potential according to the literature (MAIERHOFER et al. 2023).

4. Unpacking most promising strategies

Considering both potential for applicability in buildings (associated to technology readiness level and material availability) and potential for CO_2 storage, the literature points to two major classes of promising strategies to help to compensate for life cycle embodied CO_2 emissions in buildings, namely: biobased materials use and mineral carbonation. The following subsections further introduce these classes, while the next section discusses how their performance towards a net zero whole life carbon target is challenged by rules and context.

4.1 Biobased materials

Biobased materials absorb atmospheric CO_2 as they grow, through photosynthesis. Their potential to temporarily store CO_2 removed from the atmosphere coupled with their renewable nature has significantly increased their attractiveness as a building material. The CO_2 absorbed by these materials during growth is assumed to be enough to not only compensate the emissions associated with their own production and distribution, but also emissions associated with other materials and activities that take place within a building's life cycle.

While timber is the most used biobased material in the built environment, "fast-growing biobased materials" are mostly employed for their thermal properties as insulation and stands out for their carbon storage potential (MAIERHOFER et al., 2023). Typically covering herbaceous plants like straw and hemp, these materials do not require long rotation periods. In other words, the period between establishment of the crop and final harvest or regeneration is many times shorter than for timber. When one takes into account that buildings last for decades and fast growing biobased material crops can be replenished in much less than a decade (in some cases less than a year), their storage potential becomes more significant than that of forest products (PITTAU et al. 2018). Another well-known biobased material that falls within the fast-growing category but is not used for thermal properties is bamboo. Despite its rapid growth and lightweight features, bamboo exhibits a high strength-to-weight ratio and is able to withstand significant structural loads (SHU et al. 2020).

4.2 Mineral carbonation

Construction products containing cement and/or lime, such as concrete, mortar and bricks, have the potential to absorb CO_2 when their surfaces are exposed to the air and the contained calcium oxide (CaO) and calcium hydroxide ($Ca(OH)_2$) react with the CO_2 in the atmosphere. This natural process is known as carbonation. In this case, the carbon sequestered qualifies as a permanent storage as it will stay in the form of calcium carbonate within mineral products until they are heated to high temperatures by humans or an unlikely geological process.

Carbonation rates depend on the duration of exposure, concrete designation and the exposure conditions including any concrete surface treatments. Therefore, carbonation only affects untreated/uncoated exposed concrete elements. Moreover, there is a maximum CO_2 that can be absorbed by any given quantity of cementitious material under certain circumstances, and once reached, no further carbonation occurs.

According to studies, natural carbonation of cement products during the use stage typically plays a minor role, i.e. about 1-5% of the GHG emissions of a massive concrete building (RESCH et al., 2021; ALIG et al., 2020) and hence may be ignored. Carbonation effects in bricks are less studied, but Sambataro et al. (2023) recently found that the carbonation of calcium silicate bricks can offset 5% of building GHG emissions, for maximum carbonation potential and disregarding e.g. the presence of a render layer that would most likely reduce carbonation values.

In this context, CO_2 mineralization via curing in cementitious and lime-based products during manufacturing, and natural carbonation at the end of life have gained attention, as more promising potential carbon removal solutions associated with mineral products.

The carbonation rate of construction and demolition aggregates is faster than during service life, since the exposed surface drastically increases after demolition. As such, CO_2 uptake after demolition can be up to 50% higher in comparison with the concrete structures in service (MAIA PEDERNEIRAS et al., 2022). Saade et al. (2022) found that, on a macro-scale, if 80% of used concrete is assumed to be crushed into smaller particles and 20% to be landfilled, the cumulative proportion of carbon uptake in 2050 amount to over 9% of the cumulative global warming effect of concrete manufacturing. This places the carbonation of crushed concrete among the most promising mitigation strategies in some contexts.

In addition to influencing factors such as particle size, cement content and relative humidity (e.g. thinner recycled aggregates carbonate faster than the others), the time that the recycled aggregate has been stockpiling before being used as a ground filling material significantly affects the carbonation rate (PICCARDO; GUSTAVSSON, 2021); the more time crushed concrete is in contact with the air, the more fully carbonated the particle will be. For example, a study from the Institution of Structural Engineers (GIBBONS; ORR, 2022) suggests that up to 5% of A1-3 concrete carbon emissions can be re-absorbed at EoL (module C3) but based on the assumption that concrete crushed on site at EoL sits on site for 26 weeks before being removed. The calculation of carbon removal potential of this EoL scenario would necessitate specifying the time of carbonation to be assumed, which is what defines the level of overall importance of this effect. In the absence of national scenarios, the Swedish Environmental Research Institute (IVL) proposes fixed CO_2 uptake values of 10kgCO_2/m3 of concrete, or 20kg CO_2/m3 with improved end-of-life handling procedures (CAPON; de SAULLES, 2023).

Table 1 shows examples of commercialised cement and concrete construction products that use CO_2 in their production. Such accelerated carbonation process can have great potential not only to reduce impacts of concrete but to generate carbon negative footprints for precast elements (the effect of CO_2 curing on reinforced concrete and potential risk of steel reinforcement corrosion needs further examination). For example, this can be the case when the use of alternative binders, like steelmaking slags, which typically already leads to low carbon concrete, is combined with curing with waste CO_2, given that the transport distances also are reasonable. In the Finnish context, Mäkikouri et al. (2021) compared the A1-3 impacts of conventional concrete (243 kg CO_{2e}/m^3) to that of CO_2-cured blast furnace slag concrete using purified CO_2 or flue gas CO_2, and the carbon footprint was negative in both cases (-157 and -187 kg CO_{2e}/m^3, respectively). However, not all CO_2 utilization methods adopted in concrete production to date necessarily result in climate benefits (Ravikumar et al., 2021). Comprehensive LCAs are required that include the CO_2 impact of capturing, transporting and utilizing CO_2 to determine the benefits.

Table 1: Examples of commercialised cement and concrete construction products use CO_2 in their production, representative of (a) concrete production via CO_2 curing of cement-based materials (CarbonCure, Solidia Technologies and CO_2-SUICOM), and (b) production of blocks from industrial wastes such as steel slag (CarbiCrete and Carbstone). Information taken from Li and Unluer, 2022, and Hanifa et al., 2023. Note: "CO_2 uptake" indicates the absorbed CO_2 during the curing and not the overall reduction potential of these products due to improved mixes compared to typical concrete products.

	Technology	CO_2 absorption method	Country	TRL	Commercialization/ application phase	CO_2 uptake	Final product
CO_2 curing	Carbon Cure	Injection of CO_2 in the concrete mix	Canada	8–9	installed in over 300 concrete plants worldwide with most ready-mix concrete producers using this technology located in Alberta	100–200 kg CO_2/ton of aggregate	Concrete
	Solidia	CO_2 curing cement concrete	Canada	8	The first precaster using Solidia cement and concrete solutions was manufactured in the USA. Compliance with durability and other requirements in the USA and EU under investigation	250–300 kg CO_2/ton of cement.	Cement and concrete
	CO_2-SUICOM	γ-C2S and fly ash to reduce cement, and CO_2 curation	Japan	9	already been applied to building elements in Nakano Central Park Residence (i.e. balconies)	109 kg/m^3	Concrete
Carbonated coproducts	Carbstone	Carbonation of steel slag (CO2 from flue gas)	Belgium	9	test plant in Wallonia that produces building blocks	180–200 g CO_2/kg of steel slag	Carbonated blocks, roofing tiles
	Carbicrete	Carbonation of steel slag to replace cement (cement free concrete)	Canada	6-7	it partnered with Patio Drummond in 2021 to scale up production, and blocks are currently being produced in Quebec	1kgCO_2/ block (18 kg cinder block)	Carbonated blocks

5. What about calculation and impact assignment rules?

The potential solutions to offset residual CO_2 emissions are many-fold, and the range of compensation possibilities, technological readiness and cost deeply affect their applicability. But the complexity of addressing carbon offset solutions does not stop there. The balance of generated and avoided or removed Scope 1, 2 and 3 emissions is ideally determined through Life Cycle Assessments (LCA). As a comprehensive methodology to estimate potential environmental impacts of a product, process or service throughout its entire life cycle, LCAs provide valuable insight into carbon hotspots which not only supports reduction of environmental impact but also helps point out the most effective CO_2 compensation efforts that lead to minimal trade-off.

Conceptually, a negative environmental impact score may sound counterintuitive at first, and possibly caused the many calculation rules and approaches within the LCA method to address carbon dioxide removal (CDR) proposed to address it. While in the built environment their use has been mostly explored for biobased materials such as timber, the quest for offsetting options has turned the scientific community's gaze towards other carbon uptake possibilities, such as the ones explored in the previous sub-section. As the number of options for carbon removal grows, a similar effect is observed in the methodological framework, widening the calculation spectrum.

The European standard EN 15804 determines the rules for life cycle-based Environmental Product declarations (EPD) of construction products. It attempts to regulate the carbon balance of some of the mentioned offset solutions, following the "modularity principle" to assign emissions (and uptake) to the life cycle stage in which they occur. Still, such assignment is challenging for certain solutions, as is the interpretation as to which product's life cycle could receive the uptake benefit, especially when recycling, reuse and waste management activities are inherently part of the solution. The EN 15804 standard also introduces specific rules for the accounting of CO_2 uptake by timber and other forest-related products that have been recently revised. As the research direction shifts, further revisions may be expected, so an international consensus will most likely not be reached anytime soon.

5.1 Biobased materials

Until recently, in traditional LCA, the timing of GHG emissions was unaccounted for, which rendered the benefits of temporary storage and the differences between varying storage periods meaningless. The cycle of biogenic CO_2 - i.e. the CO_2 absorbed by biobased materials during growth - is typically considered to be neutral, as the CO_2 absorbed is expected to be released when these materials reach their end of life, either through incineration or decomposition. This approach (known as the 0/0 approach) receives criticism for neglecting the impact of rotation periods on global warming assessments and overlooking potential storage-related benefits (HOXHA et al., 2021), and for assuming carbon neutrality, as biogenic carbon emissions are expected to occur from decomposing roots, reduced soil carbon content, and a loss in carbon storage potential resulting from non-harvesting practices (PENG et al., 2023).

The so-called -1/+1 approach is another biogenic carbon accounting approach that has gained traction in built environment LCAs. While the initial principle of carbon neutrality remains, the calculations allow consideration of the biogenic CO_2 that was absorbed during growth of the biobased material, which - according to the EN 15978 standard on buildings LCA - shall be equal to the amount of biogenic CO_2 released during the end of life of the material, regardless of the scenario considered (landfilling, incineration, recycling, etc.). The main difference between the -1/+1 and the 0/0 approach is that the former provides an overview of the biogenic carbon flows which are completely disregarded in the latter (Hoxha et al 2021). Still, the previously mentioned critique remains.

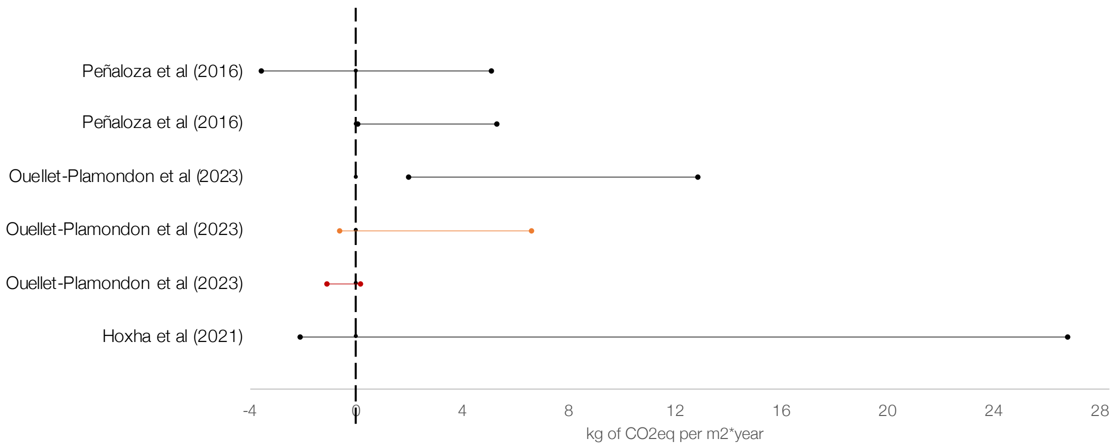
Some approaches that claim to better capture the impact of time in biogenic carbon accounting have been proposed in the specialised literature. These approaches focus mostly on proposing adjustments in the determination of global warming potential, which, very simply put, relies on "characterisation factors" that consider the different greenhouse gases' ability to increase heat in the atmosphere. Levasseur et al. (2010) introduced a time-dependent characterisation factor approach, which is based on the decay of each GHG in the atmosphere, while Cherubini et al. (2011) developed specific characterisation factors for biogenic CO_2, considering biomass rotation periods. A longer rotation period leads to a higher biogenic global warming score due to the increased duration of CO_2 in the atmosphere. Building upon Cherubini et al.'s work, Guest et al. (2013) extended the method to evaluate carbon storage in wooden products, finding that carbon neutrality is achieved when storage lasts approximately half of the rotation period.

The first mentioned approach (by Levasseur et al, 2010) has been employed assuming two different scenarios to account for uptake: (1) trees growing before the use of harvested wood products, following the natural carbon cycle; or (2) accounting for "regrowth" after harvesting, assuming the same amount of harvested trees would start growing immediately after production (PEÑALOZA et al., 2016; PITTAU et al., 2018). The regrowth approach has been favoured because, from the carbon storage perspective, if using the first scenario, the biobased material would "receive" the full benefit of CO_2 uptake even if the product is short-lived. From a sustainability perspective, preferring consideration of biogenic carbon uptake after construction would encourage future forest regrowth (Hoxha et al 2021).

The different biogenic carbon accounting approaches lead to varying outcomes, not uncommonly leading to diametrically opposed conclusions. Hoxha et al (2021) assessed a timber building in Austria using the static approaches 0/0 and -1/+1, and the dynamic approach proposed by Levasseur et al. (2010) considering the biogenic CO_2 uptake by timber *before* and *after* harvest. While the result indicated that with both static approaches the overall life cycle GWP of the building was the same, when employing the dynamic approach results varied significantly. Most interestingly, when comparing the life cycle global warming scores of that same building considering the uptake before and after harvest, the result at the end of the service life of the building changed from a negative GWP, in the former case, to a positive GWP in the latter case. The same building could therefore be perceived as a net negative whole life carbon design, which would even act as a potential offset for emissions arising elsewhere, or as a net positive design, which would require compensation to meet carbon neutrality.

Ouellet-Plamondon et al. (2023) showed the results of LCAs of the same multi-residential building carried out by experts from sixteen countries, using biogenic carbon accounting methods typically employed in their practice. One specific biogenic carbon calculation approach stood out, the so-called "-1/+1*", a variant of the -1/+1 approach which assumes permanent storage of a portion of the absorbed CO_2 if a biobased material is recycled or landfilled. The authors showed the results at the material level (a softwood beam), at the element level (the building's superstructure), and at the whole building level. At the material and element levels, the whole life carbon when employing the -1/+1* approach could reach a net negative value, which was not the case with the 0/0 and -1/+1 approaches, for which either a neutral or a net positive whole life carbon score would be obtained. Again, decision making processes relying on such results would vary considerably.

Peñaloza et al. (2016) compared the global warming potential of a hypothetical building block in Stockholm with three design variations: (i) a concrete structure, (ii) a cross-laminated timber (CLT) structure and (iii) a design referred to as "increased bio", where mineral-based insulation and cladding from the CLT design were replaced with bio-based products, namely cellulose fibre and oriented strand boards. When employing the static 0/0 approach to model the building's GWP, the two biobased designs reduced over 40% of the GWP relatively to that of the concrete building. When employing the dynamic approach considering uptake *after harvest*, the GWP reduction increased to 68% for the CLT building and 88% for the increased bio building. Finally, the dynamic approach with uptake *before harvest* resulted in a net negative GWP score for the "increased bio" design, positioning it as a potential carbon offset solution (Figure 1).



** GWP results for building and element level are shown per m2*year, while the result on the material level is given per kg of material - in this case, softwood.*

Figure 1: Oscillation of GWP of buildings (black lines), material (red line) and element (orange line) around the net zero target, depending on the approach used for biogenic carbon accounting.

The observed variation indicates that the quest towards carbon neutrality is hindered by a lack of harmonised rules, which is an additional layer of complexity to an already incredibly challenging undertaking.

5.2 Mineral carbonation

The most used model to determine the CO_2 uptake of concrete due to carbonation, especially by European manufacturers and industry, is the standardised model provided in EN 16757. The natural carbonation process occurs over the life of the concrete or brick products and is therefore accounted for in the use module B1 in the various EPDs. When it comes to EoL uptake the rules on when and how to consider it are loose. The benefit can be considered as part of waste processing (C3), otherwise it goes onto the next life cycle and is reported in module D – hence, no compensation is considered for the concrete's first user. In the case of bricks, the specific standardised rules that determine how to develop an EPD for that material class do not specify carbonation rules as clearly as the EN 16757. However, a few brick EPDs list negative CO_2 values due to carbonation in B1 (e.g. SwissModul from p + f Sursee, 2018) and C3 (e.g. the sector EPD of the Federal Association of the German Brick Industry, IBU 2021).

Similar to biogenic carbon accounting for wood, carbonation is a time-dependent process and, as such, can be taken into account in a dynamic way (e.g. PITTAU et al., 2018; SAADE et al., 2022). The time dynamic is that carbonation occurs fast at first and then at a slower rate as more depth is carbonised. After deconstruction, the material is crushed and the exposed surface increases which leads to another rapid rise in carbonation rate and a subsequent levelling off. A simplified approach (different than the previously mentioned studies) is followed by the Norwegian FutureBuilt Zero method (RESCH et al., 2022) which starts from the following assumptions: an uptake of 94 kg CO_2 per tonne of cement after a service life of 100 years, that most storage is considered to happen in the first years, and the absorptions decrease exponentially over the years. According to these assumptions, after 25 years, approximately half of the uptake that takes place over a 100-year period will have taken place. Following a square root function, the uptake that takes place in the years that are part of the building's lifetime is attributed to the building. This approach is characterised as simplified as it does not consider the different concrete strength classes and exposure levels to air.

In the case of CO_2-cured concrete the carbon removal from the atmosphere or when separated from biogas must be recorded as a negative value in A1-3 for the indicators GWPfossil (and consequently GWPtotal) according to the EN 15804+A2. The CO_2 absorbed during the curing process is not released at the end of the concrete component's life, which leads to a -1/0 allocation, if one refers to the same nomenclature for biogenic carbon accounting as previously described. As the use of such products is at an early stage, the availability of life cycle data is sparse. Therefore, clear guidelines for robust life-cycle analyses and transparent datasets are needed to inform net zero target. Furthermore, when carbon uptake of CO_2-cured concrete is sold as carbon offset to third parties, such carbon savings should not be reported as part of the building's whole life carbon to avoid double counting, for having already been collected by a third party that purchased it as an offset.

6. And what about context?

Using biobased materials like wood, bamboo and straw does not always suit all building typologies, and their durability is particularly challenged by a high temperature-high humidity combination. In such conditions, components require pre-treatment, which has a high-impact from production to end of life. Earth construction does not suit all typologies either, but has benefits and the indisputable advantage of being low-cost and can be an adequate temperature and humidity regulator for certain climates, which would otherwise demand energy to ensure habitability. Advanced use of biochar also seems promising anywhere, but has just begun. Performance of natural materials is more difficult to predict and control, and the lack of codes of practice/standards creates uncertainty and perceived risk, which can make financing harder. Such issues should be addressed urgently, to enable these elements and techniques to also play a part in the final carbon equation.

The ubiquitous use of concrete makes carbonation strategies also not limited by geography, but land-consuming swift carbonation (to allow for spreading out the crushed concrete for) without backfiring in transportation emissions might be impractical in certain situations. Contrastingly, carbonation cure has been used in countries like Canada, the United States, the United Kingdom and Japan, with increased interest across Europe. Adding this process to existing block plants is feasible at relatively low additional cost: 4-14%, for a study in Brazil (FORTUNATO et al., 2022). Those authors estimated that approximately 168,780 ton of CO_2/year would be sequestered if all Brazilian concrete block plants implemented it (smallest absorption rate considered). That CO_2 mass corresponds to roughly 10% of the emissions of the national concrete block industry.

Biochar use in soils, carbonation of cement-based materials and natural photosynthesis contribution depend on surface area, which can be limited in dense urban areas. Also, the omnipresence of cement/reinforced concrete based construction elements and techniques, which require low cost and low skilled labour, are deeply rooted in many constructive cultures, despite their impact, maintenance and waste intensities, and make it more difficult for other approaches to advance. Hence, though theoretically applicable anywhere, local limitations might rerank contribution/climate potential of technological options. It was not possible to cast an in-depth analysis in this direction herein.

Good old design plays a cheaper role and best practices should be enforced in contexts where financial resources are limited. In disadvantaged cases, reducing embodied carbon of current techniques (e.g. through enhanced earth construction or others) and smart use of passive measures to minimize operational emissions can be more reasonable to reach overall carbon neutralization than aim for financially unfeasible net zero and NET techs to all. Some embodied carbon must even be needed - "invested" in passive measures - and still make more sense towards collective goals.

7. Final remarks

As we approach the 2050 deadline to become a carbon neutral society, many unanswered questions remain. A careful portfolio of measures will have to be delineated, but ultimately cherry-picked on a case-specific basis. There is no one-size-fits-all solution, which adds challenges and complexity, but supports creativity. Compensation measures like negative emissions technologies (NET) or carbon dioxide removal (CRD) shall become increasingly sought for.

This paper does not perform an exhaustive assessment of strategies but rather focuses on how certain methods can affect estimations of the most common/promising ones and how context can even cause some rank reversal. From a methodological perspective, if we are to meet the ambitious targets, not only is harmonization key – to provide a common benchmark or benchmarking procedure, but scientific robustness must be assured.

To support global efforts in making life-cycle carbon-neutral buildings, data, and context-based benchmarks are also needed, but are still scarce and far from driving or influencing mainstream practice. Moreover, from a context perspective, regional specificities must be further studied to allow for a tailored roadmap. Recent research, regulatory frameworks and financial incentives to boost net zero initiatives are predominantly related to the global North, but, if we are to reach our Global Future, political, financial and technological partnerships and resources must be urgently directed to all nations to play their part in the collective decarbonization.

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An investigation of the operational energy and carbon savings from practicing adaptive thermal comfort theory

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Abstract

Thermally comfortable and energy-efficient buildings will play a pivotal role in radically reducing operational energy use and carbon emissions from the built environment. The emphasis in emission reduction strategies is now moving away from reliance on the marginal energy benefits of slightly more energy efficient machines for meeting emission reduction targets towards the provision of energy-sufficient buildings that not only protect occupants from the predicted more extreme climates of the future while also resulting in radical emission reductions. Buildings are responsible to nearly 40% of global Greenhouse Gas (GHG) emissions and despite huge investment in the sector over recent decades GHG emissions continue to rise alarmingly.

In the tropical countries of the global south, the recent trend has been towards designing primarily cooling-dominated workspaces in offices. This paper presents an investigation into the importance of, and potential extent of emissions savings that can result from utilizing favourable outdoor conditions in building operations in India. It then analyses the operational energy and carbon saving potentials resulting from moving HVAC operation away from using narrow set-point temperatures to those derived from the adaptive thermal comfort theory.

The study used integrated modelling approaches involving building performance analysis tools to characterize the performance of an office building located in an urban hot and dry climate. The study provides a comparative analysis of several scenarios interrogated to optimise the provision of low carbon, indoor thermal comfort for occupants. An initial deep dive into the climate analysis was followed by calculating the uncomfortable hours, operational energy consumption and resulting carbon emissions based on the ASHRAE 55 PMV model, ASHRAE 55 adaptive model, India Model for Adaptive Comfort (IMAC) AC model, IMAC Mixed mode operation model, IMAC Natural Ventilation Operational Mode. The study also investigated the impact of elevated air speeds on achieving thermal comfort and demonstrated the savings. The building's Annual Energy Consumption was reduced by between 11% to 66% compared to the reference model specified as per India's Energy Conservation Building Code 2017 for fully air-conditioned buildings. The results indicate an 18% to 29% reduction in Operational Carbon Emissions can be achieved in this way substantially helping the move towards meeting the Net Zero Emissions ambitions.

Keywords: Carbon Emissions, Adaptive Comfort, Dynamic Setpoints, Natural ventilation, Ceiling Fans, Mixed Mode.

1. Introduction

Currently, building operations are a substantial contributor to global primary energy consumption, constituting around 40 % of use, a figure that is projected to rise to 50% by 2050. The building and construction sector plays a significant role in energy consumption (36%) and Energy-related CO_2 emissions (39%). This proportion is poised to amplify given the relentless trajectory of rapid economic growth, burgeoning population, and urban expansion. As these factors converge, the energy demand maintains an upward trajectory. [1,2]

Given that the buildings serve as the primary habitat where people spend 90% of their daily time and HVAC accounts for 38% or more of the Total Building Energy Consumption in some buildings [3], it becomes imperative to adopt comprehensive strategies to improve building energy efficiency and curb CO_2 Emissions. Several studies have projected that reducing cooling demand and peak cooling power are two important strategies for reducing building cooling, ventilation demand and carbon emissions. Considering the escalating demand for building cooling, low-energy strategies as alternatives to active cooling, such as night cooling and mixed cooling strategies (Natural ventilation through operable windows, fan-assisted ventilation, and natural ventilation in conjunction with mechanical systems) to provide the required cooling to the occupied space has the potential for lowering the peak demand and overall HVAC energy consumption significantly.

Mixed mode refers to the hybrid approach for space cooling, employing free cooling by natural ventilation, where the flow is driven by wind or sometimes assisted by a fan, demonstrating the potential to minimise building energy consumption and maintain occupant thermal comfort. When the outdoor conditions such as temperature, wind speed and humidity are favourable, mixed-mode cooling relies on predetermined schedules and cooling set points to utilise natural ventilation.

Numerous studies have indicated that implementing Schedules and night setback controls demonstrates a discernible reduction in the need for mechanical cooling to precool the space, lowering peak cooling demands and significantly reducing the overall HVAC operational energy.

Additionally, there also has been a discussion about the effectiveness of ceiling fans. Ceiling fans play a multifaceted role in optimising the indoor environment as they facilitate the cooling effect by enhancing air movement, generating airspeeds ranging from 1.5 to 4.5 m/s. This cooling effect, due to the increased airspeed around the occupants, facilitates heat transfer mechanisms from their bodies through convection and evaporation.

The application of ceiling fans in conjunction with Natural ventilation is valuable, considering their ability to create increased airspeed and effectively cool the human body when employed at operative temperatures exceeding the upper acceptability band. Operative temperature is a measure of the combined effect of air temperature, mean radiant temperature (the average temperature of the surfaces in an environment), and airspeed on human thermal comfort. It represents the temperature that an individual perceives when all the heat exchange processes affecting their body are in balance. Thus, the strategic integration of ceiling fans within a mixed-mode approach improves the thermal satisfaction of the occupants and can lead to substantial Energy Savings.[16]

The objective of this study was to investigate the impact of different operational modes on the delivery of year-round comfort and quantify the energy-saving potential of the different modes. These include natural ventilation and mixed mode provision incorporating ceiling fans, also looking at optimising control sequences for window opening operation to harness favourable outdoor conditions for conditioning the building. An *Energy Plus* model was used to simulate the building and the HVAC energy consumption for each operational strategy evaluated in terms of thermal comfort and energy consumption. The study investigated the feasibility and workability of these operational strategies for cities across two Indian climatic conditions: Hot and Dry and Warm and Humid Climates. This paper reports on the impact and performance of three ventilation operational strategies under various climatic conditions to provide insight into the energy and emissions reductions possible from applying them in modelled buildings.

2. Methodology

The simulations of the medium-sized office is used in this study as a baseline building complied with a commercial Energy Conservation Building Code -2017 (ECBC) reference building. This model was then used to study the impacts of the ventilation operational strategies on Window operation, Energy Use, Cooling Loads and Thermal Environment.

The office building is a two-storey building structure with a built up of 1287m2 and houses 100 employees. The Conditioned area of the building is 1200m^2 with 25 thermal zones and WWR (Window to Wall Ratio) of 40%. A Variable Refrigerant System (VRF) provided a conditioned environment for each Thermal Zone.

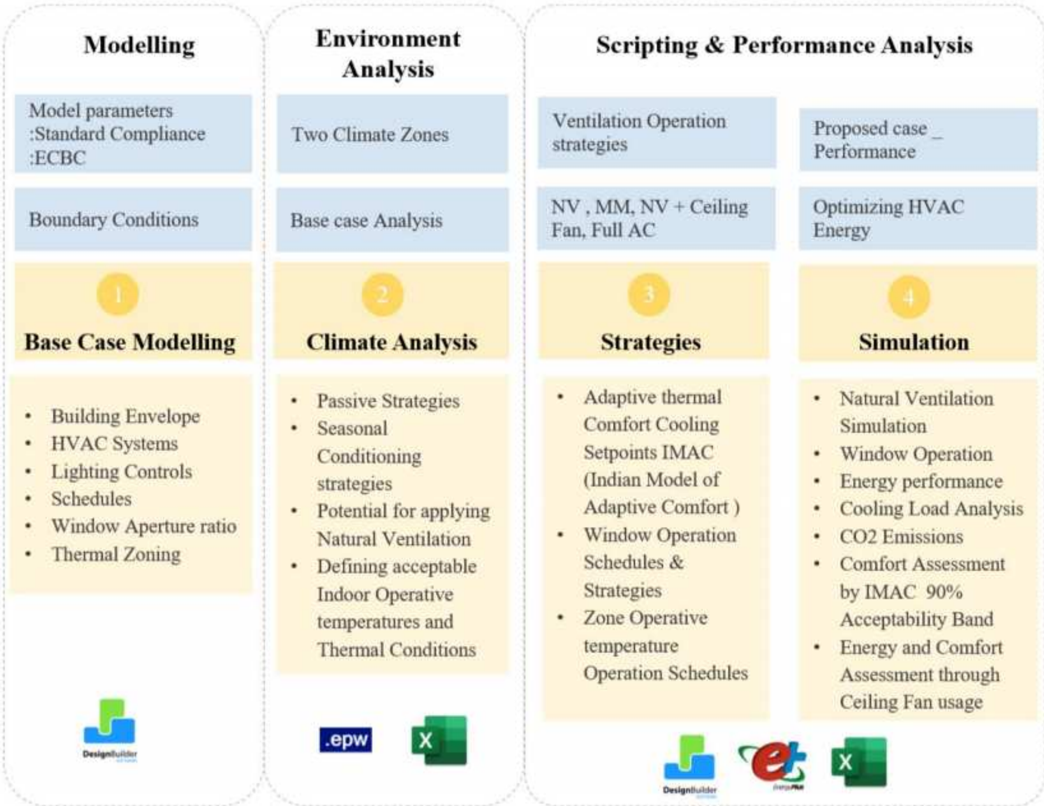


Figure 1: Workflow Diagram of the Methodology

The climatic conditions and building elements influence the effectiveness of building energy performance and energy saving. Hence, we needed to analyse the impact and the annual characteristics of the environmental constituents like temperature, humidity, solar radiation, wind speed and wind direction and their corresponding impact on the building energy consumption. The impact of the microclimatic conditions created by contextual building and its landscape also needed to be considered while evaluating the performance of the building. The method used in this study for the analysis to express the building efficiency standards was the prescriptive values as elaborated in the 2017 ECBC. *Energy Plus* was used as a simulation engine to evaluate and study the various scenarios of window operation and fan operation and its impact on HVAC and Overall Building Energy Consumption.

Thermal Zones were divided depending on schedule, occupancy, operation, function, and orientation of the space and considering the narrow floor plate. The ground floor was modelled as two separate building blocks; the atrium in the centre was modelled separately, while the first floor was modelled as a single building block. Different types of floorings on both levels were modelled separately, and each one has been assigned a specific thermal property. Ducts and Shafts were modelled but excluded from the thermal calculations. The shading devices and context of the commercial building were modelled as component blocks with their own shading and reflective properties.

Thermal Zones:

For all the zones categorized, the load calculation for each type was taken into consideration, including its unique activity schedule, occupancy density, operation schedule, equipment's density, and lighting power density and 25 thermal zones of the ground floor and first floor were broadly divided into the perimeter and core zone areas as the design of the plan is a narrow-shaped.

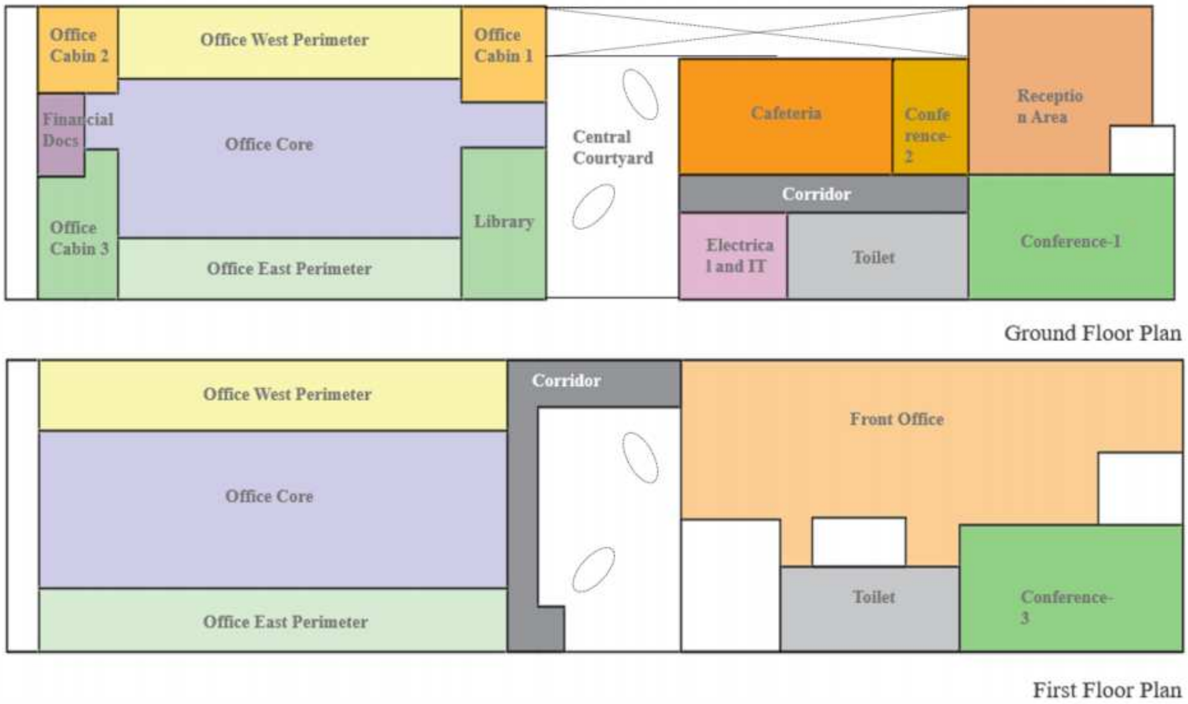


Figure 2: Ground Floor and First Floor Thermal Zoning Plan

Simulation Scenarios:

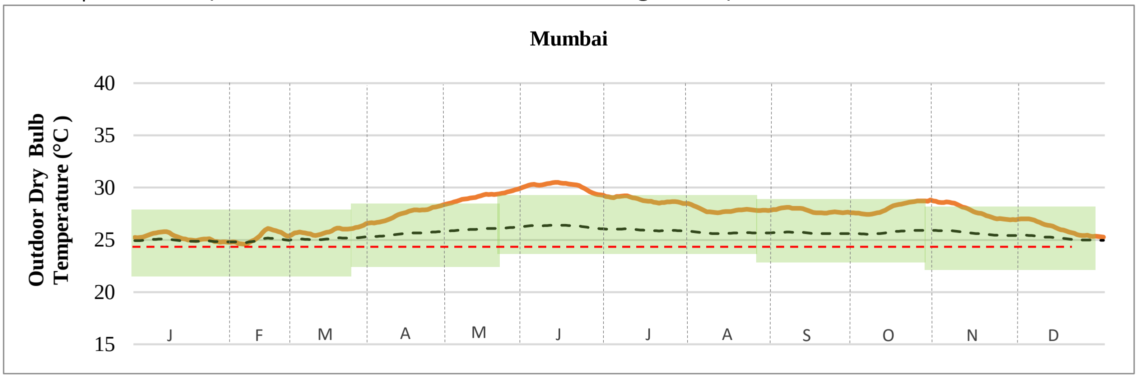
For each climate zone, four simulation scenarios with different strategies for HVAC system Operations were developed for this commercial building:

- Natural ventilation with windows open
- Ceiling fan-assisted natural ventilation.
- Mixed Mode
- Fully air-conditioned Mode

Thus, for each scenario, The HVAC equipment and system sizing were fixed according to ECBC protocols in order to exclude the variations caused due to the use of differently performing HVAC systems and their corresponding impact on occupant comfort experiences. The Thermal Zone layout and the building envelope specifications were kept same for all the scenarios. The cooling set-point baseline was set at 24°C as per ASHRAE-55 for a fixed set-point. Indoor temperatures for mixed mode operation were calculated for both the hot and dry and warm and humid climate zones, and the 90 percent Acceptability band was calculated based on the Running mean of daily average outdoor dry bulb temperatures for both climate zones, as follows:

T_{op} = 17.87° C + 0.28*T_d (Running Mean)

$T_{90\%}$ = T_{op} +3.46°C (reference: NBC- National Building Code)



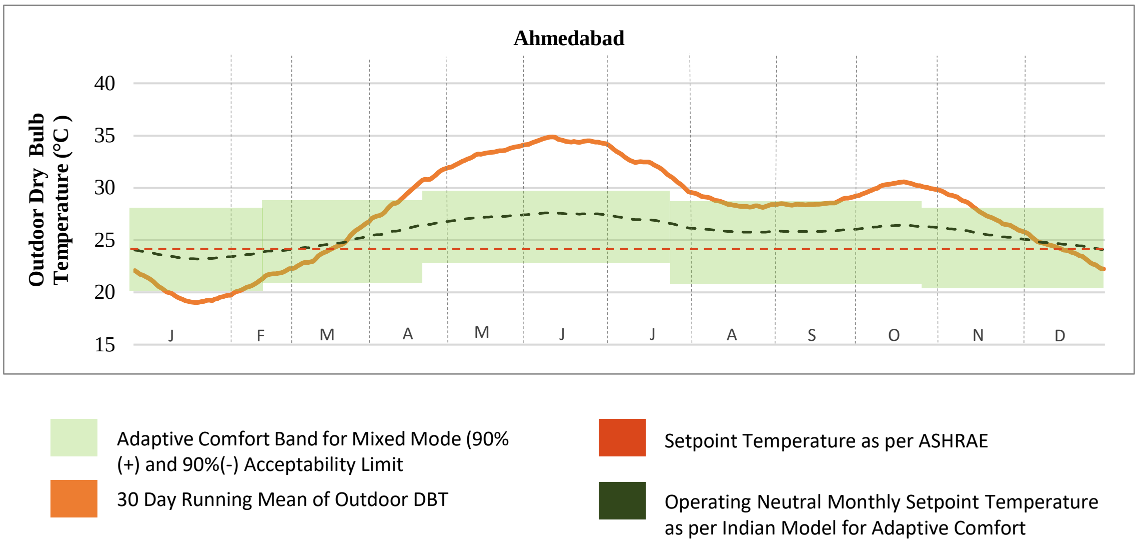
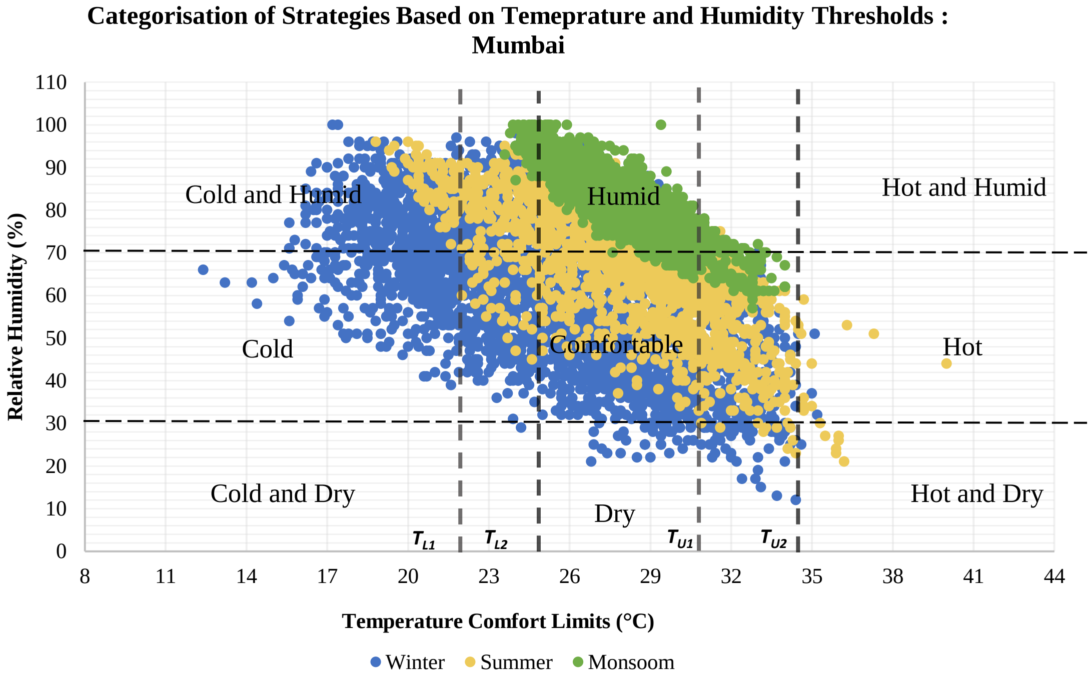


Figure 3: Graph representing Outdoor Dry Bulb Temperature, Adaptive Comfort band (90 % Acceptability Limit) as per IMAC (Indian Model for Adaptive Comfort) and Dynamic Cooling Operative Setpoint as Per IMAC

Both of these figures show the 30-day monthly running mean segregated, the green band represents the adaptive band for 90% acceptability range as per the Indian Model for Adaptive Comfort (IMAC), the red dotted line represents the steady set temperature 24°C as per ASHRAE 55 and the black line represents the Mixed mode for the Operating set temperature as per IMAC.

Climate Analysis:

The first step was to analyse the climate in order to evaluate the potential for low-energy cooling and ventilation to identify the parameters influencing the performance of the mixed



mode control in commercial buildings. This analysis helped to determine and shape the simulation scenarios discussed below.

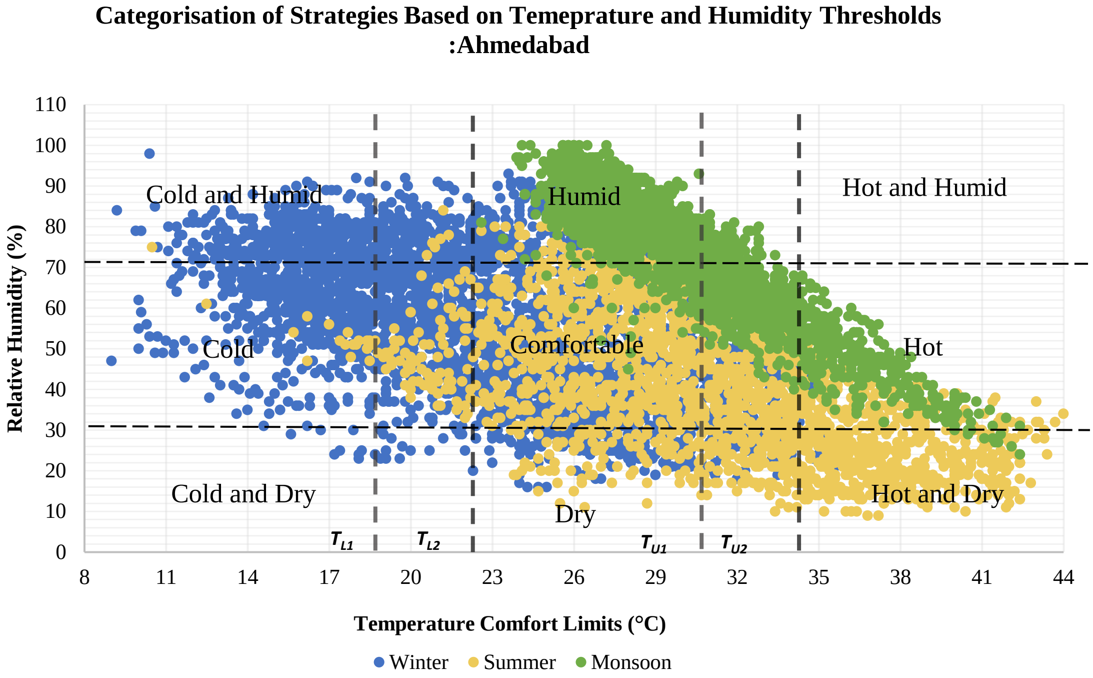


Figure 4 : Graph portraying the Comfort hours and passive strategies to Achieve those throughout the year (Reference: LecaVIR Design Guide)

These figures helped the team determine which passive strategies for maintaining thermal comfort might be suitable in both a hot and dry climate zone and a warm and humid climate zone. The graph plotting temperature against relative humidity (RH) is divided by seasons to indicate the applicable strategies for each climate and the reasons behind it. It clarifies the proportion of cooling and dehumidification needed in a city with a warm and humid climate zone, while in a city with a hot and dry climate zone, the required cooling percentage and the distribution of other strategies designed to ensure thermal comfort can also be determined.
For The warm and Humid Climate zone, which is represented by the city of Mumbai, 1.7% of the total operating hours' needed humidification, 45.4 % needed dehumidification, 8.51 % needed cooling and dehumidification, 7.58 % needed cooling and 32.52 % of the hours comfort could be provided with natural ventilation.
For the hot and dry climate, which was represented by Ahmedabad, 11.4% of total operating hours required heating and dehumidification, 5.7% required heating, 20.81% needed cooling, 17.12% of hours were comfortable with natural ventilation, 19.32% required humidification and 10.11% required cooling and humidification.
This analysis enables the team to understand the extent of the natural ventilation opportunities provided by passive strategies involving opening windows to provide low-carbon comfort. In the subsequent analyses and simulations, these derived monthly dynamic cooling setpoints were implemented in *Design Builder/Energy Plus*. The Climatic Analysis confirmed that natural ventilation could be useful in both these climate zones. Four scenarios with variations in ventilation operation strategies were then developed to inform the sizing of the HVAC equipment and systems, fixed according to the study's baseline specification to ensure comparability of results. Details of the Simulation Model used are summarised in Figure 5 and are explained in more detail in the result and conclusion sections.

Scenario 1: Natural ventilation with windows fully open
In this scenario, the model was set in free-running mode with no heating or cooling in use. The aperture ratio of the openings was set to 90%, and the window opening fraction and venting availability in Energy Plus were then set up as 1 throughout the annual simulation period. The natural ventilation cooling setpoints were set from the Indian Model for Adaptive Comfort (IMAC) based on the 30-day running mean of the outdoor air temperature set to the level of 90% acceptability for naturally conditioned Spaces. In this scenario, a temperature-based operational strategy was introduced to determine the window opening factor, which determined the percentage of that window that would be left open. The window opening factor was based on the direct relationship between indoor and outdoor temperature differences.

Window operations were based on the logic.

- $T_{\text{zone air}} > T_{\text{setpoint}}$ &
- $T_{\text{zone air}} > T_{\text{outside air}}$ & the Availability schedule value = 1

The above logic states that the windows will only open when the indoor temperature is higher than the zone setpoint temperatures, the indoor temperature is higher than outdoor dry bulb temperatures, and the availability for the windows to operate is on. The modulation of window opening is a strategy to control the degree to which the windows will open based on the temperature difference between indoor Zone Temperatures and Outdoor Dry Bulb Temperatures. Elaborating the inputs for Temperature Limits as:
Lower Limit for Maximum Opening Factor (2°C): When the temperature difference (Tin-Tout) is less than 2°C, windows will be fully closed. This prevents windows from opening when the indoor and outdoor temperatures are very close, reducing unnecessary ventilation loads.
Upper Limit for Minimum Opening Factor (15°C): When the temperature difference (Tin-Tout) exceeds 15°C, windows will be fully closed. This prevents windows from opening when there is an extreme temperature difference.
The purpose of modulating is to prevent discomfort due to hot air/cold air being introduced into the zone. The zone's operational temperature range for natural ventilation dynamically changes in response to outdoor dry bulb temperature, which is further explained in the conclusion section.
This approach leverages Natural ventilation through window control logic to regulate the window opening based on the previously outlined criteria and maintain comfortable indoor zone operative temperatures when the HVAC system is not yet providing conditioned air.

Scenario 2: Natural Ventilation with Windows Closed
In this scenario, the model was set to free running HVAC mode, in which all the HVAC operations were off, and the aperture Ratio was set to 90% and the venting availability was set to 1. The cooling natural ventilation set points followed the IMAC natural ventilation adaptive band applying the 90% acceptability limit for comfort. In this scenario, it was aimed to find number of comfortable hours with window operation. The hours that are not providing comfort hours are unmet hours. These unmet hours in the region of plus or minus one 1^0C could be made comfortable for occupants using ceiling fans, again enabling to the further reduction of the operating hours in which both the HVAC and the mechanical ventilation systems could be off.

Scenario 3: Natural Ventilation + Ceiling Fans
In both Climate zones, a primary passive mechanism to enhance indoor thermal comfort at higher temperatures is through the use of comfort ventilation. A limitation of this strategy's

success depends on their sufficient air velocity (m/s) to evaporate moisture from the skin to ensure thermal comfort. The higher the temperature, the higher the air speed needed. In this scenario, an extended analysis of scenario 2 was done where the unmet hours resulting from the natural ventilation scenario were evaluated, and then the numbers of hours where occupants could be made comfortable simply by using a fan were calculated where mechanical air conditioning was not required for Comfort. The fan energy consumption has been calculated by multiplying the number of those hours by the average power of a typical Indian ceiling fan, which was 50W (BEE,2016).

Scenario 4: Change over Mixed Mode with Adaptive Set-points.

In this scenario, when the window in the perimeter zone was open, the cooling air from the HVAC system was turned off. In this change during the operation of the Mixed mode system, there was a basic switch between the open window operations and the HVAC conditioning component. So, when the windows were open, the HVAC systems were turned off. In this case, where there is a VRF system, the system did not turn off entirely but ran on minimum energy. Thus, in this scenario, natural ventilation was utilised when the outdoor conditions were favourable and when the indoor zone temperature rose, and the outdoor conditions were not favourable, the HVAC system kicked in to maintain the weekly adaptive set-points as derived from the IMAC (Indian Model for Adaptive Comfort) for the Climate zones being studied.

Sr no.	Mode	Setpoint Indoor operative Temperatures	Window Operation	Ceiling Fan	Air Conditioner	Thermal Comfort Model
1	Natural ventilation	IMAC	Open	Closed	Closed	IMAC
2	Natural ventilation + Ceiling Fan	IMAC + Change as per Elevated Fan Speed	Open	working at 1.2m/s	Closed	IMAC
3	Mixed Mode	IMAC	Scheduled	Closed	Scheduled	IMAC
4	Fully Air Conditioned	Fixed Setpoint (ASHRAE)	Closed	Closed	On	IMAC

Figure 5 : Summary of the scenarios for Energy Analysis

All these scenarios will help quantify the impacts of window operation on Building energy usage, the Overall carbon emissions, and occupants Thermal Comfort.

3. **Result Discussion**

This section focuses on the measured demand for space cooling identified in the study as well as the energy savings that were shown to be achievable in the baseline typical commercial building by implementing the four modes of building ventilation operation with adaptive cooling set-points.

3.1 Natural ventilation and ceiling fan

The analysis of this operation is illustrated by the hourly profiles of window operations through window opening factor, unmet hours and the unmet hours after the integration of the ceiling fan use throughout the year and Subsequent understanding of the impact of window operation on building energy performance.

Average Air Speed: 0.6m/s	Average Air Speed: 0.9m/s	Average Air Speed: 1.2m/s
1.2 ° C	1.8 ° C	2.2 ° C

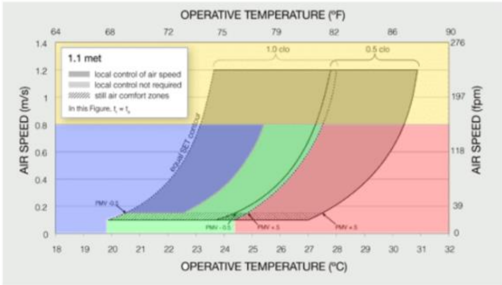


Figure 6: ASHRAE 55-2013 reference for the change in acceptable Operative temperature with Elevated Air Speed

The acceptable operative temperature limit in occupant-controlled spaces were set to be increased by 1.2°C, 1.8°C and 2.2°C in the presence of air speeds equal to 0.6 m/s, 0.9 m/s and 1.2 m/s, respectively as portrayed in Fig 6 (ASHRAE 55-2013, table 5.4.2.4)

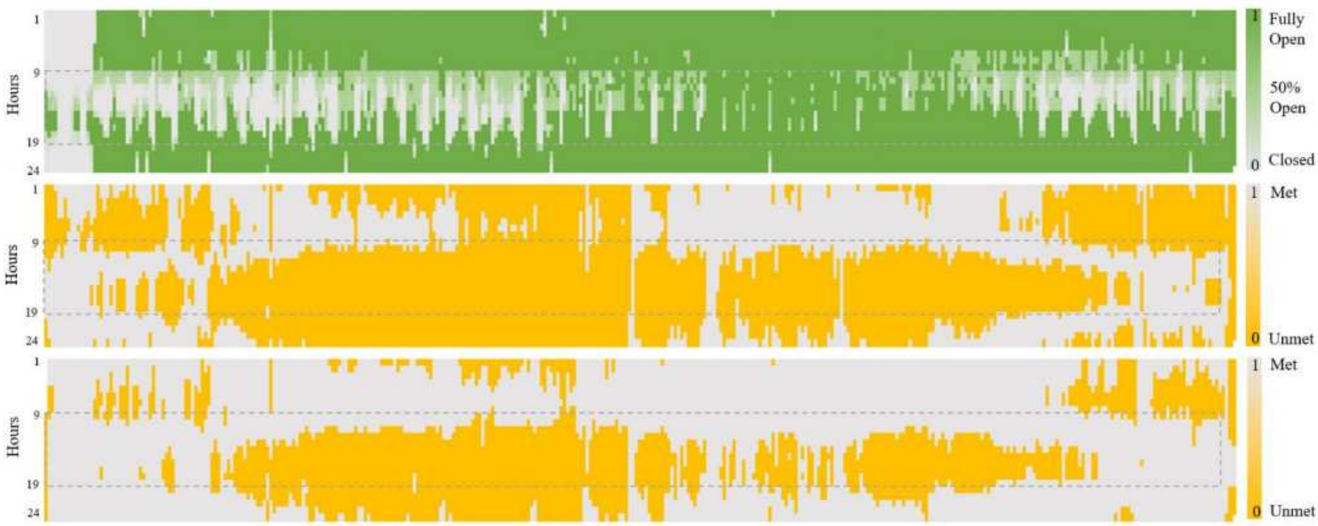


Figure 7 : Graphs Portraying the Window Operations and Unmet hours for Hot and Dry Climate

From Figure 7, it was possible to infer that the Window Opening Factor which determines the ratio of window opening depends on the logic T zone air > Setpoint (IMAC Range) & T zone air > T outside air & the Availability schedule value = 1 (Open).By adhering to this logic, as previously discussed the hours that the windows were in use was observed to be 91.9%. By taking into account the adaptive temperature thresholds the unmet hours were shown to constitute 38% of the time.

In accordance with ASHRAE Standards, as depicted in Figure 6. it is possible to conclude that the increased air speed produced by a fan creates a useful cooling effect within space

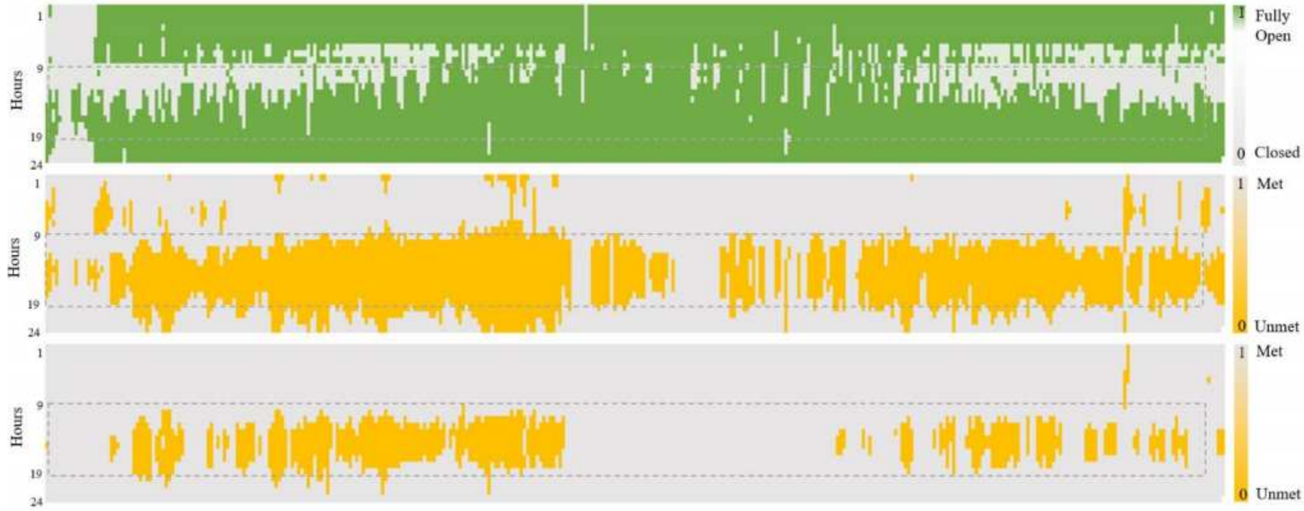


Figure 8 : Graphs Portraying the Window Operations and Unmet hours for Warm and Humid Climate

In the warm and humid climate, this airflow lowered the Relative Humidity and expanded the range of the comfort temperatures in spaces. When the ceiling fan enhanced the airspeed by 0.9 m/s, there was shown to be an acceptable temperature increase of 1.8° C.

When the Unmet hours within the scenario where natural ventilation was assisted with a ceiling fan and the window was closed, and the degree of unmet hours was calculated to be 1-2°C. then the percentage of unmet hours was reduced from 38% to 13%.

This analysis shows the potential of integrating natural ventilation as a cost-effective strategy for the provision of comfort indoors. Figure 8 shows that windows were open in this scenario for 65% of the time. The unmet hours within the 90% acceptability adaptive temperature range covered a substantial 63%.

However, the Integration of ceiling fans in a naturally ventilated space, notably reduced the unmet hours from 63% to 41%. This underscored the potential for amalgamating natural ventilation and ceiling fans to elevated airspeeds, as a really important passive technique in both climates to provide good levels of comfort while promising to significantly reduce energy consumptions in, and carbon emissions from buildings.

3.2 Mixed Mode

The following figures demonstrate the hourly profiles of the window operation, Cooling loads and Unmet hours for the changeover mode utilising both natural ventilation and air-conditioning.

Figure 9 & 10 shows that comfort can be provided indoor in warm and humid climates by opening windows for around 27% of the time. The maximum cooling load for the summer months was calculated to be 8500W. The Unmet hours observed were only 1.14%. (100 hours).

By contrast the window operations in hot and dry climate was 15% and the maximum cooling load was for the summer months to be 8340W. The Unmet hours were only 3.03% (275 hours) comfortably meeting the ECBC requirement of unmet hours below 300 hours.

During the mixed mode of operation there was a considerable reduction in the cooling loads during the Pre-office hours (22- 46%) during which natural ventilation can be utilised to maintain the setback temperatures and the air conditioner is employed as the internal Load increases.

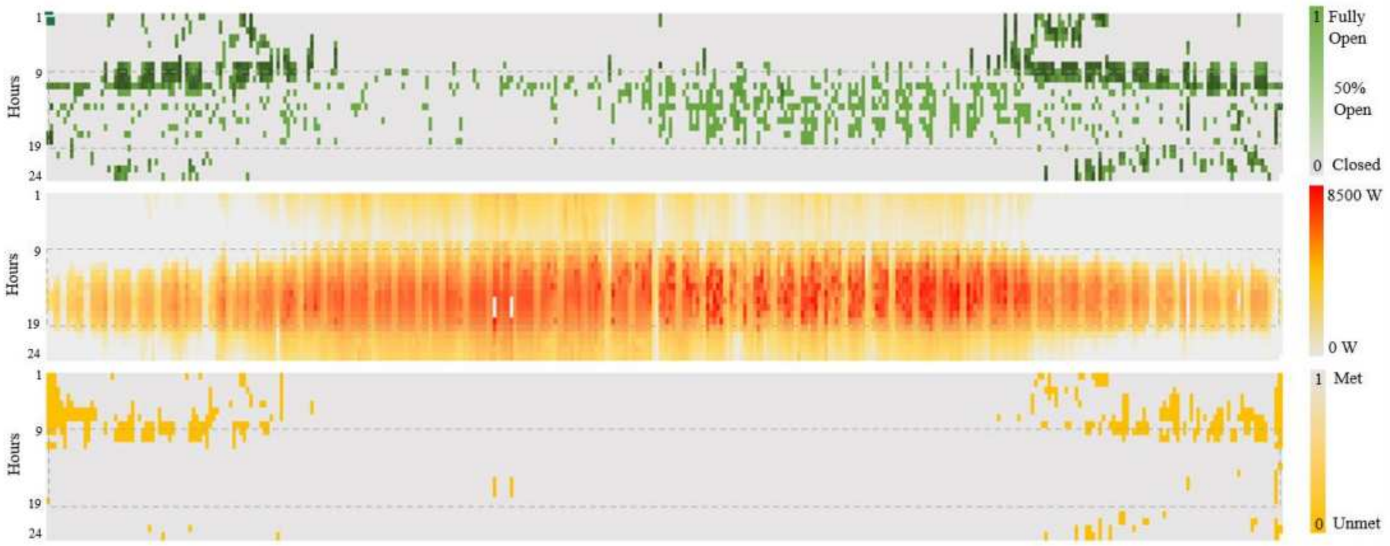


Figure 10: Graphs Portraying the Window Operations, Cooling Loads and Unmet hours in the Mixed mode for Hot and Dry Climate

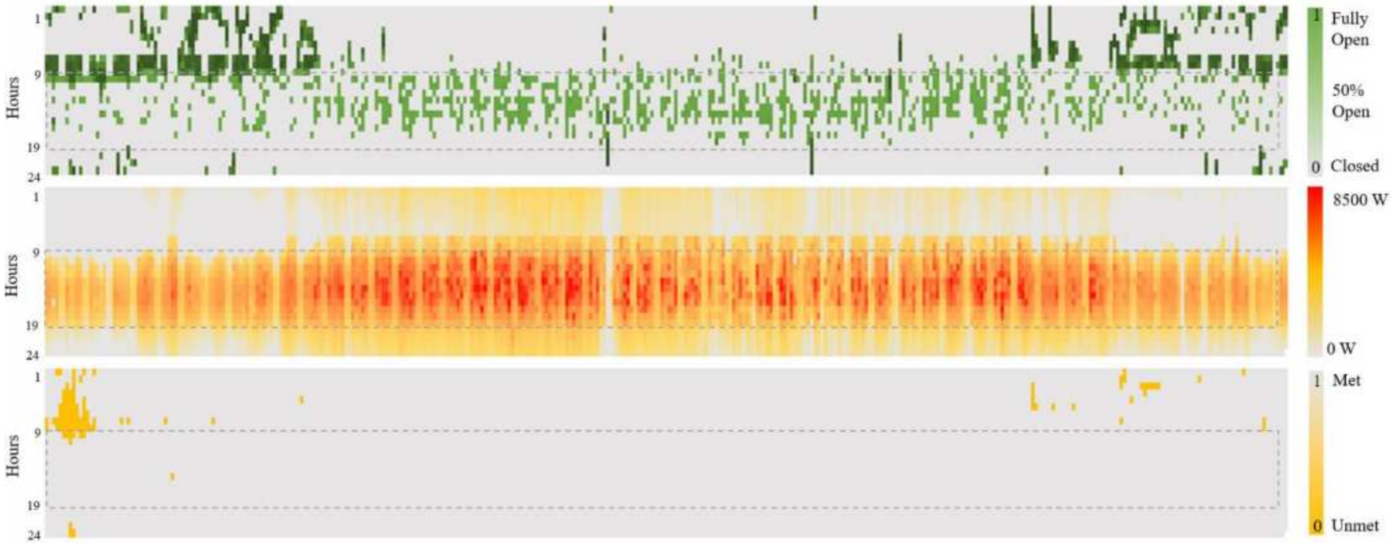


Figure 9 : Graphs Portraying the Window Operations, HVAC energy consumption and Unmet hours in the Mixed mode for Warm and Humid Climate

3.3 Energy Consumption (kW)

When comparing the energy consumption of the building under its four different modes of operation: fully AC, natural ventilation, natural ventilation, and ceiling fan and mixed mode scenarios, significant differences in the energy consumption for both the climate zones between the scenarios were observed.

Figure 11 shows the total electricity consumption in all scenarios. In fully AC mode, the electricity consumption ranged from 1.85kW to 45.36kW.While in Natural ventilation and natural ventilation + ceiling fan, the electricity consumption was between a quarter and a half of that ranging from 0.47kW to 18.56kW. In mixed mode, where natural ventilation and mechanical AC is combined, the total Electricity consumption fell between those two extremes ranging from 0.54kW to 38.25kW. The reduction in the peak electricity consumption by 48% in NV+ ceiling fan mode and 19% in the Mixed Mode for Warm and Humid Climate represents a significant drop in consumption.

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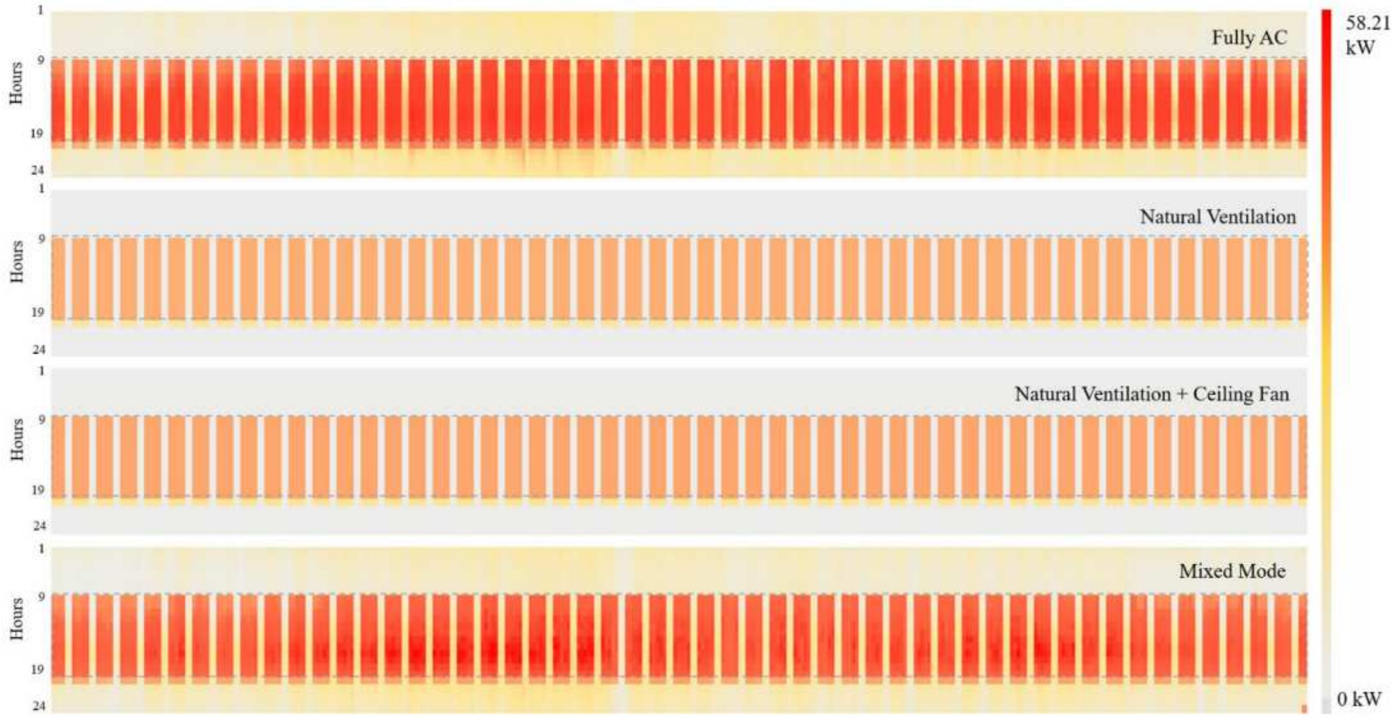

Figure 11: Analysing the variation observed in Total Building Energy Consumption during ventilation operational Strategies in Warm and Humid Climate

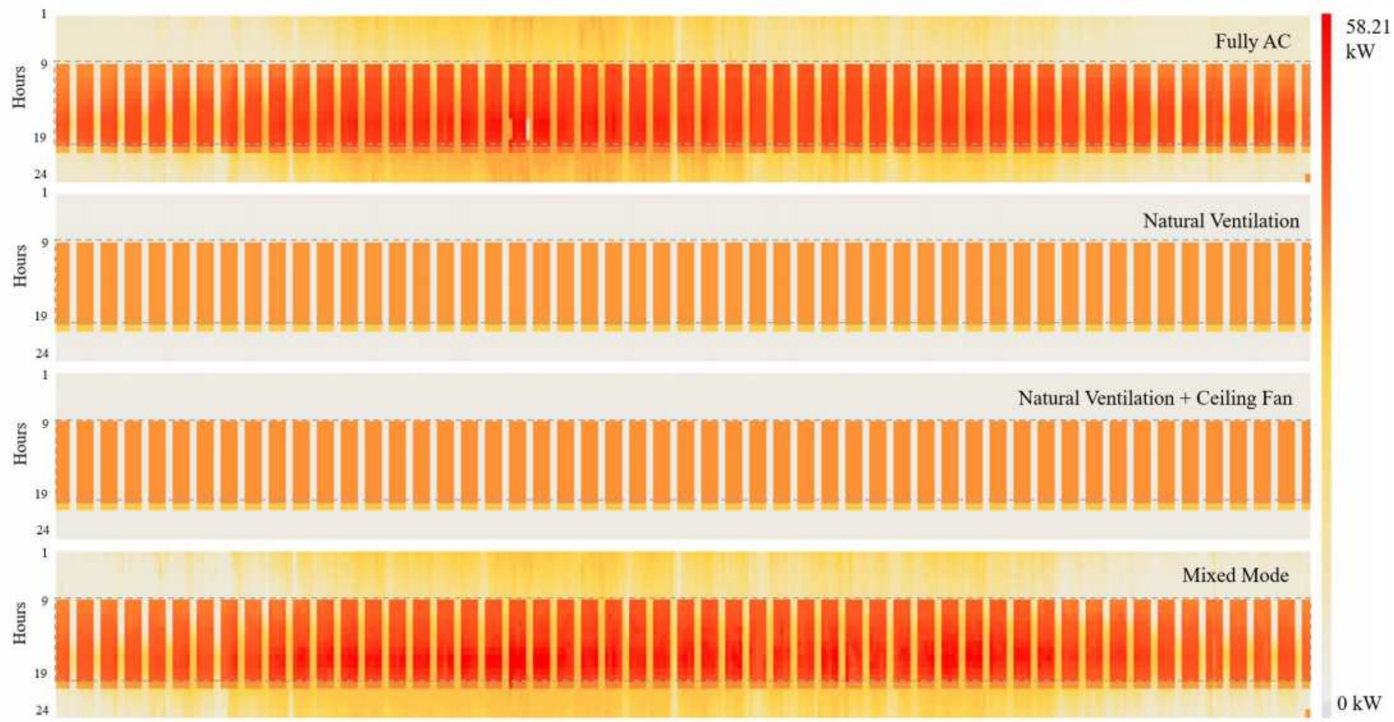

Figure 12: Analysing the variation observed in Total Building Energy Consumption during ventilation operational Strategies in Hot and Dry Climate

Figure 12 shows the change in the total building electricity consumption in all scenarios: in Fully AC mode, the electricity consumption ranged from 1.64kW to 58.21kW; in NV and NV+ ceiling fan it is from 0.47 to 19.8kW and in. In MM, where NV and AC are combined, the total Electricity consumption Ranged from 0.94kW to 52.09kW.

The reduction in the peak electricity consumption of by between 66% in NV+ ceiling fan mode and 11% in the MM for the hot dry climate was significant.

4. Conclusion: Energy Performance index and Carbon Emissions

An investigation into Energy Performance Index (EPI) and carbon emissions in a baseline Indian office block across four different building conditioning scenarios was undertaken. They included: fully AC, NV, NV with CF, and MM strategies.

Energy Performance Index (kWh/m^2.year)		
Ventilation Operation Scenarios	Warm and Humid	Hot and Dry
Fully AC	123.12	141.26
NV	57.4	58.4
NV+ Ceiling Fan	63.1	64
Mixed Mode	87.32	114.98

Figure 13: The change in the EPI observed through various scenarios.

The findings were of paramount significance as the study revealed the strong relationship between how much energy the baseline building used and in turn the carbon emissions from it and the very different approached to the ways in which thermal comfort is provided to occupants in the building as shown in Table 1. Below. The NV offices used less than half the electricity of the AC building in the warm humid climate and more than that in the hot dry climate.

This study shows very clearly that an effective way to achieve radical carbon emission reductions from standard office buildings is to run them for as much of the year as possible on NV and low energy options such as ceiling fans.

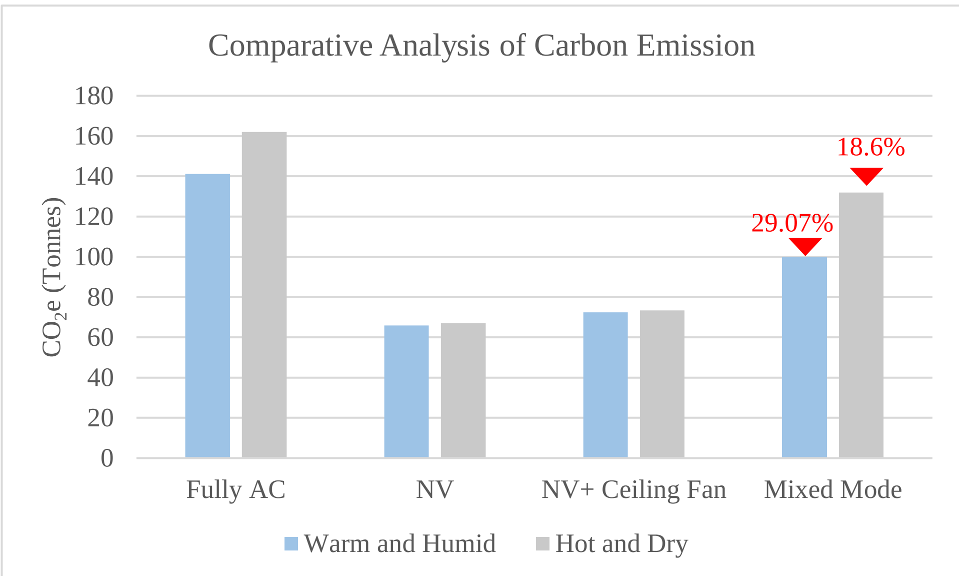

Figure 14: Graph portraying the Carbon Emissions for each Scenarios.

Figure 14 reinforces a message it is important to take forwards in a heating world, in which the costs of energy are soaring and the impacts of its use on the global climate is increasingly felt. It also shows that we already have the tools to hand to measure key dimensions of Net

Zero buildings. Building owners and users should note from this study how great the financial and environmental benefits can from occupying buildings in which the windows are capable of being accessed and opened and in which the room heights will allow for the use of ceiling fans.

A clear conclusion from this study is that for an office building of 1200 Sq. meter, savings of between 18% and 29% in energy use can be achieved in both the studied climates by utilising those two passive adaptive opportunities in conjunction with efficient HVAC Systems.

Natural Ventilation and Mixed Mode strategies must play an increasingly pivotal role in curbing the energy consumption and radically reducing peak cooling loads and carbon emissions and societies around the world urgently seek workable and affordable ways to meet the pressing Net Zero targets that are essential for stabilizing Green House Gas emissions and reducing the global impacts of climate change.

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Energy Efficiency Barriers in Public Schools: Insights from a Case Study in Argentina

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Abstract: Energy consumption analysis of public schools is crucial for promoting sustainable development and designing healthy classrooms. However, data on school energy consumption is often scarce in non-OECD countries, particularly for buildings with cultural and heritage value. This study presents an energy performance assessment applied to the oldest technical school in Argentina, which was built in the late 19th century. The results show a significant energy consumption for this school, representing a potential candidate for implementing energy efficiency measures and reductions of CO2 emissions. Additionally, challenges related to data availability and technical difficulties in applying standardised energy assessment protocols are identified. These challenges arise from a combination of factors, including centralised government control over school energy spending and maintenance, as well as technical and knowledge gaps.

Keywords energy efficiency, energy performance assessment, heritage buildings, public schools

1. Introduction

The climate crisis is intensifying, and humanity must act quickly to mitigate its impact. Energy efficiency stands out as one of the most cost-effective tools and is recognized as a key strategy for addressing climate change (Bukarica and Tomšić, 2017). The building sector is a key area when seeking to decrease greenhouse gas emissions. It accounts for approximately 40% of energy consumption and 36% of CO2 emissions in the EU (European Commission, n.d), representing around 34% of global energy demand and approximately 37% of CO2 emissions worldwide in 2021 (United Nations, 2023).

Energy efficiency emerged in the EU energy policy agenda during the 1970s and has been progressively shaped by the shifting global and EU energy and climate policies and priorities. In this context, numerous countries have well-defined energy policies aimed at reducing carbon emissions in the building sector. Policy instruments are used to stimulate demand for energy efficiency projects (Bukarica and Tomšić, 2017). As pointed out by Economidou et al. (2020), the reduction of energy demand in buildings through the adoption of an energy efficiency policy is a key pillar of the European Union climate and energy strategy.

On the other hand, some non-OECD countries have begun to implement initiatives in the field of emission reduction within the construction sector. A 2014 report (Carpio, 2014) indicates that not all Latin American countries have regulations specifically focused on energy assessment and energy efficiency in buildings. Moreover, several regulations and energy rating schemes are voluntary (Carpio, 2014; Reus-Netto et al., 2019) and the funding for promoting and developing energy efficiency primarily relies on national budgets, leading to significant limitations during implementation. The report also highlights the lack of continuity among institutions involved in promoting and developing energy efficiency, the necessity for incentives to support these projects, the limited access to information on best practices and technologies, as well as the lack of awareness among consumers regarding the benefits (Carpio, 2014).

In Argentina, the main national initiative to promote energy efficiency in the public sector is the mandatory Presidential Decree 140/07 (Programa Nacional de Uso Racional y Eficiente de la Energía, 2007), which applies to federal buildings. However, unlike other Latin American countries, Argentina does not provide tax incentives or credit support. For instance, Uruguay enacted energy efficiency legislation in 2009, including a law that established a Trust Fund to finance energy efficiency projects (Carpio, 2014). Additionally, Argentina has an energy policy that implements substantial subsidies to energy consumption, which acts as a major barrier to the implementation of energy efficiency projects.

There are numerous barriers in developing countries that contribute to the "energy efficiency gap", which refers to the disparity between the actual and optimal levels of energy (Economidou et al., 2020; Hirst et al., 1990). Cooremans and Schönenberger (2019) have identified several factors that contribute to this gap, including economic, technical, political, social, information and knowledge-related aspects. Insufficient available information for consumers and limited attention to social behaviour from policymakers are significant barriers (Dias et al., 2004). Furthermore, the importance of information and awareness in energy policies has been recognized in various countries (Economidou et al., 2020). One effective approach to spread information and raise awareness in society is through energy efficiency pilots or demonstration projects, implemented in highly relevant public buildings. These projects not only demonstrate the benefits of energy efficiency but also help identify barriers and challenges.

Educational buildings provide ample scope for energy savings and present a remarkable opportunity to promote energy efficiency in construction and environmental quality improvements for students. According to Dias Pereira et al. (2014), school buildings hold a substantial social responsibility compared to other public buildings due to their educational purpose. As a result, energy performance in these buildings holds paramount importance. Moreover, energy efficiency projects implemented in schools contribute to raising environmental awareness among students and their social environments. Also, students are more prepared to comprehend the environmental challenges and problems that characterise the current century.

The purpose of this work is to present the findings of an energy efficiency project and an audit protocol conducted in a prominent public school constructed at the end of the 19th century, situated in Buenos Aires, Argentina. Addressing three key issues: i) the lack of knowledge and data concerning energy and Indoor Environmental Quality (IEQ) in educational buildings in Argentina; ii) the knowledge gap; and iii) the barriers to energy efficiency in public buildings across Argentina. The methodology takes into account the current scenario in Argentina, encompassing laws, regulations, energy efficiency knowledge, healthy buildings, financial resources, etc. The outcomes highlight the importance of student involvement in the energy audit and provide insights into energy consumption and IEQ conditions. Finally, recommendations on reducing energy consumption will be presented to school authorities, as well as to policymakers. Most of the findings can be extrapolated and applied to similar building types in countries subject to substantial energy efficiency disparities.

2. Methodology

2.1. Case Study

During the present pilot study, which spanned one year from November 2021 to November 2022, the school had a population of 1645 students (ages range from 13 to 18 years on average), 600 teachers, and 30 non-teaching staff members. The maintenance sector is external to the school and is managed by the local government authority.

The educational approach of the school is based on two types of knowledge: theoretical and practical. Both are seen as fundamental elements of technical-industrial education. The six-year curriculum was designed taking into account the primary industrial processes of its founding era, such as mechanics, construction, electricity, and chemistry. There is a special emphasis on basic sciences, laboratory practices, and workshop learning (Gallart, 2006).

2.2. School Building

The selected school building was built in 1897, it is located in the Ciudad Autónoma de Buenos Aires, Argentina, in a neighbourhood that is part of the city's historic centre. The building was designed by Engineer Carlos Massini, drawing inspiration from models of European polytechnic institutes (Grementieri et al., 2010). Stylistically, it can be classified as eclectic and academically composed. The architecture is predominantly functionalist, characterised by a sober and austere language influenced by Germanic inspiration, as depicted in Figure 1A. The ornamentation is derived from the construction materials and textures such as brick, iron, and stone-like plaster (Grementieri et al., 2010).

As shown in Figure 1B, the building consists of two separate structures divided by an internal street in a north-south direction. One building, referred to as the "classroom building" (11,220m2, covered area), has a comb-shaped layout facing west. The other building, referred to as the "workshop building" (8,500m2, covered area), features a central courtyard and is located on the east side.

The school has two energy sources: electricity and natural gas. It has a centralised heating system with natural gas boilers and fan coil units installed in each space.

2.3. Classroom building

The building spans multiple levels, including the ground floor, first floor, second floor, and basement. It has unobstructed facades since it is not connected to neighbouring structures, resulting in an exposure factor of 1. The comb-shaped floor plan leads to a larger facade area compared to more regular and compact buildings, which could result in higher structural and energy maintenance costs (Czajkowski, 1991). The majority of the classroom surfaces face east (interior courtyards) and west (main entrance facade) orientations.

Internally, the building follows a typical layout with a central corridor and spacious areas on both sides, featuring high ceilings (height = 6m). As depicted in Figure 1C, the majority of the building's space is dedicated to study areas (classrooms and laboratories), accounting for 54% of the total area. The administrative area occupies 5%, circulation areas cover 19%, and the remaining space, including services, a museum, auditoriums, storage areas, and the caretaker's residence, accounts for 22% of the total area.

This building was selected for conducting the energy consumption inventory and energy simulation.

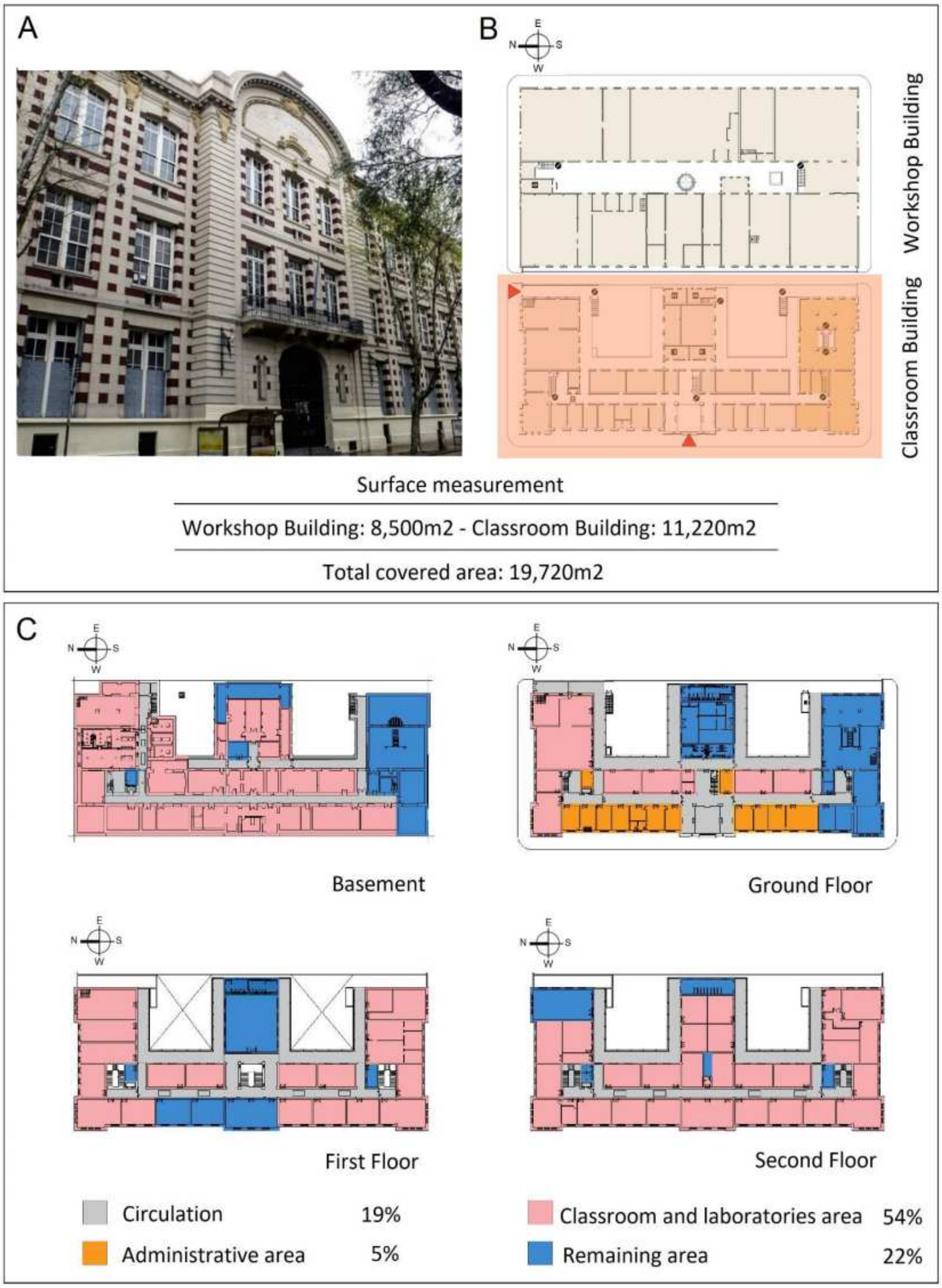

Figure 1. A, B School building and surface measurement- C Classroom Building plans with use indication (basement classrooms and laboratories are not permanently used)

2.4. Procedure

We have designed a protocol that addresses the cultural, social, and economic context, including the significant energy efficiency gap in the public sector of Argentina. Barriers such as insufficient regulations and policy measures, technical challenges, knowledge gaps, and limited funds were taken into account. A scheme of the overall protocol is shown in Figure 2.

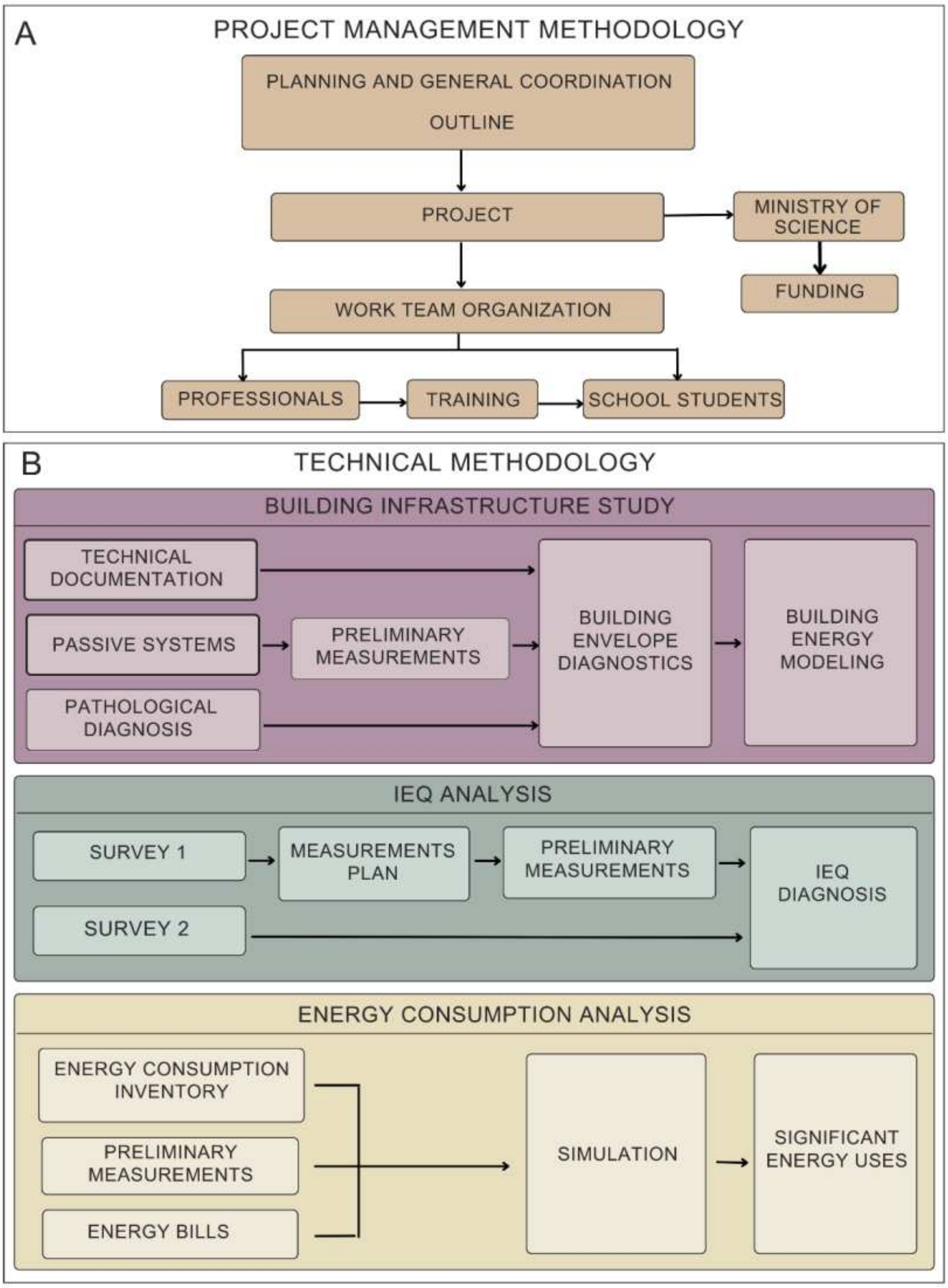

Figure 2. Procedure: project management and technical methodology.

Part A - Project Management Methodology (Figure 2A) involves:

- Planning and general coordination with school authorities.
- Validation by the Ministry of Science and funding acquisition.
- Work team organisation: We set up a work team that included 15 final-year students from all academic specialities, 1 school supervisor, and 9 professionals. A comprehensive training program was devised to equip the students with the essential knowledge and framework required to execute the project activities. This initiative was integrated into the school's curriculum. The training sessions covered a range of

topics, including energy efficiency, decarbonization, fundamental principles of energy auditing and climate change. Students were afforded the chance to familiarise themselves with various measurement devices and actively participate in strategizing the different phases of the project, including conducting surveys.

Part B-Technical methodology (Figure 2B), involves the field work conducted to assess the building and its energy systems, along with the occupants' environmental conditions. The field work encompassed three main areas that were simultaneously studied:

- Building Infrastructure Study: The focus of this study was to analyse the structural design, spatial distribution, passive elements, and building pathologies of the target building. This was achieved through the collection of technical documentation, including architectural and installation plans, as well as field data obtained from assessment forms and preliminary measurements, such as thermal imaging. Finally, the thermal envelope was characterised according to the Instituto Argentino de Normalización (IRAM) 11603:1996, 11605:1996 and 11507-4:2010 Standard and an energy model of the building was created.
- Indoor Environmental Quality (IEQ) Analysis: involved two specific surveys, survey 1, general (school community) and survey 2, specific (maintenance sector). Survey 1 aimed to gather information and opinions regarding several parameters, in this study we focused on thermal conditions, humidity, lighting, noise, air quality and ventilation. Survey 2 was designed to gather information regarding the management of climate control, water, and maintenance services with the purpose of identifying the specific types of electrical appliances and mechanical systems utilised for climate control and ventilation, along with the parameters and schedules of control systems and automated devices like thermostats and sensors. The collected data was analysed using the Likert scale (Likert, 1932). Participants were allowed to make additional comments on some questions.
- Energy Consumption Analysis: First, an analysis of the school's energy consumption was conducted using natural gas and electricity billing. With this information and according to Argentina's energy matrix, an estimation of carbon dioxide emissions was performed employing IPCC method (2006). Additionally, following the approach proposed in the literature (Geraldi et al, 2020), the calculation of Energy Use Intensity (EUI) was conducted in terms of primary energy and the school's covered area (19720 m2). Second, we focused on identifying significant energy consumption patterns. To simulate the school's energy consumption, we employed the conditional demand analysis (CDA) energy model as outlined by Swan et al. (2009). The primary data collection methods included an inventory of machine and appliance energy consumption, as well as a survey administered to the school community. The survey gathered information on the number and daily schedules of occupants, their appliance usage, and preferred settings. This allowed us to calibrate the model by comparing its predicted energy consumption with actual energy billing data. Additionally, we obtained information on the workshop building using the "sub-metering" method described by Knight et al. (2007) to supplement the model. Finally, the predicted energy end uses were presented using Sankey diagrams (Abdelalim, 2017).

3. Results and Discussion

3.1. Building Infrastructure Study

To analyse the thermal exchange mechanism between the occupied spaces and the external environment through the building envelope, a thorough examination of the individual building components (walls, floors, roof, windows, etc.) was conducted. This analysis considered their materiality and heat transmission capacity. According to the Bioenvironmental Classification of the Argentine Republic outlined in the IRAM 11603:1996 Standard the school falls within bioenvironmental zone IIIb. This classification indicates that summers have temperatures ranging from 20°C to 26°C, while winters experience average temperatures between 8°C and 12°C.

Table 1. Thermal transmittance of the envelope components.

	Thermal transmittance U [W/m2k]	**IRAM 11605:1996 Standard** (summer)			**IRAM 11605:1996 Standard** (winter)		
		A (22°C)	**B** (20°C)	**C** (18°C)	**A** (22°C)	**B** (20°C)	**C** (18°C)
U-value roof	2.51	0.19	0.48	0.76	0.32	0.83	1.00
U-value wall (opaques components)	1.42	0.50	1.25	2.00	0.38	1.00	1.85
U-value wall (opaques components and windows)	2.19						
U-value floor (over ventilated basement)	1.80	0.25	0.62	0.99	0.38	1.00	1.85
U-value window (Single glazing and wooden frame)	4.02	**IRAM 11507-4:2010 Standard** U < 4 W/m2k					

Calculated and reference values according to IRAM 11605:1996 (U calculation, 3 comfort levels: A-Recommended, B-Moderate, and C-Minimum, interior design temperatures indicated in parentheses) and IRAM 11507-4:2010 (windows).

Given the building's age of over 100 years and its construction using clay bricks, the thermal performance of the envelope is expected to be deficient due to the absence of insulation materials during its construction. During that time, the use of thermal mass for temperature regulation was common, resulting in a wall thickness of 0.49m. The architectural style and practical considerations of that era led to the inclusion of large windows throughout the building, disregarding their orientation and resulting in a high window-to-wall ratio of 30%. However, the lack of insulation in the enclosures and the materials used in the windows, such as single-pane glass and wooden frames, highlight the need to enhance the thermal properties of the envelope.

The analysis of the data presented in Table 1 demonstrates that both the roof and walls fail to meet the hygrothermal comfort standards for both winter and summer conditions. Conversely, the floor, with a U-value lower than 1.85 W/m2K, complies with the minimum comfort level required for winter. Finally, the windows do not conform to the classification levels stipulated by the IRAM 11507-4:2010 standard.

For the purpose of this paper we will exclude the analysis of building pathologies and the energy model, which will be addressed in future publications, due to space constraints.

3.2. IEQ Analysis

The objective of this analysis was to gain sufficient data to analyse and understand the classroom building IEQ performance in terms of the community school perception, through surveys. After two months of leaving the survey open, only 115 participants completed survey 1 (55% of responses came from students aged 13 to 15, 38% from students aged 16 to 18, and the remaining responses were from teaching staff and non-teaching staff) and there was only one response for survey 2.

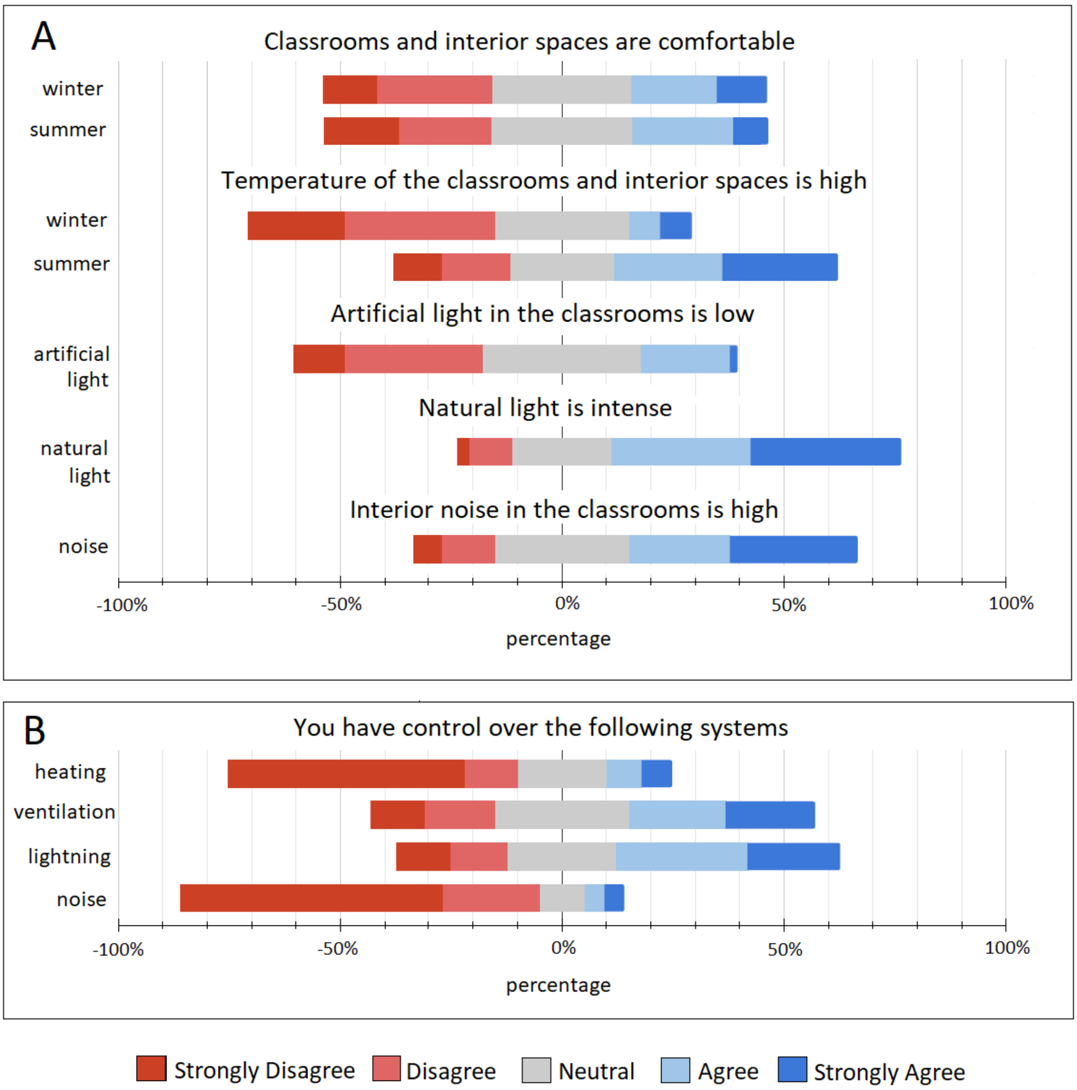

Figure 3. Community school perception of classroom building IEQ performance - Likert scale

In Figure 3A, the results are presented regarding the respondents' perception of comfort, temperature (in summer and winter), artificial and natural light and noise (in all seasons) in the school. In response to the initial statement "Classrooms and interior spaces are comfortable", it is notable that a similar proportion of respondents selected the neutral category for both the winter and summer seasons, indicating a balanced distribution of agreement and disagreement. The question about comfort does not provide substantial insights into Indoor Environmental Quality (IEQ), the subsequent question addressing temperature is more specific. Approximately 56% of the respondents agree that they feel cold in the classrooms during winter. It is surprising that during the summer, approximately 26% of the responses still indicate feeling cold. In relation to natural and artificial lighting, over 20% of the respondents agree that artificial lighting is low, while 65% indicate that natural lighting is very high. Finally, 52% of responses agree that noise is significant, which is consistent with the school's location surrounded by avenues with heavy car and public transportation traffic.

Figure 3B presents the responses regarding the level of control over the operation and settings of the electromechanical systems associated with comfort and indoor environmental quality. 65% of the respondents indicated a lack of control over the heating system, 28% over ventilation, 25% over lighting, and more than 80% over noise levels.

Table 2. Additional comments from the respondents related to the school building.

About the temperature	Opinions regarding heating in the facilities varied among respondents: . Some found the heating satisfactory, while others expressed dissatisfaction . Boilers don't work at all, and it is excessively cold during winter. . There are potential issues with the functionality of the boilers and the overall design of the heating system. . Heaters should be positioned closer to the floor to enhance warmth. . In certain areas, the use of fans becomes necessary to maintain a continuous heating supply. . The lack of glass in certain openings and the improper closure of doors and windows have a negative impact on heating efficiency during winter.
About artificial and natural lighting	. In several classrooms, the lighting is insufficient, thereby affecting the legibility of the blackboard and impeding proper writing on the desks. . Emergency lighting needs improvement in certain workshop areas, staircases, and the basement. . Some windows have blinds that obstruct the entry of natural light . In certain classrooms during the afternoon, there is excessive light that causes glare, and there are no internal curtains, hindering the use of electronic devices for educational purposes.
About noise	There are various sources of noise: . From the streets: traffic and social demonstrations. . Other classrooms and hallways (due to poorly closing doors). . Water pipes, the "building workshop", and many old fans also generate noise. . The classrooms are spacious, amplifying the internal echo of the noise.

Based on the comments provided by the respondents in Table 2, additional information can be obtained. These comments indicate serious issues related to heating, the management and operation of electromechanical systems, and maintenance. One of the highlighted aspects is the outsourcing of building maintenance, which is dependent on the school's budget allocated by the local government and their annual investment priorities. Before undertaking energy efficiency projects, it is crucial for schools to address their building infrastructure and effectively manage auxiliary electromechanical services related to indoor environmental quality.

3.3. Energy Consumption Analysis

The lack of access to all utility bills for electrical energy and natural gas, along with the absence of records on past maintenance activities and the unavailability of blueprints for electrical and gas installations, presented significant challenges. However, we were able to obtain the bills from July 2021 to June 2022, allowing us to approximate the school's energy consumption pattern. This information is presented in Figure 4, illustrating the primary energy consumed. It is worth noting that 70% of the total energy consumption corresponds to natural gas, which aligns with observations made by Filippín (2000) regarding high natural gas consumption in Argentinean schools. The months with lower consumption coincide with winter and summer school breaks. Natural gas is primarily used for heating purposes, while electrical energy is utilised for various applications such as lighting, office equipment, fans, electric pumps, machinery, and devices. Based on this data and the Argentinean energy matrix, the annual emissions amount to 244 t CO2.

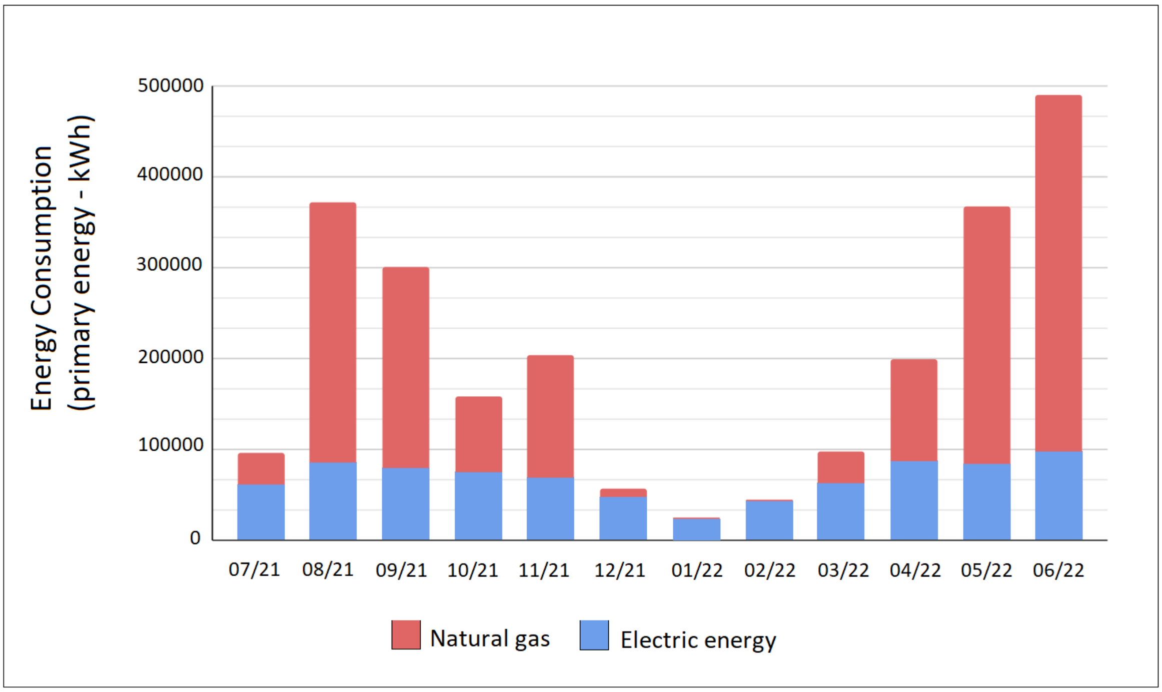

Figure 4. Primary energy consumption of school building: natural gas and electric energy

The Energy Use Intensity (EUI) is a crucial indicator for contextualising the energy performance relative to a notable characteristic of the building, as the energy consumption itself is too general. The calculated EUI value, based on the total energy consumed, is 120 kWh/m2.year. This value is remarkably lower compared to literature reports (Mairie de Paris, 2012; Dias Pereira et al., 2014; Filippín, 2000). We attribute this discrepancy to the size difference between the floor area and the covered area used in the calculation. It has been reported that a high value of this indicator is associated with a high level of thermal comfort satisfaction (Geraldi et Ghisi, 2020), this correlates with the findings of the IEQ analysis suggesting that thermal comfort is below occupants' needs.

The lack of electrical installation blueprints and gas pipe layouts, along with significant difficulties in the school's internet connectivity, prevented us from accurately identifying the energy consumption of each sector of the building and acquiring digital data on electricity usage. As a result, we were not able to use measurement instruments such as digital power analyzers, which require connection to the electrical network to gather data and provide insights into the various destinations or uses of electricity within the system. Instead, we conducted a simulation to identify significant energy consumption. From this approach, we were able to obtain electric energy uses (electrical losses are not taken into account and the model accounts for an error of ±3%), as depicted in Figure 5, Sankey diagram.

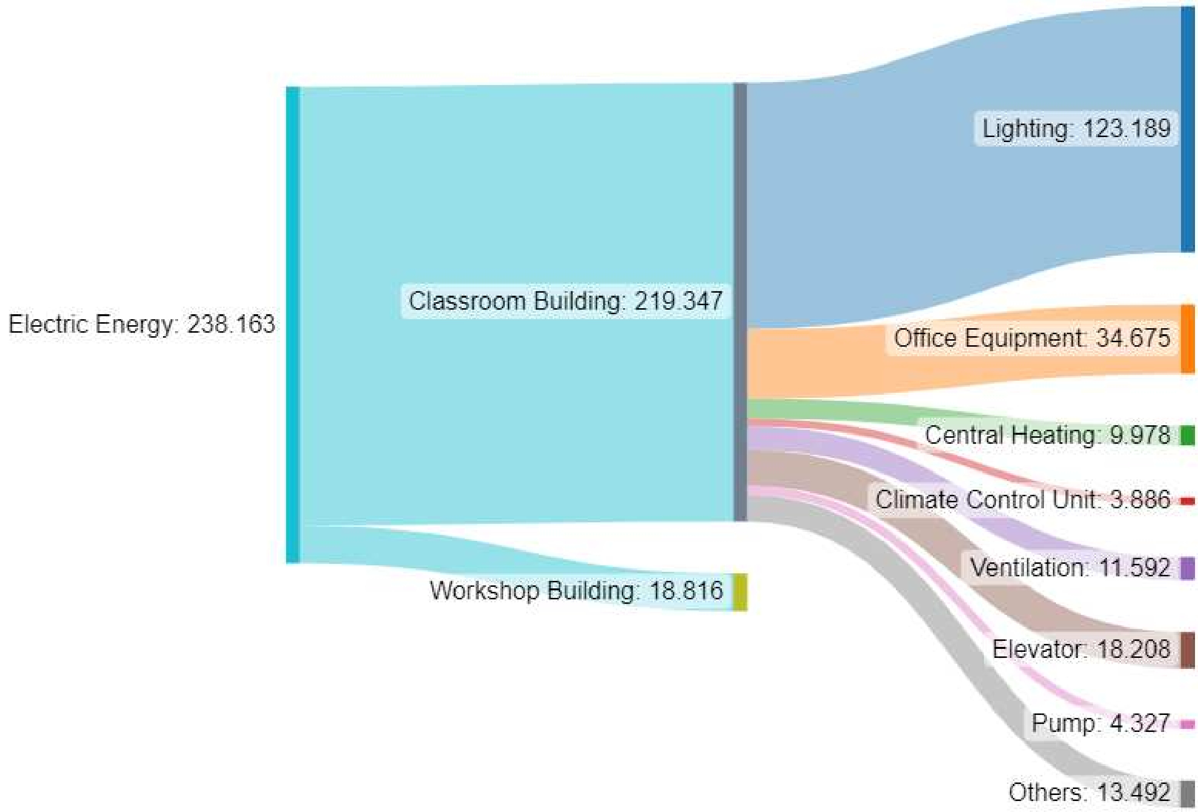

Figure 5. Most significant electricity consumption uses (kWh)- Sankey diagram

In this Figure, the primary input arrow represents the total electric energy supply to the school, the distribution in the two buildings: classroom and workshop. The multiple branches or pathways extend, representing different electricity consumptions. Results show a very high percentage of "Lighting", which can be attributed to the technology of the lamps, the dimensions of the building, a lack of awareness and the lack of automation. In the USA, for schools in general, lighting, ventilation, heating, and cooling account for 80% of energy consumption (Dias Pereira et al, 2014).

The Sankey diagram shows the most significant electricity consumption uses. Gas usage is primarily dedicated to heating purposes. In both energy sources, there are significant opportunities for consumption reduction. In terms of electricity, lighting consumption stands out as it still relies on high-consumption lamps and exhibits poor organisation and usage practices. Many lights remain on for extended periods outside of school hours. Regarding heating, we identified mismanagement and determined that further investigation is needed to understand usage patterns in greater depth. However, we identified several obvious and primary solutions for improving energy efficiency, including insulation in roofs and walls and double-glazed windows to reduce heat transfer, addressing air leaks and infiltration, improving energy management practices, and optimising energy usage patterns.

3.4. Internal barriers within the school

These barriers encompass issues related to inadequate technical documentation and building operational practices, such as the absence of detailed architectural drawings and maintenance plan documentation. These elements are crucial for gaining a comprehensive understanding of energy consumption patterns and identifying potential areas for effective project planning. The lack of gas and electrical system blueprints, energy bills, and other related documentation significantly hampers the execution of an energy audit. Without access to these relevant data, conducting a comprehensive assessment of the school's energy usage and identifying areas for improvement becomes challenging. We also identified significant deficiencies in maintenance and energy management practices. Additionally, there is a need to address the improvement of internet connectivity.

Another notable aspect is the knowledge gap. Having a permanent staff member at the school who can receive all relevant information, possess the necessary knowledge to comprehend it, and act as a qualified intermediary would be highly beneficial. Addressing these internal barriers requires improving internal processes, information management, and a commitment to improving energy-related awareness and practices among staff and students. A summary of these internal barriers is presented in Table 3.

Table 3. Most relevant internal barriers to energy efficiency within the school

Levels	Barriers
Technical	Lack of technical documentation and adequate information
	Difficult access to facilities (electricity, natural gas and water)
	Difficulty obtaining internet access
	Lack of automation tools
Organisational	Lack of maintenance technical staff
	Lack of an energy management specialist within the technical staff
	Lack of control and access to energy bills
	Lack of own budget
School Community	Low priority given to energy issues
	Gap in knowledge regarding energy related topics
	Lack of incentives

These barriers encompass challenges in energy policies, codes, regulations, and the lack of financial and economic instruments as follows: First, Argentina lacks high-impact and continuous information programs targeting the population, particularly public entities, which is a significant barrier hindering awareness and contributing to the knowledge gap. Second, there are insufficient regulations and standards pertaining to energy efficiency. For instance, the absence of building labelling systems and codes specifying minimum efficiency standards. Third, the country has implemented an energy subsidy policy for several years, aimed at reducing energy costs, alleviating the burden on low-income households, and promoting social welfare. However, prolonged and extensive use of energy subsidies creates obstacles and undermines incentives for energy efficiency measures.

The lack of technical support and expertise among stakeholders involved in implementing continuous energy efficiency programs is a critical barrier. Without proper technical support, schools and other buildings may struggle to assess energy consumption patterns, identify areas for improvement, and develop strategies to optimise energy use. In schools it is local governments´responsibility to provide technical support, which is often lacking. To address this issue, local governments must realise the importance of providing technical support for energy efficiency initiatives in schools through resource allocation, training programs, and partnerships with relevant energy agencies and organisations.

It is worth noting that local governments often do not provide sufficient funding for school infrastructure, therefore, it is necessary to address maintenance issues before undertaking energy efficiency actions. Neglected maintenance can result in energy losses, inefficient systems, and increased energy consumption. Hence, local governments should prioritise allocating adequate funds for regular upkeep of school buildings, including repairs, upgrades, and replacements of faulty equipment and systems. This will not only improve energy efficiency but also contribute to a safer and more comfortable learning environment for students and staff.

Similarly, the lack of documentation in schools, such as plans and bills mentioned earlier, should be resolved, and the information should be readily available as part of a natural policy for developing energy efficiency plans.

3.5. External barriers related to the Argentinean state and local government:

Table 4 summarises the main barriers arising from the organisation of the Argentinean state and the local government responsible for administering and allocating funds to schools within its jurisdiction.

Table 4. Most significant external barriers to energy efficiency arise from both the national and local governments within the jurisdiction of the school

Levels	Barriers
National and local Government: Information Programs	Insufficient informational tools, such as public awareness campaigns, energy audits for public buildings, and limited efforts in disseminating knowledge.
National Government: Regulatory instruments	The lack of a robust regulatory framework poses a barrier to promoting energy-efficient practices, especially in public organisations and schools.
National Government: Energy subsidies	The energy subsidies in Argentina lead to increased consumption rather than encouraging energy-saving behaviours. In some cases, subsidies may even create a disincentive for individuals and organisations to invest in energy-efficient technologies or practices.
National and local government: Economic and financial instruments	Difficulty in accessing affordable financing options and a lack of economic and financial instruments.
National and local government: Technical support and expertise	Lack of technical support and expertise. Strong knowledge gap
Local Government: Insufficient funding, resources and limited documentation	The resources allocated to the school for maintenance, infrastructure investments, and energy efficiency improvements are limited. Additionally, the local government should provide regular documentation to the school regarding maintenance tasks and electricity and gas bills.

4. Conclusions

The goal of reducing greenhouse gas emissions should be a global commitment, with international collaboration and knowledge sharing playing a crucial role. While responsibilities for emissions may vary among nations, all countries have a responsibility to contribute to the solution and achieve carbon neutrality. However, not all nations are in an identical position to undertake energy efficiency projects. In particular, developing nations often encounter challenges in implementing measures to reduce emissions due to political, social, and economic constraints, including the absence of suitable energy policies.

In this study, we have demonstrated the importance of identifying both internal and external barriers present in the case study we have chosen for a non-OECD country. The main conclusion drawn from this study is that, in these countries, there is a need to establish a more suitable framework of reference. This requires collaboration between the school and relevant government entities, advocacy for favourable energy policies, and potential financial support. To achieve this, it is necessary to develop and implement comprehensive energy policies that encompass regulatory measures, financial incentives, training programs, public awareness campaigns, and long-term planning.

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Analysis Overheating in Irish houses: Result from a large sample set

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Abstract
There is an increasing concern that well-insulated buildings in cold climates could unintentionally elevate the risk of overheating in summer months. However, there is a paucity of literature on assessing overheating in dwellings in Ireland. This work aims to introduce a methodology for assessing overheating in Irish houses. This paper presents the results of a statistical analysis of indoor temperatures of three dwellings in 2022 in Ireland followed by investigating overheating risk therein against two criteria including Chartered Institution of Building Services Engineers (CIBSE) Guide A and Passivhaus static criteria. Dwelling 1 has the maximum average temperature of 24 °C in August for both bedroom and living room among the three dwellings. The average temperature of both zones in dwelling 1 shows 8 °C higher than the average outdoor temperature. Dwelling 1 shows higher overheating frequency based on both criteria among the dwellings. Based on the monthly overheating analysis in August, findings evidence ~20% and ~14% of occupied hours exceeded the CIBSE Guide An overheating threshold of 5% occupied hours > 24°C and > 25°C in the bedroom and living room, respectively. This work establishes a platform for analysing overheating risk in a largest sample set of Irish houses yet evaluated.

Keywords: Indoor and outdoor temperature; Overheating risk; Thermal comfort; Passivhaus; Climate change.

1. Introduction

Climate change has been a key concern for legislators across Europe in recent decades (Poortinga et al., 2019). Legislation relating to buildings has been predominantly aimed at reducing CO_2 emissions associated with the operation of buildings (Attia et al., 2023, O'Hegarty and Kinnane, 2022). This addresses the impact of buildings on climate change, but of lesser focus perhaps has been the impact of climate change on buildings, particularly in the context of overheating. The climate of Europe varies widely, and the impact of climate change, is therefore likely to vary widely. As a result of climate changes, the climate classifications across Europe will change over the remainder of this century, and beyond. A past study predicted how climate classifications will change for the remainder of this century (Rubel and Kottek, 2010). The current Temperate oceanic climate (Cfb) for central Europe, UK and Ireland will transition to include much warmer summers by 2100, triggering a change in climate classification of these countries. They highlighted the gradual change expected in K-G climate classifications across Europe between 2020 and 2100, which will contribute to increased levels of summertime overheating in buildings generally within the same period (Rubel and Kottek, 2010).

Many countries, such as Denmark, Sweden, Netherlands and UK, where overheating studies have recently been conducted in passive house and nearly Zero Energy Building (nZEB) dwellings, are located in Cfb climates (Finegan, 2022). They identified that overheating is already an issue in the European nations. This problem will increase in magnitude as these countries transition to climates with warmer summers, less cloud cover, and lower summertime precipitation. In the coming decades, countries currently on the outer periphery of the current Cfb climate zone, such as Ireland and UK, will experience overheating, similar to the recent measured overheating in some of the more extreme Cfb summer climates (Finegan, 2022). There is a paucity of study of overheating in Ireland, and an evident lack of focus on it in Irish regulation (Attia et al., 2023). Consequently, a comprehensive analysis of overheating risk is needed in Irish buildings, to inform possible future regulatory revision and understanding of building operation in advance of retrofit.

1.1. Policy Relevance of Research

According to the International Panel on Climate Change (IPCC), they predict that global temperatures and solar radiation will increase in the next few decades (IPCC, 2023). Additionally, the unusually high summer temperatures that we currently experience only occasionally are projected to become the norm during summers by 2060, assuming a medium emissions scenario (McLeod et al., 2013). In this regard, it is expected that Ireland's climate will see an increase in temperature in coming decades, particularly in summer season (Attia et al., 2023). This will lead to an obvious increase in internal temperatures of dwellings. This increase will be even more pronounced due to the increase in energy efficiency of new built homes, and the focus on fabric retrofit of existing homes. This temperature rising will have a direct impact on the frequency of overheating within Irish dwellings, especially low energy buildings. Overheating in buildings can have multiple negative consequences on indoor comfort, health, and energy efficiency. For instance it has been reported that morbidity and mortality rates due to overheating have been increasing across Europe in recent decades (Attia et al., 2023, Gupta et al., 2019). In this context, it is important to identify and mitigate the risk of overheating in the buildings. However, there is a lack of regulatory focus in Ireland on overheating. This study investigates different criteria for overheating assessment in the Irish context, with the aim of evaluating which are most apt for recognising overheating. It thereby is hoped this study can inform future regulation and the criteria that might be incorporated.

2. Literature review

The method of analysing overheating, and overheating criteria referenced in the literature are reviewed in this section.

2.1. Method of overheating analysis

Several methods of quantifying overheating have been developed so far in the literature. The most used methods are static and adaptive approaches. A static approach defines that fixed temperature thresholds are considered for defining the overheating in a building (McGill et al., 2017). The adaptive approach recognizes that the temperature at which people feel comfortable indoors varies depending on the running-mean ambient temperature (Nicol and Humphreys, 1998). In other words, adaptive thermal comfort was developed taking the outdoor conditions and human adaptation into account by identifying comfort limits based on a running mean of external temperature and the quality of the thermal comfort required (McGill et al., 2017, Finegan et al., 2020, Finegan, 2022, Vellei et al., 2016, Jones et al., 2016, Tink et al., 2018, Gupta et al., 2019, Jang et al., 2022, Morey et al., 2020, Gupta and Gregg, 2020).

The use of static and adaptive approaches for analysing overheating possesses several limitations. The static method does not provide an indication of the severity (Adak et al., 2023, Nicol et al., 2009). The use of criteria that define overheating based on the percentage of annual occupied hours exceeding a particular temperature threshold may be open to abuse, given the inherent sensitivity of the assessment method and the lack of clarity of what is meant by occupied hours (Adak et al., 2023, Nicol et al., 2009). The adaptive approach may also be problematic in some circumstances as it assumes that building occupants can adapt to their indoor environment regardless of their physical circumstances. This concern is particularly true for sleeping persons, and consequently, there are no accepted adaptive criteria for bedrooms (Anderson et al., 2013). To gain a deep understanding of overheating prevalence in the monitored dwellings, both static and adaptive approaches should be employed (McGill et al., 2017, Finegan et al., 2020, Finegan, 2022, Vellei et al., 2016, Jones et al., 2016, Tink et al., 2018, Gupta et al., 2019, Jang et al., 2022, Morey et al., 2020, Gupta and Gregg, 2020).

2.2. Criteria of overheating analysis

Different static and adaptive criteria have been used for analysing the overheating in dwellings. The well-established criteria are explained in the following. The *Passivhaus Institute* defines overheating in homes as temperatures exceeding 25°C for more than 10% of the year (Institut, 2012). According to *BS EN 15251:2007* (Comite'Europe'en, 2007), the operative temperature in living room should not exceed 26°C for more than 3% of the occupied hours in a year. The operative temperature in living room should not exceed 28°C for more than 1% of the occupied hours in a year. For bedrooms, the operative temperature should not exceed 25°C for more than 3% of the occupied hours in a year. The operative temperature in bedroom should not exceed 26°C for more than 1% of the occupied hours in a year. *CIBSE Guide A* static criteria refers to a fixed definition of overheating where the internal operative temperature of living room should not exceed 25°C for more than 5% of annual occupied hours and 28°C for more than 1% of annual occupied hours. Also, the internal operative temperature of bedroom should not exceed 24°C for more than 5% of annual occupied hours and 26°C for more than 1% of annual occupied hours (Guide, 2006). For air-conditioned buildings, *CIBSE Guide A* refers to customary summer operative temperatures of between 23°C and 25°C for bedroom and living room spaces (Guide, 2006).

For adaptive thermal comfort, the BS EN 15251 (BSI 2008) criteria were developed taking the outdoor conditions and human adaptation into account by identifying comfort limits based on a running mean of external temperature and the quality of the thermal comfort required. Based on this, the *CIBSE TM52* (CIBSE 2013) (Schiermeier, 2010) document suggests a series of criteria by which the risk of overheating can be assessed or identified. For Category II, normal expectation for new buildings and renovations, the first criterion suggests that the number of hours during which the internal temperatures are 1 K higher or equal to the upper comfort limit during the period from May to September should not exceed 3% of occupied hours. The *CIBSE TM 59* adaptive criterion is based on *CIBSE TM 52* and *CIBSE Guide A*, which provides a bedroom temperature criterion for residential buildings (Guide, 2006). CIBSE TM 59, which is a design methodology for the assessment of overheating risk in homes, presents criteria and calculation methods for evaluating the overheating of naturally and mechanically ventilated residential buildings during summertime (Jang et al., 2022).

3. Methodology

In this section, the analysis method used in this study is described. The overheating risk according to the room type was evaluated using indoor temperature data from three dwellings in Ireland. The overheating risk was evaluated in three steps, as shown in Figure 1.

In step 1, indoor and outdoor temperature data were collected and arranged for the analysis of the overheating risk in three residential buildings in Ireland. In step 2, the indoor temperature patterns by room types were analysed seasonally, monthly, and daily. The indoor temperatures were compared with the outdoor temperature. In step 3, the overheating risks of the building were calculated and evaluated through the Chartered Institution of Building Services Engineers CIBSE Guide A (Guide, 2006) and Passivhaus (Institut, 2012) criteria.

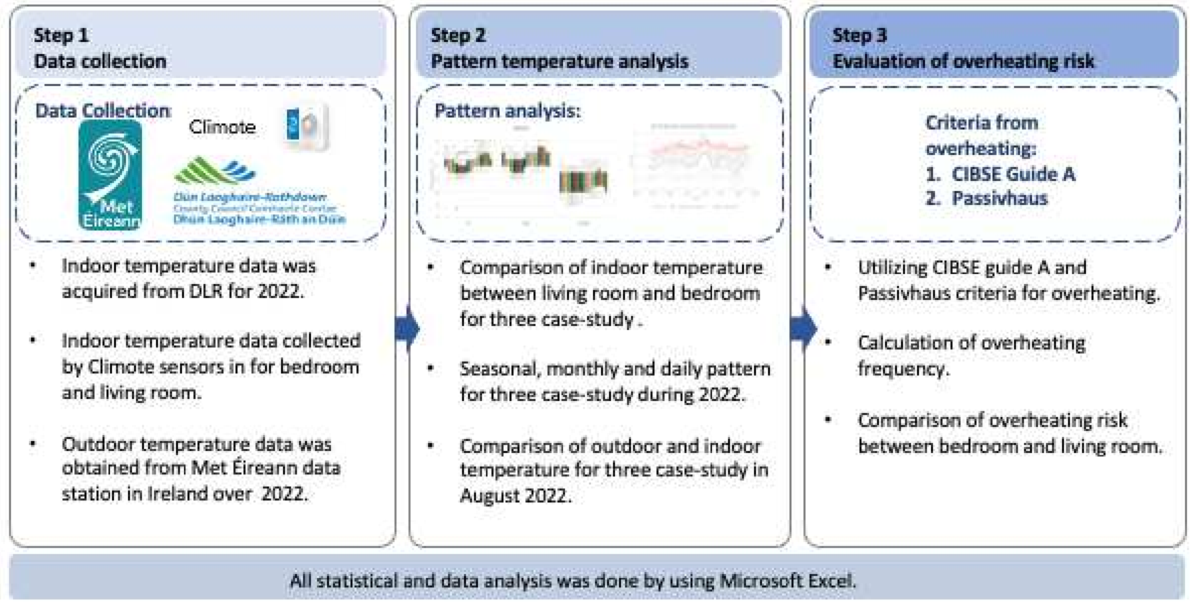


Figure 1. Flowchart of research methodology.

3.1. Data Collection

Indoor temperature data was acquired from the Dun Laoghaire Rathdown (DLR) local authority of Dublin City in Ireland. The temperature data in the living room and bedroom zones of the buildings was collected by temperature sensors fabricated by Climote smart technology company. Furthermore, the sample rate of temperature sensors is one sample per hour. Indoor temperature data was collected from the three number of dwellings over 12 months of 2022. Three dwellings have been selected as the case studies in this work because the temperature data was available for both living room and bedroom for these three homes. All dwellings in this data set are in Dublin, Ireland. The type of dwellings, tenure, construction materials, airtightness levels, and occupancy density were not defined in this data set. However, the Building Energy Rating (BER) and location of the dwellings were defined in the date set. Outdoor temperature data was acquired from specific meteorological data stations on Met Éireann data station monthly weather reports in Ireland over 2022.

3.2. Pattern temperature analysis

The data was processed to identify sensor failures that is “0” value here. Subsequently, data was cleaned by removing these failures. The indoor temperature pattern of both bedroom and living room in the case studies was analysed seasonally, monthly, and daily. The focus was on the analysis of the daily indoor temperatures during August 2022. The maximum, minimum, and average outdoor temperatures were compared with those of the indoor temperature of the living room and bedroom zones over August 2022 in three case studies.

3.3. Evaluation of overheating risk

The overheating risks of the dwellings were calculated and evaluated through the static criteria of CIBSE Guide A (Guide, 2006) and Passivhaus (Institut, 2012). These two static criteria have been extensively used for analysing overheating risk in a building (McGill et al., 2017, Finegan et al., 2020, Gupta et al., 2019, Jang et al., 2022, Morey et al., 2020, Gupta and Gregg, 2020). Also, the stated static criteria are the basic regulation in overheating analysis though they are not the best ones. CIBSE Guide A provides a more in-depth analysis by considering specific thresholds for various zones and occupancy percentages. These make it suitable for compliance assessments. The Passivhaus approach is in line with the broader goals of energy efficiency in high-performance buildings. However, its simplistic criteria might not capture the full spectrum of overheating challenges. The benefit of both these approaches lies in their clear and easily implementable guidelines. On the other hand, a drawback is that they do not take into account occupant behavior and adaptation.

In this regard, these two criteria were used in this research work. CIBSE Guide A static criteria refers to a fixed definition of overheating where the internal operative temperature of living room should not exceed 25°C for more than 5% of annual occupied hours and 28°C for more than 1% of annual occupied hours. The internal operative temperature of bedroom should not exceed 24°C for more than 5% of annual occupied hours and 26°C for more than 1% of annual occupied hours (Guide, 2006). The Passivhaus Institute defines overheating in homes as temperatures exceeding 25°C for more than 10% of the year (Institut, 2012).

Occupied hours were based on assumptions from (McGill et al., 2017) for bedrooms 24:00–07:00 and 08:00–23:00 hours for living room spaces. Thresholds were calculated from the raw indoor temperature data and analysed. Annual overheating frequency was evaluated for both living room and bedroom based on two static criteria in 2022 followed by comparing results. It has been reported that evaluating overheating solely based on an annual percentage fails to capture the variation in overheating levels on a monthly basis (Finegan, 2022, Finegan et al., 2020). On the other hand, findings evidence that overheating likely occurs in summertime (McGill et al., 2017, Colclough et al., 2018, Morey et al., 2020, Finegan et al., 2020). In this regard, monthly and daily overheating frequencies were calculated and evaluated in these three dwellings over the summer of 2022 and a whole year of 2022 for both the living room and bedroom.

4. Result and discussion

4.1. Seasonal, monthly, and daily temperature profile

Box plots were first used in this study to represent the distribution of the indoor temperature profile of three houses. Seasonal, monthly, and daily indoor temperature profiles of these three-case studies over 2022 are shown in Figures 2, 3 and 4. At this stage, summertime was chosen as the hot season and July, August and September were selected as hot months.

4.1.1 Seasonal temperature profile

Figure 2 shows the recorded indoor temperatures over 12 months in four seasons of winter, spring, summer, and autumn in 2022 for three dwellings. The data was presented for two separate functional zones including bedroom and living room. The average temperature of bedrooms in winter is 18 °C, 21 °C, and 17 °C for dwelling 1, 2, and 3, respectively. On the other hand, the average temperature of living room in winter is 19 °C, 21 °C, and 17 °C for dwellings 1, 2, and 3, respectively. In summer, dwellings 1,2, and 3 experienced the average temperature of 22 °C, 23 °C, and 22 °C for bedroom and 23 °C, 23 °C, and 22 °C for living room, respectively. It has been reported that the temperature of living room and bedroom are in the range of 17 °C - 22 °C and 16°C - 23 °C in the winter season, respectively, in Ireland and UK (Colclough et al., 2018, Coggins et al., 2022, McGill et al., 2017, Finegan et al., 2020). In summer, the average temperature of living room and bedroom have been in the range of 17 °C – 26 °C and 15°C – 26 °C, respectively, in Ireland and UK (Colclough et al., 2018, Coggins et al., 2022, McGill et al., 2017, Finegan et al., 2020, Morey et al., 2020, Jang et al., 2022, Gupta et al., 2019, Tink et al., 2018, Jones et al., 2016, Vellei et al., 2016). Our recorded data are in the range of reported temperatures in the literature for living room and bedroom.

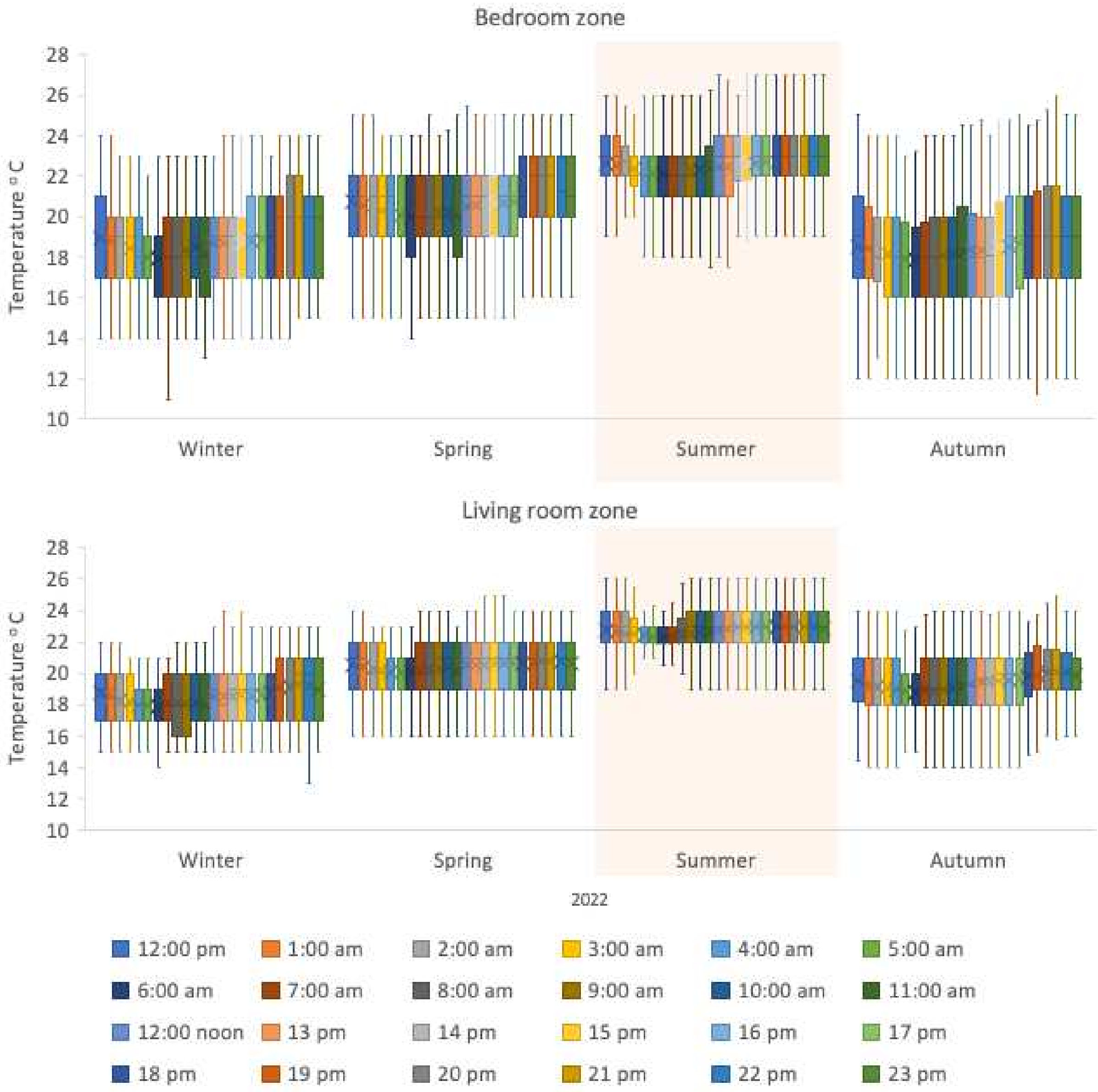
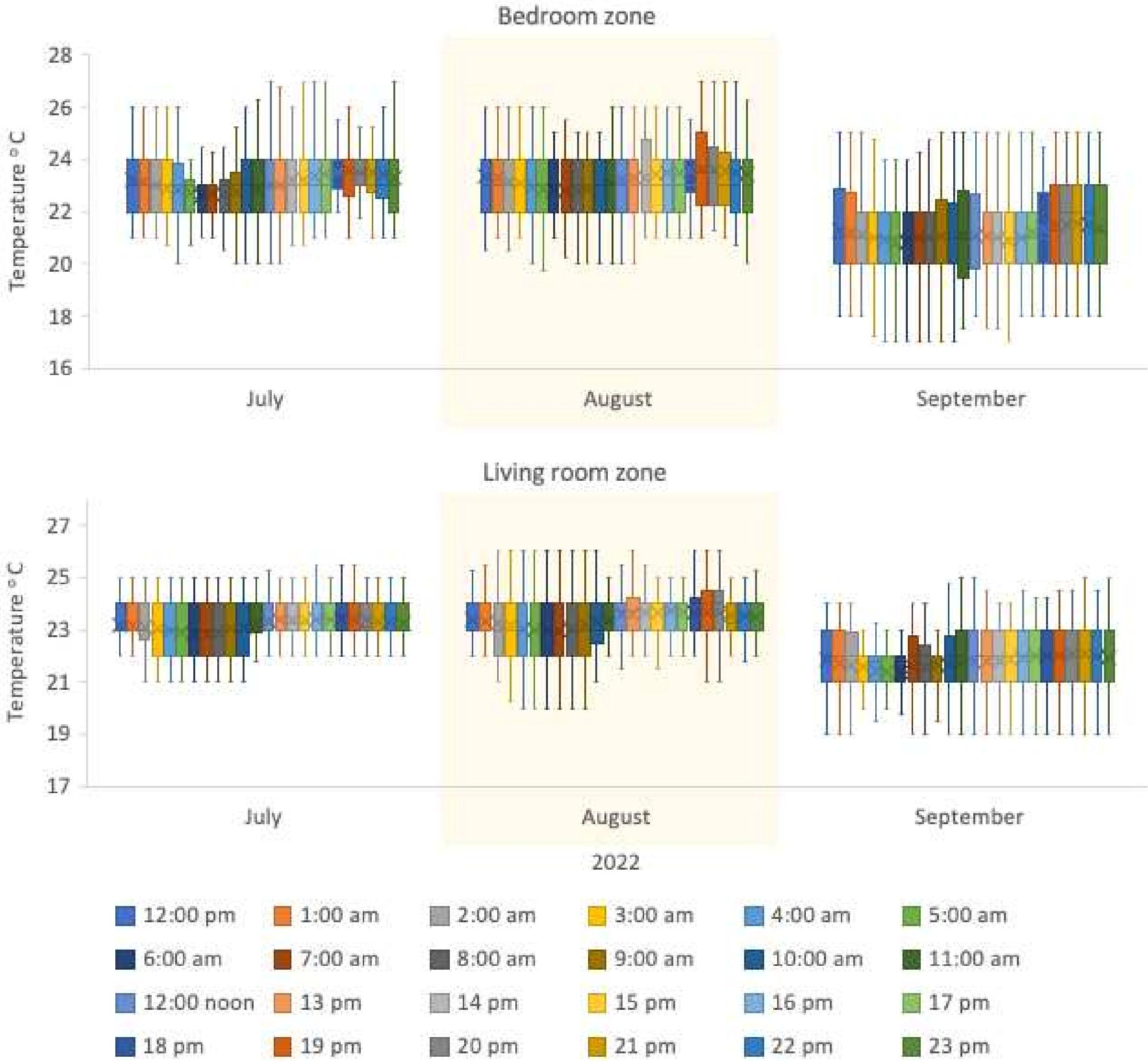


Figure 2. Indoor temperature behaviour recorded at four seasons over 2022 in both bedroom (top) and living room (bottom) zones for the three dwellings. The orange color box shows summer temperature profile.

4.1.2 Monthly temperature profile in summer

The indoor temperature profile of the living room and bedroom over 24 hours in July, August, and September 2022 for three dwellings is presented in Figure 3. The recorded temperatures of bedrooms in all dwellings are in the range of 18°C - 27 °C, 20°C - 27 °C, and 16°C - 25 °C in July, August, and September, respectively. In the case of living room, the temperatures are in the range of 17°C - 26 °C, in both July and August and 18°C - 25 °C in September. Indoor temperatures for July and August are higher than in September in both bedroom and living room for all dwellings. The maximum temperature of both living room and bedroom in all dwellings happened on common days including the 18th and 19th of July and 8th-16th of August. The average temperature of bedroom and living room in August is 24 °C, 23 °C, and 23 °C for dwellings 1, 2, and 3. In July, the average temperature of both zones is 23 °C in all dwellings. As reported above, it identifies the maximum temperature achieved during summer months, especially in August. Our data are in the range of reported temperature in literature for both living room and bedroom (see above section).



Figures 3. Indoor temperature behaviour recorded at different months in summer 2022 in both bedroom (top) and living room (bottom) zones in three dwellings. The orange color box shows August temperature profile.

4.2. Comparing outdoor and indoor temperature profiles over August

The outdoor and indoor temperature profiles over August for three dwellings are illustrated in Figure 4. The results indicate that the maximum, minimum, and average outdoor temperatures during August 2022 are 21 °C, 11 °C, and 16 °C, respectively. Dwelling 1 has the maximum average temperature for both bedroom and living room among three dwellings which is of 24 °C. Dwellings 2 and 3 show the average tempeature of 23 °C for both zones. The average temperatures of both zones in dwelling 1 shows 8 °C higher than the average outdoor temperatures. The maximum and minimum temperature of bedroom in dwelling 1 are 27 °C and 21 °C, respectively. In addition, the maximum and minimum temperature of living room in dwelling 1 experience 26°C and 18 °C, respectively. Existing literature reported that the maximum difference between living room and bedroom average temperatures with outdoor average temperature are in the range of 5 °C - 10 °C and 5 °C - 9 °C, respectively, during August in both UK and Ireland (Beizaee et al., 2013, Lomas and Kane, 2013, Tink et al., 2018).

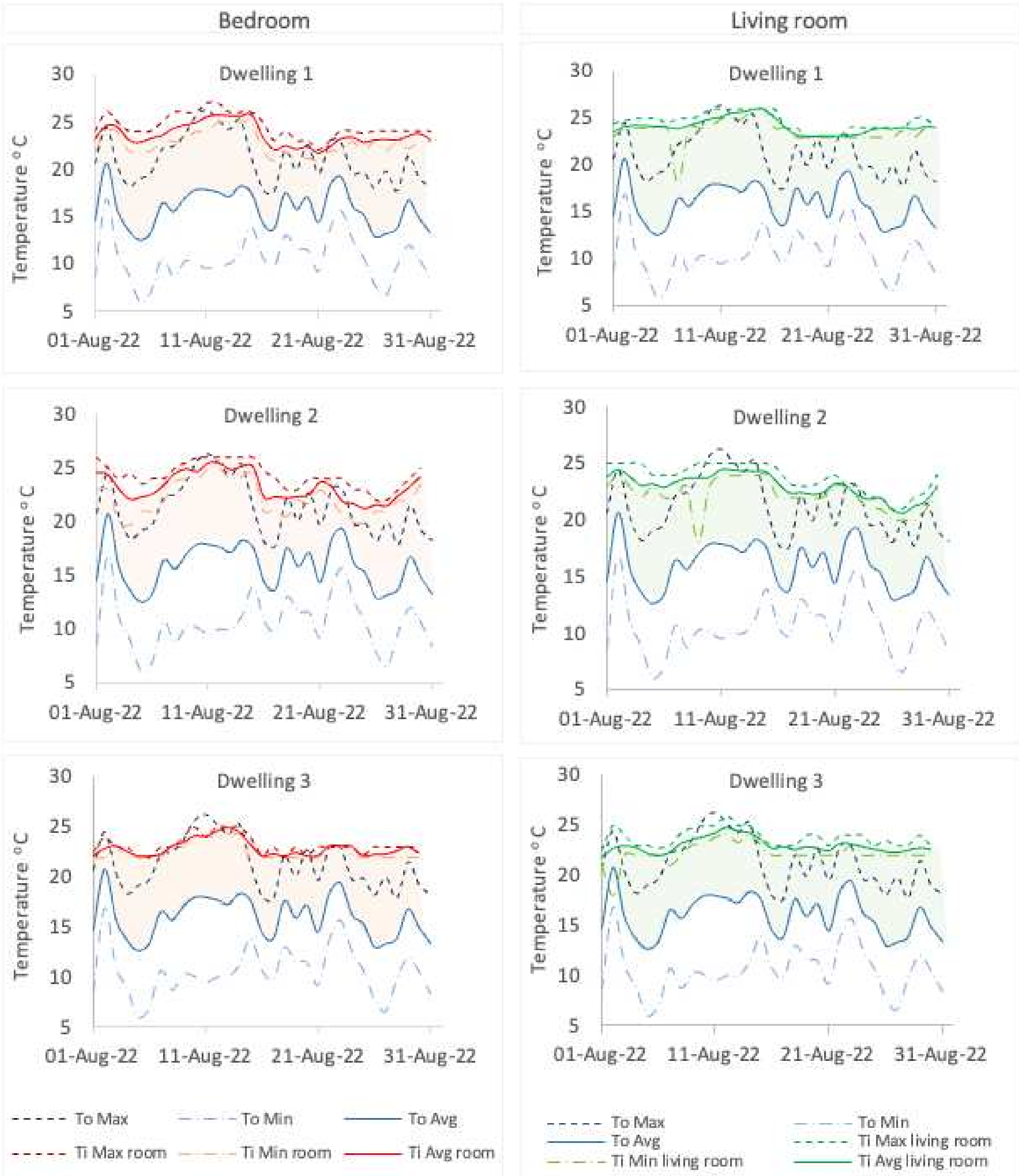


Figure 4. The maximum, minimum and average outdoor and indoor temperature during August 2022 in both bedroom (left) and living room (right) for three dwellings.

4.3. Prevalence of overheating using CIBSE Guide A and Passivhaus criteria

It has been reported that evaluating overheating solely based on an annual percentage fails to capture the variation in overheating levels on a monthly basis (Finegan, 2022, Finegan et al., 2020). On the other hand, findings evidence that overheating likely occurs in summertime (McGill et al., 2017, Colclough et al., 2018, Morey et al., 2020, Finegan et al., 2020). In this regard, monthly and daily overheating frequency were calculated and evaluated over July, August and September 2022 and a whole year of 2022 for both living room and bedroom.

4.3.1. Daily overheating frequency in July, August, and September 2022

Figure 5 shows the percentage of hours that temperatures exceeded the CIBSE and Passivhaus overheating thresholds on each day of July, August, and September in 2022 for both bedroom and living room in three dwellings. The results indicate that dwelling 1 shows higher overheating frequency based on both criteria. The most overheating frequencies happen in August rather than July and September for all three dwellings. There is no overheating risk in three dwellings in September based on Passivehaus criteria.

According to the CIBSE Guide A criteria in dwelling 1, the daily overheating frequency above 24°C in bedroom occur in 6 days of July and 9 days of August with the percentage of daily occupied hours in range of 13% -100% and 25% -100% in July and August, respectively. There is no overheating in the bedroom during July, August and September 2022 based on 1% of occupied hours > 26°C through CIBSE Guide A criteria. In the case of living room, the daily overheating during July, August and September 2022, above 25°C, are in only one day in July and 7 days in August with the percentage of occupied hours of in the range of 13% in July and 6% -106% in August. There is no overheating in bedroom during July, August and September 2022 based on 1% of occupied hours > 26°C through CIBSE Guide A criteria.

According to the Passivehaus criteria, the results of the dwelling 1 show that the daily overheating dates above the 25°C threshold in bedroom are in 3 days of July and 5 days in August with the range of 13%-75% and 25%-75% percentage of occupied hours, respectively. The daily overheating dates above the 25°C threshold in living room is in only one day in July and 7 days in August with the range of 13% and 6%-100% percentage of occupied hours, respectively. Consequently, the daily overheating evaluation illustrates the risk of overheating for both bedroom and living room in all dwellings in summer months based on both CIBSE Guide A and Passivehause static criteria.

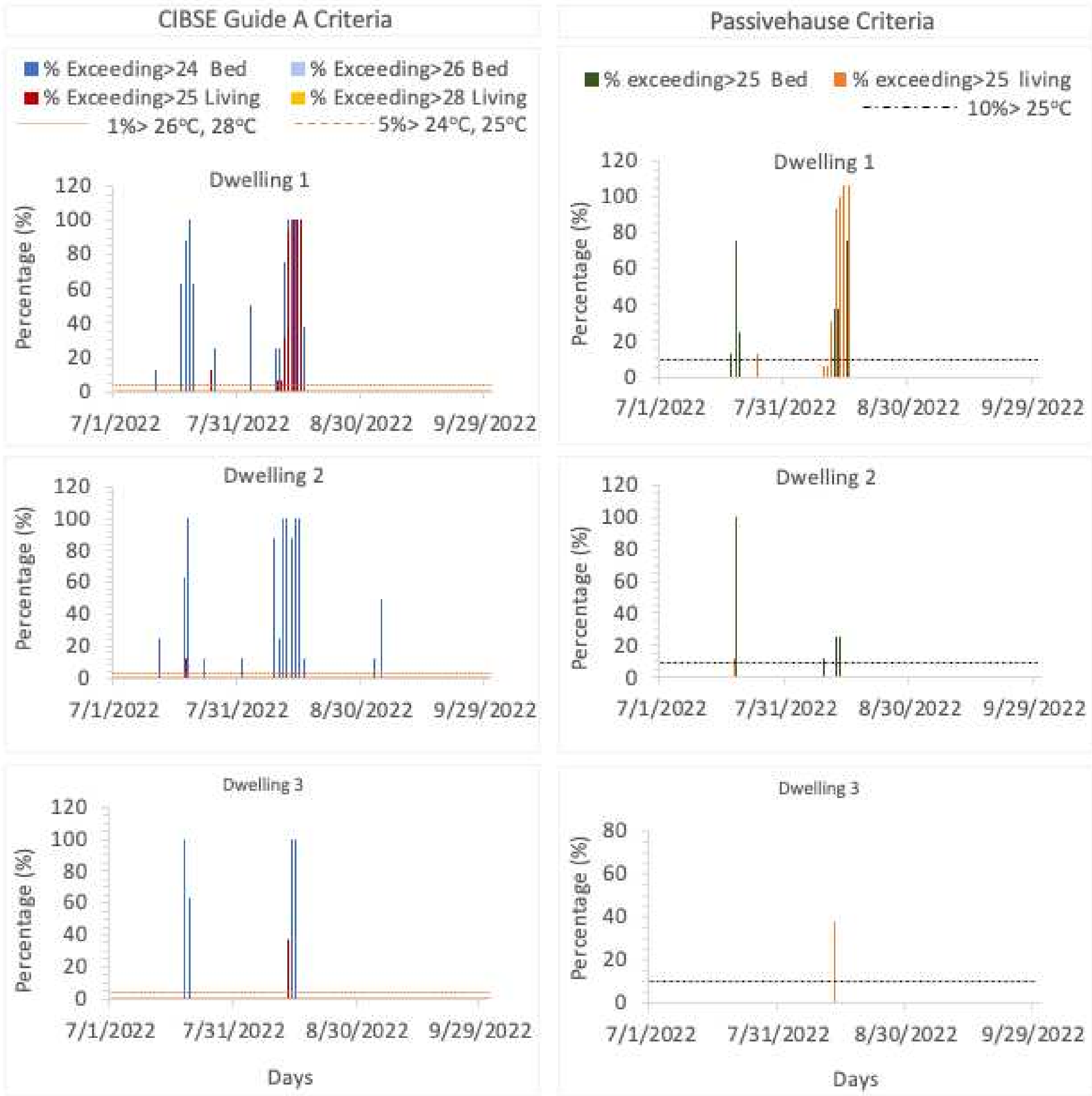


Figure 5. Daily overheating frequency in July, August, and September 2022 for both bedroom and living room based on CIBSE Guide A (left) and Passivhaus Criteria (right).

4.3.2. Monthly overheating frequency during the Summer 2022

The percentage of occupied hours that temperatures exceeded the CIBSE and Passivhaus overheating thresholds in July, August, and September 2022 for both bedroom and living rooms in three houses are presented in Figure 6. The results indicate that dwelling 1 shows higher monthly overheating frequency based on both criteria. The monthly overheating frequencies mostly happen in August rather than July for all three dwellings. There is no monthly overheating risk for three dwellings in September based on both criteria.

In the case of dwelling 1, it is evident that 12% and 20% of occupied hours in bedroom exceeded the CIBSE Guide A overheating threshold of 5% occupied hours > 24°C during July and August, respectively. There is no monthly overheating greater than 5% of occupied hours > 24°C in bedroom room in September. Correspondingly, the CIBSE Guide A overheating threshold of 1% hours > 26°C was not exceeded in bedroom in the whole of July, August, and September. The 14% of occupied hours in living room exceeded the CIBSE Guide A overheating threshold of 5% occupied hours > 25°C during August. There is no monthly overheating greater than 5% of occupied hours > 25°C in bedroom room in both July and September. There is no monthly overheating greater than 1% of occupied hours > 28°C in living room in July, August, and September.

Based on Passivehause criteria, in dwelling 1, the percentage of occupied hours above 25°C in bedrooms are 4% and 7%, in July and August, respectively. These are lower than the threshold in Passivehause criteria. There is no overheating risk greater than 10% of occupied hours >25°C in bedroom in September 2022. In the case of living room, the percentage of occupied hours above 25°C in living room are 14% in August. There is no overheating risk greater than 10% occupied hours >25°C in living room in both July and September.

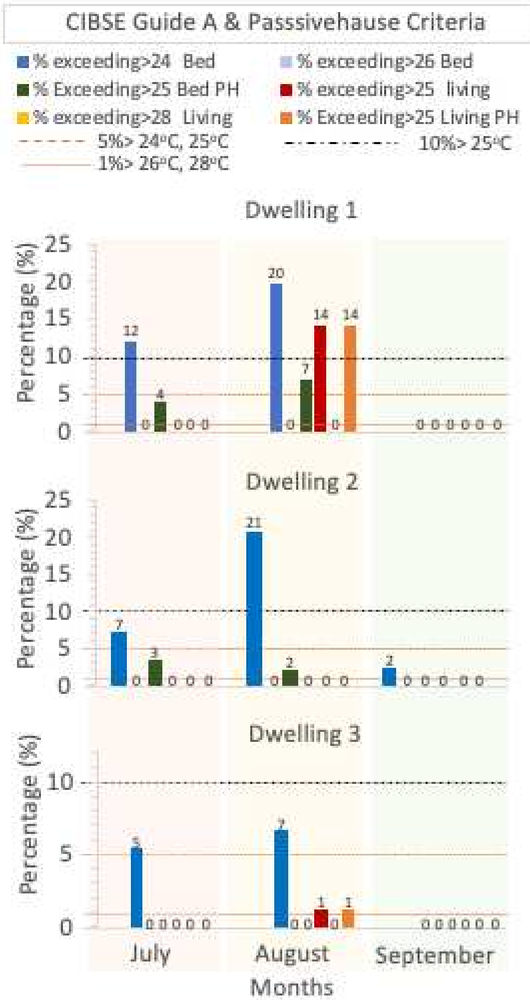


Figure 6. Monthly overheating frequency in July, August, and September 2022 for both bedroom and living room based on CIBSE Guide A and Passivhaus Criteria.

4.3.3. Annual overheating frequency in 2022

Annual overheating frequency in 2022 for both bedroom and living room in three dwellings based on CIBSE Guide A and Passivehause criteria are illustrated in Figure 7. In the case of dwelling 1, it is evident that 10% of occupied hours in bedroom exceeded the CIBSE Guide A overheating threshold of 5% occupied hours > 24°C. 1% of occupied hours in bedroom exceeded the CIBSE Guide A overheating threshold of 1% occupied hours > 26°C. Additionally, the percentage of annual occupied hours that the temperature exceeds 25°C is 1 % for living room. It is less than the overheating threshold of 5% annual hours > 25°C. There is no overheating risk in living room based on overheating threshold of 1% annual occupied hours > 28°C. Based on the Passivehause ceriteria, the percentage of annual occupied hours exceeding the overheating threshold of 25°C for bedroom and living room of dwelling 1 are 5% and 2%, respectively. These percentages are less than the overheating threshold of 10% annual occupied hours > 25°C. So, there is no annual overheating risk in dwelling 1 in 2022 based on Passivhaus criteria. In the case of both dwellings 2 and 3, there is no annually overheating risk in both bedroom and living room based on CIBSE Guide A and Passivhaus.

Overall, existing literature in overheating analysis reported a wide range of overheating frequencies. It strongly depends on the criteria of overheating analysis, building characteristics, occupant density, and duration of the study (annually or monthly) (Jang et al., 2022, Finegan et al., 2020, McGill et al., 2017, Gupta et al., 2019, Gupta and Gregg, 2020, Morey et al., 2020, Jones et al., 2016). For instance, McGill et al. (McGill et al., 2017) identified that among a sample of 53 dwelling units monitored across the UK, 57% of bedrooms and 75% of living rooms exceeded the maximum allowable CIBSE overheating threshold where temperatures should not exceed 25°C for more than 5% of the annual occupied hours throughout the year. When compared to the Passive house requirements where temperatures must not exceed 25°C for more than 5% of a typical year, this threshold was breached in 38% of bedrooms and 58% of living rooms. The CIBSE threshold which requires that indoor living temperatures do not exceed 28°C for more than 1% of occupied hours, was breached by 25% of living spaces. In some dwellings, temperatures were in excess of 25°C for more than 50% of occupied hours across the year.

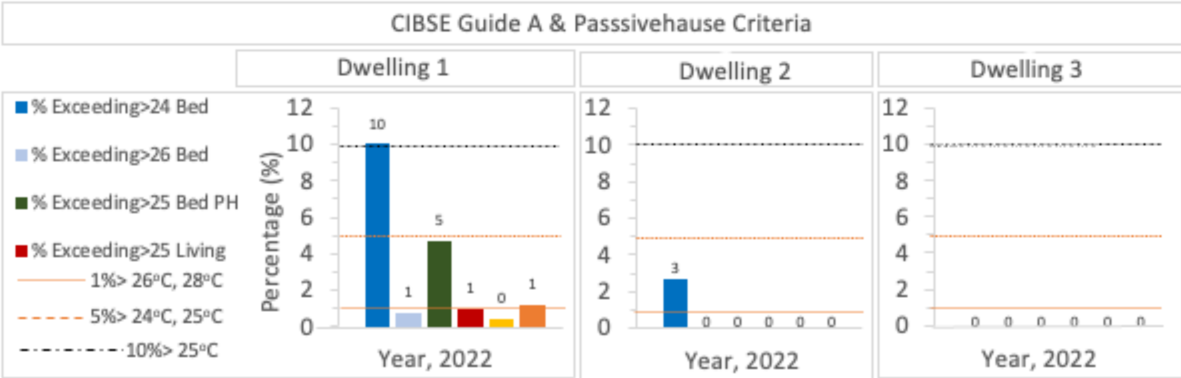


Figure 7. Annual overheating frequency in 2022 for both bedroom and living room for three swellings based on CIBSE Guide A and Passivhaus criteria.

5. Conclusion

In conclusion, this study introduced a methodology for assessing the risk of overheating in Irish houses. The indoor temperatures of three dwellings in Ireland over 2022 were statistically analysed seasonally, monthly, and daily in two different zones of living room and bedroom. The indoor temperatures of these zones were compared with outdoor temperatures in the hottest month of the year, August. The analysis revealed significant variations among the three dwellings, with Dwelling 1 exhibiting the highest average temperatures of 24 °C in August for both the bedroom and living room. Furthermore, the average temperatures in Dwelling 1 were found to be 8 °C higher than the average outdoor temperature, indicating a potential risk of overheating. These results indicate a potential risk of overheating in this dwelling. The reasons for this poor performance could be attributed to various factors, including building characteristics and design, insulation, ventilation, and occupancy patterns. It is possible that the design and insulation of Dwelling 1 were not optimised for managing heat during summer months, leading to increased indoor temperatures.

The evaluation of overheating risk based on CIBSE Guide A and Passivhaus static criteria indicated that Dwelling 1 had a higher frequency of overheating compared to the other dwellings. In August, it was observed that approximately 20% of occupied hours in the bedroom and 14% of occupied hours in the living room of Dwelling 1 exceeded the CIBSE Guide A overheating threshold of 5% occupied hours above 24°C and 25°C, respectively. There is no annual overheating risk based on Passivhaus static criteria in three dwellings.

There are correlations between overheating and nZEB buildings. As buildings aim to achieve net-zero energy consumption, energy-efficient measures could unintentionally increase the risk of overheating. For instance, building fabric retrofits can improve the energy efficiency while it can lead to higher internal temperatures during summer time. This can increase the risk of overheating and embodied carbon emission. On the other hand, the increased demand for cooling system due to overheating can potentially lead to higher operational carbon emission. This highlights a need for a balanced approach to address energy efficiency and manage overheating risks.

6. Future Work

This is an initial study of a larger dataset for Irish residential buildings. The methodology that is developed there will be applied to the larger dataset. Future data that has not yet been made available will include building energy rating, building characteristic such as age, location, and fabrics. The correlation of these features with the risk of overheating in the buildings will be identified accordingly. In addition, this data will be used to relate indoor temperatures and the risk of overheating with retrofit strategy and building fabric characteristic such as U-value, materials, etc.

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Perceived Comfort in University Classrooms Post the Pandemic: Interpretations Considering the Carbon Footprint of Learning Spaces

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Abstract: The main objective of this research is to interpret the thermal comfort perceptions of occupants and understand the implications related to the carbon footprint of learning spaces in the context of the pandemic and post-pandemic. A survey tool is used for the quantitative baseline study targeting 70 respondents to investigate the level of comfort within five university learning spaces - at the American University in Cairo, Egypt. The statistical analysis of the studied variables (related to thermal comfort, indoor air quality, and indoor environmental quality), showed that: (1) all variables are not normally distributed (used non-parametric tests); (2) overall comfort is highly correlated (positive) with temperature, air movement, and cleanliness – weakly correlated with noise and very weakly correlated with light; (3) temperature and air movement are probably sensed together; and (4) generally, there are negligible differences between the studied spaces (2 classes and 2 studios). The findings of the paper call for further research to investigate occupants' perceptions regarding thermal preferences in university classrooms, which would directly impact the occupants' learning performance. There are low-carbon strategies to be taken by architects, designers, and facility managers to improve occupants' comfort, such as: giving occupants control over the thermostat in classrooms, installing ceiling fans to improve air circulation, and maximizing daylighting within classrooms.

Keywords: Comfort, Indoor Air Quality, University Classrooms, HEIs, Carbon Footprint, HVAC

1. Introduction

Designing thermally comfortable university classrooms are essential to enabling a conducive learning environment where the performance of students and educators is optimized, and so is their well-being. In light of the pandemic, a vast body of literature has emerged to assess the effect of high ventilation rate requirements on occupants' health and thermal comfort and correlate it to the degree of learners' performance in a classroom setting. The published recommendations advocated by international technical organizations such as ASHRAE, REHVA and CDC[1] favour increasing the fresh air intake within enclosed spaces by allowing natural ventilation and operating HVAC systems under full capacities (CDC, 2020; "COVID-19: Resources Available to Address Concerns," 2021; "Indoor Environmental Quality | NIOSH | CDC," 2021; "REHVA," 2021; "Standard 55 – Thermal Environmental Conditions for Human Occupancy," 2017; "Standards 62.1 & 62.2," 2013). In turn, over-ventilated indoor spaces risk jeopardizing the thermal comfort of occupants and compromising energy efficiency. To create healthy and sustainable learning environments, it is crucial to understand the interplay of thermal comfort, indoor air quality, indoor environmental quality, and carbon footprint.

This research examines the implications of indoor air quality standards post-pandemic in educational facilities, focusing on comfort and energy considerations. The paper attempts to investigate the level of thermal comfort within five university learning spaces - at the American University in Cairo, Egypt, with two research questions in mind: (1) What measures are in place to help improve thermal comfort in an educational setting without undermining occupants' health and energy – given the experience gained from the COVID-19 pandemic? (2) to what extent can a balance be achieved between the thermal comfort, occupant's health, and HVAC energy in an educational setting – considering the means and rate of viral transmission of COVID-19 and other airborne viruses? This study provides unique insights on the degree of thermal comfort of occupants in university learning spaces within an arid zone climate and reflects on the energy performance of buildings.

Before we proceed with our analysis, it is important to define better our parameters' groups. What do we mean by thermal comfort, IAQ, IEQ and carbon footprint. To start with, thermal comfort refers to the degree of occupant satisfaction with the thermal environment. Research has shown that maintaining an optimal thermal environment has a positive impact on learning, and there is a direct constructive relationship between being in a state of thermal comfort within a classroom, and the ability to be productive, engaged in the learning interactions, and having high concentration levels (Abdul-Wahab et al., 2015; Adeleke and Moodley, 2015; Alonso et al., 2021; Anastasi et al., 2021; Balta et al., 2022; Ding et al., 2020; Hafizi and Vural, 2022; Huang and Liao, 2022). Several parameters are associated with thermal comfort – including air temperature, relative humidity, air speed, or ventilation rate in the built environment.

Indoor Air Quality (IAQ) can be considered a subset of Indoor Environmental Quality (IEQ). The levels of indoor air quality are determined by several parameters – including carbon dioxide, particulate matter, volatile organic compounds, as well as air temperature and humidity – which determine the level of thermal comfort. Indoor environmental quality (IEQ) includes a wide range of factors beyond temperature and relative humidity, the main determinants of thermal comfort. IEQ factors span to include lighting adequacy, acoustic

[1] The acronyms stand for: American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE); Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA); Centers for Disease Control and Prevention (CDC).

design, furniture design and their ability to cater to ergonomic comfort, positively impacting students' physical and emotional well-being.

Though the primary objective of this paper is to study the thermal comfort of occupants, it also considers selected parameters on the indoor environmental quality conditions of learning spaces. This research paper considers selected metrics to evaluate the quality of indoor environments – including lighting, cleanliness, and acoustics:

- *Lighting* is a broad category that includes both natural daylighting and artificial lighting. As a general rule of thumb, high daylighting permeability within learning spaces is encouraged, as it is associated with elevated well-being status of students and educators and higher productivity. Similar to artificial lighting, glare, and lighting intensity should be consistent with activities in the learning environment.
- *Cleanliness*, another attribute considered in our study, refers to the status of housekeeping work in the learning environment. Regular upkeep of learning spaces aims to protect occupants against potential allergens, maintain required hygiene levels and promote positive well-being and productivity.
- *Material selection influences the noise levels* – and echo – in learning spaces. Materials differ in their effectiveness of noise absorption. For example, glass and ceramic floor tiles are considered low-absorbing materials, while wood, or any high permeable matter is noise absorbent. Learning spaces need to be designed in accordance with the acoustics dynamics that is anticipated to take place.

What do we mean by the carbon footprint? The carbon footprint accounting exercise refers to the total amount of GHG emissions associated with constructing, operating, and maintaining the built environment (Leal Filho et al., 2021). In the paper, we are concerned with the classroom operations element, specifically the operational dynamics of mechanical ventilation in light of thermal comfort.

The relationship between thermal comfort, indoor air quality (IAQ), indoor environmental quality (IEQ), and the carbon footprint of learning spaces is significant and calls for attention from architects, designers, and facility managers. By understanding the interplay between the different parameters and sub-parameters, the objectives of the carbon footprint of educational facilities can be altered to strike a balance between occupants' health and well-being and sustainable campuses operations.

Moving forward, the document is organized as follows: (2) Methodology section details the sample population and distribution of the thermal comfort survey which is the main tool for primary data, (3) Results section provides a snapshot of the survey summary, (4) Analysis section delves into details about occupant perceptions on thermal comfort, indoor air quality, indoor environmental quality and the impact on learning, (5) Discussion section attempts to answer the main research questions linking the survey findings to insights on the topic of the carbon footprint of educational facilities post the pandemic. Finally, (6) the Conclusion summarizes the research findings and details the forthcoming research endeavors based on this baseline study.

2. Methodology

2.1. Learning Spaces Selection

The selected learning spaces vary in their built-up area, orientation, and maximum occupant capacity. Classrooms.

- **Setting.** The two classrooms are adjacent to one another, on the ground floor and are overlooking an inner courtyard at the School of Sciences and Engineering at the American University in Cairo (AUC).
- **Openings.** The doors for the classrooms and windows are aligned at one end, at the shorter end of the rectangular components of a 4m façade.
- **Lighting.** Natural lighting penetrates through the southern window façade, and the glass partition is installed within the wooden door on the same wall. The intensity of daylighting is controlled via cloth-like curtains. Artificial lighting is embedded within the tiled ceiling.
- **Cleanliness.** The facilities' housekeeping team has similar procedures in all learning spaces – including floor cleaning (either manual sweeping of floor tiles or vacuuming on carpeted spaces); regularly emptying waste baskets, as well as organizing / cleaning of furniture items.
- **Materials and Acoustics.** The architectural design of the classrooms allows for soundproofing through the installation of ceiling tiles and wall boards. The ambient noise surrounding the selected learning spaces varies in terms of intensity.
- **Ambient Noise.** The classrooms are looking towards the inner courtyard of a building, so generally, it is low decibels.

2.1.1 Design Studios.

- **Setting.** The Design Studio are located on the first floor of the Department of Architecture, SSE, AUC. The double doors opening of the Design Studio are at the opposite side of a corridor in the Department.
- **Openings**. The windows are exterior façade in the opposite orientation. The large windows have an operable curtain located in front of them.
- **Lighting.** The lighting conditions are similar to that of a classroom, however, there is higher control over the artificial lighting, to cater to the different activities taking place.
- **Materials and Acoustics**. The high ceilings, lack ceiling tiles, flooring is of ceramic tiles, however, some walls have soundproofing partitions installed which act as a double function – used for architectural drawings pin-up boards.
- **Ambient Noise.** The studios are located across from each other on the second floor of the architectural department, where other studios, and labs are located, so generally the noise level is always high due to high traffic, and the echo within the ceramic floored corridors with no soundproofing on the mortar painted walls.

2.1.2 Lecture Hall.

- **Setting.** The Lecture Hall floor plan is octagonal in shape.
- **Openings.** The two doors to the Lecture Hall are on the higher end of the Lecture Hall, and it slopes down in a stepped seating arrangement towards the podium in the centre of the room at the opposite end of the door.
- **Lighting.** The selected lecture hall is majorly dependent on artificial lighting, designed to suit the lecturing set-up where lighting controls are phased to allow for different intensities.
- **Materials and Acoustics.** The selected lecture hall is optimized for noise cancellation. The flooring is wooden, as well as the walls are soundproof.
- **Ambient Noise.** The lecture hall is located within the conference center zone, a ground-level lecture hall space. The surrounding ambient noise is generally low given that the periodic traffic is tied with the start – end schedules of events in the conference zone.

Table 1 shows the details about the selected learning spaces. Classrooms 01 and 02 are comparable in size, location, and orientation. They are adjacent to one another. Design Studio 01 and Design Studio 02 are comparable in size, and location. However, their orientation differ, as they share the same corridor, opposing one another. The Large lecture is a single case that is significantly larger in area and number of occupants than that of the Classrooms and Design Studios. The logic behind selecting the identified learning spaces is to determine whether learning spaces' configuration, spatial dimensions and design, and occupant density impact the thermal comfort of occupants.

The sample target of the survey is AUC students and staff present in the selected learning spaces where the indoor air monitors are located. The selection includes two classrooms with an average capacity of 27 students, two architectural Design Studios with an average capacity of 50 students, and a Lecture Hall with an average capacity of 100 students.

All the selected learning spaces are mechanically ventilated. The operable windows, however, are different for each of the chosen scenarios: minor operable windows for the classrooms, large operable windows for the Architectural Design Studios, and the absence of operable windows for the Lecture Hall. The small operable windows dimensions are estimated to be 25 CM by 120 CM, two at classrooms 01 and 02. The large operable windows' dimensions are 80 CM by 120 CM, with one window at each Design Studio 01 and Design Studio 02. [2]

2.1.3 Classrooms.

- **Setting.** The two classrooms are adjacent to one another, on the ground floor and are overlooking an inner courtyard at the School of Sciences and Engineering at the American University in Cairo (AUC).

[2] Floor plans are available upon request.

- **Openings.** The doors for the classrooms and windows are aligned at one end, at the shorter end of the rectangular components of a 4m façade.
- **Lighting.** Natural lighting penetrates through the southern window façade, and the glass partition is installed within the wooden door on the same wall. The intensity of daylighting is controlled via cloth-like curtains. Artificial lighting is embedded within the tiled ceiling.
- **Cleanliness.** The facilities' housekeeping team has similar procedures in all learning spaces – including floor cleaning (either manual sweeping of floor tiles or vacuuming on carpeted spaces); regularly emptying waste baskets, as well as organizing / cleaning of furniture items.
- **Materials and Acoustics.** The architectural design of the classrooms allows for soundproofing through the installation of ceiling tiles and wall boards. The ambient noise surrounding the selected learning spaces varies in terms of intensity.
- **Ambient Noise.** The classrooms are looking towards the inner courtyard of a building, so generally, it is low decibels.

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- **Openings**. The windows are exterior façade in the opposite orientation. The large windows have an operable curtain located in front of them.
- **Lighting.** The lighting conditions are similar to that of a classroom, however, there is higher control over the artificial lighting, to cater to the different activities taking place.
- **Materials and Acoustics**. The high ceilings, lack ceiling tiles, flooring is of ceramic tiles, however, some walls have soundproofing partitions installed which act as a double function – used for architectural drawings pin-up boards.
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2.1.5 Lecture Hall.

- **Setting.** The Lecture Hall floor plan is octagonal in shape.
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- **Ambient Noise.** The lecture hall is located within the conference center zone, a ground-level lecture hall space. The surrounding ambient noise is generally low given that the periodic traffic is tied with the start – end schedules of events in the conference zone.

Table 1. Selected Learning Spaces

	Space (m^2)	Average Height of Ceiling (m)	Max. Occupants	HVAC Operational	Operable Windows
Classroom 01	**22 m^2**	3.5	27	√	Small
Classroom 02	**22 m^2**	3.5	27	√	Small
Design Studio 01	**120.9 m^2**	5	50	√	Large
Design Studio 02	**120.9 m^2**	5	50	√	Large
Large Lecture Hall	**225 m^2**	10	100	√	NA

2.2. Survey Sample Size and Population

A survey was disseminated –mainly in May 2023 - to ask occupants about their level of thermal comfort in the selected learning spaces. 70 responses have been collected to date. Figure 1 and Figure 2 show the survey month of distribution and gender of respondents.

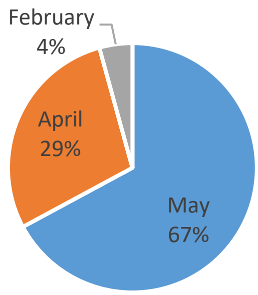

Figure 1: Responses Distribution by Month

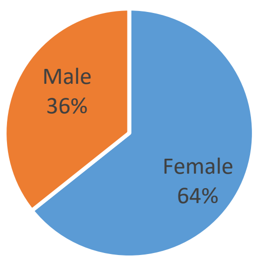

Figure 2: Gender Distribution of Sample

The survey is divided into four main sections: the respondent profile, thermal comfort, indoor air quality, indoor environmental quality, and impact on learning. The respondent profile section is focused on drawing the respondent profile (age, gender, title). Table 2 below provides a breakdown of questions and the type or format of responses required. The survey results were then exported, and data were synthesized.

Table 2. Survey Design Details

	Question(s)	Type / Format
Respondent Profile	Title	Drop Down
	Age	Short Answer
	Gender	Drop Down
Thermal Comfort	When you entered the classroom temperature was	Rating 1= Very Uncomfortable 5= Very Comfortable
	Are you wearing your Jacket / Jumper / Sweater	Y/N
	Have you ever experienced heat stress-related disorders like cramps, dehydration, heat exhaustion, and heat stroke?	Y/N
Indoor Air Quality	How do you feel about the level of mechanical ventilation in this classroom? (e.g.: air conditioning or fan)	Linear Scale Rating 1 = Too Hot 5= Too Cold
	How satisfied are you with the provision of air movement in this classroom? (e.g.: openings)	1 = Very unsatisfied 5 = Very Satisfied
Indoor Environmental Quality	How satisfied are you with the natural day lighting in this classroom?	Linear Scale Rating 1 = Too Dark 5 = Too light
	What is your rate for the overall quality of noise control in the classroom?	Linear Scale Rating 1 = Very Poor 5 = Very Good
	What is your perception of the level of cleanliness in this classroom?	Linear Scale Rating 1 = Very Dirty 5 = Very Clean
	What is your overall comfort level in your classroom area?	Linear Scale Rating 1 = Very Uncomfortable 5 = Very Comfortable
Impact on Learning	To what extent do you think your productive learning is affected by the poor indoor environmental conditions of the building?	Linear Scale Rating 1 = Much Decreased 5 = Much Increased
	Do you have any comments or suggestions on improving the learning environment?	Short answer questions

The target respondents were occupants inside the classrooms during the survey dissemination, either before the scheduled class begins or after the class concludes. Table 3 shows the responses collected per location: 14 respondents in Classroom 01, 23 respondents in Classroom 02, 15 respondents in Design Studio 01, 14 Respondents in Design Studio 02, and 5 respondents in the Lecture Hall. Another way to look at the responses categorization per learning space is 37 responses in classrooms and 29 responses in Design Studios, and five respondents in the Lecture Hall.

Table 3: Number of Responses

Respondent Profile	Class 01	Class 02	Design St 01	Design St 02	Lecture Hall
No. of Responses	14	23	15	14	5
	37		29		5

2.3. Study Limitations

The study is confronted by several limitations concerning sample size and data validation methods. The sample size and distribution do not represent classroom occupancy rate and schedule. However, the sample is wide enough to obtain accurate results. Specifically for classrooms (1) and (2), and Design Studios (1) and (2); the sample target is at approximately 50% and 25%, respectively of population size in full occupancy status. The Lecture Hall sample is not wide enough, and the results are considered a pilot for wider dissemination in the future.

Data validation is yet another lacking aspect of the research. However, the study is considered a baseline study. Future validation is planned by comparing thermal survey responses to data points acquired by indoor air quality monitors installed at selected locations. Then it would be compared at the exact timestamp of the survey.

While air movement and speed are important parameters in analyzing air-conditioned space comfort, the researchers could not collect data relating to these parameters Thus, the study has some limitations in analyzing in full the comfort. However, since the study focuses on understanding the users' perception, the lack of air movement data can be addressed in future studies which are focused on more comparative analysis between perceived and measured comfort parameters in these classrooms.

3. Carbon Footprint of Learning Spaces and Case Study Considerations

To be able to compare the perceptions of occupants regarding IAQ, IEQ, and thermal comfort to the carbon footprint of university classrooms; a set of values are identified from the literature to benchmark the selected classrooms' energy consumption against the set points (temperature when entering the classroom, HVAC ventilation rate, and operating schedule). The values include Energy Use Intensity (EUI) (Kwh/y/m^2), estimates of HVAC energy on EUI (%), and the effect of daylighting on energy savings (%).

3.1. Energy Benchmarking

The energy benchmarking technique allows for energy comparison between buildings by dividing the key performance metric by flow area, and it is known as Energy Use Intensity (EUI) (Chihib et al., 2020). Laboratories often have the highest energy use intensity within learning spaces rather than classrooms - 98 kwh/y/m^2 as cited in (Chihib et al., 2020). In another study, estimating the EUI in a university campus in Saudi Arabia, the average range of EUI for all spaces was approximately 145–155 kWh/m^2 (Alfaoyzan and Almasri, 2023). The Energy Star Performance standards gives a value of 567 kwh/m^2 for Education Buildings at source and a value of 264 kWh/m^2 at the building site. (Litardo et al., 2021) the wide range of 47–628 kWh/m2/year applies to academic buildings in hot and humid climates. As noted from the literature, estimating the EUI value in a university classroom is a factor of campus design, climate, building types, operation schedule, and the extent of energy efficiency measures in place. For our study, a range between 150 – 300 kWh/y/m2 is selected to base our comparison – using both the minimum and maximum values to highlight differences in carbon footprint scenarios.

As for estimates of HVAC energy on EUI, the range also varies according to the context of the case study: climatic zone and building envelope and systems. (Alfaoyzan and Almasri, 2023) Calculated that HVAC systems consume almost 80% of the total energy used on campus, whereby this value can be considered on the higher side of the spectrum due to the desert climate of Saudi Arabia. (Litardo et al., 2021) referenced studies point towards HVAC consumes about 50% of the total energy of campuses, and artificial lighting is on the 20% spectrum. The impact of daylighting on EUI in academic buildings; also depends on the context of the case study, and the percentage savings is a factor of measures in place to maximize the use of daylighting strategies – hence, reducing the energy consumption for artificial lighting. For the purpose of our analysis, we will estimate that HVAC's impact on EUI is in the range of 40 – 60%, and artificial lighting within the range 20 – 30 %.

Table 4 shows the ranges of each of the selected parameters, references literature where values were extracted, and then translates it to the values within AUC University Campus based on the latest carbon footprint report. It is important to note that the referenced values are approximate, as they depend on case-specific conditions.

Table 4: Benchmarking Energy Consumption

Parameter	Unit	Range	Avg. Value	Ref.	AUC Report	AUC Carbon Footprint Measurement M tCO_2 / yr (AY 20 Data)	The Magnitude of Effect
Energy Use Intensity (EUI)	**kwh/y/m²**	**150 - 300**	**225**	**(Alfaoyzan & Almasri, 2023; Chihib et al., 2020, 2020; *What Is Energy Use Intensity (EUI)?*, 2023)**	-	-	-
Estimates of HVAC energy on EUI	**%**	**40 - 60**	**50**	**(Alfaoyzan and Almasri, 2023; Litardo et al., 2021)**	**41% for HVAC and Domestic Hot-water**	**14,002 MT CO2 e**	**High**
Effect of Lighting on EUI	**%**	**20 – 30**	**25**	**(Litardo et al., 2021)**	**20% artificial lighting (non-HVAC)**	**7,037 MT CO2 e**	**Low**

3.2. Learning Spaces Pre-sets

Due to the classrooms' proximity, they are supplied by the same Air Handling Unit (AH), which applies to the Design Studios. The temperature presets for the classrooms is within the 23 – 24˚C range and the Design Studios are within the 22-23˚C range. We can deduce that the temperature presets in classrooms and design studios is not very different but could be significant when comparing it to lecture halls. The higher ventilation rates in lecture halls, double that of classrooms and design studios, means that thermal comfort perceptions must consider such conditions. The average lux at the work surface level in different rooms was measured using a lux meter. Table 5 shows these presets.

Table 5: Classroom Pre-sets

Classroom Pre-sets	Unit	Classrooms	Design Studios	Lecture Hall
Temperature Preset	**˚C**	**23 – 24**	**22-23**	**20-21**
Min % of Fresh Air in HVAC Systems[3]	**(%)**	**21.7** **(Facility Management and Operations, 2023)**	**21.7** **Assumption (Facility Management and Operations, 2023)**	**40** **(The American University in Cairo, 2021)**
Daylight	**Lux**	60 **Not controlled**	55 **Not controlled**	52 **Not Controlled**
Daylight + Artificial light	**Lux**	135	550	130

4. Survey Results and Analysis

The survey results were exported to Excel, and the answers (yes and no questions, rating from 1 to 5) were converted to weighted percentages for easier comparison and analysis – refer to Appendix I – Results Overview.

The analysis follows the same survey: the respondent profile, thermal comfort, indoor air quality, indoor environmental quality, and impact on learning. The survey findings consider both total responses to understand occupant priorities pertaining to thermal comfort, indoor air quality, and indoor environmental quality. The analysis per learning space was compared to understand specific contextual constraints.

4.1. Respondent Profile

Most participants, accounting for 98% of the total, are students, whereas a small proportion of faculty members constitute merely a 2%. Thus, the participant pool was understandably young with a mean average age of 21.69 years. Furthermore, the notable proportion of female participants – 64% - is reflective of the overall student enrolment at the Department of Architecture at AUC, suggesting a gender distribution representative of the department's demographics – specifically for Design Studio 01 and 02 – refer to Table 6.

Table 6: Respondent Profile (Gender)

Gender	Class 01	Class 02	Design St 01	Design St 02	Lecture Hall	Total
No. of Females	5	15	10	12	4	46
No. of Males	9	8	5	2	1	25
Total Responses	**14**	**23**	**15**	**14**	**5**	**71**

4.2. Thermal Comfort

The analysis of the results suggests that the perception of the initial temperature comfort, the need for additional clothing (wearing a jacket), and the occurrence of heat stress-related disorders vary among the different learning spaces and is potentially influenced by factors

[3] Also referred to as Minimum Air Flow – CFM Schedule

such as ventilation, as well as activity levels in each location. Table 7**Error! Reference source not found.** shows the percentages of thermal comfort perceptions in different learning spaces by weighted averages (i.e. showing the perception of initial comfort due to room temperature and charts the number of respondents wearing jackets and those who experienced heat stress-related disorders within the selected learning spaces).

Regarding initial temperature comfort, the Lecture Hall had the highest reported comfort level with 80%, followed by Class 01 with 72.4%. The lowest initial comfort level was reported in Design St 01 with 62.8%. Additionally, the need for additional clothing varied across different settings. Design St 01 had the highest percentage of respondents wearing jackets/jumpers/sweaters at 60%, followed by Design St 02 with 35.71%. Class 01 had the lowest percentage at 14.29%. While both outdoor air temperature – occupants still did not remove additional clothing - and indoor temperature are determinants of additional clothing, it is notable that most of the Design Studios respondents are female – 22 out of 29 respondents. Literature suggests that females are more sensitive to the thermal environment and are twice more likely to report on thermal discomfort (Indraganti and Humphreys, 2021).

The occurrence of heat stress-related disorders also showed variation among the different locations. Class 01 had the highest percentage of respondents experiencing heat stress-related disorders at 42.86%, followed by Design St 01 at 40%. The lowest percentage was reported in the Lecture Hall at (pilot case) 20%. In retrospect, the classrooms are of the highest density: volume of the space/number of occupants. On the other end of the spectrum is the large Lecture Hall – which, yet the sample needs to be enlarged for greater validity – has the most significant built-up area and notably the lowest occupant density, and in between are the Design Studios. In the case of Classroom 01's occurrence of heat-related disorders coincides with the lowest initial temperature comfort, suggesting a possible correlation. However, this does not rule out that other factors may be at play – including the state of the mechanical ventilation systems, length of lectures or classroom occupancy (activity), airflow and openings – amongst other factors. Also, at Design Studio 01 where responses indicated a low level of initial comfort level and a relatively high need for additional clothing, reported a higher percentage of heat stress-related disorders compared to other learning spaces.

There are several reasons to consider on why students report heat stress disorders when the inside temperature of the classroom is between 22 to 24 ˚C. Outdoor weather conditions during the months of April and May in Cairo, is generally associated with warm weather conditions, as Cairo is considered a hot arid climatic zone. The hot weather conditions usually have an average exceeding 30˚C. Moreover, there is a large discrepancy between outdoor air temperatures and those in HVAC ventilated learning spaces, as the HVAC systems are centralized, and occupants have low levels of control on the air condition systems. The delta difference between indoor and outdoor temperatures may lead to thermal discomfort as students navigate between both environments.The high level of clothing may be attributed to students wearing jackets for warmth inside classrooms, though when they navigate the outdoors, they opt for more lightweight and loose-fitting clothing to stay comfortable during the hot weather conditions attributed to the months of April and May in Cairo. The exact preferences would for clothing factors would differ from one person to another, but in general it is difficult to maintain a high level of thermal comfort when expected to navigate between such high temperature variations – indoor vs. outdoor.

Table 7: Thermal Comfort Survey Results

Thermal Comfort	**Class 01**	**Class 02**	**Design St 01**	**Design St 02**	**Lecture Hall**	**Total weighted Average**
Number of Responders	14	23	15	14	5	71
When you entered the classroom temperature was (%)	72.40	67.80	62.80	74.20	80.00	70.77
Are you wearing your Jacket / Jumper / Sweater (% Yes)	14.29	30.43	60.00	35.71	20.00	34.29
Have you ever experienced heat stress-related disorders like cramps, dehydration, heat exhaustion, and heat stroke? (% Yes)	42.86	30.43	40.00	28.57	20.00	34.29

4.3. Indoor Air Quality

By analyzing the indoor air quality questions in the survey, a number of observations are noted on occupants' satisfaction with the mechanical ventilation systems in selected learning spaces and air movement satisfaction. Table 8 documents the survey responses to questions related to indoor air quality, and presents the correlation between perceptions of mechanical ventilation systems and satisfaction levels on air movement in learning spaces.

In terms of mechanical ventilation perception, Classroom 01 had the highest rating for mechanical ventilation adequacy with respective scores of 70.8%, followed by Design Studio 02. It is important to note that Classroom 01 and 02 are supplied by the same Air Handling Unit (AHU), and have an identical orientation, layout and spatial design, and the classroom activities are similar – follow the same scheduling procedures. The 5% discrepancy in respondents may have to do with the higher percentage of female respondents in Classroom 02, which are prone to more thermal discomforts and sensitive to the learning spaces environment. In Design Studios, we observe the following: though the studios have the same layout and built-up area, their orientation differs and there is more dissatisfaction with the perceptions of air movement satisfaction correlated to the levels of mechanical ventilation perception; however, not identical. The highest satisfaction level are in classrooms, followed by the design studios.

Table 8: Indoor Air Quality Survey Results

Indoor Air Quality	Class 01	Class 02	Design St 01	Design St 02	Lecture Hall	Total Average
Number of Responders	14	23	15	14	5	71
How do you feel about the level of mechanical ventilation in this classroom? (e.g.: air conditioning or fan)	70.80	65.20	57.40	67.20	60.00	65.61
How satisfied are you with the provision of air movement in this classroom? (e.g.: openings)	72.40	54.80	48.00	62.80	64.00	59.90

4.4. Indoor Environmental Quality

While Indoor Environmental Quality (IEQ) spans include a large set of parameters, the survey focused on three elements: natural daylighting, noise control, and level of cleanliness, as well as getting a gest of the perception of occupants on the overall comfort level.**Error! Reference source not found.** Figure 3 charts the survey responses to questions related to IEQ, in a stacked-bar diagram.

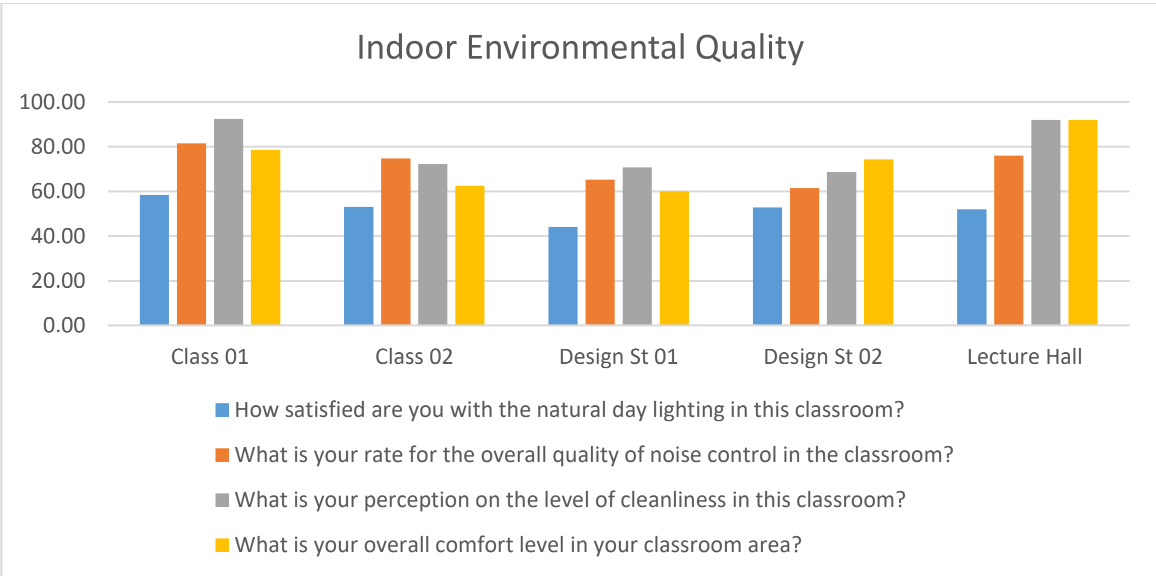

Figure 3: Indoor Environmental Quality

4.5. Impact on Learning

Regarding the overall perception of the impact of poor indoor air quality on learning productivity, a total weighted average of 53.14 % was given – refer to **Error! Reference source not found.**. This question relates to the thermal comfort of occupants to the specific location.

Table 9: Impact on Quality Survey Results

Impact on Learning	Class 01	Class 02	Design St 01	Design St 02	Lecture Hall	Total Average
Number of Responders	14	23	15	14	5	71
What is your overall comfort level in your classroom area?	78.46	62.61	60.00	74.29	92.00	70.55
To what extent do you think your productive learning is affected by poor indoor environmental conditions of the building?	60.00	53.04	44.00	52.86	52.00	53.14

4.6. Suggestions for Improvement

Several occupants provided suggestions for improving the learning environment in selected spaces. The most voiced suggestion is to gain control over the thermostat of the HVAC systems. The central HVAC systems does not permit total control over temperature. Another line of suggestions expressed the preference of occupants for more natural light permeability in classrooms to improve overall learning productivity. Noise cancellation was also mentioned as a measure to improve the learning environment. Finally, some students expressed the need for more ergonomically comfortable classroom seating. Such suggestions are important to take into consideration to enhance the learning environment: better control over temperature, adequate natural lighting, reduced noise levels and distractions, as well as comfortable seating options that correlate to the type of activity taking place in the classroom – refer to Figure 4.

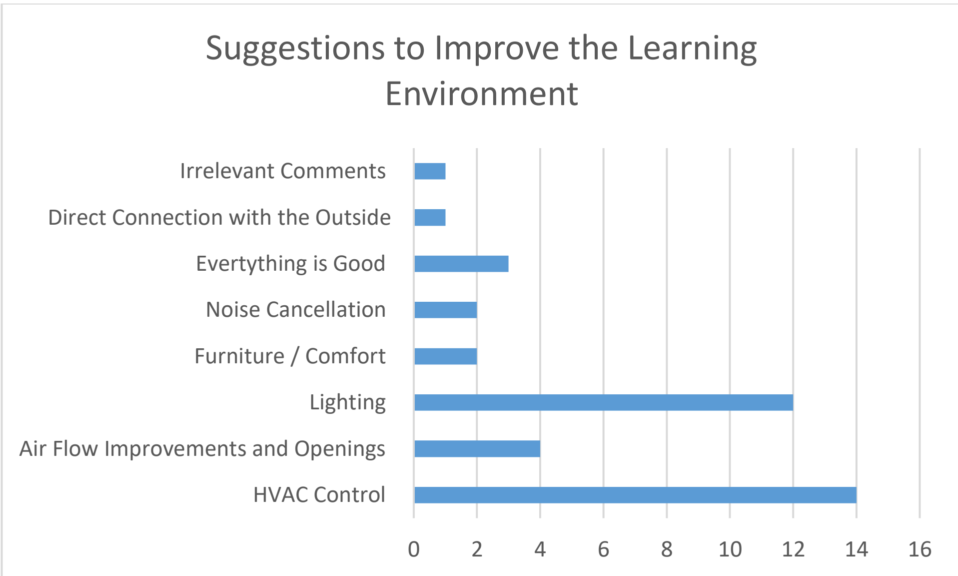

Figure 4: Suggestions to Improve the Learning Environment

5. Statistical Analysis

To further understand the collected data, several statistical tests were conducted. First, the descriptive statistics for the variables were calculated and the normality of all data was checked using the Shapiro-Wilk test (seen in Table 10). The direct reported variables (scale 1-5) are used for this analysis. The results showed that all variables are not normally distributed

– and thus, non-parametric tests were used (“Wilk Test - an overview | ScienceDirect Topics,” 2023; Zach, 2021).

Table 10: Descriptive Stats

	Satisfaction with Temp.	Jacket	Heat Stress	Vent.	Air Movement	Sat. with lighting	Noise	Cleanliness	Overall Comfort	Effect on Learning
Mean	3.47	0.34	0.34	3.23	2.94	2.6	3.57	3.81	3.47	3.11
Minimum	1	0	0	1	1	1	1	1	1	1
Maximum	5	1	1	5	5	5	5	5	5	5
Std. Deviation	0.99	0.48	0.48	0.82	1.15	0.91	1.11	1.04	1.02	1.22
P-value of Shapiro-Wilk	P<0.01									

Spearman’s correlation test analysis was used – Table 11. Spearman’s correlation describes the relationship between two variables and is helpful for non-normally distributed and ordinal data (Schober et al., 2018). Moreover, the test is relatively robust for outliers (Schober et al., 2018). The results of the correlations tests showed that:

- It is observed that occupants perceive their satisfaction with temperature and the level of air movement positively.
- Air movement, satisfaction, and cleanliness are strongly positively correlated with the perception of overall comfort in the spaces; noise is less of a predictor of overall comfort, and satisfaction with lighting is the least powerful predictor.
- As expected, there is a medium correlation between air movement and ventilation
- Also as expected, there is a weak correlation between temperature and lighting and heat stress and air movement.

Table 11: Spearmann’s Correlation

Variable	1	2	3	4	5	6	7	8	9	10
Age (1)	—									
Satisfaction with Temperature (2)	-0.041	—								
Jacket (3)	-0.023	-0.167	—							
Heat Stress (4)	-0.198	-0.156	-0.014	—						
Ventilation (5)	0.037	-0.106	0.09	-0.091	—					
Air Movement (6)	-0.076	0.438 ***	-0.017	-0.316 **	0.34 **	—				
Satisfaction with Lighting (7)	-0.048	0.236 *	-0.11	-0.177	-0.033	0.168	—			
Noise (8)	0.059	0.196	-0.108	-0.012	0.032	0.026	0.075	—		
Cleanliness (9)	0.078	0.245 *	-0.108	-0.051	0.19	0.224	0.074	0.515 ***	—	
Overall Comfort (10)	-0.039	0.434 ***	-0.069	-0.208	0.198	0.492 ***	0.25 *	0.335 **	0.472	—
Effect on Learning	-0.009	0.069	-0.137	-0.171	0.061	0.105	-0.1	-0.027	0.144	0.2***
* p < .05, ** p < .01, *** p < .001										

Further, a set of MANOVA and ANOVA tests were run to determine the Sums of Squares, Mean Squares, and F-test analysis, which is yet another method to determine the means of groups differences between three or more variables and ''includes spreading out the variance into diverse sources'' (Greenwood & Banner, 2023). The results of the ANOVA test showed that, generally, there is not many significant differences between the classes and studios. The differences are mainly concentrated on (organized by decreasing significance):

- Cleanliness (most significant at $p<.0.01$)
- Overall Comfort ($p<0.05$)
- Air Movement ($p<0.05$)

Over all, Table 12 shows the comparative differences extracted from all the statistical tests. For detailed statistical comparative analysis, refer to Appendix II – Statistical Analysis – MANOVA + ANOVA.

Table 12: Comparative Differences

	Classes	**Studios**
Classes	-	Noise and cleanness are significantly different.
Lecture Hall	Overall comfort is significantly different	Noise and cleanness are significantly different

6. Discussion

In this section, the authors aim to respond to the two core research questions - What measures are in place to help improve thermal comfort in an educational setting without undermining occupants' health and energy – given the COVID-19 pandemic? And, to what extent can a balance be achieved between thermal comfort, occupant's health, and HVAC energy (carbon footprint) in an educational setting – considering the means and rate of viral transmission of COVID-19?

Reflecting on the suggestions of occupants to gain control over the HVAC systems, the mechanical ventilation system in the specific case study either over-cools or does not work correctly on hot summer days. Integrating energy-efficient HVAC systems catering to occupants' thermal preferences can positively reduce the energy loads, thus decreasing the facility's carbon footprint This discussion is highly relevant post the pandemic, where authority organizations recommend a higher percentage of fresh air – including ASHRAE, CDC, and REHVA.

The perception of occupants on the direct relationship between poor indoor air quality levels and decreased productivity in learning is scientifically verified. Improved indoor air quality levels promote a healthy increase in concentration levels. The lack thereof, however, is associated with various health problems, including respiratory diseases, allergies, and reduced ability of cognitive functions (Marzouk and Atef, 2022). As witnessed by (Marey et al., 2023), poor ventilation leads to poor indoor air quality. Especially in the selected classrooms, which has the smallest volume, tend to accumulate a high level of carbon dioxide during scheduled lectures. The poorly ventilated classrooms, followed by studios (both by centralized HVAC systems), and best are the lecture halls (due to a highly functioning HVAC system) result in stale air, which leads to difficulties in concentration and decreased cognitive function. To address poor IAQ in learning spaces, there are several measures that could be taken including (1) conducting regular maintenance and cleaning of ventilation systems, (2) selection of low emitting materials – for example carpets can emit a high level of VOCs, (3) regular monitoring and testing of indoor air quality – which can help identify issues and enable timely interventions for improvement. This suggests that facility managers are encouraged to monitor the indoor air quality of classrooms and take informed actions based on the available data. For example, high carbon dioxide levels mean that airflow in the classroom is problematic, and the percentage of fresh air within HVAC systems should be increased. This is another measure that would enhance HVAC energy consumption, meaning that the variability in fresh air outage is based on occupants' exposure time and activity.

On the indoor environmental quality front, several observations can be denoted to reflect on the carbon footprint of classrooms based on the perceptions of occupants in learning spaces. Incorporating natural lighting into learning spaces enhances the IEQ and reduces reliance on artificial lighting, leading to energy savings. Architects should prioritize passive design strategies that optimize daylight utilization and reduce the need for excessive lighting and associated energy consumption. This depends on the architecture of the learning space (existing or new) and the type of activity taking place. One behavioural aspect not noted in the selected classrooms and Design Studios, is the opening of curtains when necessary to permit day light. Remedying the noise control within spaces depends on many factors, as discussed earlier. But when looking at noise control from the perspective of reducing the carbon footprint, the indirect link lies in the choice of materials of the classrooms – which are recommended to tick both boxes: noise absorbing and sustainable in terms of low embodied carbon.

Measurable correlation between the parameters and sub-parameters of thermal comfort, IAQ, IEQ and carbon footprint could be quantitively modelled by conducting a life cycle assessment to evaluate the environmental impact of building materials, energy consumption, and maintenance practices over the lifespan of the educational facilities, a topic for future research. Changing the operation scenarios might lead to more conclusive findings on achieving the balance between such parameters in light of changing facilities prior to safeguard the health of occupants, well-being- and comfort.

7. Conclusion

The main contribution of this research was to interpret the thermal comfort perceptions of occupants and understand its implications on the carbon footprint of buildings within learning spaces in the context of the pandemic and post-pandemic. As educational facilities navigate the challenges of spiking energy costs post the pandemic, it is crucial to understand the interplay between thermal comfort and environmental sustainability – both at the micro level of indoor environmental quality of learning spaces and at the level of sustainable operations for campuses.

The survey responses revealed intricate observations about the satisfaction levels of occupants regarding thermal comfort, IAQ and IEQ. While some of the perceptions are context-specific, others are generalisable. Factors affecting thermal comfort perception include ventilation, type of activity in the learning space, clothes or degree of body insulation, and exposure time. For example, the variations in students' votes between similar spaces, such as Classroom 1 and Classroom 2, can be attributed to differences in occupancy rates. Figure 5 shows the analysis of total weighted responses in selected learning spaces.

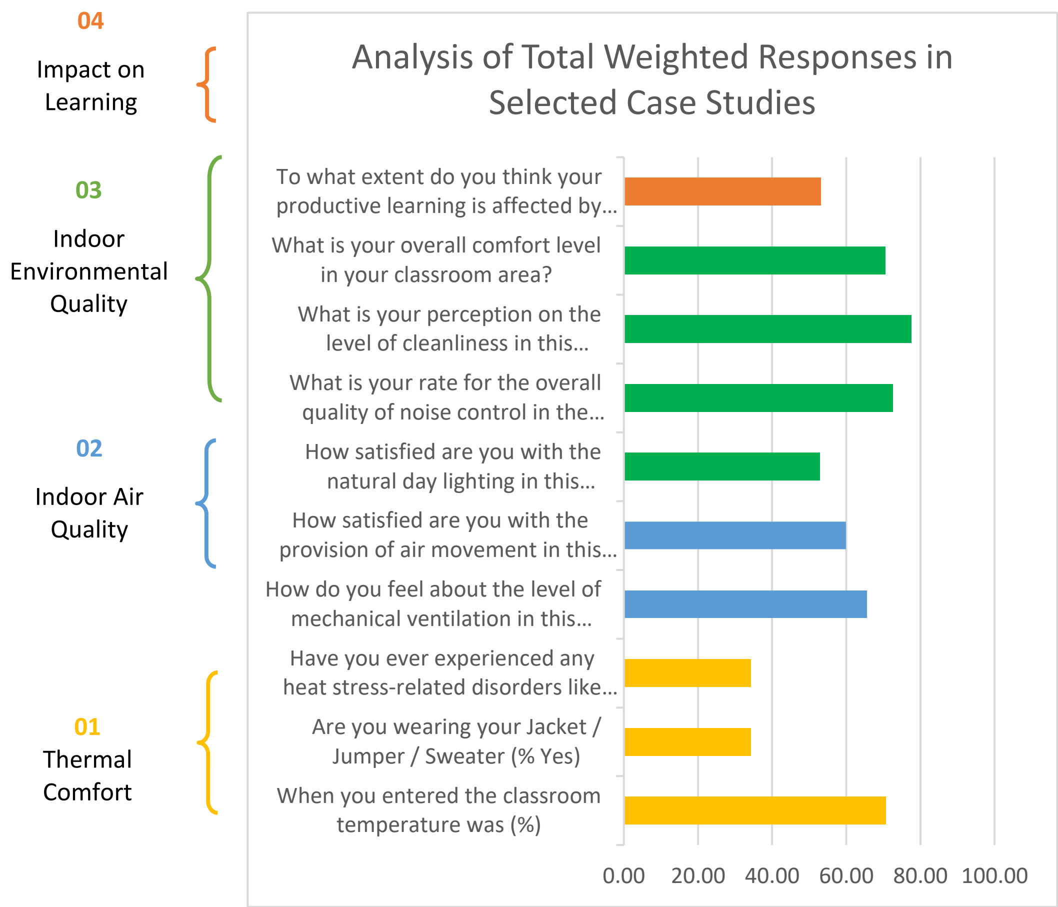

Figure 5: Analysis of Weighted Total Responses in Selected Case Studies (%)

In summary, the statistical analysis of the studied variables showed that all: (1) all variables are not normally distributed (used non-parametric tests); (2) overall comfort is highly correlated (positive) with temperature, air movement, and cleanliness – weakly correlated with noise and very weakly correlated with light; (3) temperature and air movement are probably sensed together; and (4) generally, their negligible differences between spaces (2 classes and 2 studios). Differences mainly concentrated on (organized by decreasing significance): Cleanliness (most significant at $p<.0.01$); Overall Comfort ($p<0.05$)and Air Movement ($p<0.05$). When comparing the 3 types (Classes, studios and lecture hall), the main differences are cleanness, noise, and overall comfort.

The findings of the paper call for further research to investigate occupants' perception regarding thermal preferences in university classrooms which would directly affect the occupants' ability to learn. Implementing low-carbon strategies such as giving occupants control over the thermostat in classrooms, installing ceiling fans to improve air circulation, and maximizing daylighting within classrooms significantly enhance occupants' comfort and improve the educational experience. Building on this paper's findings', future research directions could include: monitoring IAQ levels within the selected classrooms and correlating the findings to a similar survey design on occupants' perception, thus, increasing the research validity. Another direction is to study the Life Cycle Assessment of learning spaces for a reduced carbon footprint while achieving the balance between occupants' health and comfort.

The pandemic has raised awareness of the importance of healthy environments and the need for increased healthy environments. It also has changed the carbon footprint scale for institutions, especially in arid environments, where the dependence on mechanical ventilation is higher during off-thermal comfort zones. The discussion section has posed a starting thread on balancing thermal comfort, IAQ, IEQ, and carbon footprint. There are measures to be taken by architects, designers, and facility managers to reduce the carbon footprint. One example is the design of HVAC systems that enables occupant control over the thermostat, monitoring IAQ levels, and maximizing natural lighting penetration when feasible. By embracing innovative solutions and considering the long-term impact of design choices, universities can enhance occupants' health and comfort within learning spaces while contributing to higher educational productivity.

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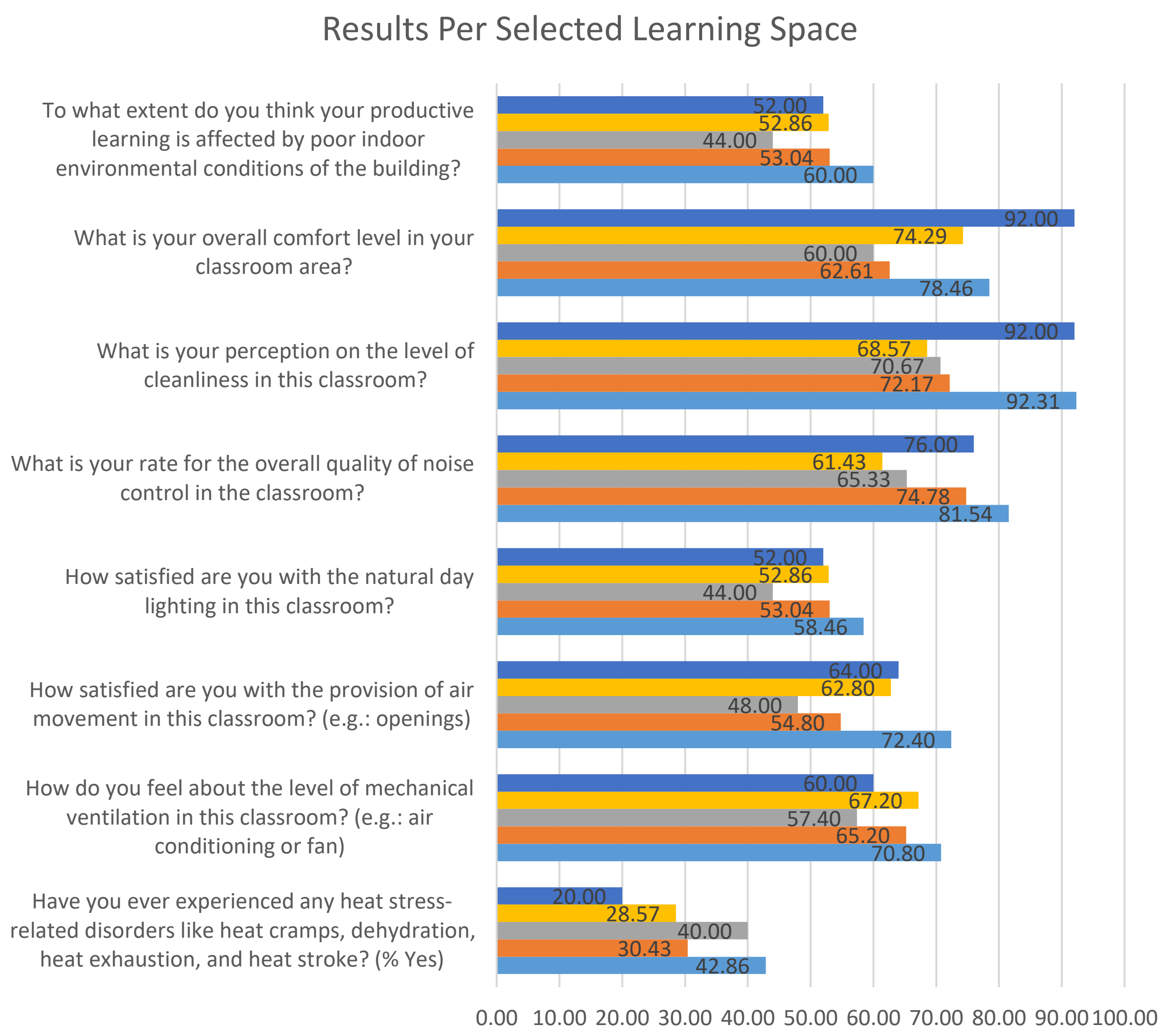
Notice

The authors would like to note that the information and views presented in this research paper are solely their own and do not reflect those of the institution. Any errors or omissions are entirely our responsibility.

Appendix I – Results Overview



	Have you ever experienced any heat stress-related disorders like heat cramps, dehydration, heat exhaustion, and heat stroke? (% Yes)	How do you feel about the level of mechanical ventilation in this classroom? (e.g.: air conditioning or fan)	How satisfied are you with the provision of air movement in this classroom? (e.g.: openings)	How satisfied are you with the natural day lighting in this classroom?	What is your rate for the overall quality of noise control in the classroom?	What is your perception on the level of cleanliness in this classroom?	What is your overall comfort level in your classroom area?	To what extent do you think your productive learning is affected by poor indoor environmental conditions of the building?
Lecture Hall	20.00	60.00	64.00	52.00	76.00	92.00	92.00	52.00
Design St 02	28.57	67.20	62.80	52.86	61.43	68.57	74.29	52.86
Design St 01	40.00	57.40	48.00	44.00	65.33	70.67	60.00	44.00
Class 02	30.43	65.20	54.80	53.04	74.78	72.17	62.61	53.04
Class 01	42.86	70.80	72.40	58.46	81.54	92.31	78.46	60.00

Figure 6: Survey Results per Specific Location

Appendix II – Statistical Analysis – MANOVA + ANOVA

Table 13: MANOVA

MANOVA: Pillai Test

Cases	df	Approx. F	$Trace_{Pillai}$	Num df	Den df	p
(Intercept)	1	352.31599	0.98546	10	52	4.40283×10^{-44}
Class	3	1.56881	0.67536	30	162	0.04065*
Residuals	61					

MANOVA: Wilks Test

Cases	df	Approx. F	Wilks' Λ	Num df	Den df	p
(Intercept)	1	352.31599	0.01454	10	52	4.40283×10^{-44}
Class	3	1.57863	0.45377	30	153.30626	0.03948*
Residuals	61					

Table 14: ANOVA

ANOVA: Satisfaction with Temperature

Cases	Sum of Squares	df	Mean Square	F	p
(Intercept)	758.21538	1	758.21538	805.59596	7.44691×10^{-37}
Class	4.37229	3	1.45743	1.5485	0.2111
Residuals	57.41233	61	0.94119		

ANOVA: Jacket

Cases	Sum of Squares	df	Mean Square	F	p
(Intercept)	8.13846	1	8.13846	37.11425	8.17767×10^{-8}
Class	1.48538	3	0.49513	2.25795	0.09064
Residuals	13.37616	61	0.21928		

ANOVA: Heat Stress

Cases	Sum of Squares	df	Mean Square	F	p
(Intercept)	8.13846	1	8.13846	34.10249	2.16933×10^{-7}
Class	0.30406	3	0.10135	0.4247	0.73598
Residuals	14.55748	61	0.23865		

ANOVA: Ventilation

Cases	Sum of Squares	df	Mean Square	F	p
(Intercept)	684.93846	1	684.93846	1028.761	6.81636×10^{-40}
Class	3.44837	3	1.14946	1.72645	0.17097
Residuals	40.61317	61	0.66579		

ANOVA: Air Movement

Cases	Sum of Squares	df	Mean Square	F	p
(Intercept)	555.38462	1	555.38462	452.76328	6.43137×10^{-30}
Class	11.78939	3	3.9298	3.20367	0.02933*
Residuals	74.82599	61	1.22666		

ANOVA: Satisfaction with Lighting

Cases	Sum of Squares	df	Mean Square	F	p
(Intercept)	439.4	1	439.4	517.89252	1.67567×10^{-31}
Class	3.84525	3	1.28175	1.51071	0.22073
Residuals	51.75475	61	0.84844		

ANOVA: Noise

Cases	Sum of Squares	df	Mean Square	F	p
(Intercept)	820.93846	1	820.93846	723.453	1.55870×10^{-35}
Class	8.84177	3	2.94726	2.59727	0.0604
Residuals	69.21976	61	1.13475		

ANOVA: Cleanliness

Cases	Sum of Squares	df	Mean Square	F	p
(Intercept)	915.93846	1	915.93846	968.03646	3.92422×10^{-39}
Class	12.34445	3	4.11482	4.34886	0.00767**
Residuals	57.71709	61	0.94618		

ANOVA: Overall Comfort

Cases	Sum of Squares	df	Mean Square	F	p
(Intercept)	744.61538	1	744.61538	835.12492	2.67683×10^{-37}
Class	8.9957	3	2.99857	3.36305	0.02429*
Residuals	54.38892	61	0.89162		

ANOVA: Effect on Learning

Cases	Sum of Squares	df	Mean Square	F	p
(Intercept)	615.38462	1	615.38462	397.93462	2.02570×10^{-28}
Class	2.28215	3	0.76072	0.49191	0.68921
Residuals	94.33324	61	1.54645		

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