

Embodied Carbon Optimization for Residential Building Design through Strategic Low-carbon Material Configurations

Zhifan Liu¹, Haibo Feng¹

¹ Department of Wood Science, The University of British Columbia, Vancouver, BC, Canada

ABSTRACT: Embodied carbon (EC) is becoming a dominant factor in energy-efficient buildings, often accounting for over 50% of their life-cycle emissions in new construction. Therefore, minimizing building EC emissions is imperative to meeting Canada's climate targets under the Paris Agreement and supporting the transition to a low-carbon built environment. Early design decisions, particularly in the selection and configuration of materials, play a critical role in achieving significant reductions in EC. Building on this premise, this paper investigates how EC performance can be optimized through the strategic use of low-carbon material combinations, selected from a curated database of low-carbon alternatives. To illustrate this approach, a case study is conducted on a single-family residential building in British Columbia (BC), Canada. The study explores a range of possibilities for material usage, performing EC assessments for various scenarios and analyzing the resulting configurations to identify the optimal design. The results of the case study reveal that strategic combinations of low-carbon materials in key building components, such as foundations, and sheathing, can reduce EC by 24.19% compared to conventional construction methods. The carbon intensity decreases from 277.17 kg CO₂e/m² to 210 kg CO₂e/m², nearly meeting the benchmark for EC in new Part 9 homes in Vancouver, highlighting the potential to reduce building EC through strategic integration of low-carbon materials during early design phases. Through computational tools and life cycle assessment (LCA), it offers practical strategies to reduce EC while maintaining performance and aesthetics, supporting sustainable construction and climate goals.

1. INTRODUCTION AND RELATED WORK

The global construction industry influences resource consumption and contributes to EC emissions. Approximately 20%-50% of the consumption of natural resources is attributed to the construction sector (Vasilca et al., 2021). The extraction, transport, and production of construction materials contribute to over 50% of lifecycle emissions in new buildings (Lützkendorf & Balouktsi, 2022). In response, the United Nations has emphasized the need for sustainable construction practices to mitigate climate change and reduce environmental impact (Ürge-Vorsatz et al., 2020). European countries have been pioneers in sustainable construction. Sweden's 'Stockholm Wood City,' the largest planned timber-built urban development, aims to reduce EC through the use of sustainable materials. In North American regions, particularly Canada, have been progressively adopting low-carbon building strategies (Keena & Friedman, 2022). In BC, Energy Step Code (Government of British Columbia, 2017) is adopted, aiming at achieving net-zero buildings to meet its climate targets under Paris Agreement (Government of Canada, 2023). While policy frameworks establish a foundation for sustainable construction, achieving meaningful reductions in EC requires strategic material selection and innovative design.

Given the high carbon intensity of construction materials, strategic choices in material selection and building design are key to achieving EC reductions. The Vancouver EC Benchmark for Part 9 homes (Magwood & Trottier, 2022) provides guidelines for mitigating EC emissions in new developments. One effective strategy is to prioritize low-carbon materials that are sourced regionally. As transportation can contribute up to 20% of a building's total EC (Gan et al., 2017), choosing local materials can significantly reduce emissions and support more sustainable construction practices.

Studies have been conducted to examine the environmental benefits of sustainable materials, emphasizing the effectiveness of low-carbon alternatives in reducing emissions compared to conventional materials. For instance, materials with high Solar Reflective Index values, recycled content, and bio-based components have shown significant potential for lowering EC (Hu & Esram, 2021; Sadar Din & Ishak, 2024). Comparative research further demonstrate that substituting materials like reinforced cement concrete and fired clay bricks with compressed stabilized earth blocks and low-VOC paints can lower embodied energy by 47% (Jesudass et al., 2022). Additionally, (Torabi & Evins, 2024) demonstrated that wood-based structures further reduce EC compared to steel or concrete, particularly when floor-to-floor height is minimized to reduce material use and structural load. Hempcrete has emerged as a carbon-negative insulation material that not only sequesters CO₂ but also offers high thermal performance and moisture regulation, as demonstrated in the BioZero building project in New York (Jankovic & Carta, 2021). However, the performance of sustainable materials can vary by climate. A study comparing wall materials in Egypt, Brazil, and Ukraine found that optimal material performance depends on environmental context, for instance, high thermal mass materials improve insulation in extreme temperatures, while moisture-resistant materials are crucial in humid regions (Felix & Elsamahy, 2017). These insights underscore the need for region-specific construction strategies, rather than universal solutions. Despite progress in sustainable material research, research remains limited on optimizing material combinations for maximum EC reduction. Existing studies primarily assess materials individually, overlooking their combined effects and regional availability. Moreover, while early-stage material selection is widely recognized as crucial, there is still limited quantitative analysis on how integrated low-carbon material systems can reduce EC in residential construction.

To address this gap, this study investigates optimal configurations of low-carbon materials for key building components, with an emphasis on regional sourcing in Canada. A case study of a single-family house in BC evaluates multiple material substitution scenarios using EC performance as the primary metric. By analyzing material synergies rather than isolated effects, this research aims to inform practical strategies for reducing EC in Canadian residential construction.

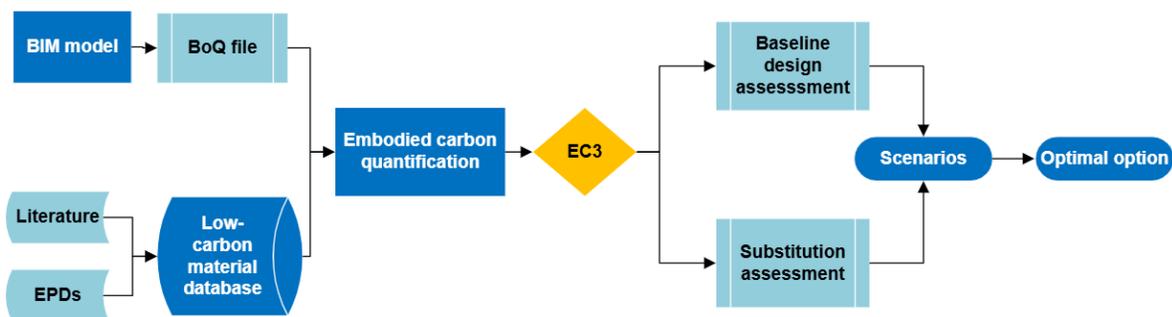


Figure 1: Methodology framework

2. METHODOLOGY

This study presents a comprehensive framework to quantify EC reduction and identify optimal material configurations. As illustrated in Fig.1, the process involves 4 phases. First, a building model is developed using BIM software, and a Bill of Quantities (BoQ) is generated. The data is then processed using Python. In the second phase, low-carbon material data is gathered from literature sources and Environmental

Product Declarations (EPDs). Next, the baseline design, is calculated using the Embodied Carbon in Construction Calculator (EC3) Tool based on conventional materials to establish a reference EC value. Finally, multiple substitution scenarios are assessed to determine the optimal configuration for EC reduction.

2.1 BIM Model Development

This research focuses on single-family residential building, as they comprise 35% of all dwellings in Vancouver (City of Vancouver, 2017). A BIM model is built up to represent a detached single-family house of the floor area 347 m², as shown in Fig. 2. The house has 2 storeys and a basement, featuring an insulated concrete form foundation, load-bearing walls, an exterior siding, and a roofing system.



Figure 2: BIM model of the single-family house

The materials used in the construction include cast-in-place concrete for the foundation walls and floors, ensuring structural integrity and thermal mass, with gravel for drainage and support. The basement walls incorporate expanded polystyrene panels for insulation and gypsum board for finishing. S.P.F. (Spruce-Pine-Fir) studs frame the walls, with fiberglass batt insulation, plywood sheathing, and engineered wood siding for the exterior. The roof consists of asphalt shingles, fiberglass batt insulation, and plywood. Interior walls are finished with gypsum board over S.P.F. studs. Flooring includes oak hardwood, timber joists, plywood, and gypsum board, with closed-cell spray foam for insulation. Doors are wood (interior and exterior), while windows include aluminum frames and flat glass, depicted in Fig.3. This BIM model provides a realistic representation of a typical single-family home in Vancouver.

2.2 Low-Carbon Material Database Development

To support EC reduction analysis, a comprehensive low-carbon material database was developed using data from EPDs and literature sources. It includes a diverse range of sustainable building materials, such as low-carbon concrete, hempcrete, laminated veneer bamboo, low-carbon gypsum board, low-carbon flat glass, low-carbon asphalt shingles, PVC window frames, recycled aluminum, sustainable siding materials, and sustainable insulation materials. These materials are assessed based on their global warming potential (GWP) across the A1 to A3 life cycle stages, ensuring a broad representation of sustainable construction options. Each material record contains key parameters, including density and GWP values, evaluated using standardized environmental impact methodologies such as TRACI 2.1, and complies with ISO 14025 and ISO 21930. By offering a structured repository of environmental impact data, this database serves as a foundation for evaluating material substitutions and optimizing configurations to achieve maximum EC reductions.

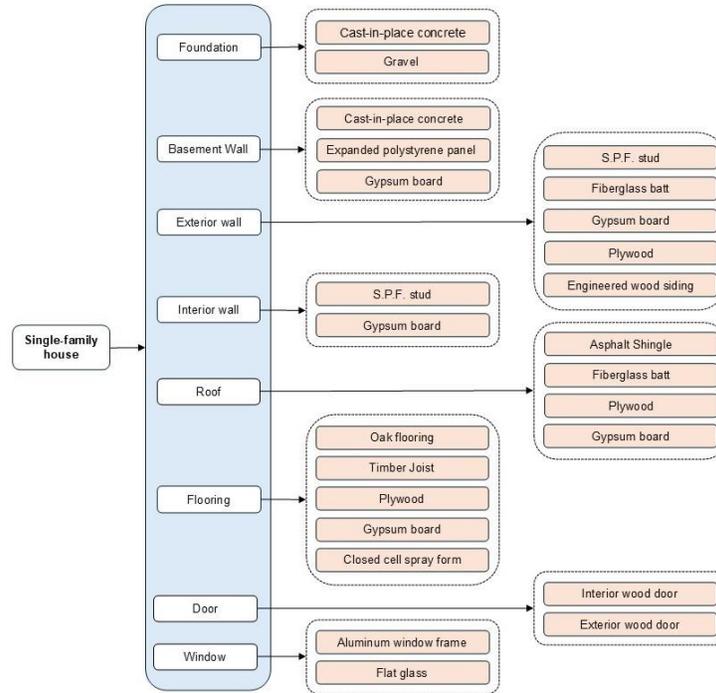


Figure 3. Materials of the single-family house

2.3 Baseline Design EC Calculation

The baseline EC multiplying the quantity of each material in the BoQ by its GHG emission factor (kg CO₂e/unit), based on data from EPDs. The GHG emissions for each material are calculated using Eq. 1, and the total EC is obtained by summing the emissions of all materials, as shown in Eq. 2. To standardize results, carbon intensity (kg CO₂e/m²) is derived by dividing total EC by the building's heated floor area (Eq. 3). This baseline serves as a reference for comparing low-carbon alternatives and supports informed design decisions.

$$[1] \text{GHG}_{\text{material}} = \text{Material Quantity} \times \text{GWP Factor}$$

$$[2] \text{GHG}_{\text{total}} = \sum \text{GHG}_{\text{material}}$$

$$[3] \text{Carbon Intensity} = \frac{\text{GHG}_{\text{total}}}{\text{Heated Floor Area}}$$

2.4 Material Substitution

2.4.1 Rationale and scope of material substitution

In this section, substitutions are applied to building components with high EC impact to achieve meaningful reductions. Based on the baseline EC assessment in section 2.3, materials with relatively low carbon footprints, such as framing elements, wood doors, floors, and gravel, are not replaced. Substitutions target components with higher GWP and good regional availability, aiming to maximize overall EC reduction.

2.4.2 Material replacement scenarios

To evaluate EC reductions, 10 scenarios are generated by substituting high-GWP materials with low-carbon alternatives. These scenarios explore various configurations of low-carbon materials and assess their impact on the overall EC.

The first 9 scenarios focus on a targeted approach, with each scenario substituting a single conventional material in a key building component. This method allows for a clear assessment of the individual impact of each material substitution on total EC. For example, cast-in-place concrete is replaced with a mix containing 20% e-plastic and 30% GGBS, fiberglass insulation with hempcrete, and aluminum window frames with PVC. Other substitutions include low-carbon asphalt shingles and western red cedar siding. The 10th scenario, in contrast, takes a holistic approach by replacing all conventional materials simultaneously with their lower-carbon alternatives. This scenario provides insight into the maximum potential reduction in EC achievable through material substitutions. This incremental analysis helps quantify both individual and combined impacts of material choices on EC, supporting more informed, low-carbon design strategies.

3. RESULTS AND DISCUSSION

3.1 Material Contribution to EC

The GHG emissions for the 298 m² heated floor area single-family residential house, constructed using conventional materials during stages A1–A3 (as shown in Table 1), were calculated to be 82,595.95 kg CO_{2e}. The carbon intensity is 277.17 kg CO_{2e}/m², which exceeds the EC benchmark for Part 9 residential buildings in Vancouver (Magwood & Trottier, 2022) by 77.17 kg CO_{2e}/m². The emission factors used in these calculations are sourced from EPDs in the EC3 database (Building Transparency, 2024). The results indicate that key building materials, including cast-in-place concrete, timber joists, S.P.F. studs, aluminum window frame, and plywood, significantly contributed to the total GHG of the building.

Table 1: Baseline calculation (Emission factors sourced from EC3 (Building Transparency, 2024))

Material	Quantity	Functional Unit	Emission factor	GHG
Concrete, Cast-in-Place (Foundation wall)	20.85	m ³	5.08E+02	10591.80
Concrete, Cast-in-Place (Foundation floor)	37.27	m ³	5.08E+02	18933.16
Gravel	35.71	t	4.89E+00	174.60
S.P.F. Studs (wall)	55.56	m ³	2.49E+02	13834.44
Engineered Wood Siding	6.13	m ³	2.79E+02	1712.91
Gypsum Wall Board	7.78	92.9 m ²	2.33E+02	1813.34
Softwood Plywood (Wood for roof)	14.72	m ³	1.20E+02	1766.40
Concrete (Foundation)	2.75	m ³	5.08E+02	1397.00
Gypsum Board (floor)	4.32	92.9 m ²	2.33E+02	1005.74
Plywood (Sheathing)	7.86	m ³	4.70E+02	3694.20
Asphalt Shingle	210.00	m ²	4.70E+00	987.00
Fiberglass Batt (Insulation)	451.00	m ²	1.20E+00	541.20
Oak Flooring	193.00	m ²	1.15E+01	2219.50
EPS (Foundation)	275.00	m ²	1.74E+00	479.60
Timber Joist (Floor)	58.40	m ³	2.49E+02	14541.60
Closed cell spray form (Insulation)	193.00	m ²	1.92E+00	370.56
Flat Glass (window)	1.16	t	1.37E+03	1588.69
Aluminum window frame	59.86	m ³	1.01E+02	6045.83
door production, inner, wood	0.90	m ³	4.83E+02	434.70
door production, exterior, wood	0.96	m ³	4.83E+02	463.68

Based on Fig. 4, concrete, particularly in the foundation floor and wall, is the largest contributor, exceeding 30,000 kg CO_{2e}, accounting for 37% of total GHG emissions, due to the high carbon footprint of cement production (Khaiyum et al., 2023). Timber joists and S.P.F. studs also have a major impact, with timber joists alone reaching approximately 14,500 kg CO_{2e}. Aluminum window frames contribute 6,045 kg CO_{2e}, reflecting the energy-intensive nature of aluminum production. Plywood sheathing and oak flooring account for approximately 5,500 kg CO_{2e} and 2,200 kg CO_{2e} respectively though at a lower scale. Other materials,

including gypsum wallboard, engineered wood siding, asphalt shingles, fiberglass batt insulation, EPS, and closed-cell spray foam, also contribute but to a lesser extent. These findings confirm concrete, aluminum, and synthetic insulation as primary EC sources, alongside notable contributions from structural wood components.

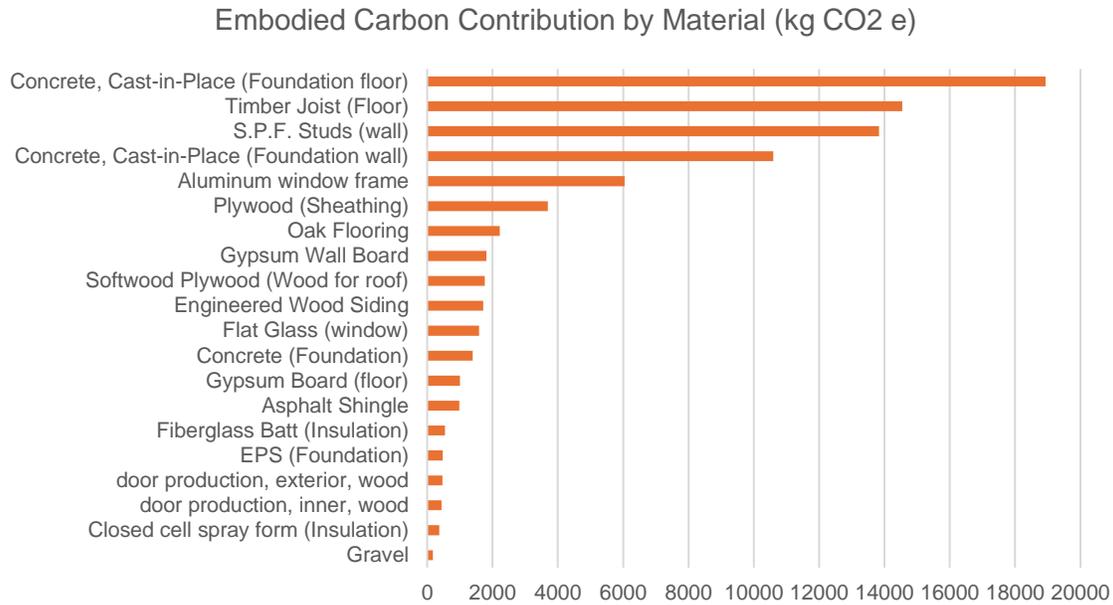


Figure 4. EC contribution by material

3.2 Comparative Assessment of Material Substitution

The comparative analysis of baseline and alternative materials, as illustrated in Table 2 and Fig. 5, demonstrates a substantial reduction in EC through material substitutions. The full material substitution scenario (Scenario 10) resulted in a 24.19% overall reduction, reducing the total EC and lowering the carbon intensity of this house to 210 kg CO₂e/m², compared to the baseline value. Among individual substitutions, low-carbon concrete had the most significant impact in Scenario 1, reducing emissions by 16.90% due to the high carbon footprint of traditional cement-based concrete. Other high-impact substitutions included replacing aluminum window frames with PVC in Scenario 2, which reduced emissions by 2.35%, substituting engineered wood siding with western red cedar bevel siding in Scenario 3, reducing emissions by 1.55%, and replacing plywood sheathing with laminated veneer bamboo in Scenario 4, which contributed a 1.38% reduction. Substitutions with reductions below 1% had minimal impact. Hempcrete insulation (0.71%) outperformed low-carbon asphalt shingles (0.50%) and flat glass (0.38%), while gypsum wall board (0.27%).

Table 2: Material substitution

Scenario	Baseline Material	Substituted Material	EC Reduction
1	Concrete, Cast-in-Place	Low-carbon concrete	16.90%
2	Aluminum window frame	PVC Window Frame	2.35%
3	Engineered Wood Siding	Western Red Cedar Bevel Siding	1.55%
4	Plywood (Sheathing)	Laminated veneer bamboo	1.38%
5	Fiberglass Batt (Insulation)	Hempcrete	0.71%
6	Asphalt Shingle	Low-carbon Asphalt Shingle	0.50%
7	Flat Glass (window)	Low-carbon Flat Glass	0.38%
8	Gypsum Wall Board	Low-carbon Gypsum Board	0.27%
9	Gypsum Board (floor)	Low-carbon Gypsum Board	0.15%
10	Baseline design	Full Material Substitution	24.19%

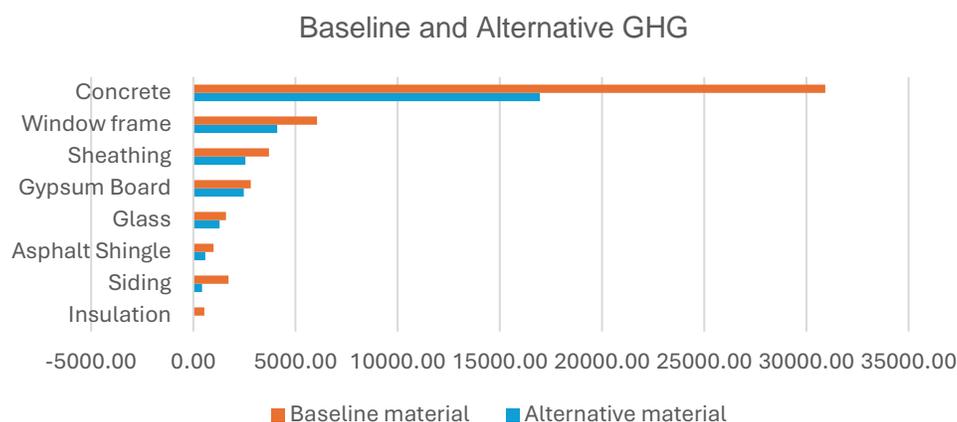


Figure 5. Baseline and alternative materials: GHG emissions by component category

The results of this study are consistent with the findings of previous research and contribute further by exploring a combined material substitution strategy. For example, (Torabi & Evins, 2024) achieved a 15–20% EC reduction through structural optimization, while (Jesudass et al., 2022) achieved a 47% reduction by replacing concrete and clay bricks with low-carbon alternatives. This study contributes further by demonstrating a 24.19% EC reduction through the integration of multiple low-carbon materials across different building components.

3.3 Alternative Materials Assessment in Detail

The analysis of GHG emissions by component category shows the effectiveness of material substitutions in reducing EC. As illustrated in Figs. 5 and 6, the most significant reductions occur in high-EC materials such as concrete, window frames, and sheathing. Concrete substitution achieves the highest absolute reduction, making it the most impactful, while gypsum board flooring shows the lowest, reflecting its smaller contribution to total EC. Notably, insulation demonstrates the highest percentage reduction (108.8%), indicating its potential for carbon sequestration. The sources of the substituted low-carbon materials are listed in Table 3.

Table 3: Low-carbon material source

Substituted Material	Source
Low-carbon concrete	Goh et al., 2022
PVC Window Frame	Thermoplast Nexttrusions, <i>EPD: PVC Casement Window (2024)</i>
Laminated veneer bamboo	Gan et al., 2022
Western Red Cedar Bevel Siding	Western Red Cedar Lumber Association, <i>EPD: Typical Cedar Siding (2018)</i>
Hempcrete	Liu et al., 2023
Low-carbon Asphalt Shingle	Owens Corning, <i>EPD: Asphalt Shingles (2020)</i>
Low-carbon Flat Glass	Guardian Glass, <i>EPD: North America Flat Glass Products (2024)</i>
Low-carbon Gypsum Board	CertainTeed Gypsum, <i>EPD: Type X 5/8" Gypsum Board (2020)</i>

Concrete is the largest contributor to total GHG emissions. Substituting it with low-carbon concrete achieves the highest absolute reduction, 13,958.7 kg CO₂e (45.1%), making it a key strategy for decarbonizing residential construction. Given concrete's dominance in the overall EC footprint, prioritizing this substitution offers a major step in reducing total emissions. The switch from aluminum window frames to PVC frames results in a substantial drop in EC. Aluminum production is highly energy-intensive, so replacing it with PVC leads to an absolute reduction of 1,939.4 kg CO₂e and a percentage reduction of 32.1%. This shows that

window frame materials can be a key target for reducing the EC, given the widespread use of aluminum in construction. Sheathing reduces EC by 1,140.2 kg CO₂e (30.9%) through plywood substitution with laminated veneer bamboo, lowering emissions from wood treatment. Though less impactful than concrete or window frames, it remains a valuable emissions reduction opportunity.

Glass, gypsum, and asphalt shingle show smaller absolute reductions but high percentage improvements. Glass achieves a 310.8 kg CO₂e reduction (19.6%), gypsum board 350.9 kg CO₂e (12.5%), and asphalt shingles 409.5 kg CO₂e (41.5%). While these materials contribute less to total impact, their cumulative effect strengthens the overall carbon reduction strategy. Siding and insulation exhibit high percentage reductions, making them excellent candidates for further carbon optimization. Siding achieves an absolute reduction of 1,278.5 kg CO₂e and an impressive percentage reduction of 74.6%, indicating a highly effective material swap. Insulation stands out with a negative baseline emission, meaning that the alternative material likely has carbon-sequestering properties, resulting in an absolute reduction of 589 kg CO₂e and a percentage reduction of 108.8%. This suggests that certain insulation materials may go beyond simply reducing emissions and actively contribute to carbon capture.

Concrete, window frames, and sheathing provide the most significant absolute reductions, making them priority targets for EC reduction. Meanwhile, siding and insulation demonstrate high percentage reductions, suggesting that material selection in these areas can greatly enhance carbon efficiency. Additionally, the cumulative impact of smaller material substitutions, such as gypsum board, glass, and asphalt shingles further contribute to an effective GHG reduction strategy. By integrating these low-carbon alternatives, this study presents a scalable approach to reducing the EC of residential buildings, aligning with sustainable construction practice.

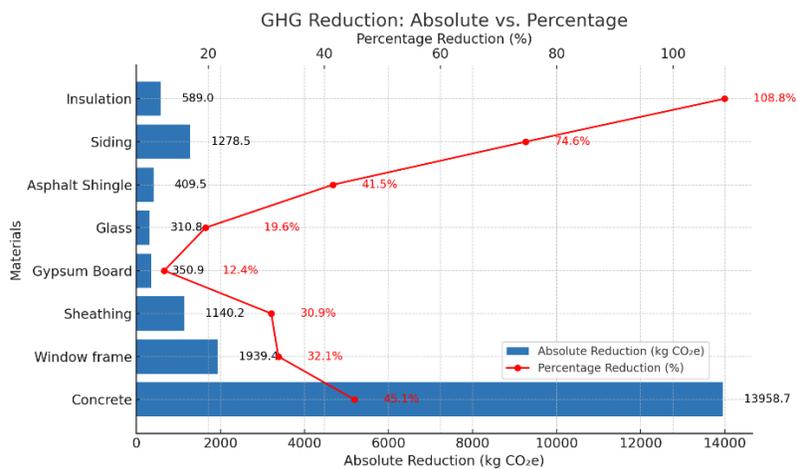


Figure 6. Baseline and alternative materials: absolute and percentage reduction

3.4 Sensitivity Analysis

To understand the role of transportation in EC reduction, a sensitivity analysis is conducted by removing A2 emissions from the LCA, focusing only on A1 and A3. This helps assess how local material availability affects EC performance. As summarized in Table 4, all material substitutions showed higher EC reductions without transportation. Overall, this leads to an additional 2.55% reduction in total EC. Concrete and asphalt shingles show the greatest change (0.51% and 0.68%), while insulation and siding show minimal differences (only 0.01% and 0.13%). Fig. 7 illustrates these changes, showing the increase in EC reduction for each material without transportation impacts. The results highlight the importance of sourcing materials locally to enhance EC performance in building design.

Material name	Reduction (A1-A3)	Reduction (A1, A3)
Concrete	16.90%	17.41%

Material name	Reduction (A1-A3)	Reduction (A1, A3)
Window frame	2.35%	2.58%
Siding	1.55%	1.68%
Sheathing	1.38%	1.64%
Insulation	0.71%	0.72%
Asphalt shingle	0.50%	1.18%
Glass	0.38%	0.58%
Gypsum wall board	0.27%	0.61%
Gypsum board (floor)	0.15%	0.34%

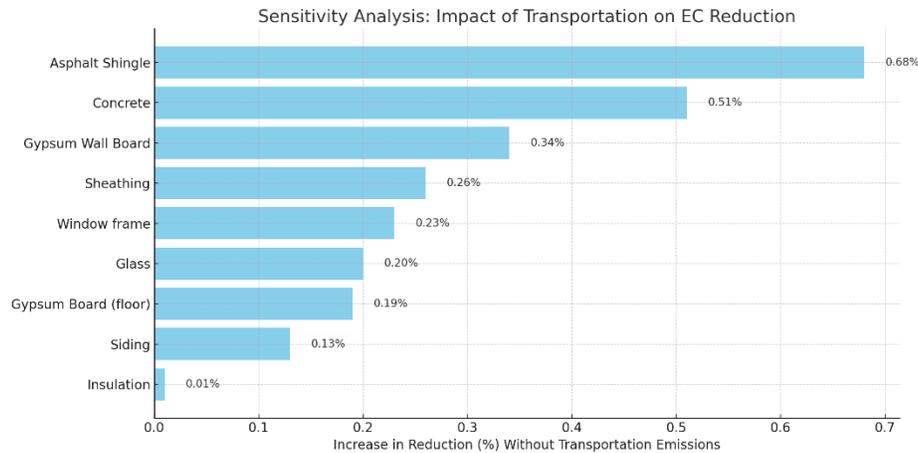


Figure 7. EC reduction change without transportation

4. LIMITATIONS

This study focuses on the environmental performance of material substitutions in terms of EC reduction. While the results demonstrate significant EC reduction through the material configurations, several key considerations fall outside the scope of this research. Economic costs, material durability, and functional performance were not assessed. These can significantly affect the practical adoption of alternative materials. The next step of this research will apply a multi-objective optimization algorithm by integrating life cycle costing and operational carbon assessment to determine trade-offs. This will provide a more comprehensive foundation for informed material selection in real-world applications.

This study focuses on a single-family home in BC; however, the methodology used to reduce EC can be adapted to other regions with appropriate modifications. Strategies such as prioritizing low-carbon materials are broadly applicable across Canada and internationally. Nonetheless, variations in material availability, building codes, and climate conditions may affect the feasibility of specific substitutions. Therefore, while the material choices in this study are tailored to the BC context, applying this approach in other regions would require adjustments to reflect local conditions and supply chain factors.

5. CONCLUSIONS

This study developed a systematic framework to optimize EC reduction through strategic material substitution. Using a BIM model and EC3 tool, various material configurations were assessed in a single-family residential case study. The results demonstrate that replacing conventional materials with low-carbon alternatives, particularly low-carbon concrete, PVC window frames, and laminated veneer bamboo, achieved the most significant reductions, leading to an overall EC decrease of 24.19%. Insulation substitution showed the highest percentage reduction (108.8%), while cumulative small-scale substitutions further contributed to emissions reduction. These findings emphasize the importance of early design decisions in minimizing EC in residential buildings.

REFERENCES

- Building Transparency. 2024. EC3. Retrieved January 20, 2025, from <https://www.buildingtransparency.org/tools/ec3/>
- Building Transparency. 2024. EC3. Retrieved January 20, 2025, from <https://www.buildingtransparency.org/tools/ec3/>
- Felix, M., & Elsamahy, E. 2017. The efficiency of using different outer wall construction materials to achieve thermal comfort in various climatic zones. *Energy Procedia*, 115, 321-331.
- Gan, J., Chen, M., Semple, K., Liu, X., Dai, C., & Tu, Q. 2022. Life cycle assessment of bamboo products: Review and harmonization. *Science of the Total Environment*, 849, 157937.
- Gan, V. J., Cheng, J. C., Lo, I. M., & Chan, C. M. 2017. Developing a CO₂-e accounting method for quantification and analysis of embodied carbon in high-rise buildings. *Journal of Cleaner Production*, 141, 825-836.
- Goh, P. G., Maghfouri, M., Onn, C. C., & Loo, S. C. 2022. Life cycle assessment on recycled e-waste concrete. *Case Studies in Construction Materials*, 17, e01412.
- Government of British Columbia. 2017. *BC Energy Step Code: A pathway to net-zero energy-ready buildings*
- Government of Canada. 2023. *Canada's net-zero emissions by 2050*.
- Hu, M., & Efram, N. W. 2021. The status of embodied carbon in building practice and research in the United States: A systematic investigation. *Sustainability*, 13(23), 12961.
- International Organization for Standardization. 2006. *ISO 14025:2006 - Environmental labels and declarations — Type III environmental declarations — Principles and procedures* (ISO Standard No. 14025:2006).
- International Organization for Standardization. 2017. *ISO 21930:2017 - Sustainability in buildings and civil engineering works — Core rules for environmental product declarations of construction products and services* (ISO Standard No. 21930:2017).
- Jankovic, L., & Carta, S. 2021. BioZero—Designing Nature-Inspired Net-Zero Building. *Sustainability*, 13(14), 7658.
- Jesudass, A., Karthick, M., Nishanth, P. A., & Anand, S. S. 2022. Optimization of Embodied energy and operational energy of school design by comparing conventional and sustainable Material configurations. *Materials Today: Proceedings*, 65, 1169-1177.
- Keena, N., & Friedman, A. 2023. Circular Economy in the Built Environment of North America: Toward Housing Affordability and Sustainability. In *Handbook of Sustainability Science in the Future: Policies, Technologies and Education by 2050* (pp. 1327-1352). Cham: Springer International Publishing.
- Khayyum, M. Z., Sarker, S., & Kabir, G. 2023. Evaluation of carbon emission factors in the cement industry: An emerging economy context. *Sustainability*, 15(21), 15407.
- Liu, C. H. J., Pomponi, F., & D'Amico, B. 2023. The Extent to Which Hemp Insulation Materials Can Be Used in Canadian Residential Buildings. *Sustainability*, 15(19), 14471.
- Lützkendorf, T., & Balouktsi, M. 2022. Embodied carbon emissions in buildings: Explanations, interpretations, recommendations. *Buildings & Cities*, 3(1).
- Magwood, C., & Trottier, M. 2022. *Material emissions benchmark report for Part 9 homes in Vancouver*. Builders for Climate Action.
- Sadar Din, K. M., & Ishak, M. S. 2024. Sustainable building construction materials in the United Arab Emirates: a review. *Sustainability*, 16(15), 6565.
- Torabi, M., & Evins, R. 2024. Towards net-zero carbon buildings: Investigating the impact of early-stage structure design on building embodied carbon. *The International Journal of Life Cycle Assessment*, 1-16.
- Ürge-Vorsatz, D., Khosla, R., Bernhardt, R., Chan, Y. C., Vérez, D., Hu, S., & Cabeza, L. F. 2020. Advances toward a net-zero global building sector. *Annual Review of Environment and Resources*, 45(1), 227-269.
- Vasilca, I. S., Nen, M., Chivu, O., Radu, V., Simion, C. P., & Marinescu, N. 2021. The management of environmental resources in the construction sector: An empirical model. *Energies*, 14(9), 2489.