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Carbon and Beyond: Mitigating Embodied Impacts Through Building Design and Material Selection Strategies

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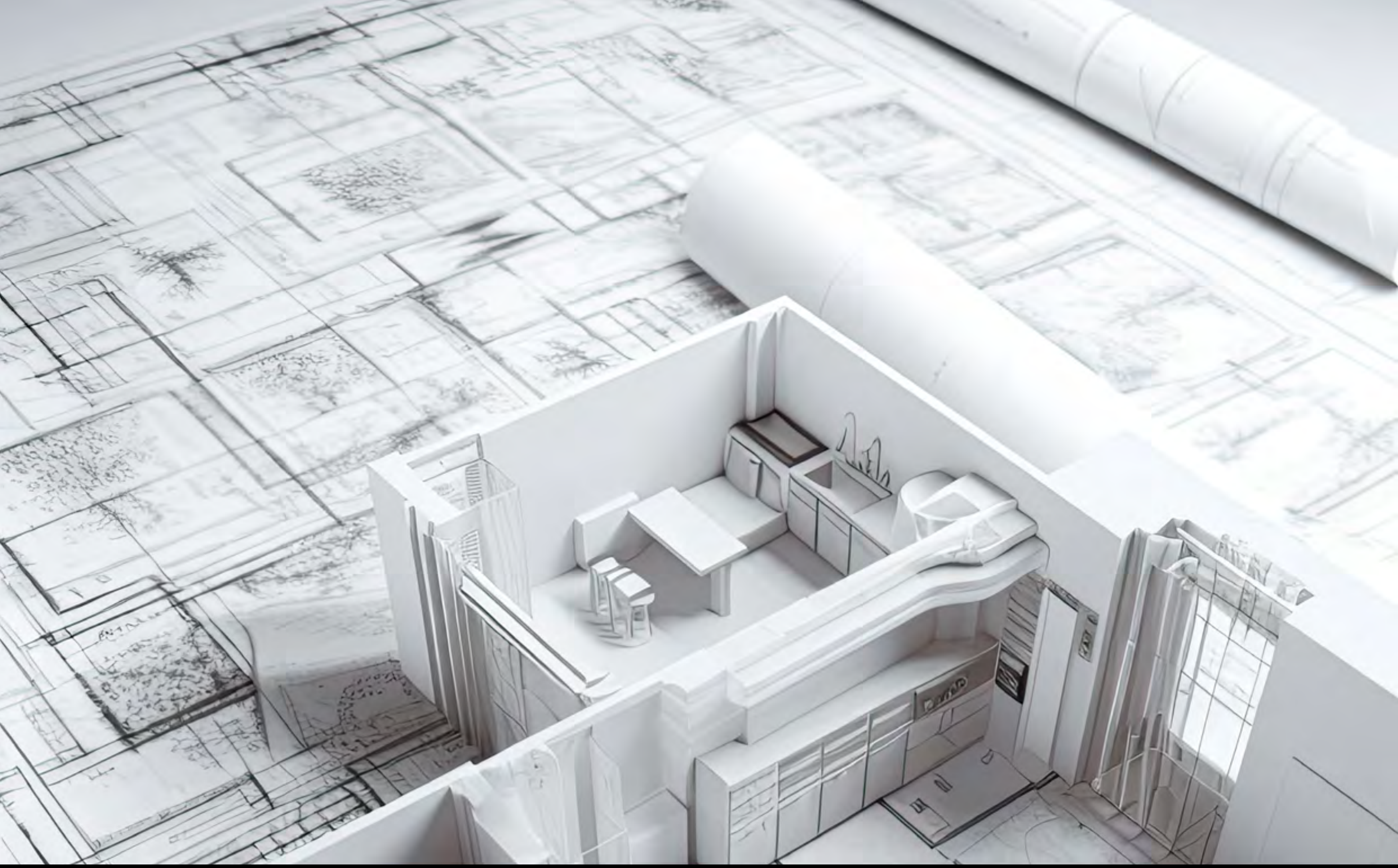
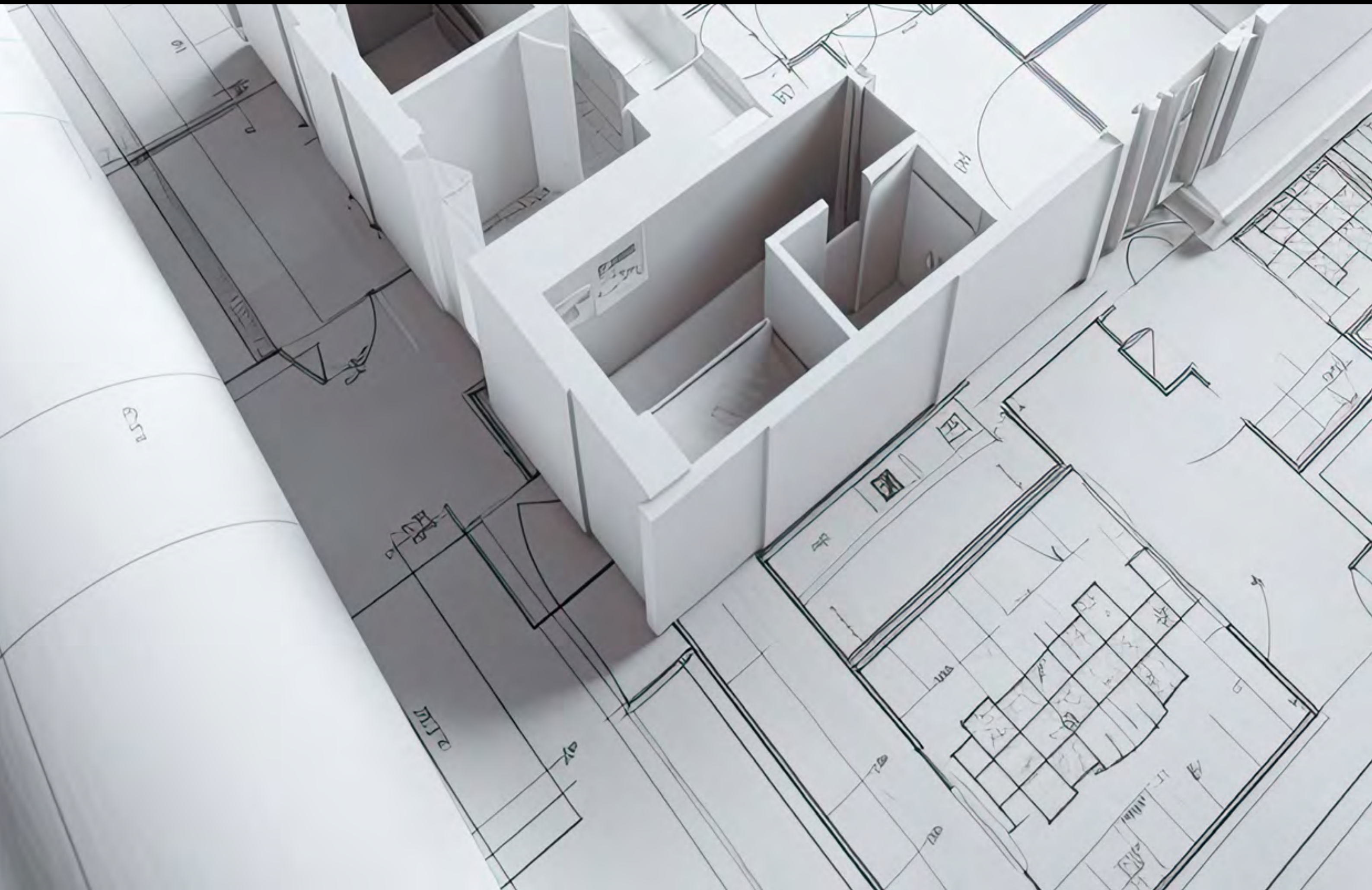


Executive Summary



Executive Summary

The built environment plays a crucial role in global efforts to mitigate climate change and promote sustainability. Buildings account for approximately 40% of global energy consumption and one-third of greenhouse gas (GHG) emissions. As the world continues to urbanize and develop, the environmental footprint of the construction industry becomes increasingly significant. While traditional sustainability efforts in the building sector have focused on reducing operational energy use, there is growing recognition of the importance of addressing embodied impacts – the environmental burdens associated with the extraction of raw materials, manufacturing of construction products, transportation, on-site construction, maintenance, and renovation, as well as end-of-life demolition and disposal.

This study aims to address the critical need for comprehensive analysis of design-phase strategies to reduce embodied impacts in buildings. By examining a large dataset of over 550 buildings across various types and regions, this research provides valuable insights into the effectiveness of different approaches in reducing global warming potential (GWP), water depletion potential (WDP), fossil depletion potential (FDP), and ecotoxicity.

The study employs a comprehensive framework to assess the environmental impacts of building materials, focusing on the “cradle-to-gate” scope, which encompasses the impacts from raw material extraction, transportation to manufacturing facilities, and final construction material manufacturing. This scope reflects the design phase approach and aligns with ISO 21930:2017 standards.

A key aspect of this research is the development and use of a simple digital workflow for rapid, screening-level Life Cycle Assessment (LCA). This approach demonstrates how design-stage digital technologies can be developed and deployed in a flexible, scalable, and simple manner, addressing one of the primary challenges in implementing embodied impact assessment in early-stage design – the need for quick, reliable, and actionable information.

The study investigates three primary impact mitigation strategies:

1. Material Substitution (MS), also referred to as Timber Substitution: Substituting the use of concrete and steel with wood, without compromising structural integrity.

2. Material Efficiency (ME): Reducing material intensity by applying scalars to reduce the quantity of the material of interest.

3. Recycled Content (RC): Increasing recycled material usage by applying a 1:1 mass-based displacement ratio between a virgin material and its recycled counterpart.

These strategies are implemented with varying percentages to cover both realistic and ideal situations, providing a comprehensive understanding of their potential impacts.

Key Findings:

1. Material efficiency and recycled content strategies are highly effective in reducing embodied impacts across all categories studied.

   For every 1% implementation of these strategies, approximately 0.7-0.8% reduction is achieved in global warming potential, water depletion potential, fossil depletion potential, and ecotoxicity. This near-linear relationship provides a clear and actionable guideline for designers and policymakers. The effectiveness of these strategies is consistent across different building types and regions, demonstrating their broad applicability in sustainable building design.

2. Four key materials - steel, cement, concrete, and bricks - significantly influence the embodied impact of buildings.

   This finding simplifies the complexity of analysis needed for screening-level Life Cycle Assessments during the design phase, allowing designers to focus on these high-impact materials. The study reveals that these materials consistently account for a large proportion of embodied impacts across all categories studied. For example, in non-residential buildings, steel and concrete contribute significantly to GWP, suggesting that targeting these materials through material efficiency and recycled materials strategies could yield substantial benefits.

3. There is a clear water-energy-carbon-ecotoxicity nexus for key construction materials.

   Strategies targeting one impact category are likely to have co-benefits in others, presenting both challenges and opportunities for holistic impact reduction. This nexus underscores the importance of considering multiple environmental impacts simultaneously when making design decisions, rather than focusing solely on carbon emissions.

4. Timber substitution shows mixed results across impact categories.

   While effective in reducing global warming potential, timber substitution shows minimal benefits or even increases in other impact categories like ecotoxicity, highlighting the need for careful consideration of trade-offs in material selection. This finding emphasizes the importance of a holistic approach to sustainable building design that considers multiple environmental impact categories.

The study’s findings have significant implications for the construction industry and sustainable building practices. By demonstrating the substantial impact of early design decisions on a building’s environmental footprint, this research emphasizes the critical importance of integrating embodied impact assessments into the design process. The near-linear relationship between strategy implementation and impact reduction provides a powerful tool for designers and policymakers to set tangible goals and measure progress in sustainable building design.

The identification of key materials that significantly influence embodied impacts offers a focused approach to material selection and optimization. This knowledge can drive innovation in the development of low-impact alternatives and encourage the scaling up of recycled material use in construction. The revealed water-energy-carbon-ecotoxicity nexus also presents an opportunity for more comprehensive sustainability strategies that address multiple environmental concerns simultaneously.

The study's use of a simple digital workflow for rapid, screening-level LCA demonstrates the potential for integrating advanced analytical tools into the design process. This approach addresses one of the key challenges in implementing embodied impact assessment in early-stage design - the need for quick, reliable, and actionable information. As these technologies continue to evolve, they will further enhance designers' ability to optimize buildings for reduced environmental impact.

The research methodology employed in this study offers several advantages:

1. Comprehensive dataset: By analyzing over 550 buildings across different types and regions, the study provides a robust and representative sample of the built environment.

2. Multi-impact assessment: The inclusion of four key impact categories (GWP, WDP, FDP, and Ecotoxicity) allows for a more holistic understanding of environmental impacts beyond just carbon emissions.

3. Flexible and scalable approach: The digital workflow developed for this study demonstrates how rapid, screening-level LCAs can be conducted efficiently, making it feasible to incorporate embodied impact assessments into early-stage design processes.

4. Practical implementation strategies: The study evaluates three concrete strategies (material efficiency, recycled content, and timber substitution) that can be readily implemented by designers and policymakers.

The findings of this study have broad implications for various stakeholders in the construction industry:

For designers and architects, these findings underscore the importance of considering embodied impacts from the earliest stages of the design process. The study shows that decisions made during the conceptual design phase can have far-reaching consequences for a building's environmental performance throughout its lifecycle. By implementing material efficiency strategies and incorporating recycled materials, designers can potentially achieve significant reductions in embodied impacts across all studied categories.

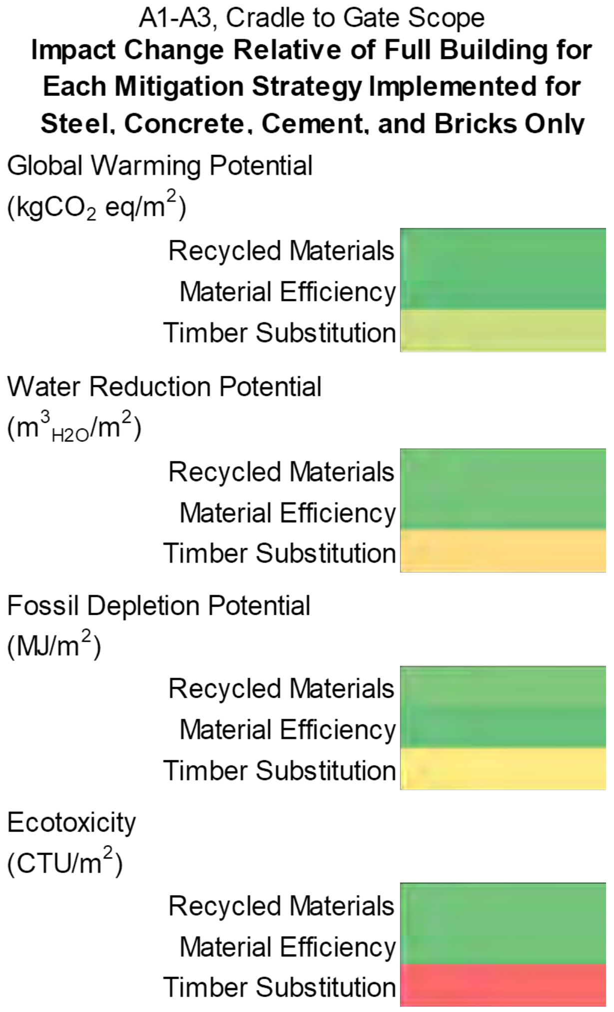
For the steel and cement industries, which are major contributors to embodied carbon in buildings, this study reinforces the urgency of decarbonization efforts. The results showing steel and concrete as consistently among the highest contributors to embodied carbon across building types highlight the outsized influence these industries have on the climate footprint of construction and buildings. This emphasizes the need for scaling up and market creation of low-carbon steel and cement products, as well as exploration of alternative materials.

For policymakers, the results provide clear evidence of the potential for significant embodied impact reductions through design-phase decisions. This underscores the need for policies and regulations that incentivize or mandate the consideration of embodied impacts in building design and construction. The near-linear relationship between strategy implementation and impact reduction offers a straightforward basis for setting targets and measuring progress.

The study also highlights the critical role of digital technologies in enabling comprehensive embodied impact assessments. The ability to rapidly assess and compare the embodied impacts of hundreds of buildings relies on advanced modeling and data analysis tools. We developed and employed a simple tool to evaluate a large data set of buildings and further demonstrated that focusing on only a few key materials provides ample information during the iterative design process to significantly influence the embodied impacts of full buildings.

This approach addresses one of the key challenges in implementing embodied impact assessment in early-stage design - the need for quick, reliable, and actionable information. As these technologies continue to evolve, they will further enhance designers' ability to optimize buildings for reduced environmental impact. Building Information Modeling (BIM) systems integrated with life cycle

Figure EX1 – **Generalized summary of the impact change to the full building for each mitigation strategy. Presented on a color scale where darker green is better, indicating a reduction in embodied impact, and red indicates an increase in embodied impact.**



assessment capabilities, for example, could allow real-time evaluation of design decisions’ impact on embodied impacts.

While the study provides valuable insights, it also identifies areas for future research:

1. Investigation of additional design phase strategies for reducing embodied impacts, including exploration of novel materials and construction techniques.

2. More integrated approaches that consider the interaction between embodied and operational impacts over a building’s life cycle.

3. Further development of digital technologies for optimizing building design, including more sophisticated modeling tools that integrate real-time embodied impact assessment into the design process.

4. Exploration of how artificial intelligence and machine learning could be leveraged to identify optimal design solutions.

5. Longitudinal studies tracking the actual performance of buildings over time compared to their predicted embodied impacts, to validate models and assumptions used in this type of analysis.

The study provides a comprehensive and actionable framework for reducing the embodied environmental impacts of buildings through design-phase decisions. By demonstrating the effectiveness of material efficiency and recycled content strategies, identifying key materials of focus, and revealing the interconnectedness of different environmental impacts, this research offers a roadmap for more sustainable building practices.

The findings call for a paradigm shift in how we approach sustainable building design, moving with carbon to include other critical environmental impacts. This shift requires collaboration across the entire building industry value chain, from material manufacturers to designers, contractors, and policymakers.

As the world grapples with the urgent need to reduce greenhouse gas emissions and mitigate climate change, the built environment offers a significant opportunity for impactful change. By implementing the strategies and insights provided by this research, the construction industry can make substantial progress towards creating more sustainable, resilient, and environmentally responsible buildings. The path forward is clear – it is now up to industry stakeholders to take action and transform these findings into tangible improvements in our built environment.

Introducing the Schneider Electric™ Sustainability Research Institute

Global awareness of the need for a more inclusive and climate-positive world is at an all-time high. This inclues reducing carbon emissions and preventing environmental damage and biodiversity loss.

Bridging the Gap Between Climate Pledges and Action. Despite growing climate pledges and sustainability initiatives, global progress is lagging. To bridge this gap, we need a multi-pronged approach:

- Alignment with UN SDGs: Ensure actions directly contribute to the UN Sustainable Development Goals (SDGs), providing a clear roadmap for progress.
- Science & Technology: Leverage scientific research and technological advancements to drive innovative solutions.
- Shift Foresight: Gain a deeper understanding of evolving energy landscapes, industries, and social, environmental, technological, and geopolitical trends.
- Policy & Finance: Strengthen legislative and financial mechanisms that incentivize and empower climate action.
- Public - Private Collaboration: Clearly define the roles and responsibilities of the public and private sectors in achieving these goals.

The Schneider Electric™ Sustainability Research Institute addresses these challenges by providing:

- Global & Local Scenarios Examining climate issues and opportunities at both global and local levels, informing solutions for businesses, societies, and governments.
- Forecasting & Actionable Insights: Analyzing current and future trends across energy, business, and behavior to anticipate challenges and identify actionable solutions.

Founded in 2020, our team is part of Schneider Electric, a leader in energy management and automation. We collaborate with experts across institutions and academia, and our research findings are published online.

In our pursuit of bridging climate pledges and action, we present a groundbreaking study on the environmental costs of buildings. While much attention has been given to operational efficiency, our research unveils the often-overlooked embodied impacts of building materials.

Our study examines the interplay between four key environmental indicators - embodied carbon, water usage, energy consumption, and ecotoxicity - as the sector transitions towards carbon mitigation. We aimed to identify potential trade-offs and synergies, and to understand when these considerations become most relevant. This study presents our findings and introduces simplified digital tools that can help industry stakeholders apply these insights in practice.

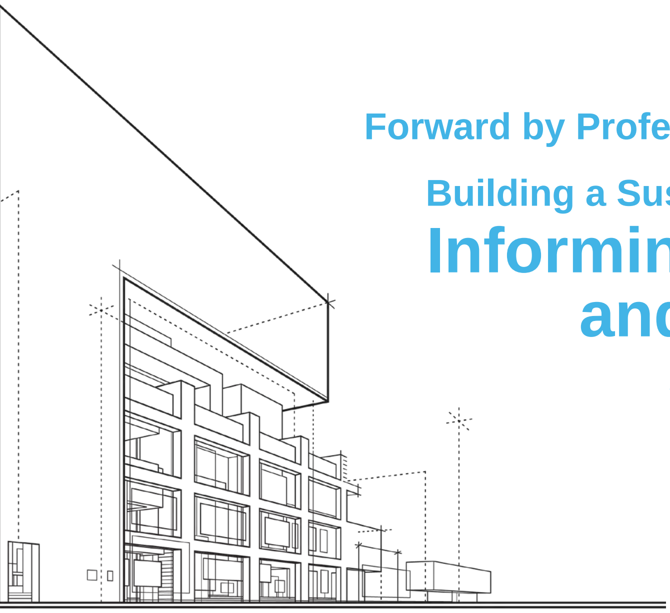
While our study focuses specifically on building materials, excluding transportation and construction processes, it represents a significant step towards holistic sustainable construction practices. The insights provided here have the potential to transform the building industry, guiding us towards practices that support our global sustainability goals.

Vincent Petit

SVP, Climate and Energy Transition Research

Dr. Thomas Alan Kwan

VP, Schneider Electric Sustainability Research Institute



Forward by Professor Qingshi Tu

Building a Sustainable Future

Informing Design and Material Selection

In the current global context, where climate change and environmental sustainability are paramount concerns, the impact of the built environment on our planet's future is a critical area of study.

Recent data indicates that buildings, which constitute the fundamental structure of our urban landscapes, are responsible for approximately 40% of global energy consumption and contribute to one-third of greenhouse gas emissions. These statistics underscore the urgent need to address the environmental impact of buildings, particularly in the realm of their embodied environmental impacts – an aspect that has historically received less attention than operational energy efficiency.

Our research aims to fill this crucial knowledge gap by conducting an in-depth analysis of the environmental footprint of buildings, focusing on the impacts that occur prior to occupancy. This includes the extraction of raw materials, the manufacturing of construction products, and the environmental implications of material choices in building design.

The study's methodology involved a comprehensive examination of over 550 buildings, encompassing various typologies and geographical regions. This extensive dataset allowed us to evaluate the efficacy of different design strategies in mitigating the environmental impact of buildings.

Our analysis centered on four key environmental indicators: global warming potential, water depletion, fossil fuel depletion, and ecotoxicity. This multifaceted approach provides a more holistic perspective on sustainability, extending beyond the singular focus on carbon emissions.

A significant finding of our research is the identification of four primary materials – steel, cement, concrete, and bricks – that exert a substantial influence on a building's overall environmental impact. This insight offers a clear direction for designers, architects, and policymakers in their efforts to meaningfully reduce the environmental footprint of buildings.

Moreover, our findings emphasize the critical importance of considering embodied impacts from the initial stages of building design. The research demonstrates that decisions made during the conceptual design phase have long-term implications for a building's environmental performance throughout its lifecycle.

While this report is primarily targeted at professionals in architecture and engineering, its implications extend to a broader audience. Anyone concerned with environmental sustainability and the future of our built environment will find valuable insights in this study. The research presents evidence-based strategies for reducing the environmental impact of our built environment through informed design choices and innovative approaches.

As you review this report, I encourage you to consider the potential applications of these findings in shaping future building practices and policies. The data and analyses presented here provide a foundation for more sustainable approaches to construction and urban development, contributing to our collective efforts in creating a more environmentally responsible world.

Prof. Qingshi Tu

Bioproducts Institute, The University of British Columbia

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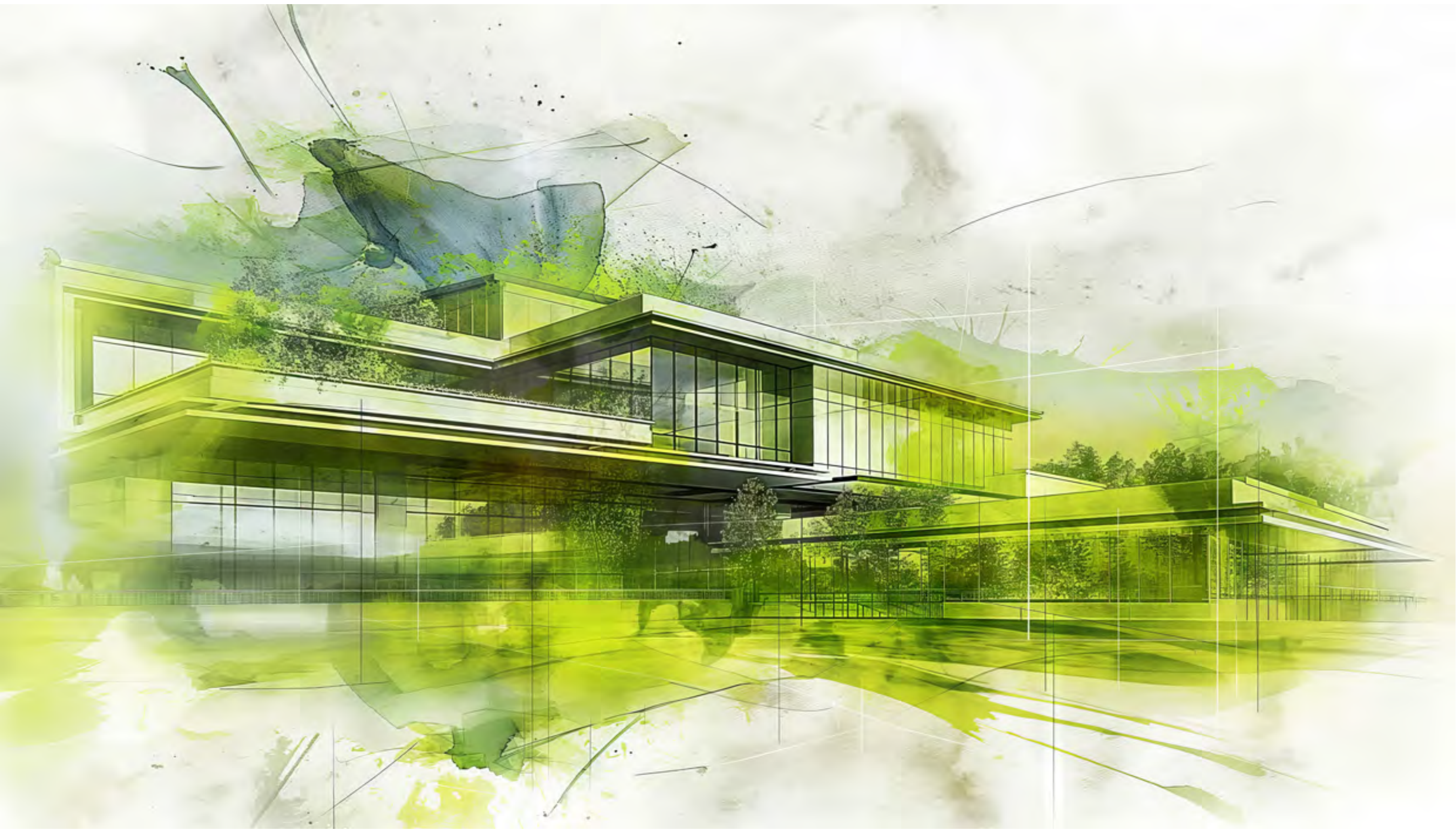


1

Introduction

Introduction

The built environment plays a crucial role in global efforts to mitigate climate change and promote sustainability. Buildings account for approximately 40% of global energy consumption and one-third of greenhouse gas (GHG) emissions [1-3]. As the world continues to urbanize and develop, the environmental footprint of the construction industry becomes increasingly significant, comprising 40% of energy use, 30% of raw materials use, 25% of solid waste, 25% of water use, and 12% of land use globally [4].

Traditionally, the focus of sustainability efforts in the building sector has been on reducing operational energy use and associated emissions during a building's use phase. This emphasis has led to significant improvements in energy efficiency standards, deployment of renewable energy technologies, and advancements in building envelope design [1]. However, as operational energy efficiency improves, the relative importance of embodied impacts is increasing [4-7].

Embodied impacts refer to the environmental burdens associated with the extraction of raw materials, manufacturing of construction products, transportation, on-site construction, maintenance and renovation, as well as end-of-life demolition and disposal [5]. Unlike operational impacts that accumulate over a building's lifespan, embodied impacts are largely incurred upfront during the initial construction phase [8]. As buildings become more energy-efficient in operation, embodied impacts can constitute an increasingly large proportion of total lifecycle impacts.

Recent studies have highlighted the growing importance of embodied carbon in buildings. Estimates of the proportion of embodied carbon relative to total lifecycle carbon emissions vary widely depending on building type, location, and methodological assumptions. Some studies have found embodied carbon to account for 10-20% of lifecycle emissions in conventional buildings, while for low energy buildings this proportion can increase to 40-60% [5]. In the UK, embodied carbon in new construction and renovation is estimated to account for about 20% of total national CO_2 emissions annually [9].

To comprehensively assess the environmental impacts of buildings, it is crucial to consider multiple indicators beyond just carbon emissions. This study focuses on four key environmental impact categories:

1. Global Warming Potential (GWP): Measured in kg CO_2 equivalent, GWP represents the embodied carbon of materials and is directly linked to climate change impacts [10-12].

2. Water Depletion Potential (WDP): Measured in m^3 of water, WDP quantifies the embodied water associated with material production and construction processes [13, 14].

3. Fossil Depletion Potential (FDP): Measured in MJ, FDP represents the embodied energy of materials and is an indicator of resource depletion (LCA.Mats, [15, 16]).

4. Ecotoxicity: Measured in Comparative Toxic Units (CTU), ecotoxicity assesses the potential toxic effects of substances on ecosystems and organisms [17-19].

Life Cycle Assessment (LCA) has emerged as a powerful tool for evaluating the environmental performance of buildings across their entire lifecycle. LCA provides a systematic approach to quantifying the environmental impacts of a product or process from raw material extraction to end-of-life disposal [20]. The development of LCA methodologies for materials and buildings has been intertwined with the evolution of embodied carbon assessment, as embodied carbon is a key component of

the overall lifecycle carbon footprint [21].

Despite the growing recognition of the importance of embodied impacts, strategies to reduce embodied carbon in the remaining life-cycle stages of a building are less defined and studied compared to operational carbon reduction strategies [22, 23]. The selection of building materials and systems is largely unregulated, as long as minimum health, safety, and performance standards are met. One challenge is that upstream energy use and carbon emissions resulting from the production of building materials and equipment are more difficult to measure and track than operational energy use and emissions.

The design phase of a building project presents a critical opportunity to influence embodied impacts. Decisions made during the early stages of design can have far-reaching consequences for the environmental performance of a building throughout its lifecycle.

Studies have shown that decisions made during the conceptual design stage can account for up to 80% of a building’s environmental impact, highlighting the outsized influence of early design choices [24, 25]. However, despite the recognition of its importance, there is a lack of comprehensive studies examining the effectiveness of different design-phase strategies in reducing embodied impacts.

Several strategies have emerged to address embodied impacts during the design phase. These include:

1. Circularity: This approach involves designing for end-of-life (EOL) considerations and incorporating recycled materials. Circular economy principles in construction aim to minimize waste and maximize resource efficiency throughout a building’s lifecycle [26, 27].

2. Material Efficiency: This strategy focuses on optimizing the use of materials to achieve the same structural integrity and functionality with fewer resources. It includes techniques such as design optimization, modular construction, and efficient waste management practices [28-30].

3. Material Substitution: This approach involves replacing high-impact materials with lower-impact alternatives. Timber substitution, in particular, has gained attention due to its potential for carbon sequestration and lower embodied carbon compared to traditional materials like steel and concrete [31-33].

To effectively minimize embodied impacts, designers require access to reliable, timely, and comprehensive information about the environmental implications of different design alternatives. However, the complexity and data-intensive nature of full lifecycle assessments often pose challenges for integration into fast-paced design workflows [34]. There is a growing recognition of the need for simplified and streamlined approaches that can provide actionable insights on embodied impacts without compromising the creative and iterative nature of the design process [35,36].

The incorporation of embodied impact considerations into design practice necessitates a shift towards more holistic evaluation methods that go beyond just operational energy performance. This requires the development and adoption of tools and frameworks that can rapidly assess and compare the embodied impacts of different design options, materials, and construction techniques [37]. Such tools must strike a balance between accuracy and usability, providing designers with clear and actionable information without overwhelming them with excessive detail or computational complexity.

Digital technologies are playing an increasingly important role in facilitating the assessment and reduction of embodied impacts during the design phase. Building Information Modeling (BIM), digital twins, and Life Cycle Assessment (LCA) tools can enable more accurate and comprehensive assessments of embodied impacts throughout the design process. BIM-based LCA tools enable designers to quickly evaluate the environmental implications of different design alternatives, material choices, and construction techniques [38-41]. These tools provide a platform for real-time feedback on embodied impacts, allowing designers to make informed decisions that balance environmental performance with other design objectives.

However, the effective implementation of embodied impact assessment in the design phase faces several challenges. These include [44-49]:

1. Data availability and quality: Accurate assessment of embodied impacts requires comprehensive and reliable data on the environmental profiles of construction materials and processes. The availability and quality of such data can vary significantly across different regions and material types.

2. Methodological inconsistencies: Different LCA methods and system boundaries can lead to varying results, making it difficult to compare assessments across projects or establish consistent benchmarks.

3. Complexity and time constraints: Conducting detailed LCAs can be time-consuming and resource-intensive, which can be challenging to integrate into fast-paced design processes.

4. Lack of standardization: The absence of universally accepted standards for embodied impact assessment in building design makes it difficult to establish consistent practices across the industry.

Despite these challenges, the importance of addressing embodied impacts in the design phase cannot be overstated. A large majority of a building’s embodied impact is committed during the design phase, with these commitments realized during construction and throughout the building’s lifecycle [46,50]. Therefore, it is imperative to consider the holistic impacts of the built environment from the earliest stages of design.

Recent advancements in LCA methodologies and tools have made it increasingly feasible to incorporate embodied impact assessments into the design process. However, there is still a need for more user-friendly tools that can provide quick, reliable, and comparative information on embodied impacts to support decision-making in early-stage design. Additionally, there is a growing recognition of the need for simplified and streamlined approaches that can provide actionable insights on embodied impacts without compromising the creative and iterative nature of the design process [34-36].

The integration of embodied impact considerations into design practice necessitates a shift towards more holistic evaluation methods that go beyond just operational energy performance. This requires the development and adoption of tools and frameworks that can rapidly assess and compare the embodied impacts of different design options, materials, and construction techniques [37]. Such tools must strike a balance between accuracy and usability, providing designers with clear and actionable information without overwhelming them with excessive detail or computational complexity.

Furthermore, the ability to conduct iterative assessments throughout the design process is crucial, as the level of detail and available information evolves from conceptual to detailed design stages [51]. This calls for flexible and scalable approaches that can accommodate varying levels of data resolution and uncertainty, allowing for progressive refinement of embodied impact estimates as the design develops [52].

While progress has been made in developing methods and tools for assessing embodied impacts, there remains a significant gap in understanding the relative effectiveness of different design-phase strategies in reducing these impacts. Few studies have comprehensively compared the potential reductions in GWP, WDP, FDP, and Ecotoxicity achievable through strategies such as material efficiency, recycled material use, and timber substitution across a wide range of building types and locations.

This research aims to address this by providing a comprehensive analysis of the effectiveness of different design-phase strategies in reducing embodied impacts. Further, we developed and used a simple digital workflow for the rapid, screening level LCA, of over 550 buildings to demonstrate the how design stage digital technologies can be developed and deployed in a flexible, scalable, and simple manner. By examining a large dataset of buildings and comparing the potential reductions achievable through various strategies, this study also seeks to provide valuable insights for designers, policymakers, and researchers working towards more sustainable building practices.

As the construction industry moves towards more sustainable practices, addressing embodied impacts has become increasingly critical. The design phase presents a unique opportunity to significantly reduce these impacts, but realizing this potential requires a more comprehensive understanding of the effectiveness of different strategies and the development of tools and methodologies to support their implementation. This research contributes to this understanding by providing a systematic analysis of design-phase strategies for reducing embodied impacts, with the ultimate goal of promoting more sustainable and environmentally responsible building practices.

2 Methods

Methods

Scope

This study focuses on the embodied impacts of building materials, specifically within the scope of product stage (A1-A3) as defined by EN 15978 and presented in Figure 1. While recognizing that a comprehensive assessment of embodied impacts extends beyond this scope and includes additional life cycle stages, this research aims to provide a focused analysis of the initial embodied impacts associated with material production.

Using the ReCiPe database, this study conducts an LCA of building materials to evaluate four key impact categories: Global Warming Potential (GWP), Fossil Depletion Potential (FDP), Water Depletion Potential (WDP), and Ecotoxicity. These impact categories are used as proxies for Embodied Carbon, Embodied Energy, Embodied Water, and Ecotoxicity, respectively. It is important to note that while these terms are used for clarity and consistency with existing literature, they represent simplified representations of more complex embodied impacts.

Global Warming Potential (GWP), reported in kg CO_2 equivalent per square meter, is used to quantify Embodied Carbon. This metric encompasses the greenhouse gas emissions associated with material extraction, transportation to manufacturing facilities, and the manufacturing process itself. However, it is acknowledged that a full assessment of embodied carbon would include emissions from later life cycle stages, such as construction, use phase, and end-of-life.

Fossil Depletion Potential (FDP), reported in MJ per square meter, serves as an indicator for Embodied Energy. This metric captures the non-renewable energy resources consumed during the A1-A3 stages. While FDP provides valuable insights into energy consumption, it is recognized that a comprehensive evaluation of embodied energy would consider additional energy inputs throughout the building's life cycle.

Water Depletion Potential (WDP), measured in m^3 water equivalent per square meter, is used to assess Embodied Water. This metric quantifies the freshwater consumption associated with material production. As with the other impact categories, it is acknowledged that a full assessment of embodied water would include water use in subsequent life cycle stages.

Ecotoxicity, derived from the TRACI 2.1 impact assessment method and measured in CTUe (Comparative Toxic Units ecotoxicity) per square meter, is employed to evaluate the potential toxic impacts on ecosystems. This metric provides insights into the environmental hazards associated with material production processes.

By focusing on these four impact categories within the A1-A3 scope, this study aims to provide a detailed analysis of the initial embodied impacts of building materials. The results of this analysis will contribute to a broader understanding of how to mitigate the environmental impacts of buildings through informed material selection and design strategies. However, it is crucial to emphasize that these metrics represent a subset of the total embodied impacts of buildings. A comprehensive assessment would need to consider additional impact categories, extend the analysis to cover all life cycle stages (including construction, use phase, maintenance, and end-of-life), and account for the dynamic nature of embodied impacts over time.

Datasets and Life Cycle Assessment

The dataset used for Bill of Materials (BoM) data is derived from Heeren & Fishman (2019) [53], which includes 301 entries of material intensity data (kg material/m² gross floor area) collected from 33 studies. These data points cover 32

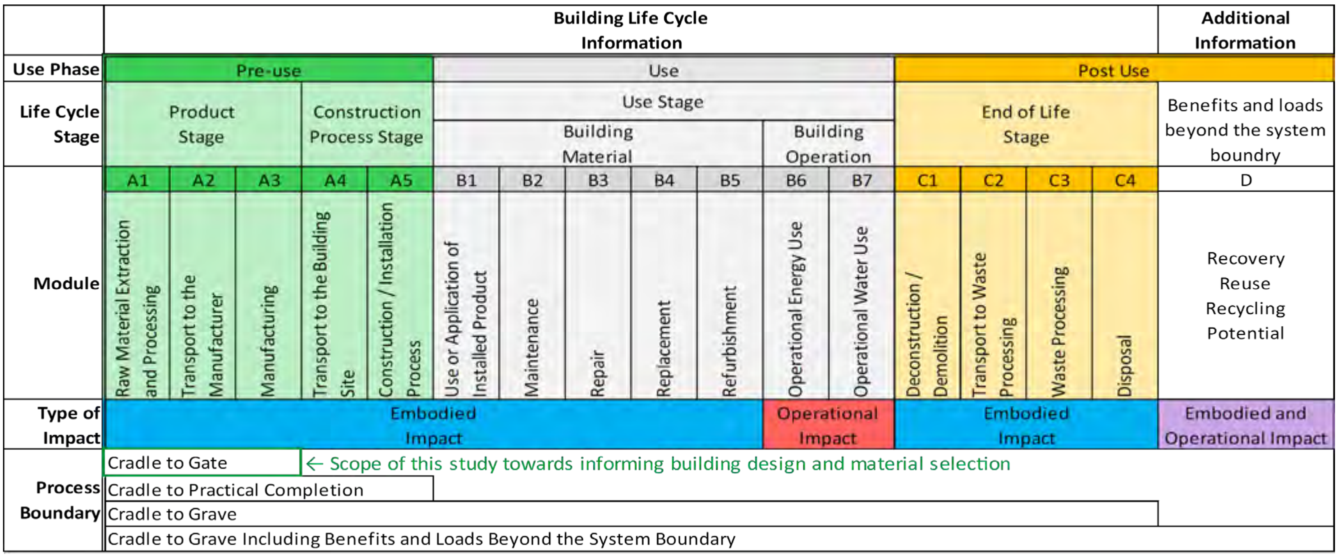


Figure 1 – **EN15978 building life cycle phases. The scope of this study was A1-A3 to inform building design and material selection.**

material categories across 21 countries and seven world regions, spanning a temporal range from the 1890s to 2018.

Life cycle environmental impacts of building materials were pre-calculated using a Python script and the Ecoinvent 3.7 (Cutoff) database. The script searches for existing building material data in the Ecoinvent database and calculates life cycle environmental impacts using the brightway2 LCA framework. The results are stored in a spreadsheet and queried during the embodied impact assessment step through another Python script. The workflow for embodied impact calculation involves the following steps:

1. Loading Building Archetypes and BoM Data: Building archetypes are loaded from the input datasheet based on occupation, building type, country, and region attributes. Users can define specific building archetypes or exhaust all combinations of these attributes present in the input datasheet automatically.

2. Matching BoM Data with Building Archetypes: The corresponding BoM data is automatically matched with the selected building archetypes based on their attribute values.

3. Applying Impact Mitigation Strategies: When an impact mitigation strategy (e.g., material substitution) is applied, the quantity of the selected material (e.g., concrete) is altered using predefined assumptions. The matching between the material name and corresponding pre-calculated impact factor can be done manually or automatically using a pre-filled matching datasheet.

4. Calculating Embodied Impacts: The calculation of embodied impacts of a given building archetype is based on the multiplication between the quantity of materials and the corresponding impact factors. The four impact categories considered: global warming potential (GWP), water depletion potential (WDP), and fossil depletion potential (FDP) from ReCiPe 2016, MidPt(H) impact assessment method, as well as ecotoxicity from TRACI 2.1 impact assessment method. Note ReCiPe reports units of kg Oil eq for FDP which were converted to Mega Joules (MJ) for ease of interpretation using the conversion factor of 1 kg Oil eq = 41.868 MJ.

Impact Mitigation Strategies

Three impact mitigation strategies are investigated:

1. Material Substitution (MS), also referred to as Timber Substitution: Substituting the use of concrete and steel with wood, without compromising structural integrity. Substitution ratios are based on assumptions from Zhong et al. (2021) [54]. Specifically:
   - 1 kg of lumber replaces 2.513 kg of concrete
   - 1 kg of lumber replaces 0.478 kg of steel

2. Material Efficiency (ME): Reducing material intensity by applying scalars to reduce the quantity of the material of interest.

3. Recycled Content (RC): Increasing recycled material usage by applying a 1:1 mass-based displacement ratio between a virgin material and its recycled counterpart.

For ME and RC strategies, a mitigation percentage was implemented equally for steel, cement, concrete, and bricks. As an example, a RC implementation of 30% means that 30% of the virgin steel was replaced with recycled steel, 30% of the virgin cement with recycled cement, and so on and so forth.

These strategies are implemented with varying percentages to cover both realistic and ideal situations. For example, single family residential buildings can be constructed primarily of timber where we analyzed up to 75% timber substitution. However, non-residential buildings, such as commercial warehouses are less likely forego steel and cement in such magnitudes. To maintain a uniform analysis, we chose to keep the bounds uniform across the data set for each strategy which likely covers unfeasible ranges at the top end of our analysis. We chose an upper bound 100% for Recycled Content given the material is a drop-in replacement.

For Material Efficiency, research consistently suggests that significant material efficiency gains are possible through optimized design for steel, concrete, and cement in buildings, typically ranging from 20-30% [55-62]. However, considering the substantial amount of on-site construction waste reported in the literature, we chose to extend the upper bound of Material Efficiency to 50%.

Studies have shown that a significant portion of building materials delivered to construction sites can end up as waste. Specifically, estimates for waste rates of steel, concrete, cement, and bricks range from less than 5% to as high as 15% [63-67]. Furthermore, the life cycle stages A4 and A5, which include transportation of the product and installation/construction, are estimated to account for 5-10% of the total embodied carbon impacts compared to A1-A3. Within these stages, steel, concrete, cement, and bricks specifically account for 2-8% of the impacts [62, 68-70].

Given these considerations, extending the upper bound to 50% allows us to explore not only the potential for material efficiency through design but also the impact of reducing on-site waste.

Critical Considerations

It is crucial to note that the scope of this analysis (A1-A3) and the normalization of material intensity to square meters are critical factors that may lead to different results compared to other studies with different scopes and normalization practices. These aspects are highlighted and focused on accordingly to ensure clarity and accuracy in the interpretation of the results.

3 Results

Results

This study analyzed the potential for reducing embodied environmental impacts in buildings through three key design strategies: Material Efficiency (ME), Recycled Content (RC), and Material Substitution (MS). The analysis covered over 550 buildings across different types and regions, focusing on four key impact categories: Global Warming Potential (GWP), Water Depletion Potential (WDP), Fossil Depletion Potential (FDP), and Ecotoxicity.

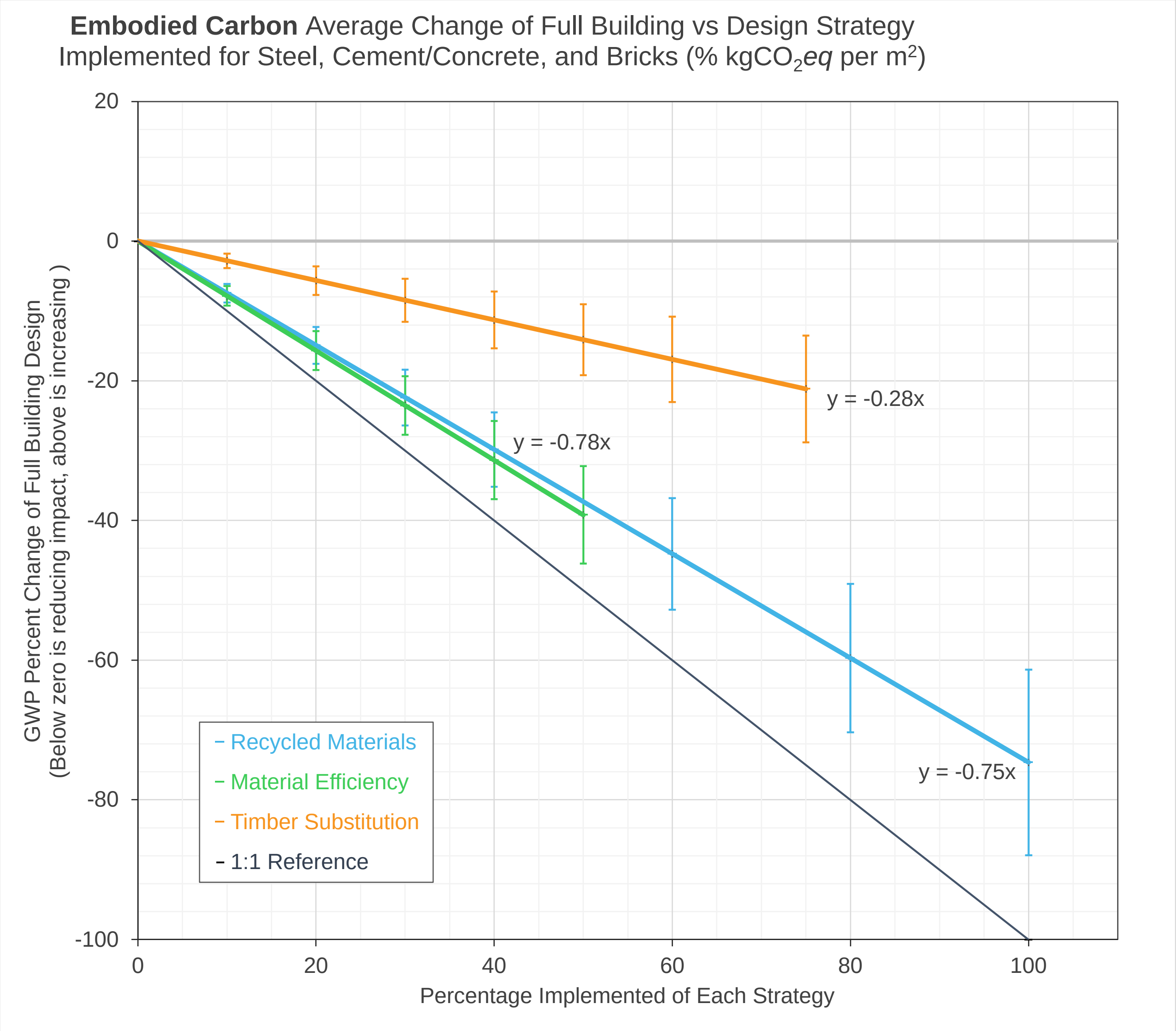


Figure 2 – **Embodied Carbon average percent change of full building versus percent implemented of each mitigation strategy. Error bars represent the standard deviation of the full data set.**

Overall Impact Reductions in Cradle to Gate Scope

Embodied Carbon (Global Warming Potential)

The study's findings on Global Warming Potential (GWP) reveal significant reductions in embodied carbon through material efficiency, recycled materials, and timber substitution strategies as indicated by the trends in Figure 2.

For every percent of material efficiency implemented, approximately 0.78% of the full building embodied carbon is reduced. This suggests that minimizing material usage in building design can lead to substantial decreases in GWP. Similarly, incorporating recycled materials shows a comparable trend, with approximately 0.75% reduction in embodied carbon for every percent of recycled materials used. This underscores the effectiveness of circular approaches in reducing environmental impacts.

Timber substitution also indicates a reduction in embodied carbon, albeit at a lower rate compared to material efficiency and recycled materials, with approximately 0.28% reduction for every percent of timber substitution as defined in this study.

The reductions in GWP achieved through these strategies are significant and highlight the potential for substantial environmental benefits in the building sector. For instance, a 30% implementation of recycled materials or material efficiency strategies can lead to a reduction of approximately 26-27% in embodied carbon for non-residential buildings and around 22-23% for residential buildings.

Comparing the strategies, material efficiency and recycled materials emerge as the most effective methods for reducing embodied carbon, with timber substitution offering a smaller but still positive impact. The detailed breakdown of contributions from different materials to the full building GWP provides valuable insights into where efforts should be focused to maximize reductions.

In non-residential buildings, steel and concrete contribute significantly to GWP, suggesting that targeting these materials through material efficiency and recycled materials strategies could yield substantial benefits. Similarly, in residential buildings, the high contribution of concrete to GWP indicates that strategies focusing on this material could be particularly effective. The material contributions can be seen in Figures 3 and 4.

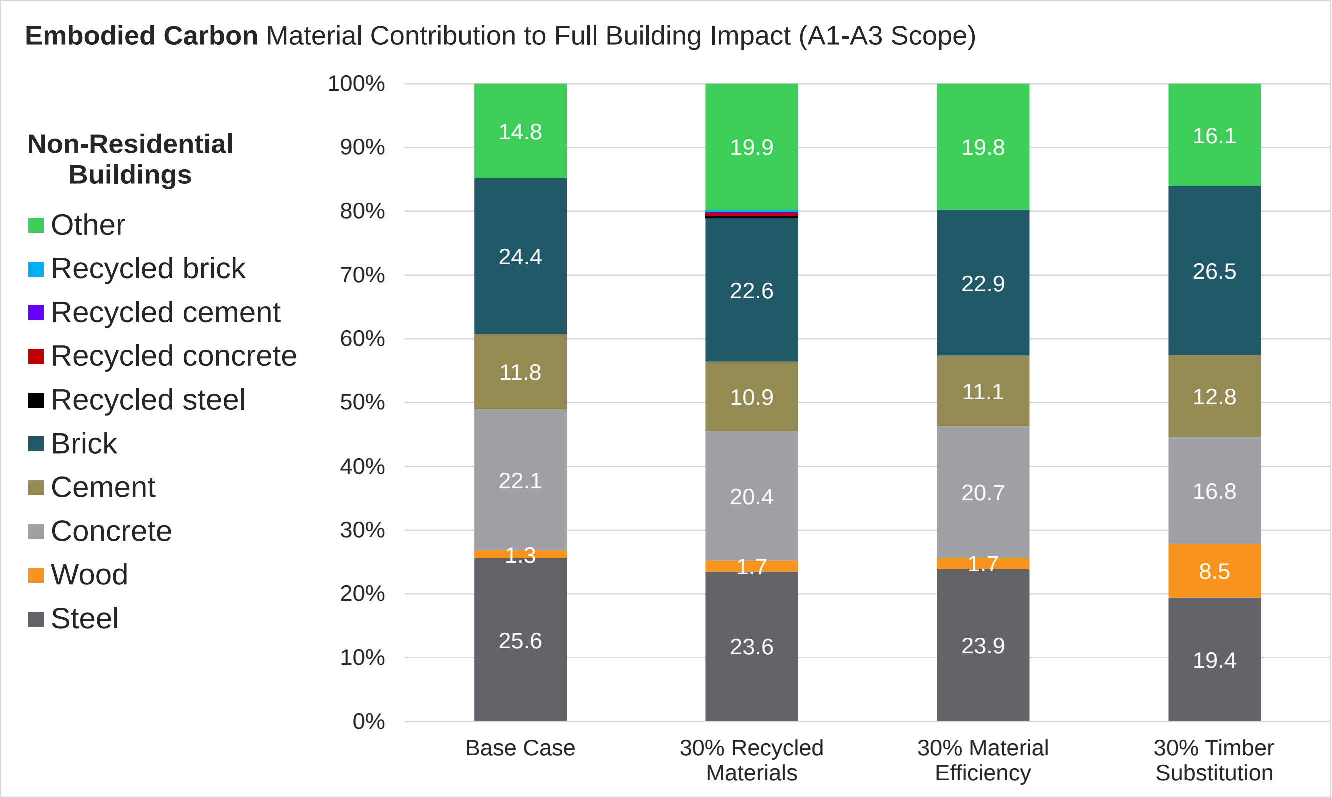


Figure 3 – **Embodied carbon material contribution in non-residential buildings at 30% implementation of each mitigation strategy and the base case.**

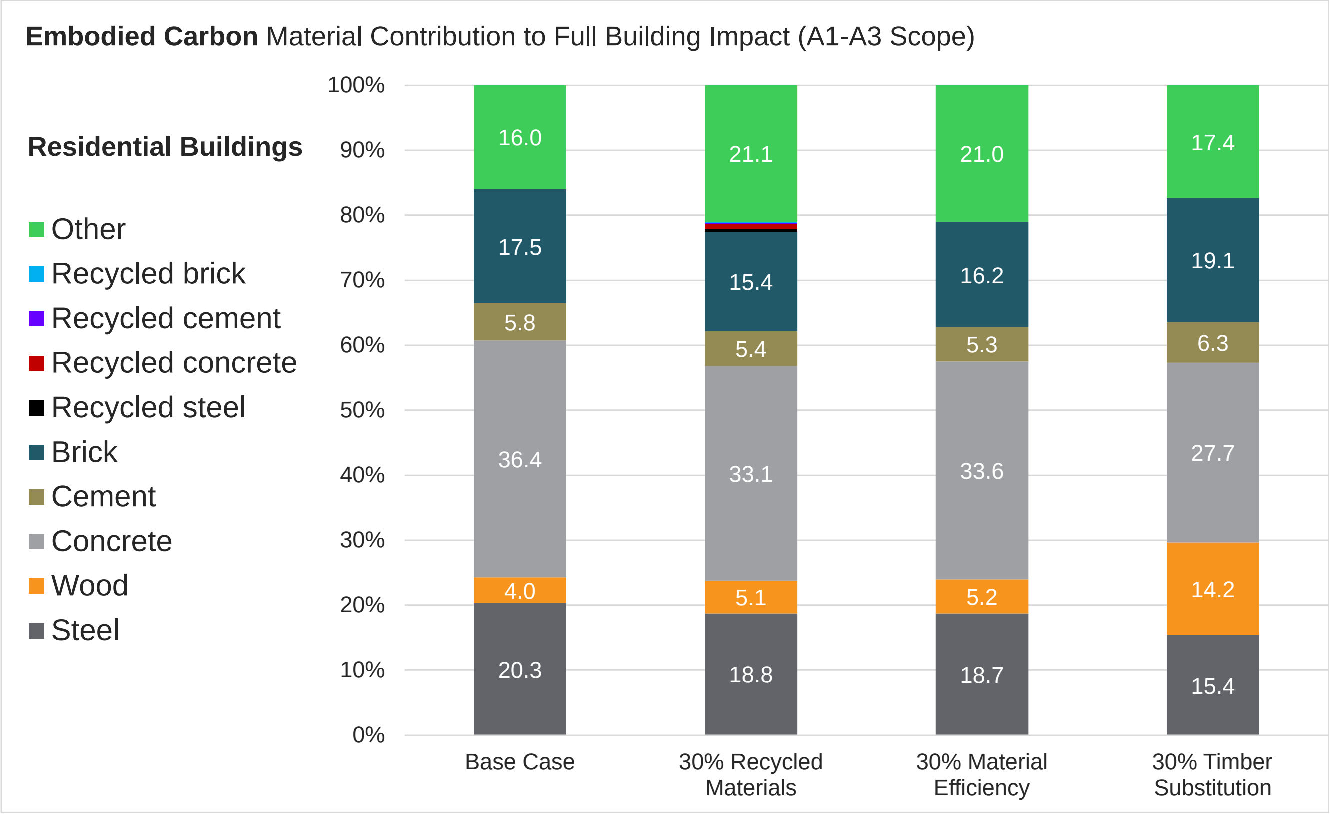


Figure 4 – **Embodied carbon material contribution in residential buildings at 30% implementation of each mitigation strategy and the base case.**

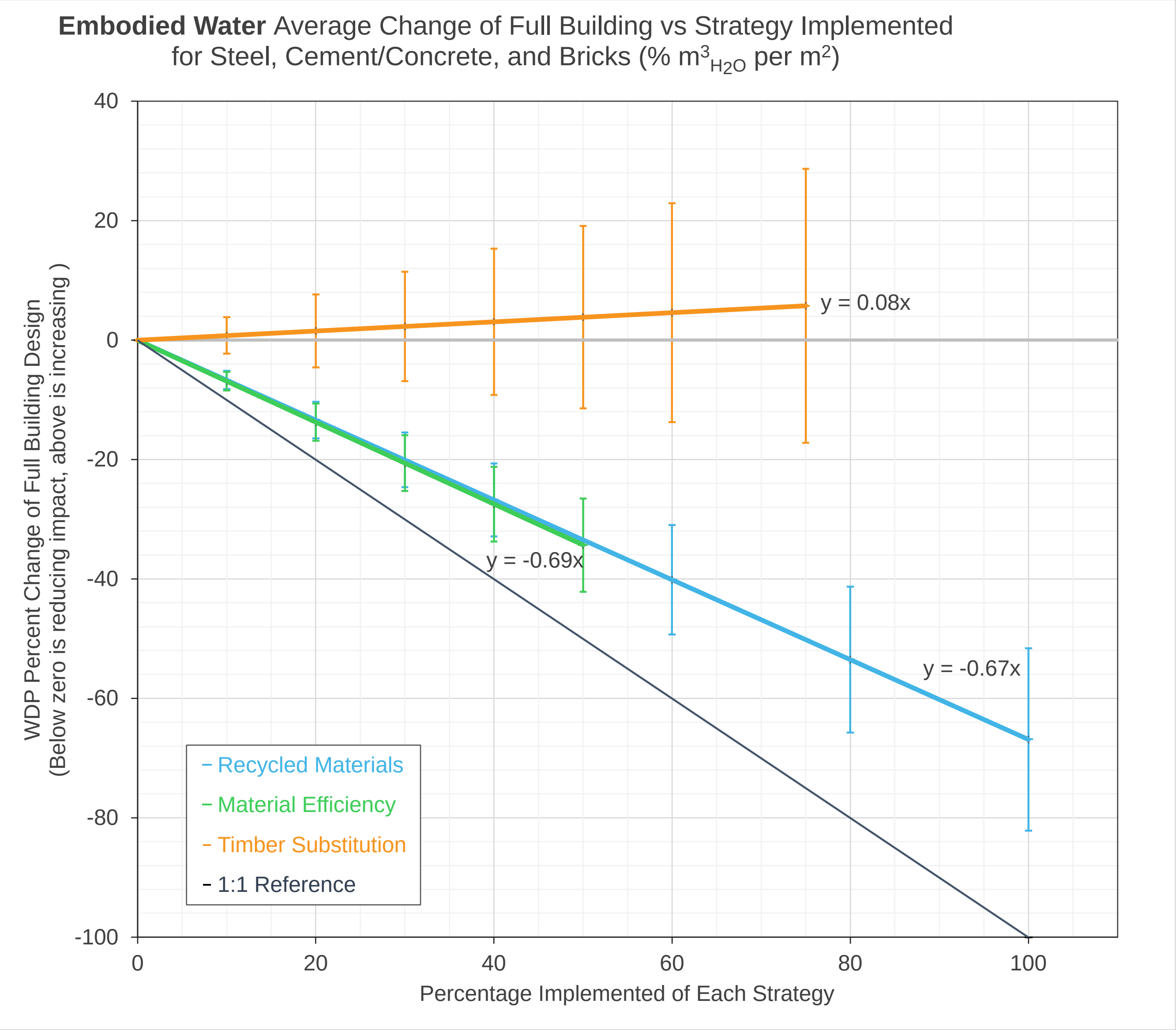


Figure 5 – **Embodied Water average percent change of full building tversus percent implemented of each mitigation strategy. Error bars represent the standard deviation of the full data set.**

Embodied Water (Water Depletion Potential)

Water Depletion Potential (WDP) results show significant reductions in water usage through material efficiency and recycled materials strategies, with mixed results for timber substitution. The average positive correlation, but wide standard deviation can be seen in Figure 5 for timber substition.

For every percent of material efficiency implemented, approximately 0.69% of the full building water depletion potential is reduced. This indicates that minimizing material usage in building design can lead to substantial decreases in WDP. Incorporating recycled materials shows a similar trend, with approximately 0.67% reduction in water depletion potential for every percent of recycled materials used.

Timber substitution, however, shows mixed and inconclusive effects on water depletion potential, with some cases showing a slight increase in water usage. This variability suggests that the impact of timber substitution on WDP is not as straightforward as material efficiency and recycled materials strategies.

The reductions in WDP achieved through material efficiency and recycled materials are significant. A 30% implementation of recycled materials or material efficiency strategies can lead to a reduction of approximately 20-23% in water depletion potential for non-residential buildings and around 15-18% for residential buildings.

Material efficiency and recycled materials emerge as the most effective methods for reducing water depletion potential, with timber substitution offering mixed results. The detailed breakdown of contributions from different materials to the full building WDP provides insights for targeted interventions.

For instance, in non-residential buildings, steel and concrete contribute significantly to WDP, suggesting that focusing on these materials through material efficiency and recycled materials strategies could yield substantial benefits. In residential buildings, the contribution of concrete to WDP is higher than non-residential and indicates that strategies targeting this material could be effective. Figures 6 and 7 show the relative contribution of the materials relative to the full building.

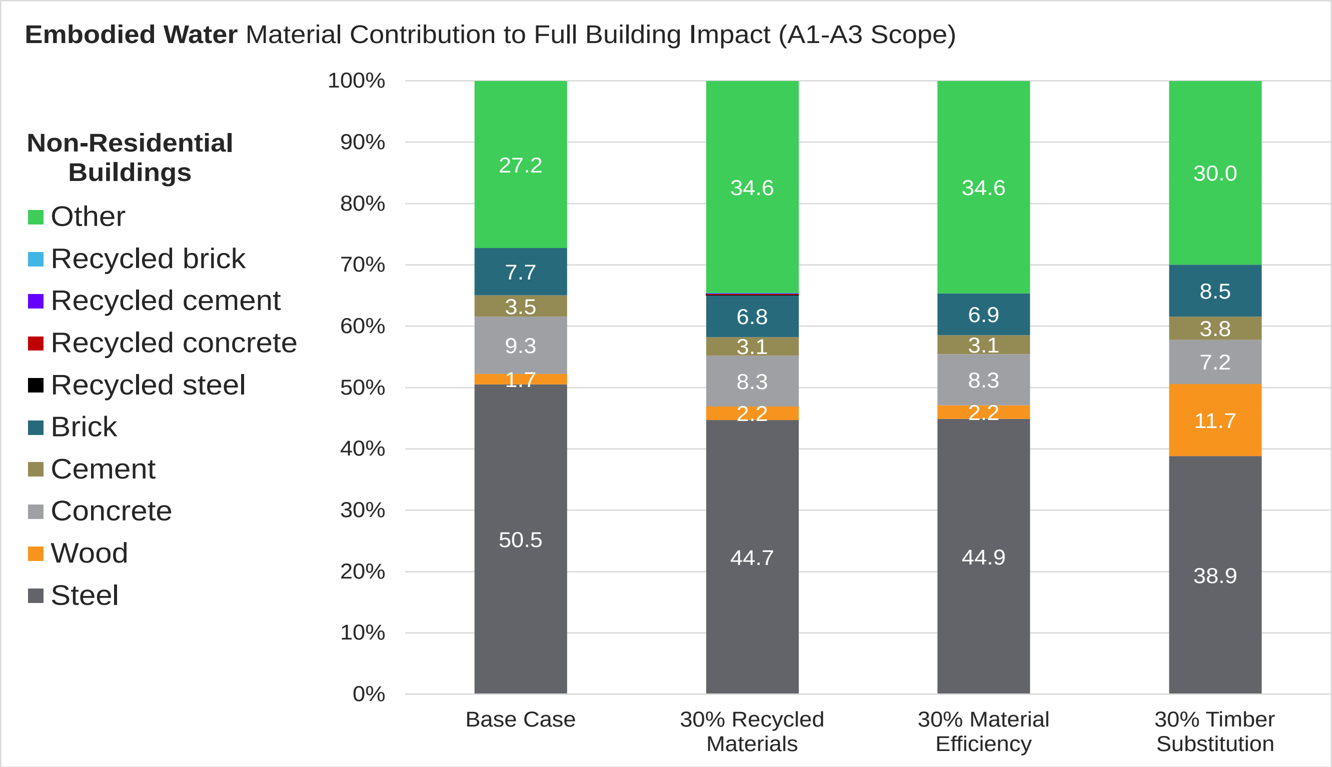


Figure 6 – **Embodied water material contribution in non-residential buildings at 30% implementation of each mitigation strategy and the base case.**

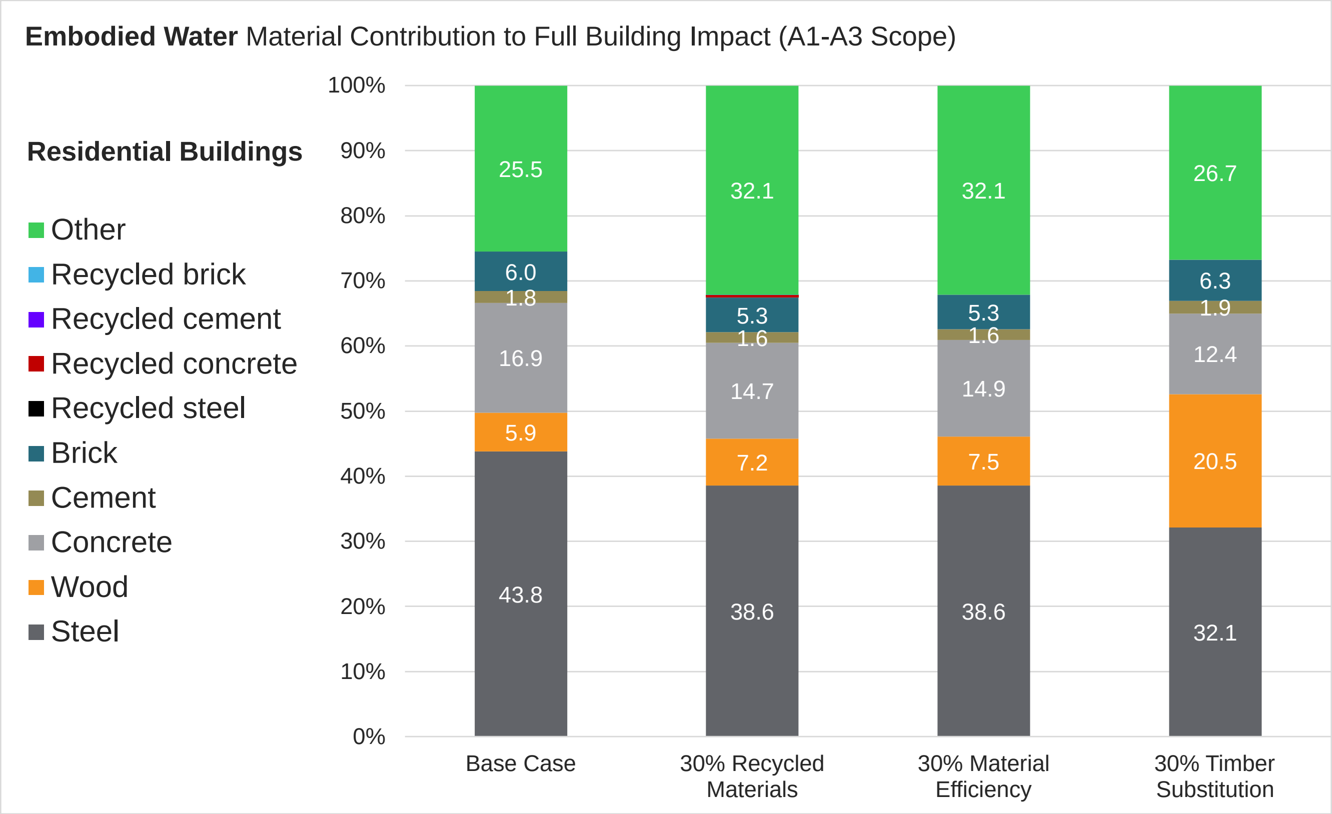


Figure 7 – **Embodied water material contribution in residential buildings at 30% implementation of each mitigation strategy and the base case.**

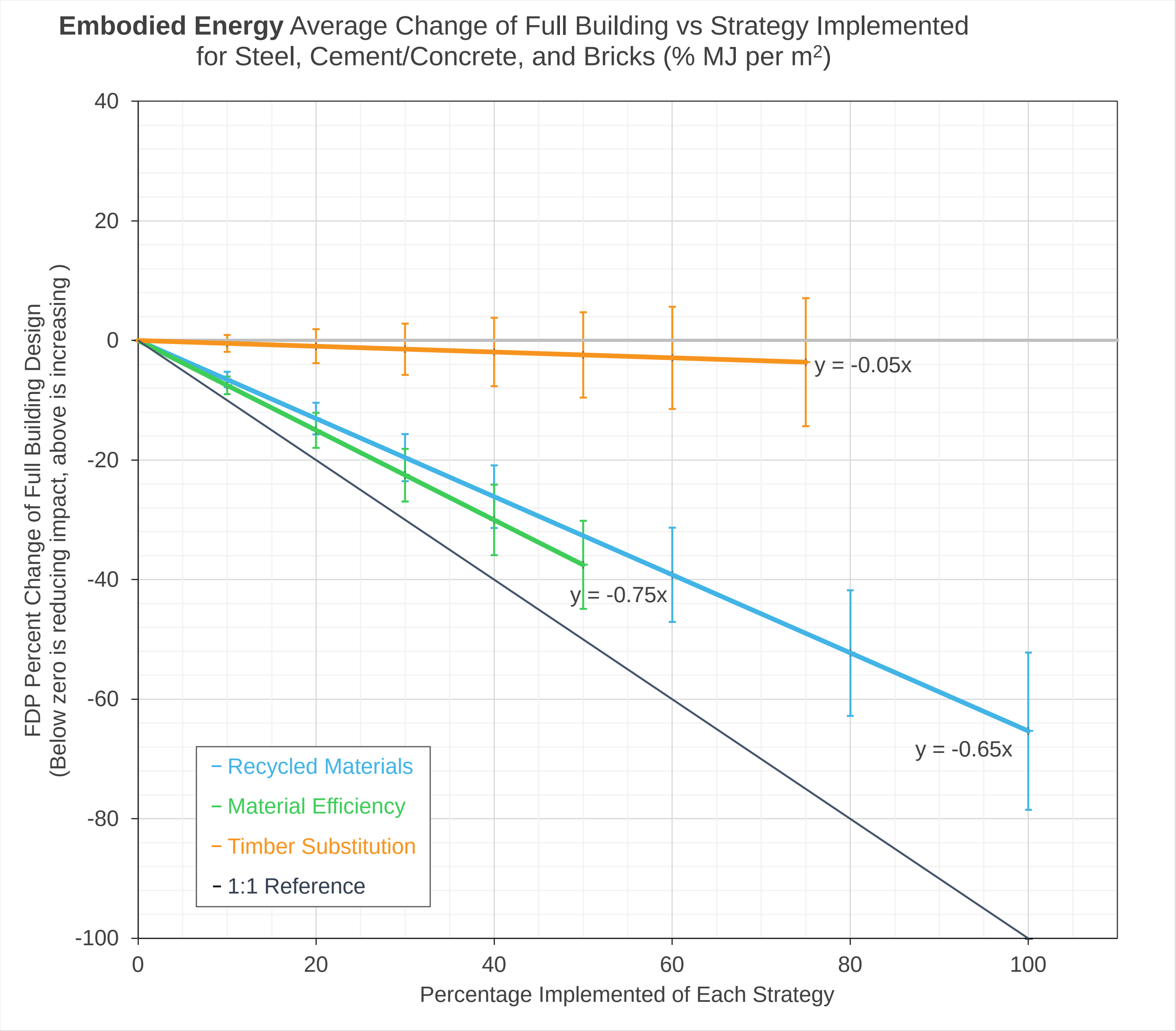


Figure 8 – **Embodied Energy average percent change of full building versus percent implemented of each mitigation strategy. Error bars represent the standard deviation of the full data set.**

Fossil Depletion Potential

Results for Fossil Depletion Potential (FDP) indicate reductions in embodied energy through material efficiency and recycled materials strategies, with mixed results for timber substitution. Figure 8 shows the similar results for material efficiency and use of recycled materials.

For every percent of material efficiency implemented, approximately 0.75% of the full building fossil depletion potential is reduced. This suggests that minimizing material usage in building design can lead to substantial decreases in FDP. Incorporating recycled materials shows a similar trend, with approximately 0.65% reduction in fossil depletion potential for every percent of recycled materials used.

Timber substitution shows mixed and inconclusive effects on fossil depletion potential, with some cases showing a slight reduction and others showing minimal increase. This variability suggests that the impact of timber substitution on FDP is not as straightforward as material efficiency and recycled materials strategies.

The reductions in FDP achieved through material efficiency and recycled materials are significant. At 30% implementation of recycled materials or material efficiency strategies can lead to a reduction of approximately 22-26% in fossil depletion potential for non-residential buildings and around 18-22% for residential buildings.

Material efficiency and recycled materials emerge as the most effective methods for reducing fossil depletion potential, with timber substitution offering mixed results. The detailed breakdown of contributions from different materials to the full building FDP provides insights for targeted interventions.

In non-residential buildings, steel, concrete, and bricks contribute significantly to FDP, suggesting that targeting these materials through material efficiency and recycled materials strategies could yield substantial benefits. Similarly, in residential buildings, the high and similar contribution of concrete, steel, and bricks to FDP indicates that strategies focusing on this material are warranted may have the most impact rather than focusing on other materials. Figures 9 and 10 show the material contribution at 30% implementation for each strategy for embodied energy.

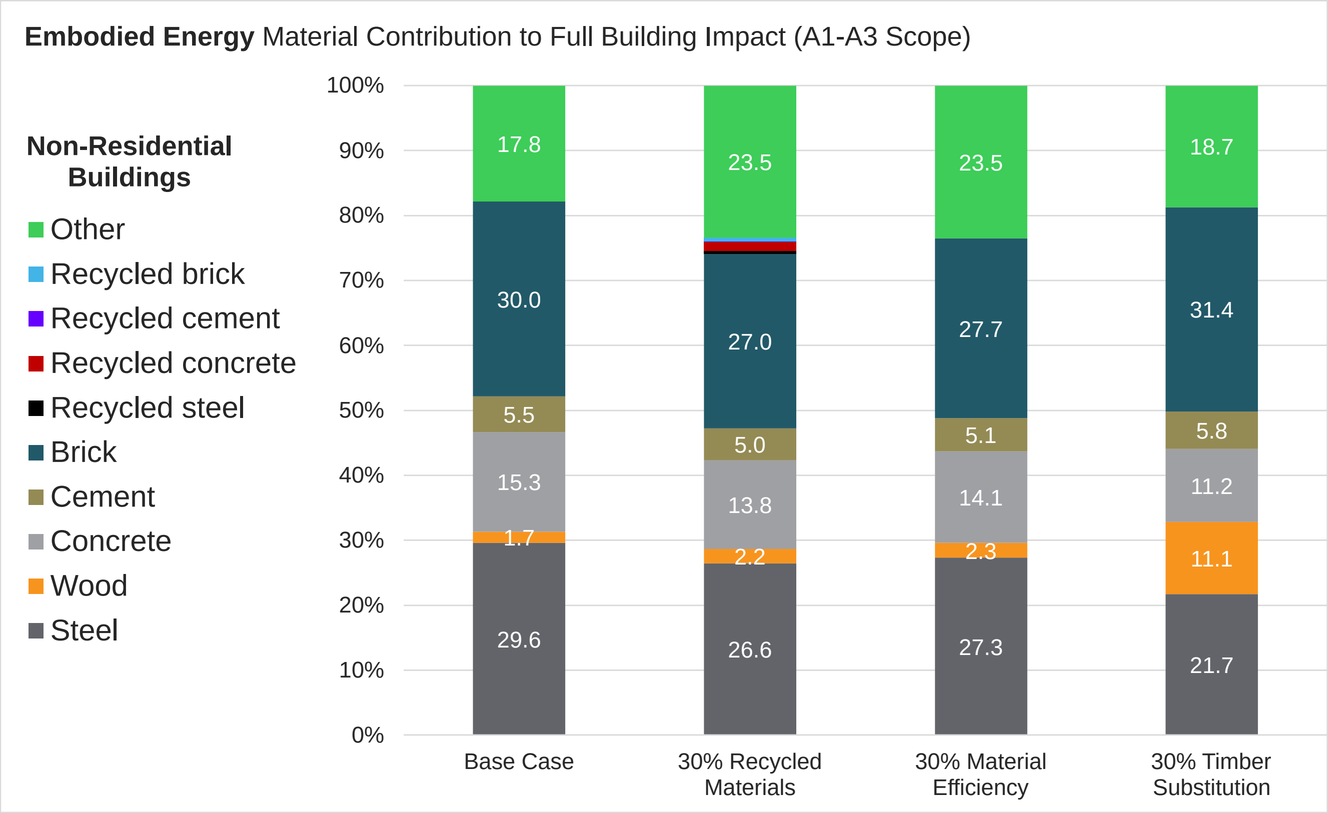


Figure 9 – Embodied energy material contribution in non-residential buildings at 30% implementation of each mitigation strategy and the base case.

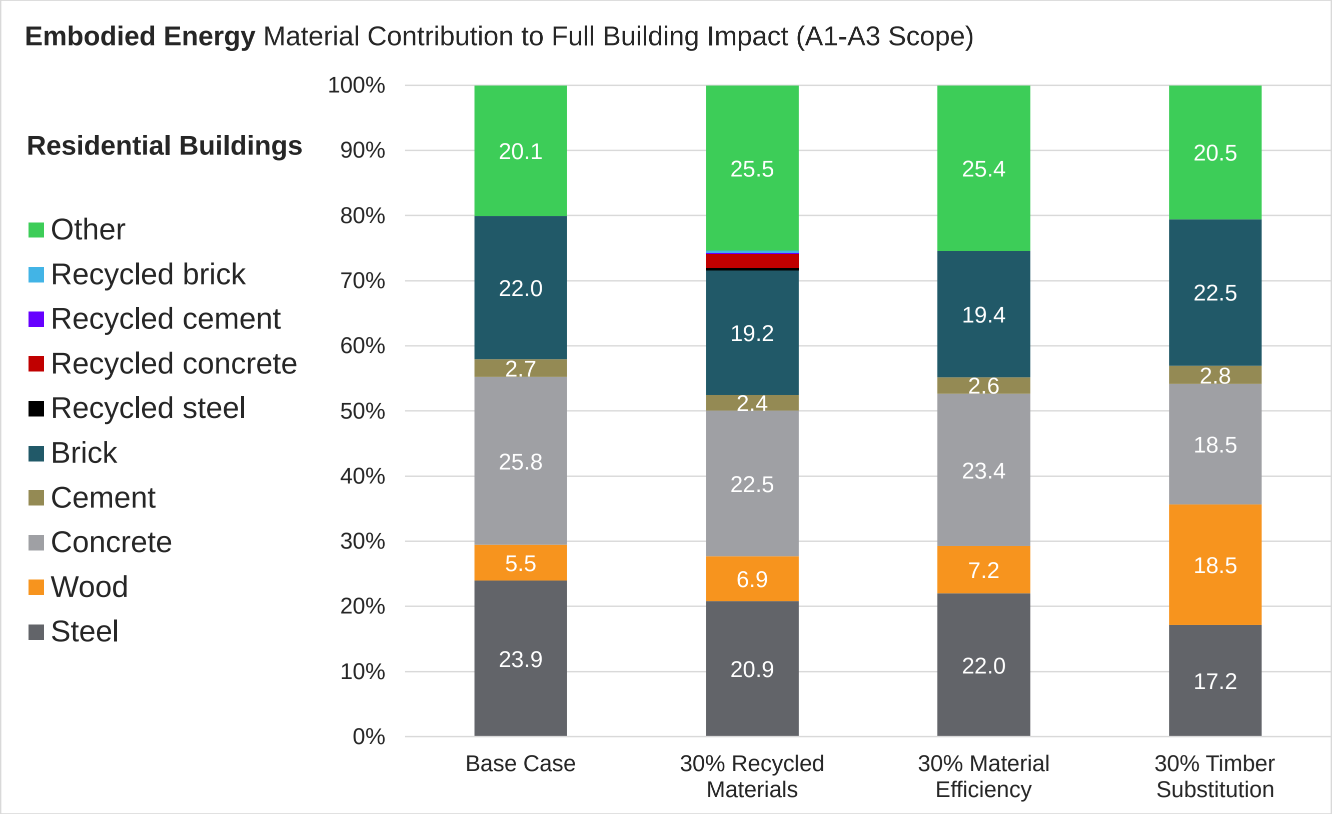


Figure 10 – Embodied energy material contribution in residential buildings at 30% implementation of each mitigation strategy and the base case.

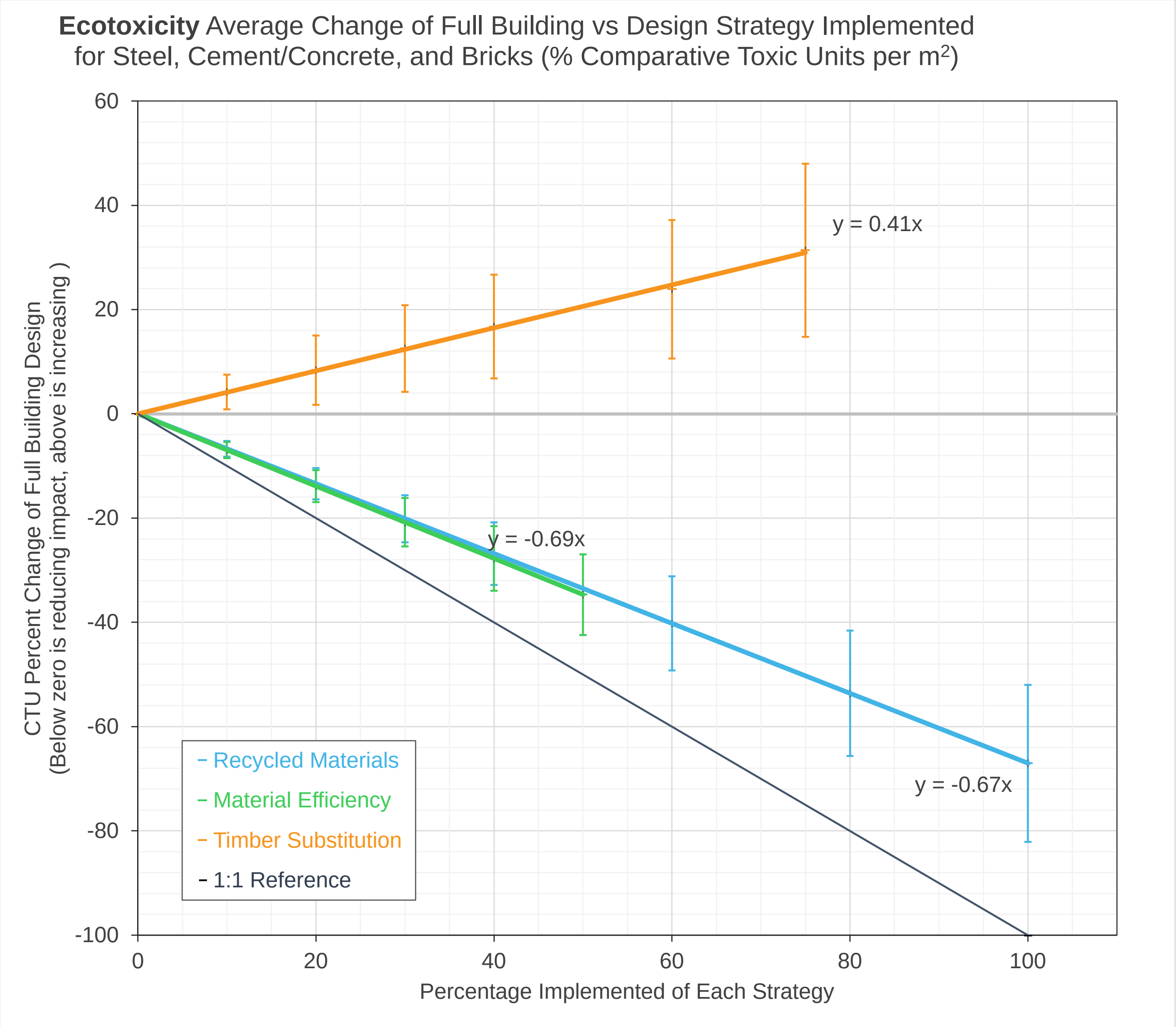


Figure 11 – **Ecotoxicity average percent change of full building versus percent implemented of each mitigation strategy. Error bars represent the standard deviation of the full data set.**

Ecotoxicity

Ecotoxicity results showed the most significant trade-offs, with substantial reductions through material efficiency and recycled materials strategies, but increases with timber substitution. Figure 11 shows the positive correlation with timber sustition strategies and ecotoxicity.

For every percent of material efficiency implemented, approximately 0.69% of the full building ecotoxicity is reduced. This suggests that minimizing material usage in building design can lead to substantial decreases in ecotoxicity. Incorporating recycled materials shows a similar trend, with approximately 0.67% reduction in ecotoxicity for every percent of recycled materials used.

However, timber substitution indicates an increase in ecotoxicity, with approximately 0.41% increase for every 1% substitution implemented. This suggests that timber substitution may not be an effective strategy for reducing ecotoxicity within the scope and methods of this study.

The reductions in ecotoxicity achieved through material efficiency and recycled materials are significant. A 30% implementation of recycled materials or material efficiency strategies can lead to a reduction of approximately 20-24% in ecotoxicity for non-residential buildings and around 15-18% for residential buildings.

Comparing the strategies, material efficiency and recycled materials emerge as the most effective methods for reducing ecotoxicity, with timber substitution showing an opposite effect. The detailed breakdown of contributions from different materials to the full building ecotoxicity provides valuable insights into where efforts should be focused to maximize reductions.

For example, in non-residential buildings, steel and concrete contribute significantly to ecotoxicity, suggesting that targeting these materials through material efficiency and recycled materials strategies could yield substantial benefits. In residential buildings, the high contribution of concrete, steel, and when employed at high levels timber, reveal a trade-off when implementing timber substition strategies. Figures 12 and 13 show the material contribution breakdown for ecotoxicity.

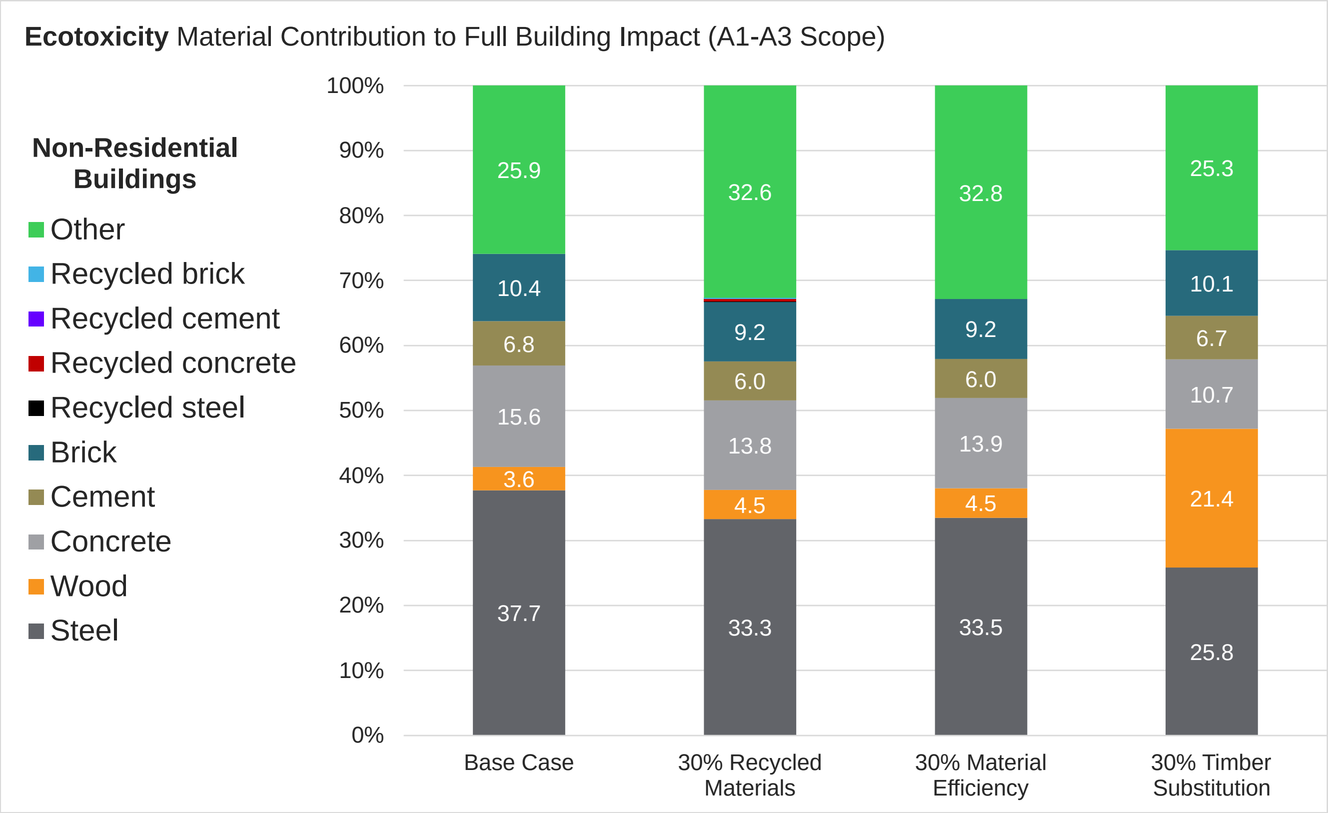


Figure 12 – Ecotoxicity material contribution in non-residential buildings at 30% implementation of each mitigation strategy and the base case.

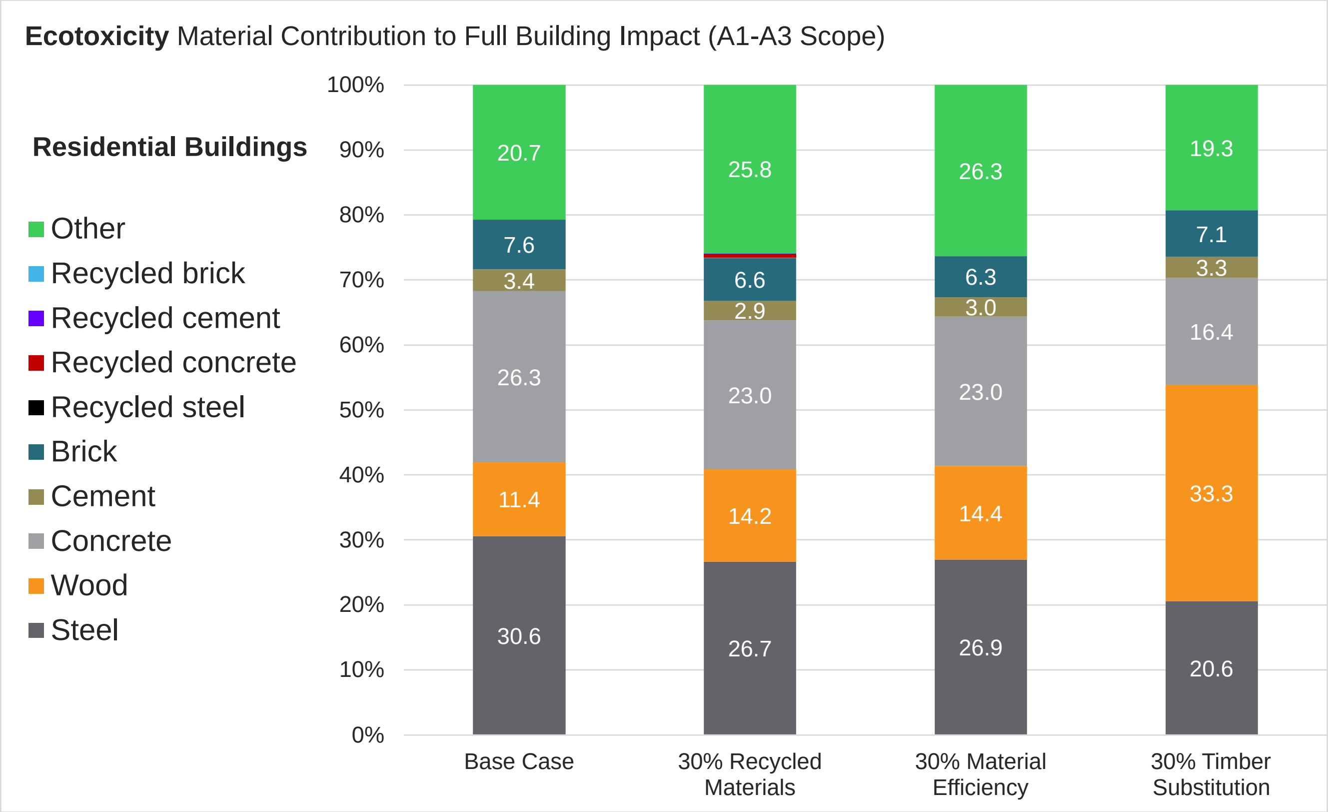


Figure 13 – Ecotoxicity material contribution in residential buildings at 30% implementation of each mitigation strategy and the base case.

Table 1– **Median percent change of each mitigation strategy relative to the full building.**

	Median Percent Change of Full Building								
	Percent Implemented of Each Strategy for Steel, Cement, Concrete, and Bricks								
	10%	20%	30%	40%	50%	60%	75%	80%	100%
Global Warming Potential ($kgCO_2$ eq/m^2)									
Recycled Materials	-8.7	-17.4	-26.0	-34.7		-52.1		-69.4	-86.8
Material Efficiency	-9.1	-18.1	-27.2	-36.3	-45.4				
Timber Substitution	-2.9	-5.9	-8.8	-11.7	-14.6	-17.6	-22.0		
Water Reduction Potential ($m^3{}_{H2O}/m^2$)									
Recycled Materials	-7.8	-15.6	-23.4	-31.1		-46.7		-62.3	-77.9
Material Efficiency	-7.9	-15.8	-23.7	-31.7	-39.6				
Timber Substitution	0.3	0.7	1.0	1.4	1.7	2.0	2.5		
Fossil Depletion Potential (MJ/m^2)									
Recycled Materials	-7.4	-14.9	-22.3	-29.7	-44.6			-59.5	-74.3
Material Efficiency	-8.7	-17.4	-26.0	-34.7	-43.4				
Timber Substitution	-0.2	-0.3	-0.5	-0.7	-0.9	-1.0	-1.3		
Ecotoxicity (CTU/m^2)									
Recycled Materials	-8.0	-16.1	-24.1	-32.1	-48.2			-64.3	-80.3
Material Efficiency	-8.3	-16.5	-24.8	-33.0	-41.3				
Timber Substitution	2.5	5.1	6.3	7.6	10.1	12.6	18.9		

Variability

Given the large dataset consisting of a wide variety of building archetypes around the world built throughout the last century, the variability in building design and type is observed in the overall results. Because of the scalar method approach, the standard deviation analyzed at 1% implementation is useful to comprehend the range of results the full dataset yielded.

For GWP at 1% implementation, the standard deviation was plus or minus 0.15% of Recycled Materials implemented and similar for other approaches, indicating that while the trends are clear, the exact amount of reduction can vary and clearly dependent on factors related to the exact building archetype and bill of materials.

As with the GWP variability in results, a wide standard deviation was observed for WDP, FDP, and Ecotoxicity, with a plus or minus 0.11 – 0.14% at one percent implemented, for recycled materials and material efficiency. The trends and variability underscore both the importance and impact of the mitigation strategies and the need for rapid, simple, and flexible assessment tools during the design process to inform practitioners and stakeholders on their choices.

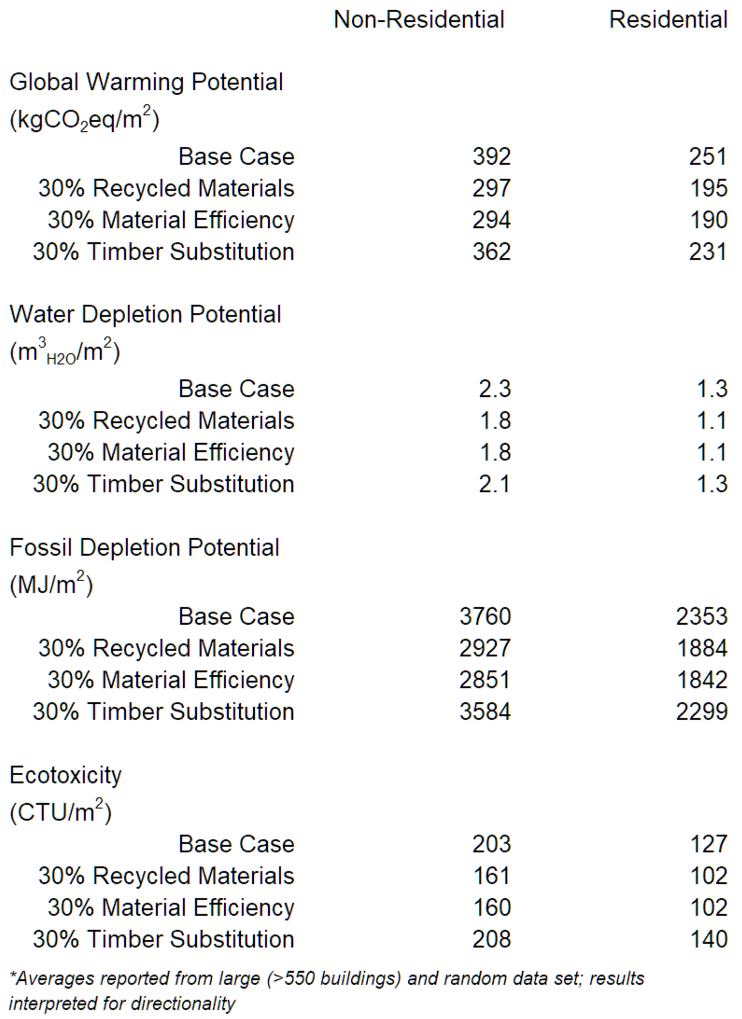
Median Results of Impact Reductions

The above analysis used the average of the results for analysis. However, given the described large and varied data set, we also performed the analysis using the median of the results. In this case, the resulting ratios of percent strategy implemented to the impact on the full building were more pronounced. For example, at ten percent implementation of Recycled Materials, using the average results indicate the full building will have a reduction of 7.5% GWP. If instead we used the median for analysis, that reduction would be greater at 8.7% GWP. The pronounced impact holds true across the board for all reductions as well as for all increases in impacts. We chose to present the more conservative ratio as the primary analysis but provide the median data here for thoroughness.

Table 1 list the median percent change of the full building for each impact category and each mitigation strategy investigated.

As expected, similar to the averaged results, material efficiency and recycled materials are the most effective strategies in reducing environmental impacts across all categories, with significant reductions observed in GWP, WDP, FDP, and ecotoxicity. Timber substitution shows mixed results, with minimal reductions or even increases in some cases.

Table 2– **Average values of base case and 30% implementation of each mitigation strategy for non-residential and residential buildings.**



	Non-Residential	Residential
Global Warming Potential ($kgCO_2eq/m^2$)		
Base Case	392	251
30% Recycled Materials	297	195
30% Material Efficiency	294	190
30% Timber Substitution	362	231
Water Depletion Potential (m^3_{H2O}/m^2)		
Base Case	2.3	1.3
30% Recycled Materials	1.8	1.1
30% Material Efficiency	1.8	1.1
30% Timber Substitution	2.1	1.3
Fossil Depletion Potential (MJ/m^2)		
Base Case	3760	2353
30% Recycled Materials	2927	1884
30% Material Efficiency	2851	1842
30% Timber Substitution	3584	2299
Ecotoxicity (CTU/m^2)		
Base Case	203	127
30% Recycled Materials	161	102
30% Material Efficiency	160	102
30% Timber Substitution	208	140

**Averages reported from large (>550 buildings) and random data set; results interpreted for directionality*

Impact Reductions by Building Type

Non-Residential vs. Residential Buildings

The study reveals significant differences in the potential for impact reductions between non-residential and residential buildings across all four impact categories. Table 2 list the results of the base case and for each mitigation strategy implemented at 30% split between residential and non-residential.

Global Warming Potential (GWP)

- Non-Residential Buildings: The base case GWP for non-residential buildings is 392 $kgCO_2eq/m^2$, with significant reductions observed through material efficiency (294 $kgCO_2eq/m^2$) and recycled materials (297 $kgCO_2eq/m^2$) strategies. Timber substitution shows a lesser reduction, with a GWP of 362 kgCO2eq/m2.

- Residential Buildings: The base case GWP for residential buildings is 251 kgCO2eq/m2, with reductions observed through material efficiency (190 $kgCO_2eq/m^2$) and recycled materials (195 $kgCO_2eq/m^2$) strategies. Timber substitution shows a minimal reduction, with a GWP of 231 $kgCO_2eq/m^2$.

Water Depletion Potential (WDP)

- Non-Residential Buildings: The base case WDP for non-residential buildings is 2.3 m^3_{H2O}/m^2, with reductions observed through material efficiency (1.8 m^3_{H2O}/m^2) and recycled materials (1.8 m^3_{H2O}/m^2) strategies. Timber substitution shows a minimal reduction, with a WDP of 2.1 m^3_{H2O}/m^2.

- Residential Buildings: The base case WDP for residential buildings is 1.3 m^3_{H2O}/m^2, with reductions observed through material efficiency (1.1 m^3_{H2O}/m^2) and recycled materials (1.1 m^3_{H2O}/m^2) strategies. Timber substitution shows no significant reduction, with a WDP of 1.3 m^3_{H2O}/m^2.

Fossil Depletion Potential (FDP)

- Non-Residential Buildings: The base case FDP for non-residential buildings is 3760 MJ/m^2, with reductions observed through material efficiency (2851 MJ/m^2) and recycled materials (2927 MJ/m^2) strategies. Timber substitution shows a minimal reduction, with an FDP of 3584 MJ/m^2.

- Residential Buildings: The base case FDP for residential buildings is 2353 MJ/m², with reductions observed through material efficiency (1842 MJ/m²) and recycled materials (1884 MJ/m²) strategies. Timber substitution shows no significant reduction, with an FDP of 2299 MJ/m².

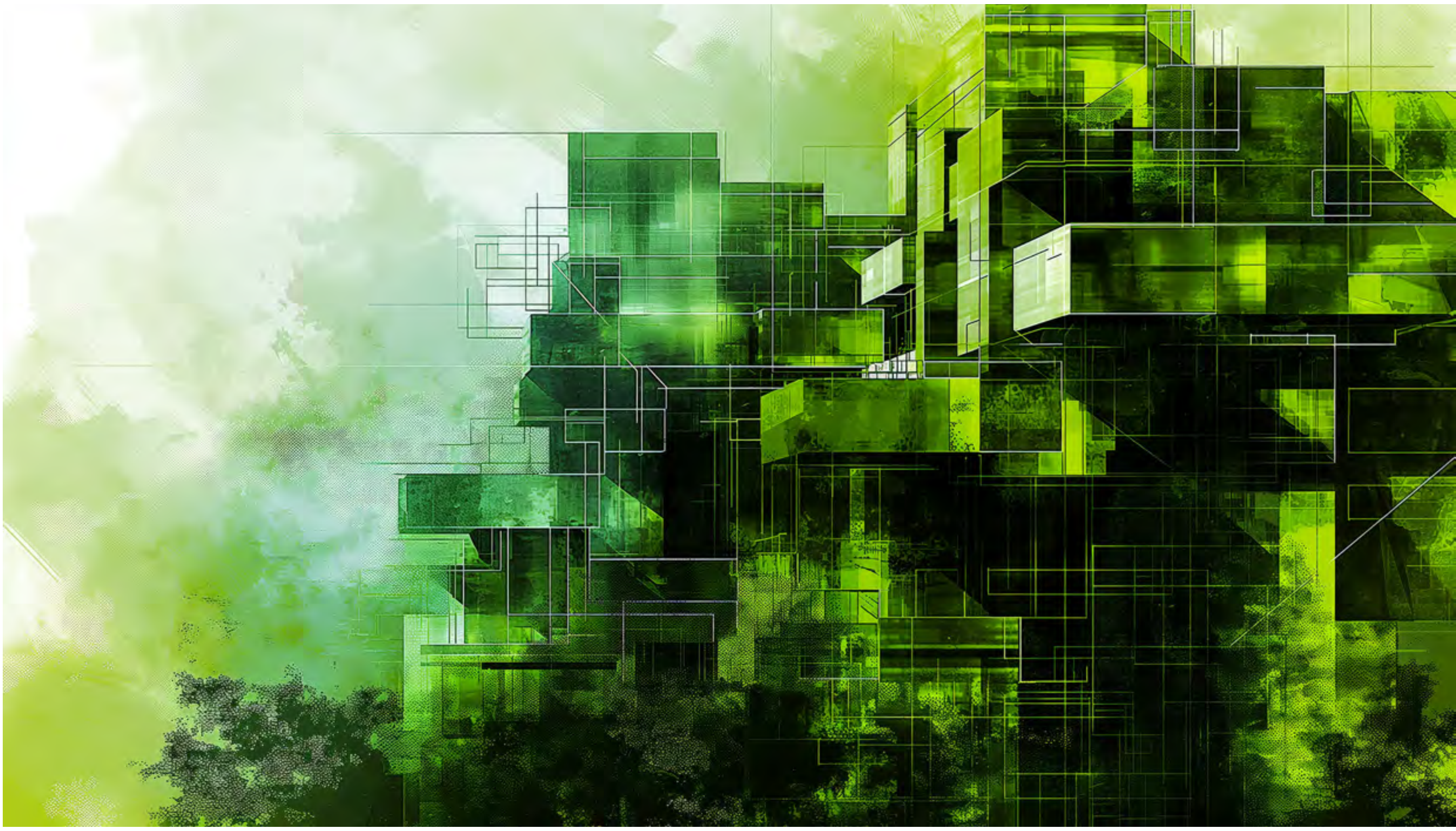
Ecotoxicity

- Non-Residential Buildings: The base case ecotoxicity for non-residential buildings is 203 CTU/m², with reductions observed through material efficiency (160 CTU/m²) and recycled materials (161 CTU/m²) strategies. Timber substitution shows an increase in ecotoxicity, with a value of 208 CTU/m².

- Residential Buildings: The base case ecotoxicity for residential buildings is 127 CTU/m², with reductions observed through material efficiency (102CTU/m²) and recycled materials (102 CTU/m²) strategies. Timber substitution shows an increase in ecotoxicity, with a value of 140 CTU/m².

Comparing the two building types, non-residential buildings generally have larger environmental impacts per square meter compared to residential buildings. This is consistent across all impact categories, including GWP, WDP, FDP, and ecotoxicity.

The effectiveness of material efficiency and recycled materials strategies in reducing environmental impacts is evident in both building types, with significant reductions observed across all categories. However, timber substitution shows mixed results, with minimal reductions or even increases in some cases.



4 Discussion

Discussion

The findings of this comprehensive study on over 550 buildings provide crucial insights into the nexus of carbon, energy, water, and ecotoxicity impacts embodied in construction materials, particularly focusing on steel, cement, concrete, and bricks. These results not only confirm previous research but also extend our understanding of the interrelationships between different environmental impact categories and the effectiveness of various design strategies in mitigating these impacts. While this study provides valuable insights into the embodied impacts of building materials within the A1-A3 scope, it is crucial to acknowledge the limitations of this approach. The full 'Embodied' impacts, including those beyond A3, are not captured in this analysis.

The study's results demonstrate that just four materials - steel, cement, concrete, and bricks - significantly influence the embodied impact of a full building. This finding is particularly important as it simplifies the complexity of analysis needed for screening-level Life Cycle Assessments (LCAs) during the design phase. Designers can now focus their efforts on reducing the quantities of these high-impact materials where possible and explore alternative low-carbon options. This targeted approach aligns with the concept of "hot-spot analysis" in LCA, where efforts are concentrated on the most impactful elements of a system.

The near-perfect positive correlation observed between the use of recycled materials and material efficiency strategies suggests that these approaches may be equally impactful in reducing embodied impacts. However, it's crucial to note that the scope of this analysis was limited to the cradle-to-gate stage, not including transportation. This means that additional embodied impacts will be accumulated with any physical material, even if recycled. In contrast, material efficiency strategies that completely forgo the use of certain materials may offer even greater benefits when considering the full life cycle of a building.

For designers, the results highlight the importance of considering embodied impacts holistically from the earliest stages of building design. The large variations observed in embodied carbon, water, and energy across different building types and materials underscore the need for designers to carefully evaluate material choices and design strategies. For example, the finding that just four materials (steel, cement, concrete, bricks) significantly influence the embodied impact of a full building reduces the complexity of analysis that is needed for screening-level LCAs during the design phase. Designers should prioritize reducing the quantities of these high-impact materials where possible and explore alternative low-carbon options.

The study reveals a strong correlation between the implementation of material efficiency and recycled content strategies and the reduction of embodied impacts.
For every percent of material efficiency implemented, approximately 0.78% of the full building embodied carbon is reduced. Similarly, incorporating recycled materials shows

a comparable trend, with approximately 0.75% reduction in embodied carbon for every percent of recycled materials used. This near-perfect positive correlation between these strategies suggests they may be equally impactful in reducing embodied impacts.

However, it's crucial to note that the scope of this analysis was limited to the cradle-to-gate stage, not including transportation. This means that additional embodied impacts will be accumulated with any physical material, even if recycled. In contrast, material efficiency strategies that completely forgo the use of certain materials may offer even greater benefits when considering the full life cycle of a building.

The study's findings regarding the four core materials - steel, cement, concrete, and bricks - are particularly noteworthy. These materials were found to significantly influence the embodied impact of a full building across all impact categories studied. For instance, in non-residential buildings, steel and concrete contribute significantly to GWP, suggesting that targeting these materials through material efficiency and recycled materials strategies could yield substantial benefits. This finding is particularly important as it simplifies the complexity of analysis needed for screening-level Life Cycle Assessments (LCAs) during the design phase. Designers can now focus their efforts on reducing the quantities of these high-impact materials where possible and explore alternative low-carbon options.

Furthermore, the study reveals a clear water-energy-carbon-ecotoxicity nexus for these key construction materials. The strong correlations observed between different impact categories suggest that strategies targeting one impact (e.g., carbon) are likely to have co-benefits in other areas (e.g., water use). This nexus presents both a challenge and an opportunity. On one hand, it suggests that these materials offer a significant opportunity to reduce holistic, embodied impacts of buildings through targeted strategies. On the other hand, it warns that continued reliance on these materials without purposeful action will lead to increased embodied impacts across all categories, not just carbon.

The role of digital technologies in facilitating the assessment and reduction of embodied impacts during the design phase is also highlighted by this study. The use of a simple digital workflow for rapid, screening-level LCA demonstrates how design-stage digital technologies can be developed and deployed in a flexible, scalable manner. This approach addresses one of the key challenges in implementing embodied impact assessment in early-stage design - the need for quick, reliable, and actionable information.

The key findings underscore the importance of considering embodied impacts from the earliest stages of the design process. The study shows that decisions made during the conceptual design phase can have far-reaching consequences for a building's environmental performance throughout its lifecycle. By implementing material efficiency strategies and incorporating recycled materials, designers can potentially achieve significant reductions in embodied impacts across all studied categories.

For the steel and cement industries, which are major contributors to embodied carbon in buildings, this study reinforces the urgency of decarbonization efforts. The unsurprising results showing steel and concrete as consistently among the highest contributors to embodied carbon across building types highlight the outsized influence these industries have on the climate footprint of construction and buildings. What is added here and insightful given the large data set, is the embodied water steel has relative to the full building. In the base case typically accounts for over 40% the total impact in residential buildings and 50% for non-residential buildings. This emphasizes the need for scaling up and market creation of low-carbon steel and cement products, as well as exploration of alternative materials.

The results also emphasize the critical importance of considering embodied impacts in the design phase of projects. With the study showing that up to 90% of a building's life cycle carbon emissions can be determined by decisions made during design, it is clear that the greatest opportunity for impact reduction lies in these early stages. This underscores the need for policies and practices that integrate embodied impact assessment into standard design processes.

Digital technologies play a crucial role in enabling the type of comprehensive analysis presented in this study. The ability to rapidly assess and compare the embodied impacts of hundreds of buildings relies on advanced modeling and data analysis tools. As these technologies continue to evolve, they will further enhance designers' ability to optimize buildings for reduced environmental impact. Building Information Modeling (BIM) systems integrated with life cycle assessment capabilities, for example, could allow real-time evaluation of design decisions' impact on embodied impacts.

While previous studies have often focused on a single impact category or a limited number of case studies, this analysis provides a more holistic view of the embodied environmental impacts of buildings. The inclusion of over 550 buildings allows for more general analysis and identification of trends across building types and design strategies.

The simultaneous consideration of global warming potential, water depletion potential, fossil depletion potential, and ecotoxicity is particularly important. This multi-criteria approach reveals important trade-offs and synergies between different environmental impacts that may not be apparent when focusing on a single metric like embodied carbon.

Investigation of additional design phase strategies for reducing embodied impacts is another important area for future work. This could include exploration of novel materials and construction techniques, as well as more integrated approaches that consider the interaction between embodied and operational impacts over a building's life cycle utilizing rapid and flexible assessment tools like the one developed and used for this study.

Further research into the role of digital technologies in optimizing building design for reduced embodied impacts would also be valuable. This could include development of more sophisticated modeling tools that integrate real-time embodied impact assessment into the design process, as well as exploration of how artificial intelligence and machine learning could be leveraged to identify optimal design solutions.

Finally, longitudinal studies tracking the actual performance of buildings over time compared to their predicted embodied impacts would provide valuable validation of the models and assumptions used in this type of analysis. This could help refine assessment methodologies and improve the accuracy of embodied impact predictions in future projects.

5 Conclusion

Conclusion

Key Findings

- Material efficiency and recycled content strategies are highly effective in reducing embodied impacts across all categories studied.
    - For every 1% implementation of these strategies, approximately 0.7-0.8% reduction is achieved in global warming potential, water depletion potential, fossil depletion potential, and ecotoxicity. This near-linear relationship provides a clear and actionable guideline for designers and policymakers.
- Four key materials - steel, cement, concrete, and bricks - significantly influence the embodied impact of buildings.
    - This finding simplifies the complexity of analysis needed for screening-level Life Cycle Assessments during the design phase, allowing designers to focus on these high-impact materials.
- There is a clear water-energy-carbon-ecotoxicity nexus for key construction materials.
    - Strategies targeting one impact category are likely to have co-benefits in others, presenting both challenges and opportunities for holistic impact reduction.
- Timber substitution shows mixed results across impact categories.
    - While effective in reducing global warming potential, timber substitution shows minimal benefits or even increases in other impact categories like ecotoxicity, highlighting the need for careful consideration of trade-offs in material selection.

Summary

This comprehensive study of over 550 buildings has revealed crucial insights into the embodied environmental impacts of construction materials and the effectiveness of various design strategies in mitigating these impacts. The research demonstrates that material efficiency and recycled content strategies are highly effective in reducing embodied impacts across all categories studied, including global warming potential, water depletion potential, fossil depletion potential, and ecotoxicity. For every 1% implementation of these strategies, approximately 0.7-0.8% reduction is achieved in the respective impact categories, providing a clear and actionable guideline for sustainable building design.

The study identified four key materials - steel, cement, concrete, and bricks - as significant contributors to the embodied impact of buildings. This finding simplifies the complexity of analysis needed for screening-level Life Cycle Assessments during the design phase, allowing designers to focus their efforts on these high-impact materials. Furthermore, the research revealed a clear water-energy-carbon-ecotoxicity nexus for these key construction materials, suggesting that strategies targeting one impact category are likely to have co-benefits in others.

Interestingly, timber substitution showed mixed results across impact categories. While effective in reducing global warming potential, it demonstrated minimal benefits or even increases in other impact categories like ecotoxicity. This highlights the need for careful consideration of trade-offs in material selection and underscores the importance of a holistic approach to sustainable building design.

It is essential to note that while these terms are used in this paper, the full ‘Embodied’ impacts extend beyond the scope of A3 and include additional life cycle stages such as construction (A4-A5), use (B1-B7), and end-of-life (C1-C4). For instance, Embodied Energy encompasses not only the energy inputs during material production (captured by FDP within A1-A3) but also energy used in construction, maintenance, and eventual demolition. Similarly, Embodied Water and Embodied Carbon include impacts from these later stages that are not accounted for within the A1-A3 scope

Broader Impacts

The findings of this study have significant implications for the construction industry and sustainable building practices. By demonstrating the substantial impact of early design decisions on a building's environmental footprint, this research emphasizes the critical importance of integrating embodied impact assessments into the design process. The near-linear relationship between strategy implementation and impact reduction provides a powerful tool for designers and policymakers to set tangible goals and measure progress in sustainable building design.

Moreover, the identification of key materials that significantly influence embodied impacts offers a focused approach to material selection and optimization. This knowledge can drive innovation in the development of low-impact alternatives and encourage the scaling up of recycled material use in construction. The revealed water-energy-carbon-ecotoxicity nexus also presents an opportunity for more comprehensive sustainability strategies that address multiple environmental concerns simultaneously.

The study's use of a simple digital workflow for rapid, screening-level LCA demonstrates the potential for integrating advanced analytical tools into the design process. We developed and employed a simple tool to evaluate a large data set of buildings and further demonstrated that focusing on only a few key materials provides ample information during the iterative design process to significantly influence the embodied impacts of full buildings. This approach addresses one of the key challenges in implementing embodied impact assessment in early-stage design - the need for quick, reliable, and actionable information. As these technologies continue to evolve, they will further enhance designers' ability to optimize buildings for reduced environmental impact.

Call to Action

In light of these findings, there is an urgent need for designers, architects, and policymakers to prioritize sustainable design decisions and consider the embodied impacts of buildings from the earliest stages of the design process. The construction industry, particularly steel and cement manufacturers, must accelerate decarbonization efforts and explore innovative low-impact materials and processes.

Policymakers should consider implementing regulations that require the assessment and reduction of embodied impacts in new construction projects. This could include setting standards for material efficiency and recycled content, as well as incentivizing the use of low-impact materials and design strategies.

Designers and architects must embrace a more holistic approach to sustainable building design, considering not only operational energy efficiency but also the full range of embodied impacts. This requires a shift in design practices to incorporate life cycle thinking from the conceptual stages of a project.

Finally, there is a need for continued research and development in this field. This includes further investigation of additional design phase strategies for reducing embodied impacts, exploration of novel materials and construction techniques, and development of more sophisticated modeling tools that integrate real-time embodied impact assessment into the design process.

By taking these actions, the construction industry can make significant strides towards reducing its environmental footprint and contributing to global sustainability goals. The findings of this study provide a roadmap for this transformation, offering clear, actionable strategies for creating more sustainable built environments.

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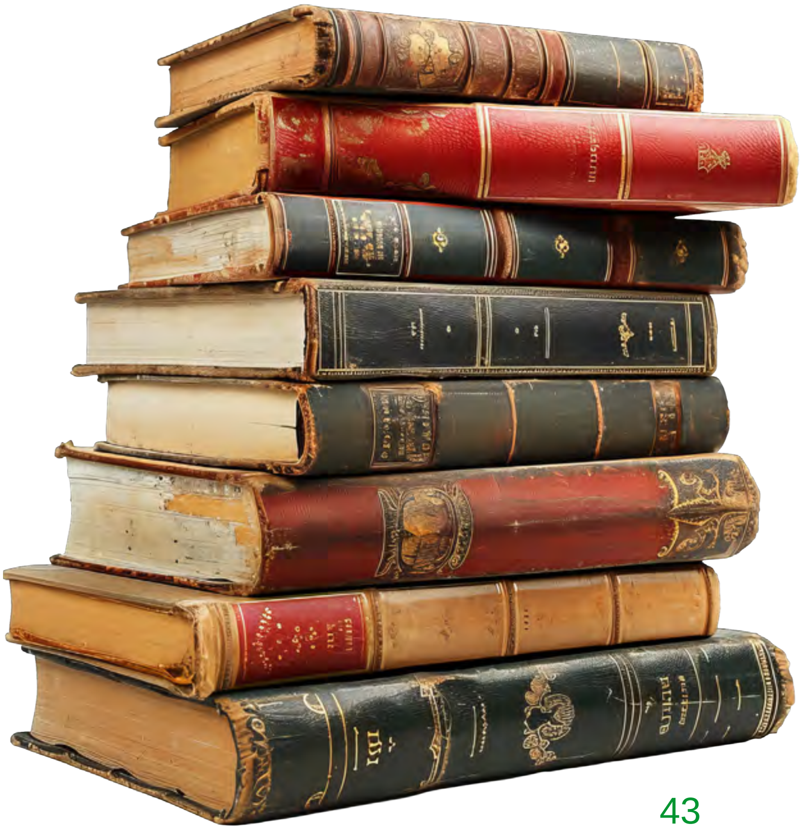

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