Greenhouse Gas Impacts of Structural Materials in Commercial New Construction

Efficiency Vermont R&D Project: Greenhouse Gas Reduction

December 2021

Karen S. Bushey

20 Winooski Falls Way
Winooski, VT 05404

Contents

Executive Summary

OVERVIEW

Greenhouse gas (GHG) emissions from the creation and use of structural building materials vary widely. Structural material choices for commercial new construction projects can greatly influence the up-front or embodied carbon in a building, which can have a significant impact on the total carbon footprint of a building over its lifetime. The construction industry is grappling with the scale of opportunity associated with alternative materials, and clarity is needed regarding additional cost and sourcing of these choices.

Structural systems in commercial buildings commonly use high embodied carbon materials such as concrete and steel, choices that designers cannot modify as easily as they could a mechanical system or interior / exterior finish product. A life cycle assessment (LCA) is an internationally accepted method[1] for quantifying embodied carbon in new building design and can be used to compare design options based on carbon emissions.

This research quantified the global warming potential (GWP) reduction of using wood and mass timber products in place of more traditional steel and concrete for a typical Vermont commercial building's structure. The study analyzed the GWP impacts of replacing wood for steel and compared those to the GWP impacts of insulation choices and concrete formulations. Researchers also obtained feedback from building professionals regarding the current state of the Vermont market and potential obstacles to the greater adoption of lower-carbon structural materials.

RESULTS

Using a life cycle assessment, researchers identified a 48% GWP reduction, over 144,000 kilograms of carbon dioxide equivalent (CO_2e) emissions,[2] by shifting the structure from steel and concrete to wood and mass timber. Researchers also identified additional GWP reduction opportunities by changing the insulation from hydrofluorocarbon closed-cell spray foam to fiberglass batts and maximizing supplementary cementitious materials in the balance of concrete used in the building foundation, resulting in a total GWP reduction of over 204,600 kilograms of CO_2e. Comprehensive redesign with wood and mass timber would lead to additional savings through further reduction in concrete and steel for the foundation.

The results of this study support further assessing lower embodied carbon materials for commercial new construction project designs in Vermont.

[1] See ISO standards 14040 and 14044 for more information: https://www.iso.org/standard/38498.html
[2] Equivalent to 144 metric tons CO_2e (One thousand kilograms equals one metric ton CO_2e.)

Introduction

Structural material choices can greatly impact the amount of embodied carbon in a new commercial building. This research project estimates the embodied carbon savings when switching from traditional steel and concrete structural building components to a predominately mass-timber structure in a typical new construction commercial office building in Vermont.

BACKGROUND

New construction building projects in the United States call for different structural systems based on the building use type and size. Small to medium-scale residential buildings (one to three stories high) often employ wood for most of the structure. Currently, the design of most large commercial buildings uses a long-spanning steel and concrete structure to accommodate larger grid or column spacing. Among nonresidential structural framing materials used in 2017 in the United States, steel accounted for 46%, concrete 34%, and wood 10% of the market share.[3]

Nationally, commercial design and construction professionals now understand that steel and concrete have greater embodied carbon than wood. Mass timber,[4] for example, has risen in popularity in recent years, bringing with it updated building and life safety codes. It is no longer unusual to see new midrise buildings fabricated with a timber structure, whereas this was unheard of 10 to 15 years ago, and high-rise, or "tall wood," buildings continue to push the threshold for height.[5] Mass timber's rise in popularity is associated with lower embodied carbon, lighter weight, easier and faster assembly, and improved aesthetics. Unfortunately, not all industry professionals grasp the scale of timber's impact or the ability for wood to be a carbon sequestering or net-negative embodied carbon material.

Researchers selected new construction as the focus of this study since structural materials generally remain in place for the lifetime of the building; even extensive renovations typically maintain the original structure of the building. The results of this work are applicable to additions that use new materials.

Researchers did not consider cost in this study as many published case studies have looked at the embodied carbon of construction materials in relation to cost.[3] New construction materials

---

[3] Esau, Rebecca, Matt Jungclaus, Victor Olgyay, and Audrey Rempher. "Reducing Embodied Carbon in Buildings: Low-Cost, High-Value Opportunities." Rocky Mountain Institute, 2021. https://rmi.org/insight/reducing-embodied-carbon-in-buildings.

[4] Shortened from *massive timber*, this structural system consists of wood beams, columns, and panels that are typically composed of smaller wood segments joined to form larger members, such as glue-laminated (glulam) beams, laminated veneer lumber (LVL), nail-laminated timber (NLT), dowel-laminated timber (DLT), and cross-laminated timber (CLT).

[5] For more on this, refer to https://www.woodworks.org/learn/mass-timber-clt/tall-mass-timber/

related to the building enclosure, interior fit-out, and HVAC systems[6] were also outside the scope of the study. Additionally, researchers did not include foundation redesign in the scope.

Methodology

A life cycle assessment (LCA) measures the environmental impacts of materials, assemblies, or buildings from extraction of raw materials through manufacturing, transportation, and installation, and can also include use and end-of-life disposal or recycling. This study employed a life cycle assessment to quantify and compare the embodied carbon of two different structural systems.

Researchers identified three common building use types most representative of commercial new construction in Vermont and leveraged Efficiency Vermont's database to choose newly constructed representatives of each use type. After exploring LCA resources and seeking document-use permissions from design professionals to perform an in-depth study based on actual plans, researchers narrowed the study to one existing building: a 21,000-square-foot two-story office building in Chittenden County, Vermont, completed in 2020. They selected this building for its average size for the use type and its steel and concrete structure, which is common to Vermont commercial construction. In addition, the grid-based structural design is replicable and scalable, and therefore could easily apply to larger or smaller buildings.

The original building structure, as built, consists of steel girders, steel beams, steel columns, corrugated steel deck, and reinforced concrete slabs. WoodWorks, a nonprofit wood products council that provides free technical support related to the design and construction of wood buildings, created a redesign for the structure that included mass timber structural elements such as cross-laminated timber (CLT) panels and glue-laminated (glulam) beams and columns. The USDA Forest Products Laboratory then performed an LCA, comparing the two different structural systems and exterior wall framing but leaving the rest of the building equivalent in the two scenarios.

REDESIGN

The goal of the redesign was to isolate the primary structural system of the building for a comparative analysis of only that portion. The result was a one-for-one replacement of steel structural members with glulam beams and columns and replacement of the corrugated steel deck and some of the concrete in the original floor slab with horizontal CLT panels.

The researchers retained some exterior steel canopies on the building in their as-built design condition for simplification. These canopies could have been replaced with wood using a comprehensive whole building design, but the small amount of steel didn't justify the significant additional work entailed in the redesign for this study.

[6] Efficiency Vermont research associated with HVAC system embodied carbon is available in the Efficiency Vermont Whitepapers archive https://www.efficiencyvermont.com/media-room/whitepapers.

For the exterior wall framing, the existing as-built condition was light-gauge metal framing, which researchers replaced with wood studs in the comparison study. They considered exterior wood sheathing for shear loads to be included equally in the two versions. All other aspects of the building remained the same for the LCA comparison study—foundation; interiors; finishes; mechanical, electrical, and plumbing (MEP) systems; and exterior enclosures. In the mass timber design, the ceiling finish was assumed to be removed from the original steel design because the underside of CLT is commonly left exposed in mass timber buildings, but the material subtraction was not included in the LCA study.

WoodWorks' redesign of the office building from steel and concrete to mass timber is detailed in Table 1.

Table 1: Materials included in two structural designs for the LCA

Steel and concrete, as built	Mass timber, wood redesign
Structural steel framing: beams, joists, columns, braced frames	Southern pine glulam framing: beams, columns; includes steel hardware, fasteners
Corrugated steel floor deck with standard-weight concrete topping, 4" thick; steel roof deck	Southern pine CLT panels floor deck with 1" acoustic mat and 1.5" standard-weight concrete topping; CLT roof deck
Steel canopy framing, minimal quantity	No change
Lightweight steel studs, 6" deep, 16" o.c.: exterior wall framing	Wood 2x6 studs, 16" o.c.: exterior wall framing, spruce pine fir (SPF)
Plywood exterior shear walls—as part of exterior nailbase panel	Plywood exterior shear walls
Concrete foundation and slab on grade	No change
All other aspects of design: interiors, MEP systems, exterior enclosures, finishes, etc.	No change

Assumptions:

- Floors are non-fire-rated (5B construction).
- Floor sound ratings are retained.
- Floor-to-floor heights and building height remained the same as baseline design. Mass timber structure is deeper than steel but eliminating ceiling finishes allowed for head heights to be maintained.
- Drop ceilings are eliminated. Underside of CLT floor is exposed. Study did not include changing exposed mechanicals such as ducts and conduit trays.

Whole building design, in which all aspects and impacts of decisions are considered together, is a preferred design strategy, but this study's limited scope meant that a concrete foundation or column layout redesign was not included. A complete redesign would have resulted in further material efficiencies – a lighter foundation with less concrete and steel rebar, owing to the lighter structure of the wood, and a more efficient structural column layout. This would have further decreased the total embodied carbon of the building.

LIFE CYCLE ASSESSMENT

The LCA comparison of the steel and wood buildings focused on six environmental indicators to measure the materials' life cycle impact: [7]

- Global warming potential (GWP)
- Ozone depletion potential
- Acidification potential
- Eutrophication potential
- Smog formation potential
- Non-renewable energy use

This analysis of the results focuses on GWP, measured in kilograms of carbon dioxide equivalent (kg CO_2e), because this is a primary impact measure of concern in the building industry.

Researchers obtained take-offs, or the sum of total mass in kg, for each category of steel and concrete in the original building design through Tally, an Autodesk Revit application that aligned with the existing design documentation in Revit, provided by the building's architect. WoodWorks supplied the mass timber redesign material quantities.

Using these supplied materials and quantities, the USDA Forest Products Laboratory performed an LCA using SimaPro software[8] and its proprietary LCA model, based on the U.S. LCI (life cycle inventory) and Ecoinvent database and using CORRIM LCA data[9] for U.S. wood products, such as softwood lumber. CLT and glulam LCA data were referenced from the published environmental product declaration (EPD) of SmartLam products[10], since SmartLam was assumed to be the mass timber supplier of this designed building.

Following ISO standards 21930 and EN 15978, this LCA study included life cycle stages A1 through A4, or "cradle to site". A1 through A3, the product stage, includes A1 raw material extraction and production, A2 raw material transportation to factory, and A3 manufacturing. Life cycle stage A4 includes transportation of the product to the building site. Researchers did not include the construction installation stage, A5, because it uses assumptions that may not be applicable.

WOOD SOURCING

Researchers wanted to keep this study focused on products sourced within the United States. However, the CLT manufacturing facility geographically closest to Vermont is in forest-rich Quebec, Canada. For U.S. CLT manufacturing, available locations were the Northwest (Montana)

[7] For more information, see https://ecochain.com/knowledge/impact-categories-lca/. Indicator categories taken from European standard EN15804 (A1+A2).
[8] For more information, see https://simapro.com/databases/ecoinvent/.
[9] For more information, see https://corrim.org/.
[10] For more information, see https://www.smartlam.com/resources/

or the Southeast (Alabama). Researchers determined that the Alabama source was the closest U.S. option, so the mass timber redesign included CLT and glulam products from that location.

For the primary LCA, researchers used SmartLam's published EPDs for the specified products and these are the data that are shared in this report. Wood species and product selection affects the outcome of LCAs due to specific attributes of the materials, where and how the wood is harvested, and the carbon associated with electricity production in the specific location.[11]

Although there is no Northeast U.S. CLT factory yet, several manufacturers have expressed interest in creating one. If one were to come online in the future, it would further reduce the greenhouse gas (GHG) emissions for timber projects in this region. Researchers did include a Quebec-based manufacturer's published EPD for CLT as a Northeast proxy for comparison, and these data are included in the results.

Results

The LCA results summarized in Table 2 indicate a 48% reduction in GWP with the mass timber design compared to the steel structure, from the steel structure GWP of over 300,000 kg CO_2e (300 metric tons CO_2e) to the mass timber design GWP of about 156,000 kg CO_2e (156 metric tons CO_2e). This represents the amount of carbon associated with 22.5 years of the building's total estimated operational energy use.[12] Table 2 presents two approaches: the top portion of the table is broken out by building assembly, the bottom portion by construction material.

Table 2: LCA embodied carbon results, steel structure vs. mass timber

A1-A4 contributions: COMPONENT	Steel structure (kg CO_2e)		Mass timber structure (kg CO_2e)		Reduction (%)
Roof and floors	66%	198,533	48%	74,577	62.4%
Foundation	25%	74,158	48%	74,158	0.0%
Canopies	1%	4,202	2.5%	4,202	0.0%
Exterior wall	8%	23,131	1.5%	2,749	88.1%
TOTAL	100%	300,044	100%	155,686	48.1%
A1 – A4 contributions: MATERIAL	Steel structure (kg CO_2e)		Mass timber structure (kg CO_2e)		Reduction (%)
Concrete	39%	116,502	30%	47,455	59.3%
Rebar	14%	40,550	23%	35,363	12.8%
Steel	48%	142,992	6%	9,128	93.6%
Wood	0%	-	37%	58,077	
Acoustic mat	0%	-	4%	5,663	
TOTAL	100%	300,044	100%	155,686	48.1%

[11] For wood EPDs, see https://awc.org/sustainability/epd.

[12] Estimated operational energy use based on final cove.tool energy model provided by building's architect.

Figure 1 breaks out the results by building assembly while Figure 2 does so by construction material.

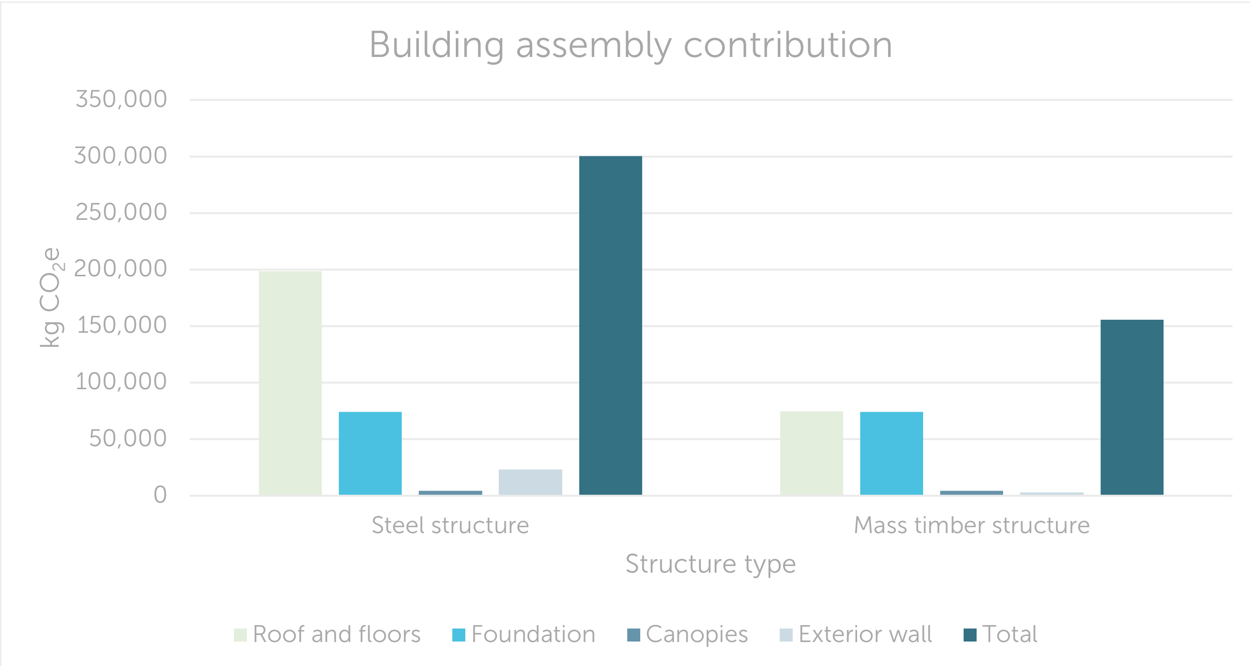

Figure 1: Building assembly contribution to GWP

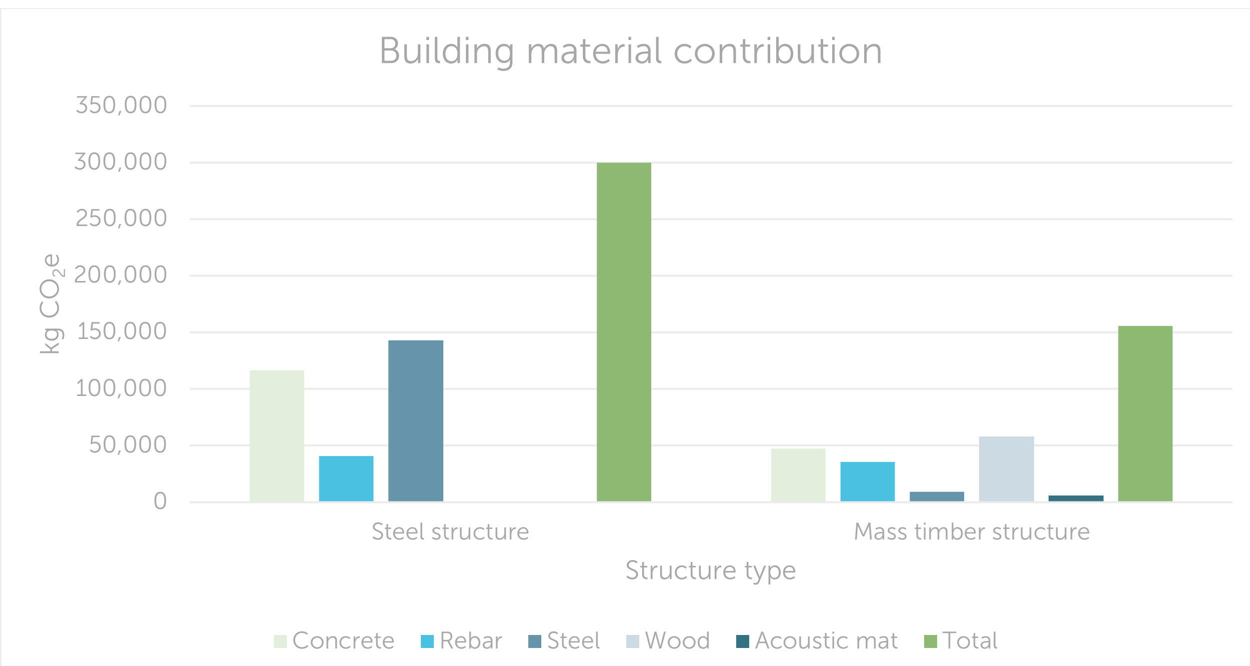

Figure 2: Building material contribution to GWP

ANALYSIS DISCUSSION

Figure 1 demonstrates roof and floors have the largest GWP reduction. This is mainly due to significant reduction in the amount of concrete, which is illustrated by Figure 2. Sixty percent of the original GWP attributed to concrete was omitted by simply limiting the amount of concrete used for floor slabs, a reduction of 69,000 kg CO_2e (69 metric tons CO_2e).

Researchers found that the specific EPDs of timber products play a substantial role in the LCA results. They were able to achieve a 10% GWP reduction from CLT and glulam using the Northeast proxy, in which a Quebec-based manufacturer was used instead of Alabama. This is due to the wood species sourced from the Northeast region and the lower GHG emissions from the regional electricity used in the manufacturing process.

It is worth noting that there were slight increases in some environmental impact indicators in the wood design. Ozone depletion potential, eutrophication potential, and smog formation potential were all larger in the mass timber building, though differences were minor. Eutrophication potential, for example, is likely higher with wood owing to wood harvesting and forest management practices, which use more electricity and environmentally degrading equipment and processes. When electricity use is higher, the EPD reflects the carbon intensity of the energy grid in that location. This led to a noticeable difference between the wood product EPD from the location selected (South) and the Northeast proxy EPD.

Cost was not considered in this study. Even without wholesale redesign, many low-cost or no-cost strategies are available and applicable to the original design which can reduce the embodied carbon of structural building materials in commercial new construction. These strategies include:

- Reduce the amount of steel and concrete used by employing strategic design methods during a project's structural design phase.
- Specify steel with higher recycled content.
- Specify supplementary cementitious materials (SCMs) in concrete formulations and replace a percentage of high-carbon cement in concrete.
- Specify cement from factories with lower carbon manufacturing processes.
- Specify carbon-encapsulating concrete products.
- Create project specifications that place carbon limits on materials with cost acceptable guidelines for material substitutions.

ADDITIONAL FACTORS CONSIDERED IN ANALYSIS

Beyond the structural materials, researchers include discussion on insulation and concrete to better understand the scale of impact.

Insulation

Stakeholders for the office building in this study worked with Efficiency Vermont energy consultants during its design and construction to achieve greater energy efficiency. Efficiency

Vermont incentivized building envelope commissioning (BECx), which allowed the project team to pivot from high embodied carbon hydrofluorocarbon (HFC) closed-cell spray foam to lower embodied carbon fiberglass batt insulation while still achieving their low air leakage target. The design team was leaning toward spray foam insulation because of its air sealing properties, but they achieved low air leakage without spray foam by working with the BECx agent.

The impact of this shift in material choices can be calculated using EPDs.[13] In this case, for the building as it was built, the total embodied carbon of the insulation materials is estimated to be 48,900 kg CO_2e, including roof, wall and foundation insulations. If the team had installed HFC closed-cell spray foam as originally planned, this total would have increased to 97,340 kg CO_2e; the swap resulted in a GWP savings of 50% (see Table 4) for the insulation.

Recent changes in state regulations, including Vermont, have resulted in the replacement of high GWP HFC insulations with those that use a lower GWP hydrofluoro-olefin (HFO) blowing agent. This project predated those changes, so HFO spray foam was not included in the analysis, but it would have reduced the embodied carbon of the spray foam insulation by 73%. Despite the GWP reduction between HFC and HFO, the HFO insulation would have still resulted in a greater total GWP over the installed fiberglass insulation package. The fiberglass insulation package saved about 11,300 kg CO_2e or 19% when compared to HFO.

In the exterior walls of the mass timber design, steel framing was replaced with wood framing, which carries a significant thermal impact owing to the high thermal conductivity of steel vs. wood. The thermal resistance of the exterior wall insulation remained unchanged in both scenarios, R-15 continuous insulation to the exterior and R-19 insulation within the framing cavities. Replacing the steel framing with wood increased the effective R-value of the exterior wall from R-24 to R-31,[14] which will notably improve the thermal performance of the building during its decades-long lifetime.

Concrete

This study confirmed that concrete's GHG emissions impact is outsized in comparison to other construction materials. In addition to using less concrete, there are several ways that building designs can reduce the embodied carbon of concrete.

A recent report by Rocky Mountain Institute found potential embodied carbon savings of 14–33% at no cost in several example commercial new construction projects, which builders could achieve by optimizing the ready-mix concrete design.[15] To look at the potential embodied carbon savings from concrete formulations in this study, researchers included a comparison of

---

[13] Summarized in *The high greenhouse gas price tag on residential building materials: True life cycle costs (and what can be done about them).* Brian Just, 2020, Efficiency Vermont R&D project: Greenhouse Gas Reduction.
[14] Vermont Department of Public Service. *2020 Vermont Commercial Building Energy Standards*, Tables C402.1(6) and C402.1(7).
[15] Esau, Rebecca, Matt Jungclaus, Victor Olgyay, and Audrey Rempher. "Reducing Embodied Carbon in Buildings: Low-Cost, High-Value Opportunities." Rocky Mountain Institute, 2021. https://rmi.org/insight/reducing-embodied-carbon-in-buildings.

using ready-mix concrete with structural engineer-recommended maximum supplementary cementitious materials (SCMs) which resulted in 25% embodied carbon savings.

Table 4 compares all GHG emissions reductions analyzed in this report. While it is not possible to combine #1 and #3 due to concrete quantity overlap, the combination of #1, #2 and #4, a 25% reduction in GWP in the balance of concrete in the mass timber design, results in total potential reduction of 204,622 kg CO_2e (204.6 metric tons CO_2e) on this project. This is a significant reduction, all attributable to design choices, and equivalent to:

- 22.5 years of total estimated operational energy use for this building
- 514,000 miles driven by an average passenger vehicle or
- 24.6 homes' energy use for one year or
- 226,000 pounds of coal burned[16]

Table 3: Summary of GHG impacts of different measures

	Material substitutions	Base GWP (kg CO_2e)	Reduction in GWP (kg CO_2e)	% GWP Reduction
1	Structure: Steel and concrete to wood / mass timber, from LCA	300,044	144,318	48.1%
2	Insulation: HFC closed-cell spray foam to fiberglass batts	97,340	48,440	50%
3	Concrete A: STEEL DESIGN - Standard mix to optimized ready-mix formulation using max, 25% SCMs	116,500	29,125	25%
4	Concrete B: MASS TIMBER DESIGN – Standard mix to optimized ready-mix formulation using 25% SCMs	47,455	11,864	25%

MARKET CONSIDERATIONS

Interviews

Researchers conducted interviews with two design professionals, an architect and a structural engineer, regarding the design and specification of lower embodied carbon structural materials. Both professionals are key stakeholders in commercial projects and are responsible for signing off on the design. The conversations offered the following insights regarding scale, accessibility, availability, and cost.

Vermont is a small state with relatively small projects compared with urban centers. Mass timber is harder to source for small, custom projects and makes more financial sense with scale. Funding available through USDA Rural Development requires the use of U.S. suppliers and

[16] Based on the EPA Greenhouse Gas Equivalencies Calculator, https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator.

fabricators. U.S. mass timber sources are limited, and builders in the New England region cannot access them easily.

Vermont building designers have considered mass timber as the structural system for numerous projects in the state. At the time these interviews were conducted, no project had moved forward with mass timber due to high cost. However, one planned addition to a public building in Vermont may move forward after switching from custom nail-laminated timber (NLT), locally sourced and fabricated, to CLT manufactured in an out-of-state factory. Many projects that have attempted to incorporate mass timber into commercial construction considered having the timber products sourced and manufactured at one or more of the mass timber facilities located in the U.S., Canada, and Europe and transported to the site, which is costly.

Regarding concrete, the design professionals interviewed mentioned the rise of more beneficial concrete technology. SCMs seem to be more available and accepted by concrete subcontractors now than they were a few years ago. Design and construction professionals are becoming more familiar with the additional benefits (such as greater strength) of replacing a portion of the cement content with SCMs, and other research has shown the cost to be on par with standard practice.

Both professionals mentioned the higher cost of lower embodied carbon structural materials and strategies, but other sources outside Vermont note that these materials can come in at less than 1% increased cost and potentially lower cost. The researchers predict that the Vermont cost will continue to decrease in comparison with traditional building materials.

Conclusion

Replacing steel and concrete with wood and mass timber in structural systems can help Vermont companies meet their carbon goals. An estimated 48% GWP reduction, 144,300 kg CO_2e, is achievable for this 21,000 square-foot two-story office building in Chittenden County, Vermont by shifting the structure from steel and concrete to wood and mass timber. An additional 60,300 kg CO_2e can be saved by replacing high embodied carbon insulation with lower embodied carbon insulation and maximizing supplementary cementitious materials in the balance of concrete used in the building, resulting in a total GWP reduction of 204,600 kg (204.6 metric tons) CO_2e.

Due to the design similarities between steel and wood framing, it is easy to make a sizeable impact in any phase of project design, however the greatest opportunity is through whole building design so that synergistic savings can be achieved through reduction in foundation load requirements and integrated system design which considers code and fire-rating requirements.

Integrating LCAs into the standard design process will lead to the identification and quantification of lower-carbon alternative material opportunities and increase designer familiarity with these products. Highlighting successful projects at the Better Buildings by Design conference and other industry events will increase market familiarity and confidence in mass timber building performance.

Tracking Vermont costs for mass timber and sharing cost-effective, lower-carbon material alternatives is necessary to support the design community in making informed design decisions. Companies seeking carbon reduction opportunities may find higher-priced, lower-carbon alternatives cost acceptable in meeting their carbon reduction goals.

As the industry at large adopts mass timber construction, prioritizing sustainable forestry management is necessary to prevent adverse impacts of wood and timber manufacturing and ensure long-term product stability in the market. For example, certification by the Forest Stewardship Council (FSC) for sustainable sourcing and forest management is highly regarded; however, FSC certified products are more costly for both consumers and manufacturers and therefore not as widely used as would be beneficial to the planet. Regulating environmental product declarations (EPDs) for building materials will support true product comparisons with increased transparency enabling informed product decisions regarding embodied carbon.

Efficiency Vermont can support the adoption of mass timber in the state through research like this study, stakeholder engagement, training, sharing, and program incentives supporting mass timber project designs. Policy levers and GHG emissions targets in construction could drive greater action.

Acknowledgments

The research team thanks Ricky McLain of WoodWorks and Hongmei Gu of the USDA Forest Service for their role in initiating and performing the design work and LCA study and fostering collaboration with Efficiency Vermont.