Comparing the city-wide cost and CO_2 emissions by adopting Alternate Zero Carbon Material: Mass-Timber vs. Low-Carbon Concrete

Akihiro Okuyam[a*]

[a]*Princeton University, Department of Civil and Environmental Engineering*

Abstract

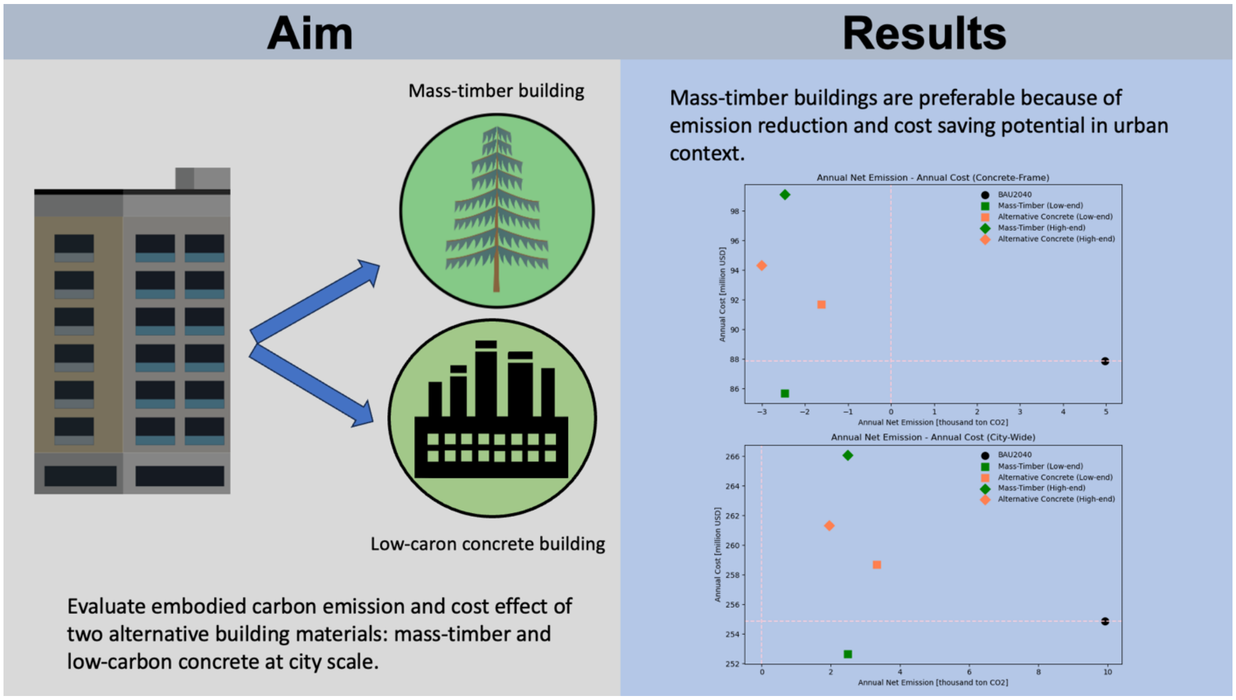
The construction sector can significantly reduce carbon emissions by decreasing cement usage, which accounts for 9-10% of global energy related CO_2 emissions. To address this, this study explores alternative materials: mass-timber and low-carbon cement due to expected urbanization with increasing cement demand. However, the potential emission reduction and cost-saving prospects at the city scale remain uncertain. Here, this paper creates future scenarios and compares mass-timber and low-carbon cement in terms of carbon mitigation and cost savings. Results indicate that mass-timber buildings offer net-negative emissions and cost savings compared to conventional concrete-frame buildings. While low-carbon concrete buildings can achieve net-negative emissions, they require a cost increase. Both alternative building materials reduce emissions by ~80.4% at a city-wide scale, with mass-timber buildings emerging as the superior choice due to environmental and economic factors.

Keywords – Carbon Emission, Cost, Mass-Timber, Alternative Cement, Low-Carbon Cement, Construction Materials

∗Corresponding author

✉ ao3526@princeton.edu (A. Okuyama)

Graphical Abstract



1 INTRODUCTION

Building and construction sector has a significant carbon footprint, consuming 36% of global energy and producing 39% of carbon dioxide (CO_2) emissions (Abergel, Dean, and Dulac 2017). Every year, we produce 17.7 Gt of concrete and 4.1 Gt of cement, the second most used material by mass after water (Monteiro, Miller, and Horvath 2017) globally, emitting 3.1 Gt of CO_2. The total emissions from cement manufacturing account for 9 - 10% of global energy-related CO_2 emissions (Cao et al. 2021). By 2050, the contribution to total anthropogenic CO_2 emissions could increase to 26% (Beyond Zero Emissions 2017) without significantly altering current cement production practices. Decarbonizing cement production is challenging because of underlying chemical reactions, requiring high temperatures for its processing (up to 1450 $\circ$C). The transformation of $CaCO_3$ to CaO, i.e., the calcination process, accounts for 60 - 65% of production-related CO_2 emissions (Antunes et al. 2022).

To reduce the usage of cement, the use of biomass-based construction materials such as wood in residential buildings has been gaining popularity because of its low environmental impact compared to concrete and iron/steel (Asdrubali et al. 2017; Kosny et al. 2014; Teng et al. 2018; Pauliuk et al. 2021; Mishra et al. 2022). Mass-timber building is constructed mainly of engineered wood, a composite wood product made by bonding layers or strands of wood fibers. A mass-timber building can reduce emissions from the construction sector because wood has a lower carbon footprint than steel and concrete (Nässén et al. 2012; Ryberg et al. 2021; Konnerth et al. 2016). Life cycle assessment of mass-timber shows that it can achieve a net-negative by using wood residue even though excluding biogenic carbon storage benefit (Dodoo 2019). Mass-timber can achieve net-zero without any significant system change. On the other hand, low-carbon cement technologies require significant system change to achieve net-zero such as carbon capture and utilization (CCU) and new facilities to manufacture low-carbon chemistry. Thus, shifting mineral-based construction material to biomass-based construction material has the potential to mitigate the environmental impact of the construction industry.

Replacing conventional Portland cement (PC) with advanced low-carbon cement seems straight forward solution to reduce CO_2 in the cement industry. Different types of low-carbon cement have been invented, showing that they emit 6-100% less CO_2 than PC clinker in their production (Miller and Myers 2020; Shi, Jiménez, and Palomo 2011). In addition, previous research reveals that low-carbon cement can be used as an alternative to ordinary PC and has a lower embodied CO_2 (McLellan et al. 2011; Elahi et al. 2020; Luukkonen et al. 2018; Alsalman et al. 2021). Unlike mass-timber constructions, low-carbon cement constructions require significant system change to achieve net-zero (Watari et al. 2022).

However, only some studies investigate and compare construction materials' environmental and economic impact from adopting alternative construction materials at the city scale. The understanding of emission reduction and cost saving of alternative materials at the city scale is limited because much of the literature focused solely on individual buildings or a global scale (Churkina et al. 2020; Petrovic et al. 2019; Shubbar et al. 2020; Gu et al. 2021). Furthermore, most of the studies only compared the environmental and economic aspects of either low-carbon cement or mass-timber with conventional buildings and not comparing low-carbon cement and mass-timber buildings (Dodoo 2019; Gu, Liang, and Bergman 2021; Miller and Myers 2020). Several existing studies have estimated current building material use and their embodied CO_2 emission in cities (Gontia, Thuvander, and Wallbaum 2020; Guo et al. 2021; Han et al. 2018; Liu et al. 2022;

Yang et al. 2022; Peled and Fishman 2021; Soonsawad, Martinez, and Schandl 2022; Reyna and Chester 2015) with limited insights into reductions in emissions through supply or demand side interventions. Although there is little research to investigate how demand-side or supply-side interventions mitigate cement use and embodied emissions at the national scale (Gregory et al. 2021; Watari et al. 2022), they overlook the other primary building material such as iron/steel and wood and how much cost requiring to implement those actions. This study is the first to examine and compare the environmental and economic potential of low-carbon cement and mass-timber buildings by focusing on mineral and bio-based materials at the city scale. This study contributes to reducing the environmental impact of primary construction materials in cities by quantitatively studying alternative building materials' CO_2 emissions and cost savings. In addition, this study provides the answer to what kinds of alternative construction material is suitable in cities regarding both environmental and economic aspects.

Intergovernmental Panel on Climate Change (IPCC) states that urban accounts for 67-72% of global greenhouse gas emissions in 2020 (Lwasa et al. 2022). They also claim that the urban areas could increase by up to 211% compared to the urban areas in 2015 by 2050. Therefore, decarbonizing cities is necessary to achieve global carbon emission reduction goals. There are some studies to analyze how cities can reach net-zero through mitigation strategies in different sectors, but most of them have yet to consider embodied emissions from the construction materials production (Lazarus, Chandler, and Erickson 2013; Zhang, Liu, and Qin 2014). The demand for construction materials will increase as the growth of urban areas. This studies provide ways to mitigate building materials' environmental and economic impact in future cities through supply-side interventions.

This study considers two low-carbon cement chemistries: calcium sulfoaluminate (CSA) cement and alkali-activated cement (AAC) derived from coal fly ash. These two low-carbon cement's technological features show that they can alternate PC, and their environmental and economic features are well studied (Juenger et al. 2011). CSA cement contains a ye'elimite and is an up-and-coming alternative to traditional binders (Juenger et al. 2011). CSA cement requires less calcium per ton of cement than PC, reducing CO_2 emissions from the calcination process (Gartner 2004). The availability of the source of CSA would not be a concern since annual sulfur production is sufficient to produce enough CSA cement to cover the current world demand for cement (Hanein, Galvez-Martos, and Bannerman 2018).

Another type of low-carbon cement, AAC, emits less CO_2 in its production because it does not need a calcination process. AAC does not contain calcium but aluminosilicate powders, such as fly ash and alkaline activating solution. AAC is a Portland clinker-free cementitious material whose material source can rely on local materials, reducing transport costs and CO_2 emissions. Additionally, they can frequently attain similar performance levels as PC when using suitable mix proportions and surpass them in terms of acid and fire resistance (Scrivener, John, and Gartner 2018; Moon et al. 2014; Živica, Palou, and Križma 2015). Regarding environmental impact, AAC demonstrates a significant advantage over PC, with a 75% lower CO_2 emission than PC (Pol Segura et al. 2023). Over time, scientific and engineering advancements have addressed early developmental challenges associated with AAC, leading to its widespread application in significant infrastructure projects (van Deventer et al. 2010; Davidovits 2002). This study provides essential findings for policymakers to design future cities by comparing the potential of mass-timber, CSA cement, and AAC regarding environmental impact and cost saving.

2 METHODOLOGY

This study uses a data-driven bottom-up approach to estimate embodied CO_2 emissions by distinguishing the building types. Two approaches are widely used to estimate the material use and their embodied environmental impact in cities: top-down and bottom-up approaches (Tanikawa, Guo, and Fishman 2022). The top-down approaches utilize materials flow statistics, while bottom-up approaches use inventory data of end-use objects such as floor area to determine the material's environmental impact in cities. One of the promising approaches to reducing CO_2 emissions from the construction sector is substituting mineral-based materials with low-carbon alternative materials. This research considers a supply-side strategy for alternative construction materials to replace conventional mineral-based construction materials.

Residential buildings have distinct construction characteristics, occupant needs, and design considerations that differ from commercial, industrial, or pavement structures. By narrowing the focus to residential buildings, this paper can delve deeper into understanding construction materials in a residential context. Hence, this study only focus on residential buildings in this study. The study area is St. Paul, the central city in Minnesota, U.S. St. Paul is a metropolitan city expected to experience stable development in the future with less than a 10% population increase from 2018 to 2040. The findings of this research in St. Paul can have practical applications to other cities in the U.S. and even globally that face similar situations beyond the region itself.

This research uses a bottom-up approach to estimate construction materials' embodied CO_2 emission and cost in St. Paul. I first obtained data related to the number of households from the Met-Council government and the average floor area for single-family houses (SFHs) and multiple-family houses (MFHs) in 2018 and 2040 from the Tax Parcel data (Minnesota Geospatial

Information Office). This study focuses on the advanced material and building technologies in the construction industry: mass-timber buildings and low-carbon cement. Low-carbon cement and mass-timber have a significantly lower environmental impact than ordinary PC. This research examines and compares the economic and environmental effects of these emerging construction technologies., assuming that all new reinforced concrete (RC) frame buildings are built as mass-timber or low-carbon concrete. This research looked into two cases. The first case is only looking at all RC frame buildings, excluding other type of buildings in cities. This case helps us to understand how alternative building materials can reduce CO_2 emissions and cost compared to traditional RC buildings. Another case focused on all residential buildings in the city. The result of this case presents the overall environment and economic impact on all type of residential buildings, including alternative materials.

In pursuit of achieving net-negative emissions in low-carbon concrete buildings, a mere substitution of PC with low-carbon cement chemistries falls short of the desired outcome. This study proposes a comprehensive approach that combines multiple strategies to address this challenge. The methodology considers the potential emission mitigation and cost implications of incorporating low-carbon concrete chemistries, CCU, and fuel decarbonization technologies into cement production. For evaluating CCU and fuel decarbonization, I draw upon findings from relevant prior studies (Hepburn et al. 2019; Larson et al. 2021). On the other hand, the life cycle assessment (LCA) of mass-timber buildings has revealed promising results, demonstrating negative net emissions primarily due to the utilization of biomass residue, even without considering the biogenic carbon storage (Dodoo 2019).

2.1 Floor Area

This study estimates the total floor area of light-frame (LF) and RC frame SHFs and MFHs in 2018 and 2040. Most of assumptions on building types are based on the U.S. Census Bureau Field (Bureau) report. This study presumes that 94% of the SFHs in 2018 were built as LF buildings and 8% as RC buildings. In 2040, this study assumes that 84% of SHFs are LF and the rest are RC frames. This study distinguishes LF MFHs and RC MFHs, considering that 73% of MFHs were built as LF in 2018 and the rest of MFHs are built as RC frames. 70% of MFHs in 2040 are LF buildings, and the rest are RC frame buildings.

2.2 Embodied CO_2 emission

Embodied CO_2 emission of each building type for the BAU case and each strategy are estimated by using the following equation:

$$Annual\ Emission_{i,2040} = \frac{Total\ New\ Floor\ Area_{i,2040} \times EF_i}{22\ years} \qquad (1)$$

where *Annual Emission* refers to the annual embodied emission of buildings, *Total New Floor Area* presents the total floor area of newly built buildings from 2018 to 2040, and *EF* is the emission factor of buildings [$kgCO_2/m^2$]. The indices *i* presents building types (LF, RC, mass-timber, and low-carbon concrete). This derives the emission factor (EF) for LF, RC, and mass-timber from previous studies (Dodoo, 2019). This study estimates EF for low-carbon concrete buildings based on the (Hepburn et al. 2019; Larson et al. 2021; Hanein, Galvez-Martos, and

Bannerman 2018; Pol Segura et al. 2023). The scope of LCA implemented to estimate (EF) is cradle-to-gate (Table 1).

2.3 Cost Calculation

This research calculates the annual cost of implementing every strategy based on each building type's total life cycle cost, including the production stage, construction process stage, use stage, and end-of-life phase (Equation 2).

$$Annual\ Cost_{i,2040} = \frac{Total\ New\ Floor\ Area_{i,2040} \times CF_i}{22\ years} \qquad (2)$$

In equation 2, *Annual Cos*t indicates the total life cycle cost of a building per year. *CF* is a cost factor that refers to the entire life cycle cost of the building per floor area [USD/m^2]. This derives the total life cycle cost of LF, RC, and mass-timer from (Keoleian, Blanchard, and Reppe 2000; Gu, Liang, and Bergman 2021). Upon this cost, I estimate the cost of concrete buildings by applying the cost of low-carbon cement manufacturing, CCU, and fuel decarbonization (Hepburn et al. 2019; Larson et al. 2021; Hanein, Galvez-Martos, and Bannerman 2018; Pol Segura et al. 2023) (Table 2).

Table 1: Emission Factor

Building Type	Net Emission Balance [kgCO_2/m^2]
LF	57.30
RC	204.97
Mass-Timber	-101.94
Low-carbon concrete (Low-end)	-66.91
Low-carbon concrete (High-end)	-124.21

Table 2: Cost Factor

Building Type	Life Cycle Cost [USD/m^2]
LF	1932
RC	3628
Mass-Timber (Low-end)	3537
Mass-Timber (High-end)	4092
Low-carbon concrete (Low-end)	3785
Low-carbon concrete (High-end)	3895

3 RESULTS

3.1 Concrete Frame Buildings

This study first investigated environmental and cost impact of mass-timber and low-carbon concrete by only focusing on RC frame buildings at city-scale. In this case, this research finds that mass-timber buildings possess the potential to achieve net-negative emissions while also offering cost reductions when compared to the BAU scenario in 2040. Replacing conventional RC frame buildings with either mass-timber or low-carbon concrete constructions presents a promising opportunity to diminish the embodied emissions of RC frame buildings. Mass-timber and low-carbon concrete exhibit the potential to become net-negative buildings, but implementing low-carbon concrete strategies entails increased costs compared to the BAU scenario (Figure 1). The analysis for RC frame buildings shows that mass-timber buildings can reduce embodied CO_2 emission by 149.7% compared to the BAU case in 2040. Similarly, the low-carbon concrete strategies offer significantly lower net emissions, ranging from 132.7% to 160.6% less than the BAU scenario.

Regarding cost implications, adopting mass-timber and low-carbon concrete technologies may lead to varied outcomes. The cost of mass-timber construction could range from -2.51% to 12.79% compared to the BAU, indicating potential cost savings. On the other hand, implementing low-carbon concrete results in cost increases of 4.35% to 7.36% relative to the BAU scenario.

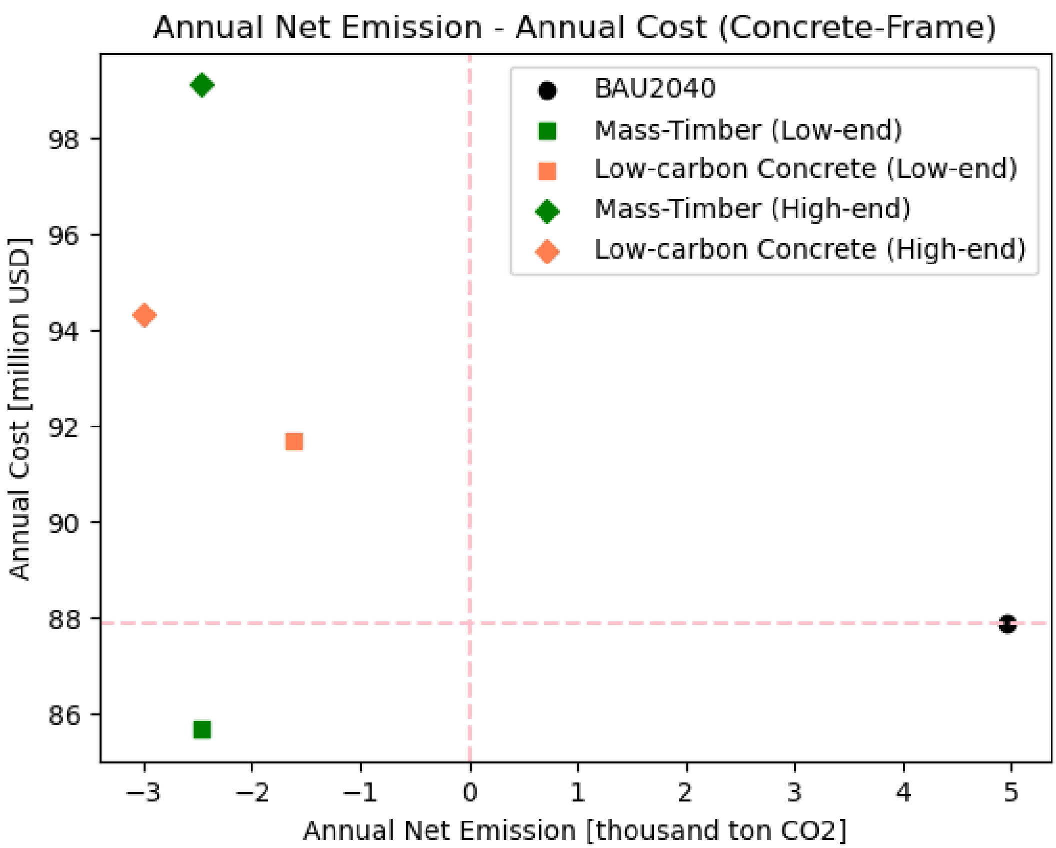


Figure 1: Annual Net Emission and Cost for RC frame buildings. The red horizontal red line indicates annual cost of BAU scenario, and vertical red line shows net zero emission.

3.2 City-Wide Scale Estimate

Now, I estimated the environmental and economic impact of alternatives by considering all type of residential buildings in the city. The city-wide scale analysis includes embodied emission and life cycle costs of all types of buildings. All scenarios contain conventional LF buildings. The BAU scenario comprises RC frame buildings, the mass-timber method includes mass-timber buildings, and the low-carbon concrete scenario incorporates low-carbon concrete buildings in addition to conventional LF buildings. City-wide scale analysis indicates that transitioning RC frame buildings to mass-timber or low-carbon concrete buildings cannot reach net-negative emission at the city scale. But both scenarios show significant potential for reducing embodied carbon emissions within the construction sector. Similar to the analysis for concrete-frame buildings, the adoption of mass-timber buildings presents a cost-saving benefit compared to the BAU scenario, while the low-carbon concrete scenario results in increased costs (Figure 2). The results show that mass-timber and low-carbon concrete strategies can effectively reduce emissions by 75.0% and 66.4~80.4%, respectively, compared to the BAU scenario. Regarding costs, the mass-timber approach offers potential cost reduction, with expenses ranging from -0.9% to 4.4% compared to the BAU scenario. This suggests a cost-saving potential when implementing a mass-timber strategy at a city-wide scale. Conversely, the low-carbon concrete strategy results in 1.5% to 2.5% cost increases relative to the BAU case.

Overall, the results highlight the significance of mass-timber and low-carbon concrete strategies in substantially lowering carbon emissions in the construction sector at the city level. While both strategies may not achieve net-negative emissions, they offer valuable opportunities for emission reduction and, in the case of mass-timber, potential cost savings compared to conventional building approaches.

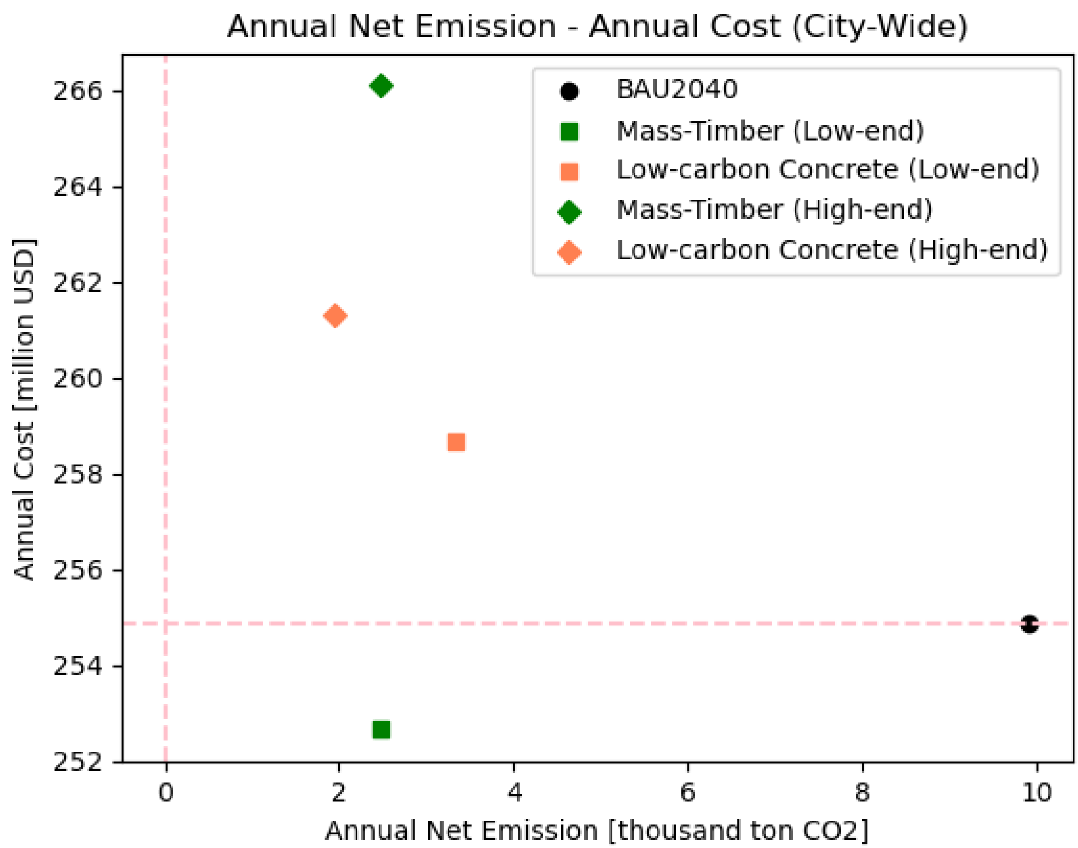


Figure 2: Annual Net Emission and Cost for City-Wide Scale. The horizontal red line is annual cost of BAU case and vertical red line presents net zero emission.

4 DISCUSSION

The results show that mass-timber buildings can achieve net-negative carbon emission and cost reduction compared to the BAU scenario when considering only RC buildings in the city. Low-carbon concrete buildings also have the potential to obtain net-negative but require an increased cost than the BAU case. The city-wide scale analysis presents that the transition of RC frame buildings to mass-timber and low-carbon concrete buildings can significantly reduce embodied emissions of buildings. We need to reduce embodied emissions of LF buildings to achieve net-zero at a city-wide scale. In addition, mass-timber can have cost-saving benefits, while the low-carbon concrete strategy requires more cost than the BAU case on a city-wide scale.

The key finding of this study is that mass-timber is a preferable strategy over low-carbon concrete strategy to reduce embodied carbon emissions in the construction sector due to its cost-saving benefit. Furthermore, unlike the low-carbon concrete strategy, the mass-timber approach does not require significant manufacturing system change. The results contribute to understanding and comparing alternative concrete materials' environmental and economic potential at the city scale. Mass-timber is preferable to implement in the city than low-carbon cement technology regarding embodied emission and life cycle cost of buildings.

This paper shows the uncertainty of cost and emission reduction benefits of mass-timber and low-carbon strategies for multiple reasons. One of the critical determinants of the cost associated with mass-timber buildings is their service life span. For mass-timber buildings to exhibit a lower life cycle cost than RC frame buildings, they should ideally have a service life of over 75 years (Gu, Liang, and Bergman 2021). Low-carbon cement strategies' cost and emission outcomes exhibit variations due to several factors. The uncertainty surrounding low-carbon cement chemistry, carbon capture and utilization (CCU) technologies, and fuel decarbonization significantly influence the results. The intricate interplay of these factors underscores the complexity of assessing and implementing mass-timber and low-carbon strategies. While achieving favorable cost and emission reductions is feasible, it requires a comprehensive understanding and consideration of the multiple contributing elements. This paper's findings emphasize the importance of making informed decisions and developing holistic approaches when integrating mass-timber and low-carbon strategies in construction and infrastructure development.

It is worth noting that the widespread adaption of low-carbon cement faces numerous challenges related to regulation, supply chain, product durability, cost-effectiveness, and sustainability issues, despite the environmental and economic advantages of low-carbon cement. The whole cement industry's supply chain and construction standards are deeply intertwined with PC production, which often leads to reluctance towards emerging new cement technologies, particularly those without clinkers. Some prior studies have pointed out that low-carbon cement has several issues with technology, cost, and availability of resources, making it challenging to replace PC immediately (Gartner 2004; Scrivener, John, and Gartner 2018). Overcoming these obstacles is essential for utilizing the significant environmental benefits of emerging low-carbon cement in cities.

On the other hand, mass-timber is a technology that can be used currently rather than a technology that may become available in the future. There are already some mid-rise and high-rise mass-timber buildings globally, including in some U.S. cities. Since replacing the entire PC with low-carbon cement as an alternative for PC is difficult in the current situation, we should prioritize mass-timber buildings over low-carbon concrete buildings in urban cities. Moreover, mass timber buildings not only offer environmental benefits but also enhance the resilience of cities by providing increased fire and disaster resistance (Churkina et al., 2020). Therefore, the city government and planners should encourage their residents and construction companies to build more mass-timber buildings through policy interventions, for example, financial support to cover building costs.

5 CONCLUSION

This paper investigates and compares the future scenarios of the environmental and economic impact of mass-timber and low-carbon concrete to determine which technologies are more suitable for cities. This study finds that mass-timber buildings can have net-negative emissions with cost savings than BAU in 2040. Although both alternative concrete strategies can reduce carbon emissions significantly, the results show that the mass-timber approach is a suitable strategy over low-carbon concrete buildings regarding the mass-timber strategy's cost-saving benefit at the city scale.

This study contributes to understanding the potential environmental and economic benefits of mass-timber and low-carbon concrete buildings in the construction sector. The findings can aid policymakers, city governments, and planners in making informed decisions to design future cities prioritizing low-carbon and sustainable building materials. Further research is needed to address the uncertainties associated with cost and emission reduction benefits and overcome the challenges in the widespread adoption of low-carbon cement technologies.

REFERENCES

Abergel, Thibaut, Brian Dean, and John Dulac. 2017. "Towards a Zero-Emission, Efficient, and Resilient Buildings and Construction Sector." UN Environment and International Energy Agency.

Alsalman, Ali, Lateef N. Assi, Rahman S. Kareem, Kealy Carter, and Paul Ziehl. 2021. "Energy and CO2 Emission Assessments of Alkali-Activated Concrete and Ordinary Portland Cement Concrete: A Comparative Analysis of Different Grades of Concrete." *Cleaner Environmental Systems* 3 (December): 100047. https://doi.org/10.1016/j.cesys.2021.100047.

Antunes, Mónica, Rodrigo Lino Santos, João Pereira, Paulo Rocha, Ricardo Bayão Horta, and Rogério Colaço. 2022. "Alternative Clinker Technologies for Reducing Carbon Emissions in Cement Industry: A Critical Review." *Materials* 15 (1): 209. https://doi.org/10.3390/ma15010209.

Asdrubali, F., B. Ferracuti, L. Lombardi, C. Guattari, L. Evangelisti, and G. Grazieschi. 2017. "A Review of Structural, Thermo-Physical, Acoustical, and Environmental Properties of Wooden Materials for Building Applications." *Building and Environment* 114 (March): 307–32. https://doi.org/10.1016/j.buildenv.2016.12.033.

Beyond Zero Emissions. 2017. "Zero Carbon Industry Plan: Rethinking Cement." Beyond Zero Emissions. Australia. https://apo.org.au/node/103031.

Cao, Zhi, Eric Masanet, Anupam Tiwari, and Sahil Akolawala. 2021. "Decarbonizing Concrete: Deep Decarbonization Pathways for the Cement and Concrete Cycle in the United States, India, and China."

Churkina, Galina, Alan Organschi, Christopher P. O. Reyer, Andrew Ruff, Kira Vinke, Zhu Liu, Barbara K. Reck, T. E. Graedel, and Hans Joachim Schellnhuber. 2020. "Buildings as a Global Carbon Sink." *Nature Sustainability* 3 (4): 269–76. https://doi.org/10.1038/s41893-019-0462-4.

Davidovits, Dr Joseph. 2002. "30 Years of Successes and Failures in Geopolymer Applications. Market Trends and Potential Breakthroughs." In .

Deventer, Jannie S. J. van, John L. Provis, Peter Duxson, and David G. Brice. 2010. "Chemical Research and Climate Change as Drivers in the Commercial Adoption of Alkali Activated Materials." *Waste and Biomass Valorization* 1 (1): 145–55. https://doi.org/10.1007/s12649-010-9015-9.

Dodoo, Ambrose. 2019. "Lifecycle Impacts of Structural Frame Materials for Multi-Storey Building Systems." *Journal of Sustainable Architecture and Civil Engineering* 24 (1): 17–28. https://doi.org/10.5755/j01.sace.24.1.23229.

Elahi, Md Manjur A., Md. Maruf Hossain, Md Rezaul Karim, Muhammad Fauzi Mohd Zain, and Christopher Shearer. 2020. "A Review on Alkali-Activated Binders: Materials Composition and Fresh Properties of Concrete." *Construction and Building Materials* 260 (November): 119788. https://doi.org/10.1016/j.conbuildmat.2020.119788.

Gartner, Ellis. 2004. "Industrially Interesting Approaches to 'Low-CO2' Cements." *Cement and Concrete Research*, H. F. W. Taylor Commemorative Issue, 34 (9): 1489–98. https://doi.org/10.1016/j.cemconres.2004.01.021.

Gontia, Paul, Liane Thuvander, and Holger Wallbaum. 2020. "Spatiotemporal Characteristics of Residential Material Stocks and Flows in Urban, Commuter, and Rural Settlements." *Journal of Cleaner Production* 251 (April): 119435. https://doi.org/10.1016/j.jclepro.2019.119435.

Gregory, Jeremy, Hessam AzariJafari, Ehsan Vahidi, Fengdi Guo, Franz-Josef Ulm, and Randolph Kirchain. 2021. "The Role of Concrete in Life Cycle Greenhouse Gas Emissions of US Buildings and Pavements." *Proceedings of the National Academy of Sciences* 118 (37): e2021936118. https://doi.org/10.1073/pnas.2021936118.

Gu, Hongmei, Shaobo Liang, and Richard Bergman. 2021. "Comparison of Building Construction and Life-Cycle Cost for a High-Rise Mass Timber Building with Its Concrete Alternative." *Forest Products Journal* 70 (4): 482–92. https://doi.org/10.13073/FPJ-D-20-00052.

Gu, Hongmei, Prakash Nepal, Matthew Arvanitis, Delton Alderman, Hongmei Gu, Prakash Nepal, Matthew Arvanitis, and Delton Alderman. 2021. "Carbon Impacts of Engineered Wood Products in Construction." In *Engineered Wood Products for Construction*. IntechOpen. https://doi.org/10.5772/intechopen.99193.

Guo, Jing, Tomer Fishman, Yao Wang, Alessio Miatto, Wendy Wuyts, Licheng Zheng, Heming Wang, and Hiroki Tanikawa. 2021. "Urban Development and Sustainability Challenges Chronicled by a Century of Construction Material Flows and Stocks in Tiexi, China." *Journal of Industrial Ecology* 25 (1): 162–75. https://doi.org/10.1111/jiec.13054.

Han, Ji, Wei-Qiang Chen, Lixiao Zhang, and Gang Liu. 2018. "Uncovering the Spatiotemporal Dynamics of Urban Infrastructure Development: A High Spatial Resolution Material Stock and Flow Analysis." *Environmental Science & Technology* 52 (21): 12122–32. https://doi.org/10.1021/acs.est.8b03111.

Hanein, Theodore, Jose-Luis Galvez-Martos, and Marcus N. Bannerman. 2018. “Carbon Footprint of Calcium Sulfoaluminate Clinker Production.” *Journal of Cleaner Production* 172 (January): 2278–87. https://doi.org/10.1016/j.jclepro.2017.11.183.

Hepburn, Cameron, Ella Adlen, John Beddington, Emily A. Carter, Sabine Fuss, Niall Mac Dowell, Jan C. Minx, Pete Smith, and Charlotte K. Williams. 2019. “The Technological and Economic Prospects for CO2 Utilization and Removal.” *Nature* 575 (7781): 87–97. https://doi.org/10.1038/s41586-019-1681-6.

Juenger, M. C. G., F. Winnefeld, J. L. Provis, and J. H. Ideker. 2011. “Advances in Alternative Cementitious Binders.” *Cement and Concrete Research*, Conferences Special: Cement Hydration Kinetics and Modeling, Quebec City, 2009 & CONMOD10, Lausanne, 2010, 41 (12): 1232–43. https://doi.org/10.1016/j.cemconres.2010.11.012.

Keoleian, Gregory A., Steven Blanchard, and Peter Reppe. 2000. “Life-Cycle Energy, Costs, and Strategies for Improving a Single-Family House.” *Journal of Industrial Ecology* 4 (2): 135–56. https://doi.org/10.1162/108819800569726.

Konnerth, Johannes, Marcel Kluge, Georg Schweizer, Milica Miljković, and Wolfgang Gindl-Altmutter. 2016. “Survey of Selected Adhesive Bonding Properties of Nine European Softwood and Hardwood Species.” *European Journal of Wood and Wood Products* 74 (6): 809–19. https://doi.org/10.1007/s00107-016-1087-1.

Kosny, Jan, Andi Asiz, Ian Smith, Som Shrestha, and Ali Fallahi. 2014. “A Review of High R-Value Wood Framed and Composite Wood Wall Technologies Using Advanced Insulation Techniques.” *Energy and Buildings* 72 (April): 441–56. https://doi.org/10.1016/j.enbuild.2014.01.004.

Larson, Eric, Chris Greig, Jesse Jenkins, Erin Mayfield, Andrew Pascale, Chuan Zhang, Joshua Drossman, et al. 2021. “Net-Zero America: Potential Pathways, Infrastructure, and Impacts.”

Lazarus, Michael, Chelsea Chandler, and Peter Erickson. 2013. “A Core Framework and Scenario for Deep GHG Reductions at the City Scale.” *Energy Policy* 57 (June): 563–74. https://doi.org/10.1016/j.enpol.2013.02.031.

Liu, Yupeng, Jiajia Li, Wei-Qiang Chen, Lulu Song, and Shaoqing Dai. 2022. “Quantifying Urban Mass Gain and Loss by a GIS-Based Material Stocks and Flows Analysis.” *Journal of Industrial Ecology* 26 (3): 1051–60. https://doi.org/10.1111/jiec.13252.

Luukkonen, Tero, Zahra Abdollahnejad, Juho Yliniemi, Paivo Kinnunen, and Mirja Illikainen. 2018. “One-Part Alkali-Activated Materials: A Review.” *Cement and Concrete Research* 103 (January): 21–34. https://doi.org/10.1016/j.cemconres.2017.10.001.

Lwasa, Shuaib, Karen C Seto, Xuemei Bai, Hilda Blanco, Kevin R. Gurney, Şiir Kılkış, Oswaldo Lucon, et al. 2022. “Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.” IPCC. doi: 10.1017/9781009157926.010.

McLellan, Benjamin C., Ross P. Williams, Janine Lay, Arie van Riessen, and Glen D. Corder. 2011. “Costs and Carbon Emissions for Geopolymer Pastes in Comparison to Ordinary Portland Cement.” *Journal of Cleaner Production* 19 (9): 1080–90. https://doi.org/10.1016/j.jclepro.2011.02.010.

Miller, Sabbie A., and Rupert J. Myers. 2020. “Environmental Impacts of Alternative Cement Binders.” *Environmental Science & Technology* 54 (2): 677–86. https://doi.org/10.1021/acs.est.9b05550.

Minnesota Geospatial Information, Office. n.d. “Minnesota Geospatial Commons.” Accessed May 22, 2023. https://gisdata.mn.gov/.

Mishra, Abhijeet, Florian Humpenöder, Galina Churkina, Christopher P. O. Reyer, Felicitas Beier, Benjamin Leon Bodirsky, Hans Joachim Schellnhuber, Hermann Lotze-Campen, and Alexander Popp. 2022. “Land Use Change and Carbon Emissions of a Transformation to Timber Cities.” *Nature Communications* 13 (1): 4889. https://doi.org/10.1038/s41467-022-32244-w.

Monteiro, Paulo J. M., Sabbie A. Miller, and Arpad Horvath. 2017. “Towards Sustainable Concrete.” *Nature Materials* 16 (7): 698–99. https://doi.org/10.1038/nmat4930.

Moon, Juhyuk, Sungchul Bae, Kemal Celik, Seyoon Yoon, Ki-Hyun Kim, Kang Su Kim, and Paulo J. M. Monteiro. 2014. “Characterization of Natural Pozzolan-Based Geopolymeric Binders.” *Cement* *and Concrete Composites* 53 (October): 97–104. https://doi.org/10.1016/j.cemconcomp.2014.06.010.

Nässén, Jonas, Fredrik Hedenus, Sten Karlsson, and John Holmberg. 2012. "Concrete vs. Wood in Buildings – An Energy System Approach." *Building and Environment* 51 (May): 361–69. https://doi.org/10.1016/j.buildenv.2011.11.011.

Pauliuk, Stefan, Niko Heeren, Peter Berrill, Tomer Fishman, Andrea Nistad, Qingshi Tu, Paul Wolfram, and Edgar G. Hertwich. 2021. "Global Scenarios of Resource and Emission Savings from Material Efficiency in Residential Buildings and Cars." *Nature Communications* 12 (1): 5097. https://doi.org/10.1038/s41467-021-25300-4.

Peled, Yoav, and Tomer Fishman. 2021. "Estimation and Mapping of the Material Stocks of Buildings of Europe: A Novel Nighttime Lights-Based Approach." *Resources, Conservation and Recycling* 169 (June): 105509. https://doi.org/10.1016/j.resconrec.2021.105509.

Petrovic, Bojana, Jonn Are Myhren, Xingxing Zhang, Marita Wallhagen, and Ola Eriksson. 2019. "Life Cycle Assessment of a Wooden Single-Family House in Sweden." *Applied Energy* 251 (October): 113253. https://doi.org/10.1016/j.apenergy.2019.05.056.

Pol Segura, Isabel, Navid Ranjbar, Anne Juul Damø, Lars Skaarup Jensen, Mariana Canut, and Peter Arendt Jensen. 2023. "A Review: Alkali-Activated Cement and Concrete Production Technologies Available in the Industry." *Heliyon* 9 (5): e15718. https://doi.org/10.1016/j.heliyon.2023.e15718.

Reyna, Janet L., and Mikhail V. Chester. 2015. "The Growth of Urban Building Stock: Unintended Lock-in and Embedded Environmental Effects." *Journal of Industrial Ecology* 19 (4): 524–37. https://doi.org/10.1111/jiec.12211.

Ryberg, Morten Walbech, Pernille Krogh Ohms, Eva Møller, and Tove Lading. 2021. "Comparative Life Cycle Assessment of Four Buildings in Greenland." *Building and Environment* 204 (October): 108130. https://doi.org/10.1016/j.buildenv.2021.108130.

Scrivener, Karen L., Vanderley M. John, and Ellis M. Gartner. 2018. "Eco-Efficient Cements: Potential Economically Viable Solutions for a Low-CO2 Cement-Based Materials Industry." *Cement and Concrete Research*, Report of UNEP SBCI WORKING GROUP ON LOW-CO2 ECO-EFFICIENT CEMENT-BASED MATERIALS, 114 (December): 2–26. https://doi.org/10.1016/j.cemconres.2018.03.015.

Shi, Caijun, A. Fernández Jiménez, and Angel Palomo. 2011. "New Cements for the 21st Century: The Pursuit of an Alternative to Portland Cement." *Cement and Concrete Research*, Special Issue: 13th International Congress on the Chemistry of Cement, 41 (7): 750–63. https://doi.org/10.1016/j.cemconres.2011.03.016.

Shubbar, Ali Abdulhussein, Monower Sadique, Hayder Kamil Shanbara, and Khalid Hashim. 2020. "The Development of a New Low Carbon Binder for Construction as an Alternative to Cement." In *Advances in Sustainable Construction Materials and Geotechnical Engineering*, edited by Sanjay Kumar Shukla, Sudhirkumar V. Barai, and Ankur Mehta, 205–13. Lecture Notes in Civil Engineering. Singapore: Springer. https://doi.org/10.1007/978-981-13-7480-7_18.

Soonsawad, Natthanij, Raymundo Marcos Martinez, and Heinz Schandl. 2022. "Material Demand, and Environmental and Climate Implications of Australia's Building Stock: Current Status and Outlook to 2060." *Resources, Conservation and Recycling* 180 (May): 106143. https://doi.org/10.1016/j.resconrec.2021.106143.

Tanikawa, Hiroki, Jing Guo, and Tomer Fishman. 2022. "Spatial-Temporal Views on Urban Construction Material Flow and Stock towards Sustainability." In *Routledge Handbook of the Extractive Industries and Sustainable Development*. Routledge.

Teng, Yue, Kaijian Li, Wei Pan, and Thomas Ng. 2018. "Reducing Building Life Cycle Carbon Emissions through Prefabrication: Evidence from and Gaps in Empirical Studies." *Building and Environment* 132 (March): 125–36. https://doi.org/10.1016/j.buildenv.2018.01.026.

Watari, Takuma, Zhi Cao, Sho Hata, and Keisuke Nansai. 2022. "Efficient Use of Cement and Concrete to Reduce Reliance on Supply-Side Technologies for Net-Zero Emissions." *Nature Communications* 13 (1): 4158. https://doi.org/10.1038/s41467-022-31806-2.

Yang, Dong, Mengyuan Dang, Jing Guo, Lingwen Sun, Ruirui Zhang, Feng Han, Feng Shi, Qian Liu, and Hiroki Tanikawa. 2022. "Spatial–Temporal Dynamics of the Built Environment toward Sustainability: A Material Stock and Flow Analysis in Chinese New and Old Urban Areas." *Journal of Industrial Ecology* n/a (n/a). https://doi.org/10.1111/jiec.13335.

Zhang, Lijun, Gangjun Liu, and Yaochen Qin. 2014. "Multi-Scale Integrated Assessment of Urban Energy Use and CO2 Emissions." *Journal of Geographical Sciences* 24 (4): 651–68. https://doi.org/10.1007/s11442-014-1111-5.

Živica, Vladimír, Martin T. Palou, and Martin Križma. 2015. "Geopolymer Cements and Their Properties: A Review." *Building Research Journal* 61 (2): 85–100. https://doi.org/10.2478/brj-2014-0007.

APPENDIX

Table A1: Base Assumption (Based on U.S. Census Bureau)

Category	Assumption	Rationale
In 2018		
SFHs built as LF	94%	The average of SFHs built as wooden light-frame building between 2009-2018
MFHs built as LF	73%	The average of MFHs built as wooden light-frame building between 2009-2018
In 2040		
SFHs built as LF	84%	The SFHs built as LF in 2020 is 92%. Through 2010 to 2020, the percentage of concrete-frame SFHs increase from 4% to 8%. Thus, concrete-frame SF is added 8% from 2020 to 2040.
MFHs built as LF	70%	The MFHs built as LF in 2020 is 70%. Through 2010 to 2020, the percentage of concrete-frame MFHs are the same. Thus, the percentage of concrete-frame MFHs in 2040 is the same 2020.

Code Availability

The code and data are available in:

https://github.com/akiokuyama/Mass-Timber-v.s-Low-Carbon-Concrete/tree/main