Chapter-28

Towards Decarbonisation in the Built Environment

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Abstract

The built environment is a major contributor to global energy consumption, greenhouse gas emissions, and material use, making it central to efforts aimed at mitigating climate change. Buildings and infrastructure account for a significant share of carbon dioxide emissions due to energy-intensive construction practices, fossil fuel–based operations, and inefficient use of materials. This paper examines the concept of decarbonisation in the built environment as a systemic and life-cycle–oriented approach that integrates energy efficiency, low-carbon technologies, renewable energy systems, material optimization, and circular construction practices. It explores theoretical foundations of decarbonisation, carbon accounting and boundary setting, energy systems and building performance, embodied carbon in materials and construction, and the influence of urban form and policy frameworks. The study further highlights the role of modelling, digital twins, life-cycle assessment, and stakeholder governance in enabling effective transitions toward low- and zero-carbon buildings. Drawing on international policy targets and case-based insights, the paper underscores the urgency of coordinated near-, mid-, and long-term strategies to achieve carbon-neutral built environments by mid-century, while ensuring social equity, resilience, and economic feasibility.

Keywords: Decarbonisation; Built Environment; Carbon Emissions; Energy Efficiency; Embodied Carbon; Low-Carbon Technologies; Renewable Energy; Life-Cycle Assessment; Sustainable Construction; Urban Planning

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1. Introduction

The anthropogenic influence on Earth’s climate is vigorously altering climate patterns and driving temperature increases worldwide. Existing international treaties and voluntary instruments are inadequate to deal with the climate crisis because they do not necessitate emissions reductions and do not encompass the most substantial contribution to climate change: carbon dioxide (CO2) emissions from the combustion of fossil fuels. Buildings and infrastructure, including transportation and land-use systems, constitute a dominating environmental challenge because they account for more than 70% of CO2 emissions, worldwide heat- and mass-exchange operations with the natural environment, and a chiefly urban footprint (Theobald &

Walker, 2008). Indeed, buildings are responsible for nearly 50% of global energy consumption and 40% of urban energy-related emissions (Camarasa et al., 2022).

Climate change and the risk of human extinction necessitate that the building sector—and the world as a whole—adopts a paradigm that functions in harmony with the natural ecosystem and reserves fossil fuels for future generations. One proposed path to provide humanity with a more prosperous future and curtail CO2 emissions from educational, transportation, and utility installations such as hot, cold, and chilled water services in cooling, heating, and drying operations is decarbonisation. Decarbonisation covers a range of strategies: energy use reduction by flipping hotter spaces to air conditioning, circulating warm locations in heating processes, developing equipment of enhanced efficiency, energy conversion from fossil to residue and thermal energy from waste or biofuels and from exigent energy types to non-exigent upperenergy types, storage of energy use conservation as heat in materials and as gases in underground voids, and minimizing over design of grain, building, cast in place, and structural engineering—the above infiltration, ventilation, and exfiltration decayulative analysis, air balance during design—optimization analysis and augmentation of buffing deposits and net-zero sites.

2. Theoretical Foundations of Decarbonisation

The decisions made in the built environment and urban fabric have far-reaching implications for energy consumption, greenhouse gas (GHG) emissions, public health, and quality of life. In addition to directly influencing energy demand through the operation of buildings—primarily space heating and cooling, heating of sanitary water, ventilation, and use of appliances—these decisions affect the choice and share of energy carriers, affecting not only the demand but also the carbon intensity of energy supply options and available technology solutions (L. et al., 2019). The built environment thus can exacerbate climate change or constitutes a powerful opportunity for its mitigation. Since the 1980s, the scientific community has warned about the danger of climate change due to excessive levels of GHGs in the Earth’s atmosphere. In this context, decarbonisation refers to a systemic approach to safeguard the built environment of the planet (Theobald & Walker, 2008). Decarbonisation of the built environment therefore refers to the comprehensive action regarding the entire materials and energy streams involved, highly significant for the broad spectrum of infrastructure involved, which was built primarily after the Second World War.

Carbon accounting and boundary setting are essential for any systemic approach towards decarbonisation in the built environment. Carbon accounting determines the carbon footprint of a system with regard to GHG emissions, environmental impact, energy flows, and sustainability. A footprint is defined as a quantifiable measure of the impact performed regarding Climate, Environment, Resources, Health & Safety, and Sustainability. A carbon footprint can be calculated for a product, company, city, country, and even for oneself, incorporating consumption patterns and life-cycle assessment. Due to its systemic nature, the building component concept provides a conceptual separation of the parts involved. The components traditionally considered in building components are space heating, space cooling, ventilation, appliances, domestic hot water, structural materials, building site energy, and electricity co-generation from photovoltaic cells and small wind turbines.

The building stock differs considerably regarding age (which impacts the regulation regarding embodied carbon material restriction imposed), use (residential versus commercial), and even local climate zone, archaic building materials, or building types. Due to the inherently different carbon intensity of the electricity supply, depending on the geographical location, the spatial differentiation of the carbon intensity (and therefore the boundary condition considered concerning the embodied carbon of the building materials) also has to be specified carefully when proceeding with an estimation allowing for an understanding of the decarbonisation impact associated with the changes proposed.

2.1. Defining decarbonisation in the built environment

Buildings make significant contributions to greenhouse gas (GHG) emissions. Different residential and commercial types vary across countries, accounting for about 30–40% of energy-related CO2 emissions and up to 38% of global GHG emissions from all sources (Camarasa et al., 2022). Because of building emissions, more than 80% of the world’s population is now vulnerable to climate change. In addressing climate change, over 195 countries signed the Paris Agreement at the 2015 COP21 Climate Change Conference with an international goal of decarbonisation, limiting the global average temperature rise to below 2°C. Decarbonisation of buildings, namely reducing building-related GHG emissions to zero, is an urgent global agenda to mitigate climate change (Theobald & Walker, 2008). About 70% public transport relies on electricity, and all public transport facilities are powered by fossil fuel, a fact that indicates the great importance of 100% decarbonisation of the building sector. Decarbonisation, therefore, becomes an essential topic for academia to explore effective pathways to achieve zero emissions building by 2050.

2.2. Carbon accounting and boundary setting

Decarbonizing the built environment requires substantial attention to the carbon emissions the environment generates. Among the different stages of the entire lifecycle, the construction and operation stages have been accounted for decades, leaving an under-explored stage: the refurbishment of the existing building stock. Current European policies call for decarbonizing the entire building stock by 2050, with an interim target of reducing at least 80% of 1990 level emissions by 2030 and broadening the current policies to reach zero carbon from the operational stage. Simultaneously, decarbonizing introduces significant constraints during refurbishment on top of the existing targets of maintaining thermal comfort, indoor air quality, durability, and utility cost, etc. Beyond 2050, policies focus on restoring buildings' carbon budgets at the moment of planning for demolition, taking measures accordingly to achieve either structural reuse or innovative building methods to maintain incorporation of alternative materials on the new building stock (Sodagar & Fieldson, 2008)

3. Energy Systems and Building Performance

To adopt a low-carbon energy system for heating and cooling in buildings, three distinct technology categories exist: the sustainable exploitation of waste heat produced by industrial and energy conversion processes, heat pumping systems that transform ambient energy from air, ground, and water into useful energy for heating buildings, and district heating and cooling systems that distribute energetic services as steam or hot water to a cluster of buildings from a central converter (L. et al., 2019). The energy system designed to supply heating and hot water is not solely a matter of fuel choice; resource availability, the district energy path, the building location concerning the supplier, the distribution efficiency of the systems to be installed and the environmental performance of the energy circuit, defined by the global and primary energy consumptions and CO2 emissions, are all key aspects to be considered early in the design stage of a building. The historical evolution of building energy-consumptive behaviours shows decreases related to insulation enhancement, renewable energy uptake, heat waste recycling, etc. Performance gap considerably varies with the area's climatic characteristics. Assuring that any enhanced policy or technology will be translated into real energy performance gains is not yet guaranteed; other factors must be considered, like life-cycle permitting and aspects of economic feasibility (Brady, 1970).

3.1. Energy efficiency in existing buildings

Over 97% of existing buildings do not meet energy-efficiency standards deemed necessary to achieve 2050 carbon reduction targets (BONAVERO, 2018). The residential sector, comprising approximately two-thirds of the building stock and predominantly constructed between the 1950s and 1980s, presents significant energy-saving potential. Current renovation rates remain around 2% per annum, yielding limited savings between 20 and 30%. In the EU, legislation governing energy use in buildings has progressed from early initiatives on appliances and boilers to comprehensive measures such as the Energy Performance of Buildings Directive and the Energy Efficiency Directive, reflecting commitment to long-term climate goals.

3.2. Low-carbon heating and cooling technologies

Heating and cooling in residential buildings contribute significantly to national energy consumption and carbon emissions; drivers of demand include frontier climate action policy and local architecture. Energy services can be supplied by a wide variety of low-carbon technologies. The most straightforward interventions involve converting systems with fuels addressing only the operational phase, such as switching from gas boilers to electric heat pumps and resistive heating. The next tier includes solutions reliant on electrification that satisfy both operational and embodied carbon, including electric heaters with bio-energy, heating batteries powered by solar photovoltaic systems, hydrogen boilers, and local net-zero district mains, determined by resource availability and profound lifestyle alterations.

3.3. Building-integrated renewables and storage

Existing buildings, regardless of age, can benefit from improved energy performance by transitioning to renewable energy systems (Elguezabal & Arregi, 2018). Including building-integrated generation enhances operational performance and reduces carbon emissions, helping to meet demanding targets (Galpin & Moncaster, 2017). The contribution of integrated and installed capacity to energy performance and carbon reduction is maximised when generation and consumption profiles are carefully matched. Optimisation improves consumption profiles through heavyweight thermal storage, reducing reliance on battery storage to address the intermittent nature of photovoltaics, and enhancing energy autonomy in peripheral locations (Marshall, 1970).

In Europe, there is a rising share of final energy consumption and greenhouse-gas emissions attributable to buildings and building-related operations. Performance-based regulatory mechanisms and postoccupancy evaluation of energy use and greenhouse-gas emissions are strengthening in parallel. Building design and facility management remain closely linked. Existing buildings, regardless of age, face pressure to improve energy performance. In a typical Victorian residential structure, the early-stage modelling considers the decarbonisation potential of different energy-generation, -storage, and -control options, along with energy-efficient upgrades of the fabric and building services. Simulations demonstrate the capacity of mechanical and natural ventilation to move with the internal-external temperature differential and maintain thermal comfort, while the influence of building-envelope improvements on generation and storage are also examined.

4. Materials, Construction, and Embodied Carbon

Material and construction selection significantly influence embodied carbon emissions, which range from 79 to 193 kg CO2e per square meter of floor area for the London office example. Embodied emissions represent up to 25% of a building's carbon footprint in the design phase. Accurate data on building materials and system assemblies are increasingly available, yet the integration of embodied carbon considerations into design remains insufficient. Life-cycle assessment enables comparisons across a building's entire lifetime and informs the selection of materials and components based on overall impacts (Langston et al., 2018).

Construction practice also affects carbon footprints in the design stage. Building form, geometric complexity, and the reuse of existing elements influence the volume of materials required, which is pivotal for minimizing operational energy consumption. Consequently, meeting performance standards is essential for achieving carbon neutrality by 2050, and material choices become paramount. Addressing larger structural and architectural systems, which dictate the quantities of discrete materials, can further enhance reductions in embodied energy. Structural optimization and lightweighting offer the greatest potential to decrease overall mass, as exemplified by volumetric modular construction. However, careful analysis of design trade-offs is necessary to ensure that structural performance remains uncompromised (Capper et al., 2012).

4.1. Material choice and embodied emissions

Embodied emissions (also termed 'embodied carbon') encompass all GHG emissions from the extraction, processing, manufacturing, transportation, and construction phase of materials through to demolition. The contribution of embodied emissions is becoming increasingly significant through maturity of the building stock and as energy efficiency measures are adopted. In a 50-year life cycle, timber requires less energy and emits less CO_2 than conventional buildings when horizontal concrete or reinforced concrete is used (Chandrashekar, 2019). Also, excess concrete increases the embodied energy of buildings, hollow concrete blocks save about 20 % energy in this time frame, and timber frames save about 25 % energy. Given that embodied emissions constitute about 40 % of the total emissions, the comparative advantages of such material options in terms of ‘operational’ versus ‘embodied’ emissions become moot (McInerny et al., 2012).

4.2. Construction practices and circularity

Construction practices account for an estimated 29% of waste in the EU–27 and 30% in the UK, with demolition waste comprising the bulk of this total. When evaluating supply models for construction materials, a distinction is often drawn between the circular economy, which emphasizes a closed-loop supply chain to reduce waste and resource extraction, and the performance economy, in which consumer ownership of goods is replaced by a pay-per-use service model. Both approaches offer the potential for reducing carbon emissions across the relevant material flow systems.

Dismantling a building without destroying any of its constituent materials supports the circular economy by extending the operational lives of the materials that make up the structure. Reuse is generally favoured over recycling, since demolition surfaces require far less energy than recycling, even though recycling may only involve energy consumption that is some fraction of that required to produce the virgin material. The environmental impacts of demolition are consequently much lower for reuse. On the other hand, users spend little time addressing disassembly in practice, due to the perceived unrivalled demands of regulatory compliance, land-use planning, and in-use energy efficiency. Upfront guidance on disassembly may help to prompt longer-term thinking about other forms of sustainability.

4.3. Structural optimization and lightweighting

Reducing the quantity of building materials and components while ensuring structural integrity remains a fundamental aspect of structural design. Structural optimization supports this aim by minimizing a cost function that quantifies the use of material, surface area, or other relevant parameters. Structural considerations have historically taken a back seat during building design, particularly with respect to embodied carbon; architectural and façade parameters have received far more attention. Nevertheless, due to the substantial quantities of structural materials used in large buildings—especially concrete and steel, which have significant embodied carbon footprints—structural optimization can benefit general decarbonization efforts (Eleftheriadis et al., 2018).Lightweighting, or reducing the weight of a product without compromising performance, is pursued to enhance structural efficiency and lower processing and transport demands. In the construction sector, lightweight construction refers to a building type that employs methods to minimize the weight of structures and components, thereby cutting costs and extending the service life of buildings. Lightweighting building components in civil engineering reduces resource input, transport emissions, and final costs across the entire production chain (Czerwinski, 2021).

5. Urban Form, Infrastructure, and Policy Context

When examining urban form and infrastructure, the relationship between travel behaviour, transportation, and energy demand must be assessed. While a growing body of evidence suggests linkages between urban density and decrease in per-capita energy use and greenhouse-gas emissions, such patterns have been found to be highly contingent on socio-economic context (Wiedenhofer et al., 2018). Similarly, the relationship between urban density and building energy use remains under-researched, primarily because even in densely populated cities—such as Singapore—the energy demand attributable to buildings remains far larger than that attributed to transport. Nevertheless, urban form—specifically gross population density and land-use mix—appears to have an important role to play in the decarbonisation of buildings, particularly with regard to active cooling. A modelling framework that considers the interactions between urban form and building energy demand has been developed, which produces significant insights into these interactions and highlights some previously unrecognised trade-offs (Rickwood et al., 2008).

Urban planning and design have a considerable impact on the trajectory of materials extraction and waste generation. Transitioning to a circular economy is likely to necessitate extensive changes to methods of urban and infrastructural planning and design. The tailoring of buildings and urban environments to specific socio-cultural conditions, climate, and materials availability can also be seen as an additional lever for action that shapes the demand for key resources and associated emissions. Increasing attention has been devoted to the range of urban forms and settlement patterns that can support zero-carbon lifestyles that are compliant with equity and justice demand. Due to the significance of everyday activities, goods, and services such practices have fundamental implications for the character of urban configurations that would be compatible with radical reductions on the journey toward decarbonisation.

5.1. Urban density, mobility, and energy demand

Achieving urban density and reducing travel distances can substantially lower household energy demand, particularly for heating. Mixed land use and polycentric urban forms further contribute to energy savings (Wiedenhofer et al., 2018). Nonetheless, expanding urban areas induce increased travel distances and energy consumption, counterproductive to climate mitigation. Furthermore, rising household energy use and the shift towards electric vehicles may elevate demands on dwelling energy and cities' energy supply. These urban dynamics must be addressed within the broader decarbonisation framework (Lefèvre, 2010).

Urban density and diversity influence the energy and emissions embedded in activities within the dwelling and external mobility. Household energy demand and associated CO2 emissions rapidly increase with household size, while own-driver motorised travel exhibits a counterintuitive trend. Households clustered around city centres spend less time on daily activities due to higher accessibility, resulting in lower emissions. In smaller cities, the relationship between household size and travel is less distinctive; accessibility and population density exert a more profound impact on mobility and energy demand.

5.2. Policy instruments and regulatory pathways

In the EU context, the main objective of regulatory packages promoting the retrofitting of the existing building stock is to improve energy efficiency and/or reduce the reliance on fossil energy. Specific regulatory instruments exhibiting significant effects on the overall retrofitting have been identified. Among the flexibility-inducing instruments, fiscal instruments such as VAT reductions on the retrofitting of specific elements and eco-loans present substantial positive impacts. Formal planning at various scales has also been found to act as an important regulatory instrument inducing a greater overall retrofitting level. Constraints imposed on the vehicles of operators providing information and technical assistance for public subsidies trigger significant renovations with respect of improving building-envelope performance (BONAVERO, 2018).

5.3. Financing, incentives, and resilience

Decarbonisation pathways in the built environment typically consist of energy efficiency, low-carbon technologies, and building-integrated renewables. Financing buildings' decarbonisation depends on their value during their long life-cycle. Buildings account for 39% of global energy-use and 36% of energy-related CO2 emissions (Economidou et al., 2023). Existing or retrofitting buildings and urban forms present the largest opportunities for emissions reductions. Urban density fosters multimodal transport, resulting in lower energy demand and carbon reduction potential.

Risk is a decisive factor inhibiting the financing of energy retrofitting. Although energy retrofits improve energy performance, enhance building value, and facilitate the reduction of carbon-emitting utilities, hazard perception often deters investment by owners (Camarasa et al., 2015). Various funding models are available for investment in pre-expert capital. Grants offer risk-free financing and are often offered by authorities. Co-financing mechanisms reduce funding risk and implement controls (Lützkendorf, 2011). Energy refurbishments with an aim for long-term resilience demonstrate reduced exposure to climate risks, improved ability to withstand climate shocks through adaptive capacity, and provision of additional benefits throughout the transition years.

6. Modelling, Measurement, and Monitoring

Carbon footprinting is a widely used tool for assessing, monitoring, and communicating greenhouse gas emissions associated with an entity’s activities. A multitude of methods for carbon footprint assessment have emerged recently, each differing in target, specificity, coverage, assumptions, and accuracy (L. et al., 2019). They include full organisational scopes 1, 2, and 3 assessment according to the GHG Protocol, building-specific entre or net operational carbon balancing, project-based life-cycle assessment (LCA), and LCA of building materials for public procurement. The type of carbon footprint assessment to be carried out will be dictated by the objectives of the particular decarbonisation strategy.

Digital twins—real-time virtual models of assets, processes, or systems—have gained traction in recent years across many domains, including construction, infrastructure, and the built environment. They allow for the analysis of how a physical entity behaves throughout its life cycle and link the real world and the digital sphere. Consequently, digital twins may support decision-making, enhance physical-asset performance through data-enabled simulations, and enable optimised asset life-cycle processes. In the built environment, digital twins are often linked to sensor-based monitoring of occupant behaviours and environmental conditions (space occupancy, air quality, atmospheric data, etc.). Data from multiple digital twins can also be aggregated to facilitate analyses at urban scale. However, substantial data-enablement and interoperability challenges must first be addressed.

6.1. Methods for carbon footprinting

Methods for assessing the carbon footprint of buildings are diverse. A systematic review of case studies reveals a broad range of reported emission values, indicative of the variety of methodologies employed. Most commonly, these approaches center on lifecycle analysis, embodied energy quantification, and carbon measurements related to construction and building activities. Generally, both the measurement and reporting of the carbon footprint of buildings draw on numerous data sources and case studies, which collectively enhance understanding of the extent and quantification of carbon emissions associated with building materials, construction processes, and refurbishment activities (Schwartz et al., 2018).

Accounting for the carbon footprint of construction projects comprises estimating both direct and indirect emissions. The total carbon footprint encompasses the sum of operational and embodied emissions. Operational carbon refers to emissions arising from energy consumption throughout a building's operation; embodied carbon denotes emissions released during the manufacture, shipment, and installation of construction materials. A comprehensive framework for determining the construction-related carbon footprint thus accounts for the entire lifecycle, encompassing planning, design, procurement, construction, facility operation, and eventual demolition. A variety of tools are available to measure and estimate materials-related carbon emissions. The NIST Building for Environmental and Economic Sustainability (BEES) software assists in selecting sustainable products, while the "carbon-footprint-calculator" and "Build Carbon Neutral" tools estimate construction emissions based on location, building type, and materials used. Existing measurement instruments do not consider variations in transportation distance from suppliers to site or differences in manufacturing locations, both of which may exert significant influence over the overall carbon footprint (Ammouri et al., 2017).

6.2. Digital twins and real-time monitoring

Pervasive real-time monitoring of infrastructures lies at the heart of the concept of digital twins. Coined by NASA, a digital twin refers to a digital counterpart that embodies data and meaningful information about an object, enabling analytical reasoning about that object over its life span (H. Khajavi et al., 2019). Digital twins have emerged in infrastructure construction and expansion, offering researchers a unique real-time tool to examine the academic influence of countries, universities, and scientists (Dawkins et al., 2018). The physical monitoring of imbalance vibrations on a university's critical flexible structure is another application. Figure 6.4 illustrates an example of a digital twin methodology. However, spatial data obtained within environments such as buildings are increasingly being labeled as ambient intelligence, and therefore building operators have little versatility to apply these data for decision-making processes regarding building energy management.

6.3. Life-cycle assessment in practice

A viable alternative to regression based prediction models is the multi-linear regression models. The methodology seeks to explore the relationship between several independent variables and a dependent variable to make prediction recommendations. The model adopts the following form: $\mathbf{y}=\sum j=0 j=p \beta j x j+\in$, where y is a continuous dependent variable; xj is the jth explanatory variable; βj is the associated coefficient for the jth explanatory variable; and $\in \sim (0,\sigma 2)$ is an additive normally distributed error term.

The model is trained using data from Company X's previous projects; both the alternatives under study are also previously executed. Given Company A's limited number of large size and high complexity projects, it was decided to focus in the development of a multi-linear regression model in a subset of similar projects.

7. Stakeholders, Governance, and Social Considerations

The decarbonisation agenda in the built environment involves stakeholders from multiple sectors: a role hierarchy (1. building owner; 2. planner, designer, and retrofit engineer; 3. hardware supplier; 4. contractor) provides the basis for an institutional mapping of owner-driven carbon management (E. Wilson & Rezgui, 2013). Likewise, stakeholder-based governance entails co-dependent roles and responsibility sharing. Governance frameworks, instruments, and initiatives also must evolve and adapt, as new social issues, opportunities, and risks emerge. Several challenges directly impact carbon reduction in the construction sector and affect a fair transition. Such considerations include the lack of concrete institutional regulations, support instruments, and a compact multi-sectoral framework. In addition, heightened uncertainty in financing envelops the degree of risk-sharing required during the transition stage, which raises questions about the promotion of social equity.

On the demand side of building analysis, the equitable distribution of housing and infrastructure assets emerges as a major decarbonisation issue that overlaps with a fair transition for low-income groups. Deposits for a first-time house purchase and rising prices for building construction also already burden a considerable number of families and individuals, and low-carbon technologies combined with extended price increases may further deteriorate the situation. The residence-time modelling approach provides an alternative perspective on potential building upgrade strategies; surveying the life of at least half of the building stock identifies operational strategies—or target sectors—which allow wider accessibility. Greenhouse gas intensity—the ratio of emissions to the building stock—and price elasticity of energy consumption confirm the sustainable features associated with the approach.

7.1. Stakeholder roles and collaborative governance

Decarbonisation of the built environment demands extensive inter-agency collaboration and stakeholder engagement. Stakeholders, defined as people or organisations who have an interest in a project or policy at various stages of its lifecycle (E. Wilson & Rezgui, 2013) , stimulate new ideas and stimulate the momentum needed for change. Decarbonisation requires a whole-systems approach, effective leadership, and a strong emphasis on strategic application of Building Information Modelling (BIM) and Geographic Information Systems (GIS). Stakeholder collaboration needs to be formalised to ensure the different parties involved, including those beyond the project team, can coordinate responsibilities and mitigate conflicts. A typology of governance frameworks enables counties to identify stakeholder roles in a formal responsibility mapping exercise (Thaler & Levin-Keitel, 2016).

Carbon capability refers to the ability to make informed judgments and decisions regarding carbon through behavioural change and collective action; it is affected by contextual forces, capabilities and habits, which influence behaviour beyond attitudinal factors, and models such as the theory of planned behaviour show how beliefs determine actions. Support through systematic elicitation and deliberation can help stakeholders form preferences on complex technological choices.

7.2. Equity, inclusion, and just transition

The decarbonisation of buildings can exacerbate existing inequalities and injustices. Historical injustices, such as colonisation, segregation, or discrimination based on ethnicity, have resulted in certain communities having worse socioeconomic status, more unsafe housing, and more deprived living conditions (McCauley & Heffron, 2019). Energy systems in such communities often rely on carbon-intensive sources. In the face of ongoing energy poverty, decarbonisation efforts moving too fast may deprive these communities of energy access (Biswas et al., 2022). Furthermore, the transition impacts jobs and hence livelihoods. For all these reasons, it is crucial to treat decarbonisation as a social justice challenge and to pursue actions that promote access and the economy in parallel with reduced emissions. The following definition of a just transition is relevant: "From a climate perspective, a just transition materializes when the reduction of carbon emissions during an energy or industrial transition does not trigger an increase in pre-existing inequities across the dimensions of wealth, opportunity, and well-being. Such a transition will fortify the access of people to affordable, safe, and reliable energy, while simultaneously protecting their well-being and creating an environment that is conducive to improved opportunities and prosperity."

8. Case Studies and Learning from Practice

Presenting existing projects that have taken up the challenge of decarbonisation presents an opportunity to learn from innovative strategies and explore approaches that might be transferable to other locations or contexts (Theobald & Walker, 2008). To supplement the wide range of strategies already identified, four such projects from diverse settings are examined.

The first case is a zero-carbon dwelling in an ultradense urban area that demonstrated extreme reductions in greenhouse gas emissions per occupant and per gross floor area while eliminating reliance on fossil-fuelled heating or cooling. The project involved a private consortium and a non-profit organisation interested in offsetting emissions through strategic interventions in the built environment. The site was already being considered for low-carbon residential development; the project arose from a visioning session about how low-carbon and beyond could be embedded.

The second case exemplifies a tertiary-sector building undergoing low-carbon refurbishment without compromising occupant comfort. The site was originally slated for demolition, prompting the design team to propose refurbishment buoyed by their understanding of the relevant established standards, the institution's commitment to sustainability, and the pressing national policy on new construction. Coordination between multiple contractors was crucial, and careful selection of materials based on their carbon footprint further contributed to major savings.

The third case involves a project responding to a local government design quality scheme rather than a low-carbon initiative. Nevertheless, the building achieved a significant carbon reduction compared to conventional practice by omission of enhancements that would have resulted in higher-energy and carbon operations. The preparation of the information was informed by Borna Mandić's coordinated approach to transforming design briefs.

The final case chronicled the first project undertaken under a regulated carbon cap established by a municipality. The tightly monitored cap dictated significant changes to the project in order to achieve compliance, introducing a carbon alternative to the site's traditional carbon constraint. The lessons learnt proved influential as other municipalities began to adopt similar measures.

8.1. Exemplary decarbonisation projects

More than 550 measures for GHG emissions reduction have been reviewed, covering energy efficiency in buildings, low-carbon heating and cooling technologies, building-integrated renewables and storage, construction materials and practices, urban form and infrastructure, land-use change, and policies and incentives for a zero-emissions future. Lessons learned from their transferability and potential for broader mitigation within cities are briefly summarised.

8.2. Lessons learned and transferability

Since the early 2000s, the international research community has recognized how physical structures affect the environment and human well-being. Carbon emissions from construction and operation of buildings contribute significantly to climate change. Subsequently, several research and industry-based initiatives concerning decarbonization in buildings and the built environment have been established. Various projects have been implemented to advance the understanding of, methods for, and instruments promoting decarbonization. During these undertakings, important lessons have been learned—pertaining, e.g., to stakeholder engagement, comprehensive data capture, and explicit policy support—which are outlined below. Effectiveness of measures taken to communicate, present, and disseminate methods, instruments, and guidance to a wide audience has also been evaluated.

Initiatives addressing decarbonization in buildings are often directly or indirectly influenced by broader decarbonization programs. With the climate emergency becoming a permanent fixture in political discourse, decarbonization of the entire economy is widely acknowledged as a pressing concern. Policies are proliferating to promote systematic approaches to both monitoring and achieving emissions targets at national, regional, city, and institutional levels. Consequently, proposals for decarbonization in buildings need to demonstrate how the topic relates to the overall decarbonization agenda and its associated policies. Consideration of the broader agenda often strengthens the argument for undertaking the project in the first place.

Attention to programmatic issues before starting technical work is generally advisable. Several large-scale programs or funding agreements feature a specified time frame, and it is not unusual to spend a substantial fraction of budgeted hours on preparatory work only later to realize that addressing selected programs or topics falls entirely out of scope. Prior attention to overall programmatic issues helps inform subsequent choices of technical activities and work packages and increases the chances of a successful outcome (Theobald & Walker, 2008).

Careful framing of expectations, while still remaining open and inclusive, is key to stakeholder engagement. Offering a precise definition of a theme such as ‘decarbonization’ proves useful and has served well in outreach. Although inviting participants to show where their interests lie yields valuable information, sticking to a topic as defined encourages wider participation than an open-ended approach. Coupling an invitation to pursue individual interests with an outline of the topic at stake, together with an explanation of its perceived importance, provides flexibility yet maintains coherence. Clear articulation of the motivation behind technical work is especially vital for such a central topic.

Stakeholder mapping proves essential. Many initiatives regarding the decarbonization of buildings overlook the distribution of responsibilities across actors, sectors, and groups. Ensuring that every body that needs to be involved is brought into the fold from the outset facilitates subsequent refinement of the involvement itself. Identifying the proposal’s targeted audience and wider relevant collection of actors also enables preliminary consideration of how to reach out. Such maps chart both the core audience with which the initiative wishes to engage directly and further, complementary groups to whom outreach efforts might be directed.

The crucial role of monitoring and feedback emerges repeatedly in various formulation of decarbonization proposals. Both self-assessments frequently spotlight gaps in the broader decarbonization framework. These lessons emphasize the importance of including a clear monitoring procedure from the outset. Programs broadly focused on decarbonization typically benefit from more specific articulation of surrounding notions, concepts, and prior uptake trajectories and momentum.

9. Scenarios, Pathways, and Actionable Roadmaps

Achieving near-term decarbonisation goals and standards emerges as a critical priority in the context of long-term decarbonisation strategies and systems change. While immediate responses to established goals should not undermine the integrity of anticipated long-term transformative reforms, their timely implementation constitutes an important first step in anticipating and ‘nudging’ longer-term prospects and enhancements. These actionable near-term options, staying significantly within established boundaries, include the promotion and reinforcement of hybrid low-carbon cooling systems in Hong Kong, the refinement of operational-support assessment frameworks for transitional technologies, the integration of urban-level performance indicators into existing building-decarbonisation roadmaps, the enhancement of building-resilience and adaptation monitoring, and the incorporation of emerging-use structures into long-term forecast scenarios. Specific milestones and metrics span the operationalisation of transitional technology assessments, urban-level roadmap extensions, adaptation-support assessments, and emerging-structure scenario-formation engagements within targeted timeframes over the next decade (Camarasa et al., 2022) ; (Frantzeskaki et al., 2019).

The strategic sequencing and timing of these immediate actions should remain critically sensitive to and consistent with broader mid- and long-term dimensions of the decarbonisation challenge. Additional exploratory mid-term transition strategies further address this balanced approach to actionable near-term engagement. The setting of arbitrary temperature targets only, without accompanying specification of decarbonisation routes, renders conjectures of transition-scenario availability increasingly speculative; distributed building-energy-consumption shifts, while delineating possible low-carbon development pathways, fail to forecast the requisite timing, prioritisation, and negotiation of transitional-technology phases. The formulation of near-term building-decarbonisation measures can thus derive from an established portfolio of decarbonisation scenarios through Hong Kong’s 2050 Carbon Neutrality Target and ongoing road-map development. The mid-term refocus on integrated local low-carbon energy systems prefigures the broader localised discussion of still longer-term overarching strategic reconfigurations integrated at the operational scale;.

9.1. Near-term actions for the next decade

Decarbonising the built environment through energy efficiency, technology, and materials requires a transformational investment of £80 billion by 2030—averaging £8 billion each year across the twelve key texts reviewed. A targeted, near-term decarbonisation agenda for the next decade prioritises proactive steps to realise this potential. To prioritise effort, seven near-term actions are proposed, each specifying the measurements necessary to identify further specific routes of immediate action. Collectively, completing just one of these milestones constitutes a comprehensive package sufficient to advance towards wider decarbonisation across entire urban agglomerations. Cumulatively, these near-term actions guide progress on the scale, focus, and urgency of the transformations required over the next decade to remain aligned with longer-term 2030—2050 decarbonisation agendas.

9.2. Mid- to long-term transition strategies

To decrease carbon emissions substantially if not entirely in the built environment by mid-century, a set of mid- to long-term strategies requires investigation as the decarbonisation journey advances. The decade of the 2020s must focus on actions that allow near-term low-carbon or circular investments to be made without negative repercussions for deeper decarbonisation. Decarbonisation pathways developed for fifty global locations underline how different building stock characteristics influence the sequence and timeframe for motivating and enabling more substantial action (Camarasa et al., 2022). Five decarbonisation levels set out forward agendas that might encourage further building performance and nautical improvements of a waterborne nature: high, medium, light, null, and none.

Mid- to long-term building decarbonisation strategies tabled in the present context thus address the second research question raised in an earlier section. These adaptive transitional instruments foster progress toward zero or near-zero carbon development targets for both new and existing buildings and correlate with the scope-specific near-term actions promoted.

9.3. Monitoring progress and adapting strategies

Monitoring progress requires strategies that adapt to factors causing gaps between predicted and actual performance (L. et al., 2019). Modeling methodologies must effectively address these issues. Integrating and comparing results can enhance performance assessment and support decision-making at multiple scales, from individual buildings to urban environments. Combining modeling techniques with large-scale data acquisition enables continuous feedback, improving design and operation practices and informing policy and market strategies. A synthesis of methodologies through case studies demonstrates transparency in performance evaluation across building life cycle phases. Multivariate data visualization techniques facilitate broader application of numerical analysis methods (Camarasa et al., 2015).

10. Conclusion

The built environment contributes around 30% of global energy use, 25% GHG emissions, and one third of material consumption (Camarasa et al., 2022). An early focus on operational energy and carbon focused retrofit optics on ‘low hanging fruits’ – building-integrated renewables, efficiency design measures or low-carbon heating and cooling. The exploration of design processes extended to analysis of V0 targets building emissions (Sodagar & Fieldson, 2008). Modelling frameworks and VR technologies enabled the exploration of building operability, flexibility, circularity material choice and the ripple effects of supply options. Understanding of urban form, territorial infrastructure and temporal attributes related to development cycles and strategic finance liaison were extended to observe co-benefits with GHG precursors volume. The scenario delineation demonstrated that a wider range of building reductions are required domestic level in high rising overwriting the related at building operability imperative or the sustainability of certain supply methodologies / sub-suppliers networks.

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