# Assessing the Carbon Balance for Mass Timbers Beyond the First Life

Christina Bjarvin

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Committee:
Dr. Indroneil Ganguly
Dr. Francesca Pierobon
Dr. Kent Wheiler
Dr. Tomás Mendez Echenagucia

Program Authorized to Offer Degree:
School of Environmental and Forest Sciences

Christina Bjarvin

University of Washington

# Abstract

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Chair of the Supervisory Committee:
Dr. Indroneil Ganguly
School of Environmental and Forest Sciences

Forests are an important carbon sink in the global carbon cycle and the carbon they store can be transferred into the built environment via wood products to maximize the forests' carbon storage potential and mitigate global climate change. Mass timbers, specifically cross-laminated timber (CLT) and glulam, are engineered wood products of growing interest regarding their carbon storage benefits, due to their long lifespan. However, given that CLT is a relatively new product, there is a limited understanding of how CLT can be treated at the end-of-life (EOL) phase to maximize its carbon storage potential. This research focuses on (*a*) determining the proportions of mass timber in a building to be allocated to four EOL scenarios (reuse, recycle, incinerate, and landfill) (*b*) evaluating the climate benefits of each EOL scenario, and (*c*) determining the substitution effects associated with the products created in each scenario. Reusing and recycling demolition mass timber demonstrated the best net climate impacts due to the low embodied emissions and large amounts of temporal carbon storage. Conversely, substitution effects were highest for the bioenergy products created from incineration and landfilling; however, this

benefit can only be realized once while the benefits of the products created from reuse or recycling can occur multiple times if a cascading recycling approach is considered.

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# I. Introduction

The role of natural forests as terrestrial sinks in the global carbon cycle is well-understood. Trees sequester atmospheric carbon dioxide ($CO_2$) in their tissues as they grow, and eventually release this stored carbon back into the atmosphere when they die and decay. This continuous capture and release of carbon in forests is part of the biogenic carbon cycle, which consists of carbon emissions from all biologically based materials, including live organisms. It makes up a portion of the global carbon cycle, alongside other large sources and sinks such as the terrestrial biosphere, the oceans, the atmosphere, and more recently, fossil fuels.

However, the role of working forests which are harvested for wood products in the biogenic carbon cycle is an area of growing interest, particularly regarding climate change. Forests can be classified as either natural forests or working forests. Natural forests are preserved for ecological, recreational, or cultural values instead of being harvested while working forests are actively managed and harvested in cycles to produce wood fibers and wood products. It is crucial for the health of natural ecosystems and the sustainable development of our future to have both natural forests and working forests, which allows us to maximize the invaluable benefits they provide without exceeding their capacity to produce these resources.

Working forests can act as a sink for carbon, where the total carbon stock increases over time. When forests are harvested, their stored carbon is transferred from the standing forest to the built environment via wood products. Carbon makes up 50% of the mass of wood on average (Bergman et al., 2014). This carbon remains stored for as long as the wood products are in use, which can benefit the climate by delaying the decay of the stored carbon. Longer-lived products such as lumber or plywood have greater climate benefits than short-lived products such as paper since the carbon is kept out of the atmosphere longer (Ganguly et al., 2020). The production of each product emits greenhouse gases (GHGs) and thus has a negative impact on the climate, but if the benefits of storage are greater, the product can be considered a carbon sink. Extending the lifespans of wood products after the end of their functional lives highlights an opportunity to maximize their benefit to the climate.

In addition, harvesting trees makes room for new trees to grow and sequester carbon. At the beginning of a plantation's growth phase, growth rates are fast so that it can increase its access to resources such as sunlight, water, and soil nutrients. Of course, once the trees are large enough, their growth rates start to decline. Mature, natural forests have a large amount of $CO_2$ sequestered in their large trees, but have low rates of new sequestration due to the limited space for additional growth. They continue to store more carbon as they grow, but at a certain inflection point, this rate starts to decline in tandem with decreasing growth rates. Contrary to this, working forests have higher rates of sequestration since they are young and rapidly growing in the space created by harvesting operations. They are often harvested before the inflection point of declining carbon sequestration rates, which helps maximize the amount of carbon that is stored in wood products. Young growing forests sequester more carbon annually than mature, old-growth forests (Pugh et al., 2019). However, due to the countless benefits old-growth forests provide in terms of ecosystem services such as air and water purification, preservation of diversity, or habitat provision, it is necessary to protect these forests from harvesting.

Finally, allowing private landowners to earn revenue from their forested lands through harvesting incentivizes them to keep reforesting their lands, and discourages them from converting the land to non-forest uses such as commercial, residential, or industrial applications. In the United States, the estimated forest cover in 1630 was 46% of total land area, which declined to 34% by 1910 with an estimated loss of 256 million acres of forest, primarily due to conversion to agricultural uses (Oswalt and Smith, 2014). However, the forest area has been stable over the last 100 years, with today's forest cover being around 33%. Roughly two-thirds of forested lands are managed for timber production, and the other third is protected as natural forests. A key driver behind the stable forest stocks has been the ability of private landowners to grow and sell timber on their land.

Considering wood products as a carbon sink is dependent on the assumption of wood carbon neutrality. Wood products produced in the United States (U.S.) can be assumed to be carbon neutral since the emissions from the eventual decomposition of the product are recaptured by the regrowing forest it was harvested from. This assumption of carbon neutrality depends on many factors, such as rotation times, product functional lifetimes, and sustainable management. Additionally, belowground carbon in soils and roots is often not accounted for in this assumption, given that soil emissions from harvesting are difficult to quantify, which reflects uncertainty in total carbon neutrality. However, a general approach to determining carbon neutrality is assessing sustainable management. In terms of carbon, sustainable management can be defined by the rate of annual forest growth compared to the rate of annual harvest: if removals exceed growth, the system is not sustainable in terms of carbon. Studies have shown that standing forest stocks in the U.S. have remained constant or increased, suggesting sustainable harvesting is occurring and thus, U.S. wood products can be considered carbon-neutral (Gray et al., 2016).

Recent research has quantified the climate benefits of carbon storage in wood products produced by Washington State's private timberlands in 2015, including lumber, plywood, paper, and miscellaneous panel products (Ganguly et al., 2020). Wood products can have both positive and negative effects on climate change, with the positive (i.e., mitigative) effects resulting from carbon storage, and the negative (i.e., contributive) effects resulting from GHG emissions during production. The emissions and carbon storage associated with a product can be evaluated through a lifecycle assessment (LCA), which translates the emissions into a metric called the global warming potential (GWP). Conversely, the amount of carbon stored in a product is translated into the global warming mitigation potential (GWMP). Conducting an LCA involves compiling data on the materials and processes used in raw material extraction (A1 stage), transportation to manufacturers (A2), production of the product (A3), and can also include the use (B) and end-of-life (C) stages of a product. For buildings, the A-stages also include transportation to the construction site (A4) and construction processes (A5).

Ganguly et al.'s research simulated forest growth in Washington's private working forests, determined how much of the harvest would be used for each type of product, and then conducted an LCA to compare the negative and positive effects on the climate from emitting and storing carbon, respectively. Through this, it was found that the GWMP outweighed the GWP for all products except paper, and the total annual carbon storage in wood products in 2015 was 1.7 million tons of $CO_2$ equivalent ($CO_2e$)[1], which is equivalent to mitigating 12% of Washington's annual GHG emissions. This demonstrates the potential of wood products and panels to mitigate global warming.

A key application in which biogenic carbon storage in wood products can offset GHG emissions on a massive scale is in the building industry. Buildings have different types of carbon storage and emissions associated with them: embodied carbon and operating carbon. Embodied carbon

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[1] To compare the global warming potentials of different GHGs, GHGs are converted to a common reference unit, such as $CO_2e$. While $CO_2$ is a gaseous compound, $CO_2e$ is a measure of the greenhouse effect.

refers to the emissions resulting from raw material extraction, transportation, and production of building materials, as well as emissions from construction processes. On the other hand, operating carbon refers to emissions from operations during a building's functional lifetime, such as heating, cooling, lighting, ventilation, and more. For this research, reductions in embodied carbon will be the primary focus. When comparing a building constructed with traditional building materials such as concrete and steel to a building comprised of wood products, the concrete building typically has a higher amount of embodied carbon than the wood building. Reducing the amount of GHG emissions associated with construction materials used during building construction by swapping concrete for wood can help to mitigate the climate crisis: this benefit is often referred to as the *substitution effect*.

The construction and building industries are responsible for 40% of global GHG emissions, with 11% of these emissions resulting from material production (Thibaut et al., 2018). The four billion tons of annual global cement production accounts for roughly 8% of global GHG emissions. Given that cement is the adhesive used in concrete, the substitution of wood for concrete represents a promising opportunity to tackle climate change (Lehne et al., 2018). As such, the organization Architecture 2030 issued a challenge to designers and architects to reduce the building industry's contributions to global warming through reductions in embodied carbon emissions, eventually achieving carbon neutrality by 2030 (*Architecture 2030*, n.d.). A viable method of achieving this goal is substituting traditional, fossil-fuel intensive materials with wood products when appropriate since the manufacturing processes of concrete and steel emit more GHGs than wood product manufacturing. The structural and nonstructural elements of high-rise buildings are commonly made from traditional materials but can be substituted by cross-laminated timber (CLT) and glue-laminated timber (glulam), which belong to a family of wood products called mass timbers (MT).

CLT is a large, structurally-sound, and heavy wood panel composed of layers of dimensional lumber (primarily softwood), laminated together with resins. In the first layer, the lumber is aligned in the same direction, but in the next layer, the lumber is aligned perpendicular to the first layer. This pattern continues to produce CLT made up of 3, 5, or 7 layers. Some commonly used resins include melamine-formaldehyde (MF) and polyurethane (PUR). Glulam is similar to CLT but has layers of dimensional lumber aligned in the same direction rather than perpendicular directions. Additionally, it uses melamine-urea-formaldehyde (MUF) or phenol-resorcinol-formaldehyde (PRF) resins instead of MF. Glulam can be used as structural elements in buildings such as beams and columns, while CLT can be used in flooring, walls, ceilings, and other applications. They can be customized in terms of length, width, and thickness depending on the application.

CLT and glulam are typically used in hybrid buildings alongside non-wood materials, and recent changes to the International Building Code (IBC) have allowed for the expansion of mass timber buildings into 18-story high-rises (Breneman et al., 2019). One such example of a mass timber high-rise is Brock Commons, an 18-story (54 meters) residential hall in Vancouver, Canada, at the University of British Columbia. Brock Commons is comprised of CLT floorplates and glulam wood columns, with a concrete ground floor and core for stabilization purposes. It is estimated that there are 1,753 metric tons of $CO_2e$ stored in the wood and 679 metric tons of avoided $CO_2e$ emissions from the reduced use of concrete and steel for a combined benefit of 2,432 metric tons of $CO_2e$ (Forestry Innovation Investment, 2018). The benefit to the climate from avoided $CO_2e$ emissions is referred to as the substitution effect. In this case, the stored carbon is roughly equivalent to mitigating the carbon emissions from flying 10 million miles on an average domestic commercial flight (*Carbon Footprint Factsheet*, 2021). This demonstrates the potential to mitigate climate change by storing carbon in hybrid timber high-rises across the United States.

Some other benefits of building with MT are aesthetic appeal, health and productivity benefits, efficient construction, and structural strength and flexibility (Graham, 2020; Falk et al., 2016). Mass timber buildings can be designed to meet seismic performance, fire protection, and moisture performance standards (Pei et al., 2014; Barber, 2017; Schmidt et al., 2019). Additional materials such as gypsum wallboard or gypsum concrete can be attached to improve the fire, moisture, and acoustic performance. Because CLT panels and glulam beams can be prefabricated in production facilities, they outperform traditional building materials such as steel and concrete in terms of quicker construction times (Wahlstrøm et al., 2020; Scouse et al., 2020; Laguarda-Mallo et al., 2016). MT construction processes also generate less onsite waste since the panels are prefabricated and assembled on site. Additionally, fewer trucks are needed to haul waste and pour cement, which results in less traffic. There is less noise pollution from construction since MT installation is quieter than traditional construction methods. However, a key driver behind the growing interest and demand for MT products is the carbon storage benefits associated with the wood panels, which can be fully realized by maximizing the use and lifespan of the product beyond its first functional lifetime in a building.

At the time of a building's demolition, the materials comprising the building can be reused, recycled, incinerated, or sent to a landfill, depending on the condition of the material. The carbon in used MT will therefore be subjected to different environments depending on the product's end-of-life (EOL) fate, which can have consequences on the amount and duration of carbon storage, as well as the transformation of the carbon molecules over time. For example, reusing a CLT panel would keep the carbon intact for as long as the panel is intact and in use, but some GHG emissions would be produced during any trimming or reshaping that might occur. Landfilling a CLT panel would also keep the carbon intact initially, but once the panel begins decomposing, some of the carbon would be emitted as methane ($CH_4$). Since $CH_4$ is more potent than $CO_2$, landfilling could potentially have a larger negative impact on the climate than other EOL scenarios. Alternatively, recycling a CLT panel into a particleboard panel would reduce the amount of carbon stored in the product, since some would be lost as waste during the chipping process, and some GHG emissions would be generated during the production of the particleboard. However, the lifetime of the particleboard may be longer than the time it takes for CLT to decompose in a landfill, which would provide more climate benefits overall. Finally, incinerating CLT for energy production would result in an immediate release of all the stored carbon, but in the form of $CO_2$ instead of $CH_4$. The uncertainty behind the difference in global warming potential is a major driving force of this research.

Other benefits provided by reusing or recycling MT products after the building's end of life can be divided into three categories: forestry, products, and the capacity of landfills to store waste. The forestry benefits of recycling MT are improving the efficiency of wood use and reducing the pressure on working forests to supply timber. Though wood is considered a renewable resource because it can be replenished through natural reproduction, working forests cannot provide an infinite amount of wood, largely because of the time it takes for trees to grow. The continued increases in human population and demand for raw materials such as wood place further stress on forest ecosystems. As such, it is necessary to find ways to increase material efficiency as much as possible. One study demonstrated that reusing CLT panels has the potential to increase the carbon stock of plantation forests by reducing the demand for virgin timber (Passarelli, 2018). This implies that not only can reusing MT allow for a continuation of its temporal carbon storage benefit in the built environment, it can also increase carbon storage in the forest.

On the product side of the benefits, reusing, recycling, or even incinerating MT can displace the use and need for fossil-fuel intensive products, such as steel, concrete, plastic, or fossil fuels. The best EOL scenario in terms of value would be to reuse the product in its original form in new buildings to displace concrete and steel. It could also be trimmed and reused in houses, barns, sheds, or various other small structures. Another example of reuse involves trimming and using MT in solid wood products, such as stair balusters and rails, posts, or other products which need to be milled into a desired shape. MT products could also be recycled into lower-value particleboard. Mass timber recycling may be limited to particleboard since particleboard can use recovered sawn wood as material input, but other products such as MDF, plywood, OSB, and wood-plastic composites only use fresh wood (Vis et al., 2016). The substitution effects of these second-life products can be quantified to provide a more holistic picture of the climate benefits associated with storing carbon in MT over multiple lifetimes.

Finally, the waste capacity benefits of CLT recycling lie in reducing the burden on landfills. Similar to the finite capacity of forests to supply wood, landfills have a limited capacity to store waste. The demand for landfill space is increasing steadily alongside the rise in human population, and potent $CH_4$ emissions from landfills are increasing atmospheric GHG concentrations. While some landfills have gas flare systems to reduce $CH_4$ emissions by recovering and treating waste gases to produce electricity, fuel, and heat, the majority of emissions are not captured, and not all landfills have this technology in place. To adequately address the global waste issue, finding alternate uses for products that have reached the end of their functional lifetimes and adopting them into a circular economy is crucial.

This research will focus on the product benefit of improving wood use efficiency. Advancing our current understanding of the environmental impacts of the products created from the reuse, recycle, and incinerate EOL scenarios will enable a comparison of their net climate impacts. Furthermore, the quantification of substitution benefits for each product and EOL scenario will further demonstrate the ability of MT to mitigate climate change after its first functional lifetime.

Though there are a large number of existing case studies and life cycle assessments (LCA) on the environmental performance of hybrid MT buildings compared to traditional buildings, there are few studies on the end-of-life (EOL) phase of MT buildings. Since CLT is a relatively new wood product that has only been in use for roughly 20 years in Europe and less than 10 years in the United States, most existing CLT buildings have not yet reached the end of their functional lives and thus, all EOL analyses as of this point have been hypothetical. However, research has modeled different treatment scenarios for CLT panels in buildings that have reached the end of their lifespan. Common scenarios include reusing, recycling, incineration for energy, and landfilling (Stora Enso, 2020; Robertson et al., 2012). Some studies have found that reuse is the best option in terms of lowering the embodied carbon of buildings and other environmental impacts associated with CLT (Darby et al., 2012; Chen, 2019). Another study demonstrated that recycling has the potential to offset energy consumption and embodied emissions of buildings (Liu et al., 2016).

Given that glulam has been in use for roughly 100 years, there is a more definitive understanding of which EOL treatments can be applied to glulam after a building is demolished. Several studies have included end-of-life phases in their LCAs for glulam buildings from Europe and Canada, with similar EOL treatments as CLT: reusing, recycling, incineration for energy, and landfilling (Sandin et al., 2014; Laurent et al., 2018; Robertson et al., 2012). The inclusion of EOL phases has been demonstrated to be a “critical” influence on the LCA results of glue-laminated timber, but the extent of this influence remains unclear (Sandin et al., 2014). A comparative LCA modeling a hybrid glulam structure found that energy valorization from the incineration of glulam reduced embodied GHG emissions by 1.7% for the total structure (Laurent et al., 2018). Reuse of mass timbers such as glulam was found to be feasible, given that mass timber structural members were originally created and produced as prefabricated, individual elements (Robertson et al., 2012). The same study also determined that MT elements could be reprocessed and recycled into lower grade wood products such as particleboard or OSB, incinerated with energy recovery in the form of heat or electricity generation, or landfilled. However, this study did not provide definite conclusions about the environmental impacts of the EOL scenarios, nor did it determine if EOL processing of materials from the mass timber structure was environmentally advantageous to the materials in a functionally equivalent concrete structure.

Despite a demonstrated demand for research on the climate impacts of EOL scenarios for mass timber products, there remains uncertainty around this topic (Campbell, 2020; Buss & Cesaero, 2021). Though reusing and recycling MT panels has been demonstrated to be valuable and desirable in terms of a transformation to a circular economy, it remains unclear how these scenarios compare to landfilling or recycling in terms of the impacts on climate change (Jarre et al., 2020; Campbell, 2018). Furthermore, no EOL studies have been conducted on a nation-wide scale for mass timber in the United States.

### A. Research Objectives

The objectives of this research are to (*1*) demonstrate the substitution effects of mass timber (MT) and its EOL products, (*2*) produce a model to compare the climate benefits of each EOL scenario, and (*3*) further our understanding of the climate implications of different EOL treatments aimed at increasing the global wood supply through the promotion of a circular economy.

### B. Research Questions

This research will aim to address the following questions:

1. Which mass timber EOL products have the largest substitution effects?
2. How can used mass timber be treated at a building's end-of-life to maximize its GWMP?
3. Which building elements have the greatest potential for maximizing substitution effects and GWMP?

## II. Methodology

### A. Evaluating Building Models

To realistically evaluate the climate benefits and substitution effects for EOL MT, a set of modeled MT buildings must be selected as case study buildings. Determining the amount of MT used in these buildings and the materials in contact with MT in each building element will allow for a building profile to be constructed. The EOL options depend on the building element where MT is used: for example, CLT in floors is often covered with gypcrete or concrete for soundproofing purposes, and thus can only be allocated to the landfill EOL scenario. A primary assumption of this research is that if MT is attached to materials such as concrete or gypcrete, it will need to be landfilled. However, if it has easily removable hinges or binders attached, it can be reused, recycled, or incinerated, depending on the condition of the CLT. The same can be assumed for other materials such as gypsum wallboard, vapor barriers, insulating materials, etc. Knowing how much MT is used in each element and whether it is in contact with removable materials or not will be useful in establishing how much MT will be allocated to each EOL scenario.

The hybrid mass timber models selected for analysis were created by Susan Jones in AutoDesk REVIT 2015 for a comparative whole building life cycle assessment (Puettmann et al., 2021). These models compare 8, 12, and 18-story mass timber buildings to their concrete equivalents in the Pacific Northwest (PNW), Northeast (NE), and Southeast (SE) regions of the United States (Figure 1). In this model, there are nine pairs of MT and concrete buildings for a total of eighteen individual buildings. For each MT building, CLT is used in the floors, interior walls, and exterior walls, while glulam is used in the columns and beams. Examining the type of materials in contact with the mass timbers in each building element allows for the selection of appropriate EOL scenarios available for the CLT and glulam, depending on the element. It should be noted that these models provide the “skeleton” of the building, but lack an outer layer (i.e., the building façade and exterior).

**Figure 1.** 8, 12, and 18-story buildings modeled by Susan Jones (Puettmann et al., 2021).

In the supplementary material for the LCA conducted by Puettmann et al., the bill of materials for each building is listed, which shows the types and quantities of materials used in each building element (Appendix I). The building designs were identical for the NE and SE buildings (i.e., the same quantity of materials was used), but since the wood used in each region had different densities, the GWP for the NE buildings differs from the SE buildings.

The PNW buildings required a more robust lateral (structural) system due to the high seismic activity in the region. As such, all MT panels in the lateral core of the PNW buildings have steel connections between them, but these connections were estimated as percentages of additional steel in the bill of materials instead of being modeled in REVIT.

Two cases will be developed for EOL scenario allocation, with the first case taking the landfill assumption of MT into account, while the second case will assume hypothetical technological advances can reduce the amount of landfilled MT. Each case will have a certain proportion of demolition MT allocated to the four EOL scenarios of reuse, recycle, incineration and landfill.

## B. Emission Profiles

In previous research, emission profiles were created for lumber, plywood, particleboard, and paper/pulp products, showing the net balance of the global warming impact of each product by determining its total embodied emissions and climate benefits (Figure 2) (Ganguly et al., 2020). With these profiles, the red portion of the graph represents the GWP, while the green portion represents the GWMP. Products that have larger green portions than red portions, such as lumber, are considered to have a net benefit to the climate.

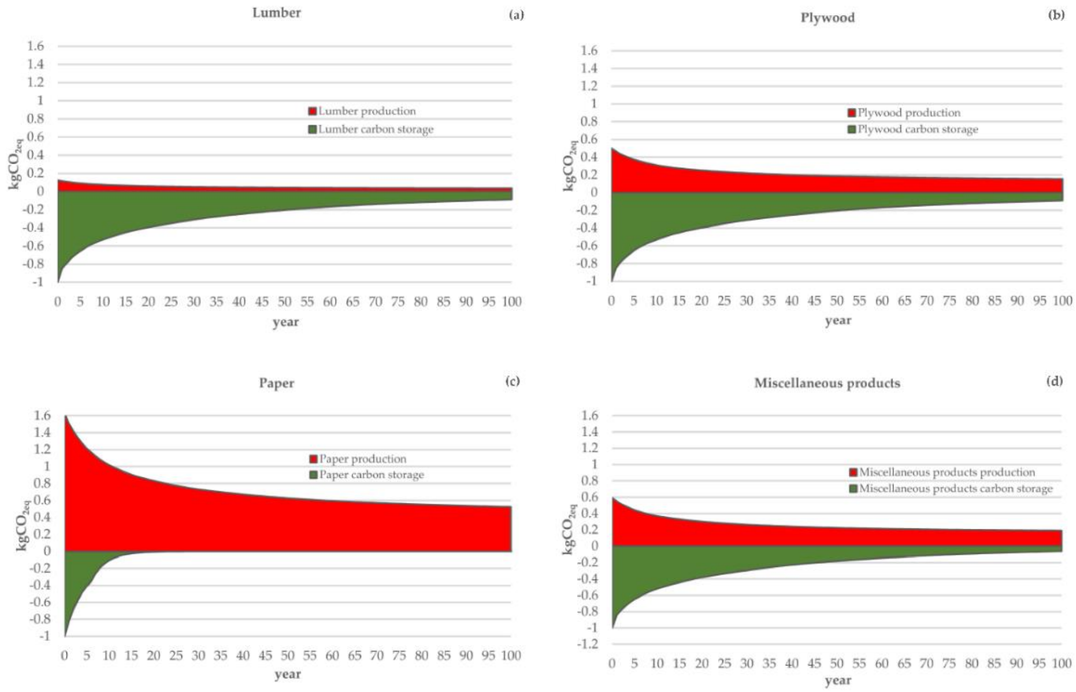

**Figure 2**. “Comparison between the $CO_2$ decay from wood products manufacturing fossil fuel-based life cycle emissions (red), and avoided $CO_2$ decay from wood products carbon storage (green), for 1 kg of (a) softwood lumber; (b) softwood plywood; (c) paper products; (d) miscellaneous products (particle boards and roundwood from lumber production sold off-site). The time horizon of the evaluation is 100 years” (Ganguly et al., 2020).

Unlike traditional LCAs that do not consider the impact of time on emissions, this study adopts a dynamic LCA approach, which factors in a temporal scope to assess the impact of emitting

GHGs at different times in a given period. The total climate impact of the emissions was modeled by a temporal radiative forcing (RF) analysis, which integrates the climate impact of a single pulse GHG emission over a given period of time. The three types of GHGs considered in this analysis are $CO_2$, $CH_4$ and $N_2O$ (nitrous oxide). The standard IPCC GWP metric has a time horizon is 100 years; however, given that the building lifetime is estimated to be 80 years, this study occurs on a 160-year time horizon to allow for two full lives of MT in the reuse scenario. Furthermore, given that particleboard has an average functional life of 40 years and can be recycled into itself more than once, the 160-year time horizon allows for two instances of recycling in the second life (Chang et al., 2014).

The RF is calculated by multiplying the radiative efficiency (RE) of a GHG by its atmospheric abundance, which can be determined by modeling the decay of the GHG in the atmosphere. RE is a measure of the strength, or potency, of a GHG in terms of the greenhouse effect: in the atmosphere, GHGs intercept and absorb heat radiating upwards from the earth. When a GHG molecule absorbs heat, it emits and reradiates it in all directions, resulting in the heat being redistributed to lower layers of the atmosphere, instead of being released back out to space. This heat can be absorbed by other GHG molecules, and due to this spatial redistribution, it becomes trapped in the atmosphere for extended periods of time, bouncing between different layers of the atmosphere as it is absorbed, emitted, and re-absorbed.

Due to differences in atom sizes and molecular structures, REs of different GHGs can vary greatly. For example, the RE of $CH_4$ is roughly 70 times stronger than the RE of $CO_2$, since its molecular geometry allows it to absorb more energy at a greater number of frequencies than $CO_2$. The RE values for each GHG assessed in this research are $1.76 \times 10^{-15}$ W $m^{-2}$ $kg^{-1}$ for

$CO_2$, $1.28 \times 10^{-13}$ W m$^{-2}$ kg$^{-1}$ for $CH_4$, and $3.85 \times 10^{-13}$ W m$^{-2}$ kg$^{-1}$ for $N_2O$ (Stocker et al., 2014).

The lifespan (or residence time) of a GHG in the atmosphere is also an important factor to consider in terms of RF. $CO_2$ has a longer residence time than $CH_4$, allowing it to capture more heat than $CH_4$ over time. $CO_2$ is mostly removed from the atmosphere through oceanic dissolution, rock formation, and chemical weathering, all of which are relatively slow processes. On the other hand, $CH_4$ is removed through atmospheric chemical reactions and thus has a much shorter residence time. Using the residence time, exponential decay functions can be constructed for each GHG to determine the relative abundance of GHG remaining at any time during a given period after a single pulse emission.

The decay function for $CO_2$ is based on the Bern carbon cycle model (Strassmann et al., 2018) (Equation 1):

**Equation 1**. Concentration of $CO_2$ in the atmosphere at time t, where $a_0 = 0.2173$, $a_1 = 0.2240$, $a_2 = 0.2824$, $a_3 = 0.2763$, $t_1 = 394.4$ years, $t_2 = 36.54$ years, and $t_3 = 4.304$ years.

$$[CO_2](t) = a_0 + \sum_k a_k e^{(-\frac{t}{t_i})}$$

The decay function for other greenhouse gases is given by Equation 2:

**Equation 2**. Concentration of a given GHG in the atmosphere at time *t*, where $t_i$ = refers to the residence time of the $GHG_i$ (given as t = 12.4 years for $CH_4$ and t = 121 years for $N_2O$ by Stocker et al., 2013).

$$[GHG_i](t) = e^{-\frac{t}{t_i}}$$

The decay function for a GHG can be used to determine the relative abundance of a GHG at a given time, and multiplying that by the RE gives the RF value (Equation 3).

**Equation 3**. Radiative forcing of a given GHG at time t.

$$RF_{GHG_i} = RE_{GHG_i} * [GHG_i](t)$$

Integrating the RF values for each year in a given period gives the cumulative radiative forcing of a single GHG pulse. Converting the cumulative radiative forcing value to a $CO_2$e (carbon dioxide equivalent) is done by multiplying the concentration by the ratio of $RE_{GHG}$ to $RE_{CO2}$: in the case of $CH_4$, this is $1.28 \times 10^{-13} / 1.76 \times 10^{-15}$. Once all GHG concentrations are expressed in the same unit of $CO_2$e, the cumulative climate impact can be estimated by adding the impact from each GHG resulting from a process together (Equation 4).

**Equation 4**. Cumulative radiative forcing for k GHGs considered.

$$CRF_{GHG_{i_k}}(t) = \sum\nolimits_k RF_{GHG_{i_k}}$$

Applying the cumulative RF to the total positive emissions from each EOL scenario will give each scenario's positive part of the emission profile. The negative emissions (i.e., the avoided emissions used for factoring in the sequestration) follow a similar methodology for some of the EOL scenarios, but others take different approaches. The positive emissions associated with each scenario and the methodology for the negative emissions are outlined in the following sections. A line representing the total biogenic $CO_2$e storage in the building during the first lifetime of MT will also be shown.

### *1. First Lifetime*

In the first lifetime of CLT and glulam in a building, the total GHG emissions embodied in each of the nine MT buildings modeled by Susan Jones were derived for the positive emissions in the

RF analysis (Puettmann et al., 2021). This was calculated by multiplying the GWP impact per $m^2$ of building (of A1 – A5 life cycle stages) by the respective total area of each building, given as 9,476 $m^2$, 14,214 $m^2$, and 21,321 $m^2$ for the 8, 12, and 18-story structures, respectively. The total emissions were applied to the atmospheric decay functions and RF equations outlined in Equations 1 – 4. It should be noted that this is a conservative estimate of each building's A1-A5 impacts since the models did not provide exterior layers and thus more materials would be included in the final building.

Puettmann et al.'s LCA did not include impacts from the B (use) and C (end-of-life) stages; however, since a key purpose of this research is to estimate the climate impacts of end-of-life treatments, the C life stages should be estimated and included. A whole building life cycle assessment of a 12-story, 8,360 $m^2$ MT building was selected for this estimation (Chen et al., 2020). This building had similar A1 – A5 impacts as the 8-story buildings from Puettmann et al.'s study (245 kg CO2e/$m^2$ vs. 271 kg $CO_2$e/$m^2$, respectively), suggesting it is an appropriate model to adopt the C1 (demolition) impact from. The C1 impact is estimated as 0.12 kg $CO_2$e/$m^2$ of building, which was applied to the nine case study buildings used in this research. The C2 (transportation to waste facilities) impact was not included, since this impact is modeled in the specific EOL scenarios detailed in the next sections. Different EOL treatments have different transportation impacts depending on which facility MT is transported to, making the assignment of the C2 impact specific to an EOL scenario a more accurate method of assessment. All biogenic carbon emissions were considered neutral and not counted towards the GWP, since it is assumed that these emissions will be recaptured by the regrowing forest.

To estimate the climate benefits associated with storage, the climate impacts of the atmospheric decay of a molecule of $CO_2$ must first be considered. Since using mass timber prevents its biogenic carbon from being decayed, there is a benefit from delaying this decay that corresponds directly to the $CO_2$ atmospheric decay function outlined in Equation 1. If the climate warming impacts from a single emission of $CO_2$ are estimated over 160 years, storing an equivalent amount of $CO_2$ over that period will have the same benefits as the emission, only negative (Figure 3). This is the primary approach taken by the Lashof carbon accounting method, one of the major methods for the climate impacts of carbon sequestration or storage (Fearnside et al., 2000).

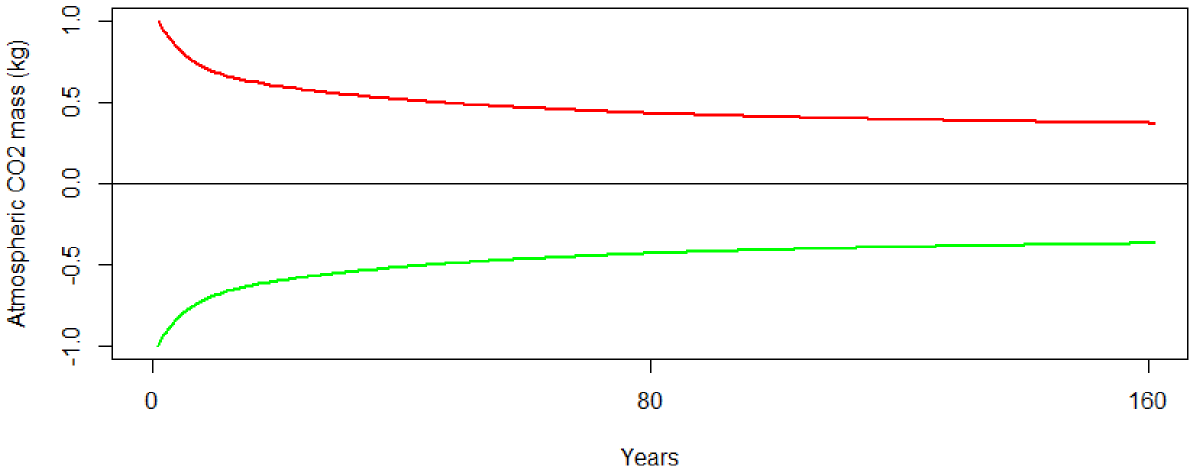

**Figure 3**. Decay of a pulse emission of 1 kg $CO_2$ in the atmosphere (red), with the inverse function showing the benefit of preventing the decay of the pulse emission (green).

As such, the storage benefits of MT in the first life can be calculated by applying the first 80 years of the green storage benefit function to the mass of stored $CO_2e$ in each building. The mass of $CO_2e$ per kg of MT is estimated to be 1.797 kg CO2e (Equation 5):

**Equation 5**. Mass of $CO_2e$ per kg MT, based on the assumption that 49% of mass timber's mass is carbon, and the molar masses of $CO_2$ and C (44 g/mol and 12 g/mol, respectively) (EPA, 2020*a*).

$$M_{CO_2e} = \frac{0.49\ kg\ C}{1\ kg\ MT} * \frac{44\ kg\ CO_2}{12\ kg\ C}$$

The total mass of MT is given in Puettmann et al.'s LCA, and the total mass of stored $CO_2e$ was derived from Equation 5 and applied to the first 80 years of the storage benefit function.

### 2. *Reuse*

The positive emissions associated with reuse were taken from the Environmental Protection Agency's (EPA) Waste Reduction Model (WARM) (EPA, 2020*a*, *b*). WARM is a tool that estimates the GHG emissions of different waste management practices for municipal solid waste (MSW) materials. Practices include landfilling, recycling, anaerobic digestion, incineration, and composting, which makes WARM suitable for comparison to the model created in this research.

The emissions associated with different EOL practices are given as MT CO2e per Wet Short Ton (WST) of wood in WARM. Since WARM does not contain data for any mass timbers, dimensional lumber was selected as a proxy material. The processes associated with the reuse of dimensional lumber are transportation from the old building to the reprocessing facility, reprocessing or refurbishing, and transportation from the facility to the new construction site. WARM estimates the reuse impact as 0.06 MT of $CO_2e$ per WST of dimensional lumber, which is equivalent to 0.066 kg $CO_2e$ per kg MT (Exhibit 12-11, EPA, 2020*a*). This impact was applied to the amount of MT allocated to reuse in each case, and these cumulative positive emissions were applied to the atmospheric decay and RF functions (Equations 1 – 4).

The negative emissions associated with reuse were modeled similarly to the first life, where the storage benefit function was applied to the amount of biogenic carbon stored in the reused MT. However, since the storage benefits are a continuation of the first lifetime, the function's final 80 years (years 80 – 159) were used rather than the first 80 years.

### 3. *Recycle*

Given that the lifespan modeled for the EOL scenarios was 80 years, two instances of recycling were modeled since particleboard has a functional lifespan of 40 years (Chang et al., 2014). As such, two pulses of positive emissions occurred. WARM models the GHG emissions from recycling waste wood the same as reusing wood, perhaps because the processes required for reusing are similar enough to those needed for recycling. WARM also states that since "while recycling of dimensional lumber [as] an open-loop process is feasible, dimensional lumber that is recovered at end-of-life is more commonly reused" (EPA, 2020*a*). As such, the reuse impact of 0.066 kg $CO_2$e per kg MT is also used as the positive emission associated with recycling (EPA 2020*a*). At year 120 (i.e., 40 years into the EOL lifespan), the second pulse of emissions occurred, with a GWP impact equal to the first pulse. These impacts were applied to the MT diverted to the recycle scenario to give the cumulative positive emissions, applied to Equations 1 – 4.

The negative emissions were modeled with a similar approach to reuse, applying the final 80 years of the storage benefit function to the carbon stored in particleboard. The amount of carbon stored inside the final products of both the second and third lifetimes is assumed to decrease by

20%, due to the allocation of 20% of the particleboard to incineration during the second instance of recycling[2].

### *4. Incinerate*

Incineration of wood products generates $N_2O$ and biogenic $CO_2$ emissions. However, given that biogenic carbon is assumed to be neutral in terms of climate impacts, only the $N_2O$ emissions from combustion are accounted for in this model. The fossil $CO_2$ emissions from transportation to combustion facilities are also included. WARM cites an impact of 0.04 MT $CO_2e$ per WST of lumber for $N_2O$ emissions, and an impact of 0.01 MT $CO_2e$ per WST for transportation, which are equal to 0.044 and 0.011 kg $CO_2e$ per kg MT, respectively. Since these estimations are for dimensional lumber which contains no resins, the impact of resins was calculated by extracting the GWP associated with the incineration of polyurethane (PUR) from the US-EI 2.2 database in SimaPro version 9.0.

Resins are estimated to compose 1.22% of glulam’s total mass, and 1% of CLT’s total mass (Bowers et al., 2019; Stora Enso, 2020). Since PUR was the only resin available for incineration in SimaPro, 0.01 kg of resin was analyzed per kg of CLT, which produced a GWP of 0.024 kg $CO_2e$ per kg MT. The resin impact was summed with the WARM impacts for the total incineration impact.

Applying the total impact to the amount of MT allocated to the incinerate scenario in each case resulted in the cumulative positive emissions to be applied to Equations 1 – 4. There was no

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[2] As a simplifying assumption, the incineration emissions were assumed to be negligible and excluded from the model.

storage benefit (i.e., negative emissions) associated with incineration since combustion results in all stored carbon being emitted into the atmosphere. However, incineration does have benefits from the substitution of fossil fuels for energy, a benefit which is addressed in the Substitution Effects section.

### *5. Landfill*

Determining the positive and negative emissions of landfilling MT requires a different decay function than the previous scenarios, given that landfill conditions are anaerobic, so more $CH_4$ is generated. A new decay model was created for the landfill scenario, using assumptions from WARM's landfilling model (EPA, 2020*b*). WARM lists MSW landfill decay rates (*k*) for different landfill moisture contents, based on research conducted to determine component-specific decay rates (De la Cruz & Barlaz, 2010). The five moisture content scenarios listed in WARM include Dry, Moderate, Wet, Bioreactor, and National Average, with conditions as follows:

1. *Dry*: annual precipitation is less than 20 inches
2. *Moderate*: annual precipitation is between 20 - 40 inches
3. *Wet*: annual precipitation is greater than 40 inches
4. *Bioreactor*: water is added until the moisture content is 40% on a wet-weight basis to accelerate decomposition
5. *National Average*: a weighted average based on the proportion of waste received at each of the prior moisture scenarios

The decay rates of mixed MSW for each moisture scenario are *k* = 0.02, 0.04, 0.06, 0.12 and 0.052, respectively. These decay rates can be applied to a first-order decay equation for mixed MSW to determine the methane generation rate for each moisture scenario (Figure 4). As shown in the figure, decomposition is faster under wetter landfill conditions.

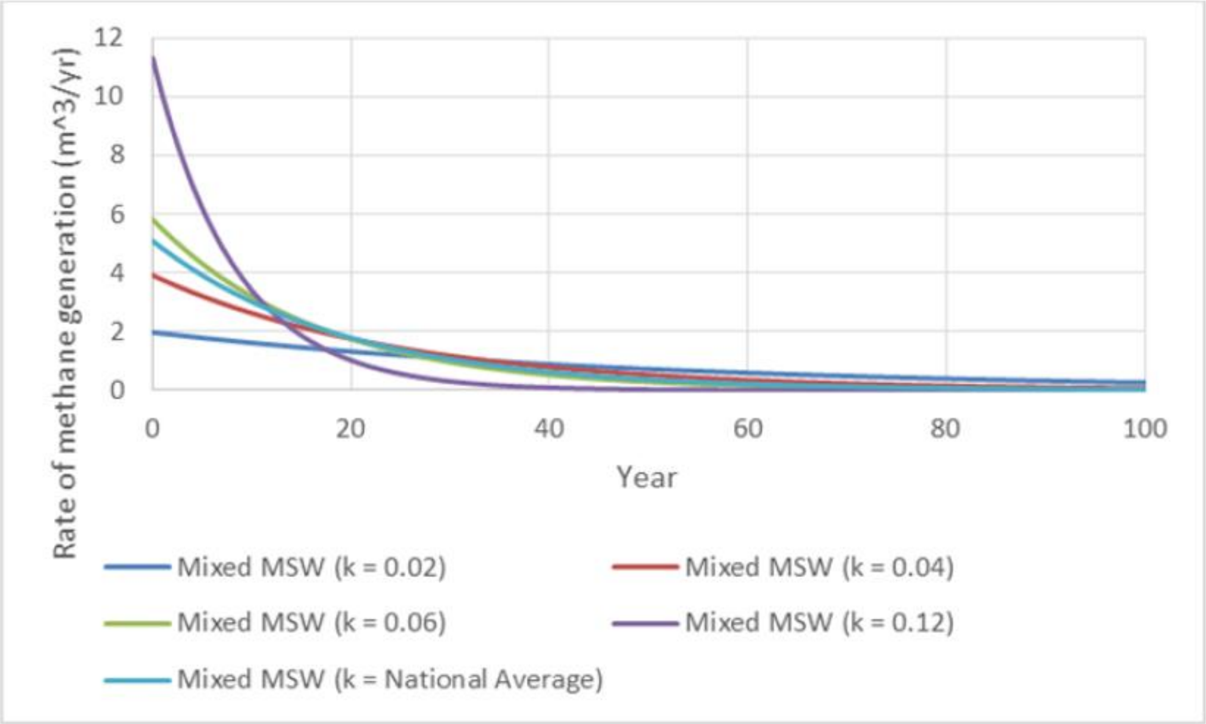

**Figure 4**. "Rate of methane generation for mixed MSW as a function of decay rate" (EPA, 2020b).

The decay rates specific to dimensional lumber are as follows: *k* = 0.04, 0.08, 0.12, 0.25, and 0.11 for the Dry, Moderate, Wet, Bioreactor, and National Average scenarios. Given that this research is intended to apply to mass timber buildings on a national scale in the U.S., the national average value (*k* = 0.11) was selected for this landfill decay model.

The second assumption taken from WARM concerns the amount of permanent carbon storage from wood in landfills. Experimental values from previous studies were used to estimate the percentages of initial carbon either stored permanently, emitted as $CH_4$, or emitted as $CO_2$ (Barlaz, 1998; Wang et al., 2011; Wang et al., 2013). The initial biogenic carbon content of dimensional lumber is reported as 49% of the lumber's mass. Carbon emissions from lumber decay depend on the type of carbohydrates present in wood, of which there are three main types: cellulose, hemicellulose, and lignin. Holocellulose (cellulose and hemicellulose) can be microbially converted and emitted as $CO_2$ and $CH_4$ during anaerobic decomposition, but lignin can resist decomposition (Wang et al., 2013; Stinson and Ham, 1995). However, not all holocellulose can degrade since the presence of lignin can physically and chemically inhibit the biodegradation of holocellulose.

The percent composition of each carbohydrate in softwoods and hardwoods has been reported as 34.1% – 41% cellulose, 16.1% – 22.6% hemicellulose, and 24.7% – 31.6% lignin, with softwoods typically containing more lignin (Wang et al., 2013). The holocellulose to lignin ratios for softwoods and hardwoods are reported as 1.8 and 2.3, respectively (Wang et al., 2013). Since more holocellulose is present in wood, one might expect a large amount of the initial carbon should degrade. However, since the presence of lignin can prevent holocellulose degradation, the majority of the initial carbon does *not* degrade. EPA studies have shown that 88% of the initial carbon in dimensional lumber is assumed to be permanently stored in landfills (EPA, 2020*b*).

In WARM, 1% of the initial carbon present in lumber is assumed to be emitted as $CH_4$. Biogenic $CO_2$ emissions are not accounted for since they are assumed to be neutral. With this, a $CH_4$ generation function can be constructed for MT decomposition in a landfill (Equation 6).

**Equation 6**. Mass of $CH_4$ emissions from the decomposition of MT at time t, where k = decay rate, and 0.01 refers to the proportion of initial carbon present in MT emitted as $CH_4$.

$$M_{CH_4}(t) = -k * 0.01^{-kt}$$

The atmospheric decay of $CH_4$ was modeled by creating an emissions matrix for each GHG, which takes the atmospheric lifespan of $CH_4$ into account to estimate atmospheric GHG concentrations. Applying this atmospheric decay function to the $CH_4$ generation function in Equation 6 (and factoring in the RE number for $CH_4$) resulted in the cumulative decay function for $CH_4$ generated from MT decomposing in a landfill. This function was applied to the mass of MT diverted to the landfill in Cases 1 and 2 to provide the positive emissions for the emission profiles.

Since there are impacts associated with landfilling outside of the landfill from transportation from the demolition site to the landfill, these emissions were modeled with the same methods as the previous EOL scenarios. WARM gives a transportation impact of 0.02 MT $CO_2$e per WST lumber, or 0.022 kg $CO_2$e per kg MT. This impact was applied to the mass of MT in the landfill scenario, and the cumulative impact was applied to Equations 1 – 4. These emissions were summed with the emissions from Equation 6.

The negative emissions associated with landfilling MT draw on WARM's assumption that 88% of the initial carbon in landfilled dimensional lumber is permanently stored (EPA, 2020*b*). Of that 12%, some of the carbon is emitted as $CO_2$, emitted as $CH_4$, or leached into the soil.

However, 88% of the carbon is stored permanently and can be credited as permanent negative emissions, which corresponds to 1.58 kg $CO_2$e per kg MT of the initial 1.79 kg $CO_2$e per kg MT. As such, the negative emissions were modeled with a decay function that retains a certain proportion of carbon relative to the initial mass (Equation 7).

**Equation 7**. Mass of $CO_2$e permanently stored in landfilled MT at time *t*, where 1.58 refers to the final mass of landfilled $CO_2$e per kg MT, 0.217 refers to the mass of emitted $CO_2$e per kg MT, and *k* = decay rate.

$$M_{CO_2e}\ (t) = \ -1.58 - 0.217^{-kt}$$

$CH_4$ emissions from landfills can be reduced with gas recovery systems that flare or combust $CH_4$ for energy generation. Flaring $CH_4$ is the practice of converting the gas to $CO_2$ via combustion before releasing it into the atmosphere, but this does not capture any of the energy generated during this process. WARM states that the national average percent of landfills that do not flare or combust construction debris is 96%, while 2% of landfills flare and the other 2% of landfills combust for energy. Given the low incidence of gas recovery systems, flaring or combustion for energy was not modeled for this research, which produces a more conservative estimate of the climate impacts of landfilling MT.

### C. Substitution Effects

The substitution effects associated with the products created by each EOL scenario (CLT, particleboard, and bioenergy for reuse, recycle, and incinerate, respectively) can be determined with a metric called a displacement factor. A displacement factor (DF) is a unitless metric of efficiency at which a unit of wood can displace GHG emissions by replacing a non-wood material (Sathre & O’Connor, 2010). The DF can be calculated as shown in Equation 8.

**Equation 8**. Displacement factor calculation, where $GHG_{nw}$ and $GHG_w$ refer to GHG emissions embodied in a non-wood product and a wood product, respectively, while $WU_w$ and $WUn_w$ refer to the amount of wood used in the wood product and non-wood product.

$$DF = \frac{GHG_{nw} - GHG_w}{WU_w - WU_{nw}}$$

In this equation, the unit for both the numerator and the denominator must be the same, whether it is in kg $CO_2$e or kg C since the DF is unitless. For this analysis, the selected unit for GHG emissions and wood used is kilograms of $CO_2$e. Higher DFs indicate better effectiveness of wood at reducing GHG emissions, while negative DFs imply that substituting wood in place of another product actually *increases* the GWP and thus, contributes more to global warming than if the substitution had not occurred. The DF is typically used for entire buildings, but can also be applied to single products. When calculating the DF of a product, the non-wood alternative product must be functionally equivalent to the wood product.

While substitution benefits explain the quantity of GHG emissions displaced when wood substitutes for other materials, a DF provides this quantity per unit of wood used; thus, DFs contain insight into how effective mass timbers are at displacing GHG emissions when subjected to different EOL scenarios. For example, CLT may be more effective at displacing GHG emissions when it is incinerated to replace natural gas than if it is landfilled with energy recovery to also replace natural gas.

The DF of MT in its first life will be calculated for the case study buildings selected in the *Evaluating Building Models* section, where each MT building will be compared to a concrete equivalent building. The comparative LCA conducted for previous research lists the GHG emissions associated with each building, which can be applied to Equation 8 (Puettmann et al., 2021). The amount of mass timber used in each building can be taken from Supplementary

Material of the LCA (Appendix 1). Since the LCA has a functional unit of 1 $m^2$ of building, the unit for the numerator and denominator of the DF equation must be adjusted to kg $CO_2e/m^2$.

For the reuse scenario, the DF will be the same as the first lifetime DF. For recycling, incineration, and landfilling with gas recovery, the DFs of particleboard and bioenergy can be found in existing literature (Suter et al., 2017; Knauf et al., 2015; Lippke & Puettmann, 2013; Dodoo et al., 2019). The DF of mass timbers can also be found in previous studies for comparison to the calculated DF in this study (Suter et al., 2017; Knauf et al., 2015; Dodoo et al., 2019; Freuhwald et al., 2014).

In addition to the whole building DF, the DFs of individual building elements were calculated to help explain differences in whole building DFs across different regions or building types. With this analysis, building elements that used MT were the columns/beams, floors, and interior/exterior walls. The GHG values for each assembly were calculated based on information provided in the unpublished white paper on the comparative LCA (Puettmann et al., n.d.). In the white paper, the life cycle impacts of each element were provided, as well as the contribution of each building material to the GWP (Appendix II). To determine the GWP of each material in each element, the mass of each material in each element first had to be determined.

The bill of materials in Appendix 1 provided the proportion of each material across the different elements, but not all materials had units of mass. These proportions were used alongside the total mass of each material in the building: for example, a total of 1,114,261 kg of CLT was used in the 8-story MT PNW building. 8.3% of the CLT in the building was used in the exterior walls, so approximately 92,273 kg of CLT went into the exterior walls. With this information, the A1-A5 GWP impact for CLT could be distributed to each application of CLT: the total 41 kg $CO_2e$ ended up as 4 kg, 28 kg, and 9 kg $CO_2e$ in the exterior walls, floors, and interior walls, respectively. This process was conducted for each material in each element, and the GWP for each element was compared to the GWP listed in the white paper. This allowed for the calculation of the numerator of the DF equation, and also permitted the comparison of each material's contribution to GWP. The calculation of the mass of wood in each element also helped determine the amount of wood used for the denominator of the DF equation.

Given that the weights of MT buildings were lower than those of their concrete counterparts, less concrete and rebar were required in the foundations of the MT buildings. The reduction of these material quantities resulted in a substitution effect specific to the foundation element; however, given that no wood was used in the foundation, it is not possible to calculate a foundation DF. However, the GHG reduction associated with the foundation can be distributed to the other building element DF calculations to accurately account for the full climate benefits of building with mass timber. As such, the foundation GHG reduction value was distributed proportionally to the other elements based on the weight of the MT in that element.

# III. Results

## A. Evaluating Building Models

In each building model, the CLT used in the flooring system was in contact with concrete, gypcrete, or both, requiring that all CLT used in floors must be landfilled. Anywhere between 39% - 46% of the total CLT use in a building was used for the floors (Table 1). Alternatively, the CLT in the interior and exterior walls could be reused, recycled, or incinerated in most building types. The average percentages of CLT use are presented in Table 2. However, in the 18-story buildings, concrete was used in the interior walls alongside CLT to meet fire code requirements (per the IBC, wood is not allowed to be visible in 18-story buildings, so concrete was used to cover CLT in interior walls). Thus, the CLT in the interior walls of 18-story buildings must be landfilled in addition to the CLT in floors.

**Table 1**. Average percentages of total MT use in three building elements for 8, 12, and 18-story hybrid mass timber buildings. CLT is used in the floors and walls, while glulam is used in the columns and beams.

| | **8-story** | **12-story** | **18-story** |
|---|---|---|---|
| **Floor** | 44% | 39% | 46% |
| **Int Wall** | 27% | 29% | 25% |
| **Ext Wall** | 5% | 7% | 8% |
| **Columns/Beams** | 24% | 24% | 29% |

Based on these findings, the EOL scenarios possible for each element were determined, and each building type had unique proportions of CLT in different EOL scenarios. The CLT in floors was all allocated to the landfill scenario, while the CLT in interior and exterior walls was allocated to the reuse, recycle, and incinerate scenarios (except CLT in interior walls for 18-story buildings, which was allocated to the landfill scenario). Glulam in columns and beams was allocated to reuse, recycle, and incinerate. The total percentages of MT allocated to each EOL scenario for the different building types are shown in Table 2.

**Table 2**. Percentages of MT diverted each EOL scenario in two different cases.

| | **PNW** | | | **NE/SE** | | |
|---|---|---|---|---|---|---|
| | *8-story* | *12-story* | *18-story* | *8-story* | *12-story* | *18-story* |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Case 1** | | | | | | |
| Reuse | 20% | 22% | 20% | 23.5% | 25% | 13% |
| Recycle | 20% | 22% | 20% | 23.5% | 25% | 13% |
| Incinerate | 11% | 12% | 10% | 12% | 13% | 6% |
| Landfill | 49% | 44% | 50% | 41% | 37% | 68% |
| **Case 2** | | | | | | |
| Reuse | 37.5% | 39% | 37.5% | 40% | 41% | 33% |
| Recycle | 37.5% | 39% | 37.5% | 40% | 41% | 33% |
| Incinerate | 0% | 0% | 0% | 0% | 0% | 0% |
| Landfill | 25% | 22% | 25% | 20% | 18% | 34% |

Case 1 is based on the landfill assumption of MT attached to concrete/gypcrete, and 40% of the remaining MT is sent to reuse, 40% to recycle, and 20% to incinerate, based on estimates of wood waste recovery (Bratkovich et al., 2014). Case 2 is a hypothetical situation where the landfill percentage is halved, based on the assumption that technological advances make the separation of MT from concrete/gypcrete a feasible and economically viable option after demolition. Additionally, incineration is removed as an option to increase the supply of longer-lived wood products in the bioeconomy. The remaining MT is allocated equally to the reuse and recycle scenarios.

## B. Emission Profiles

### *1. EOL Comparison*

To provide insight into the differences in GWP and GWMP between the EOL scenarios, the emission profiles for 1 kg of CLT over an 80-year time horizon were constructed for each scenario, which is representative of the longest lifespan of the second life scenarios (i.e., reuse) (Figures 5 – 8). Though the EOL modeling for the building profiles started at year 80 of CLT's life, these emission profiles start at year 0 under IPCC LCA guidelines.

Glulam production has slightly higher GWP impacts than CLT production, but the remaining impacts in terms of first life storage and the EOL emissions/storage are identical between the two MTs, so only CLT was analyzed for these profiles.

The positive portion of the y-axis represents GWP impacts from GHG emissions (shown in red), while the negative portion represents GWMP impacts from the climate benefit of storing carbon in the wood products (shown in green). The scale of the y-axis was kept constant across this set of emission profiles for comparison.

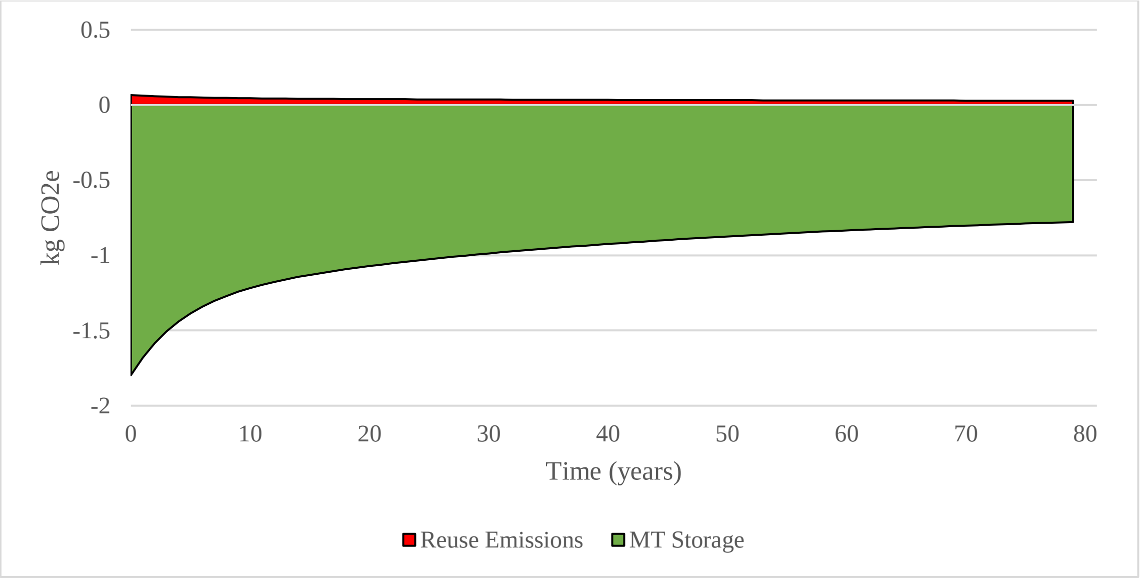

**Figure 5**. Emission profile for 1 kg of CLT, reused as CLT in the second lifetime.

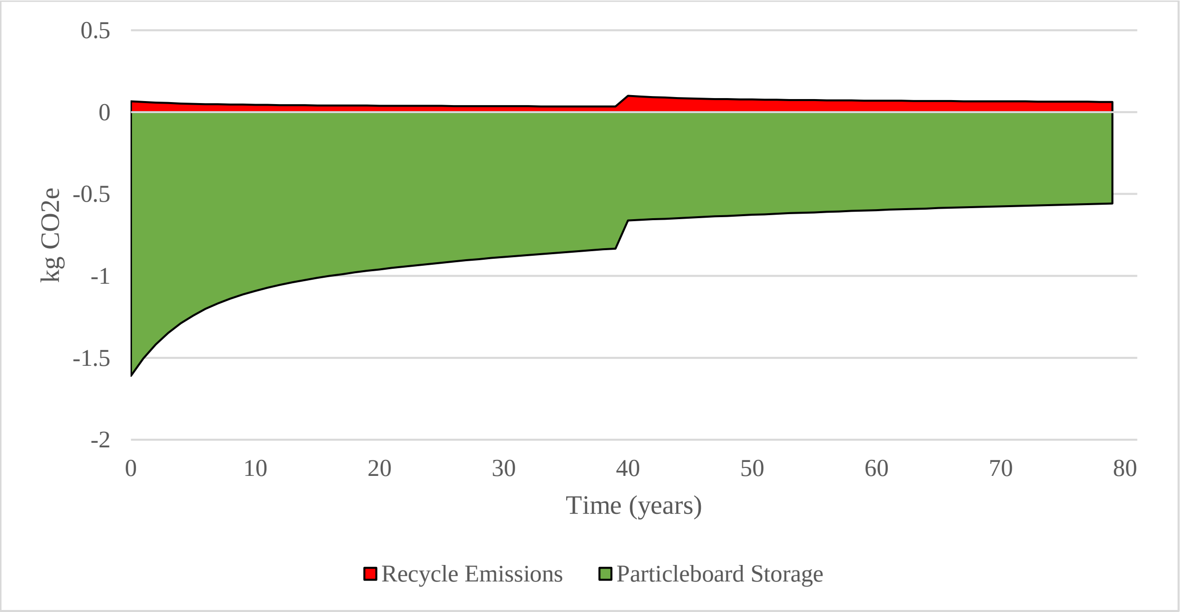

**Figure 6**. Emission profile for 1 kg of CLT, recycled as particleboard twice in the second lifetime: once at year 0, and again at year 40.

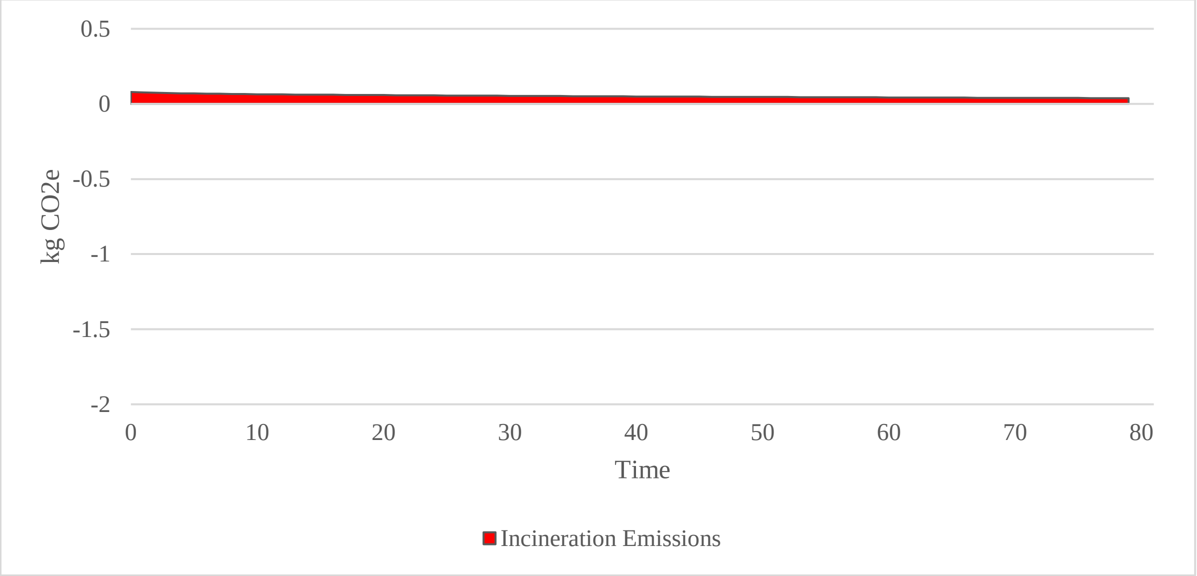

**Figure 7**. Emission profile for 1 kg of CLT, incinerated in the second lifetime.

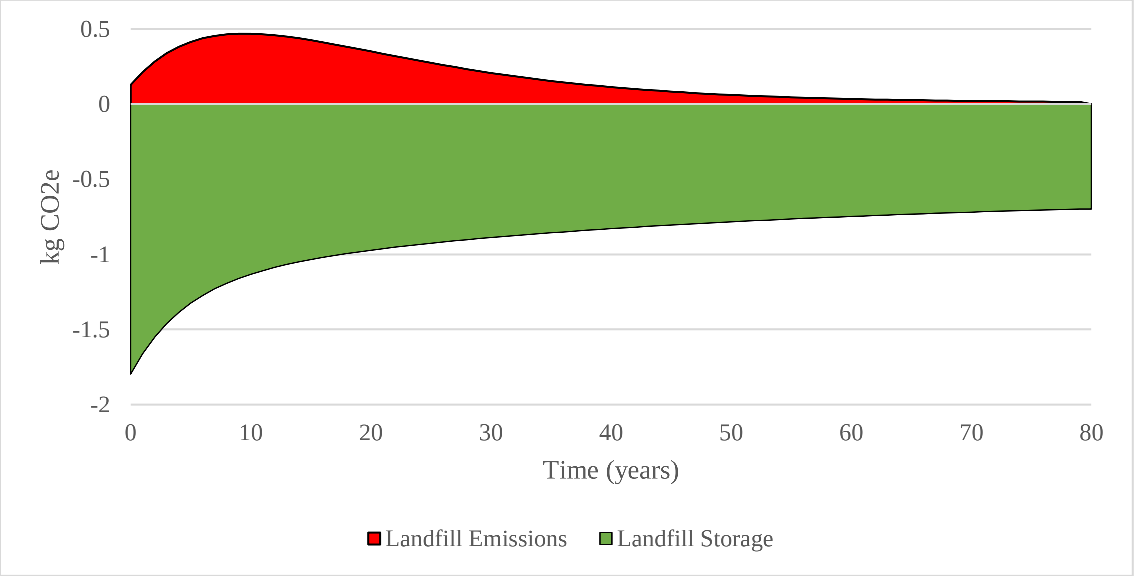

**Figure 8**. Emission profile for 1 kg of CLT, landfilled in the second lifetime.

The net climate impacts are summed to compare the cumulative impacts of each EOL scenario, calculated by averaging the negative impacts over 80 years, and summing that with the average positive impacts (Figure 9). More negative (green) impacts indicate a larger benefit to the climate, while positive (red) impacts indicate a contribution to global warming rather than mitigation.

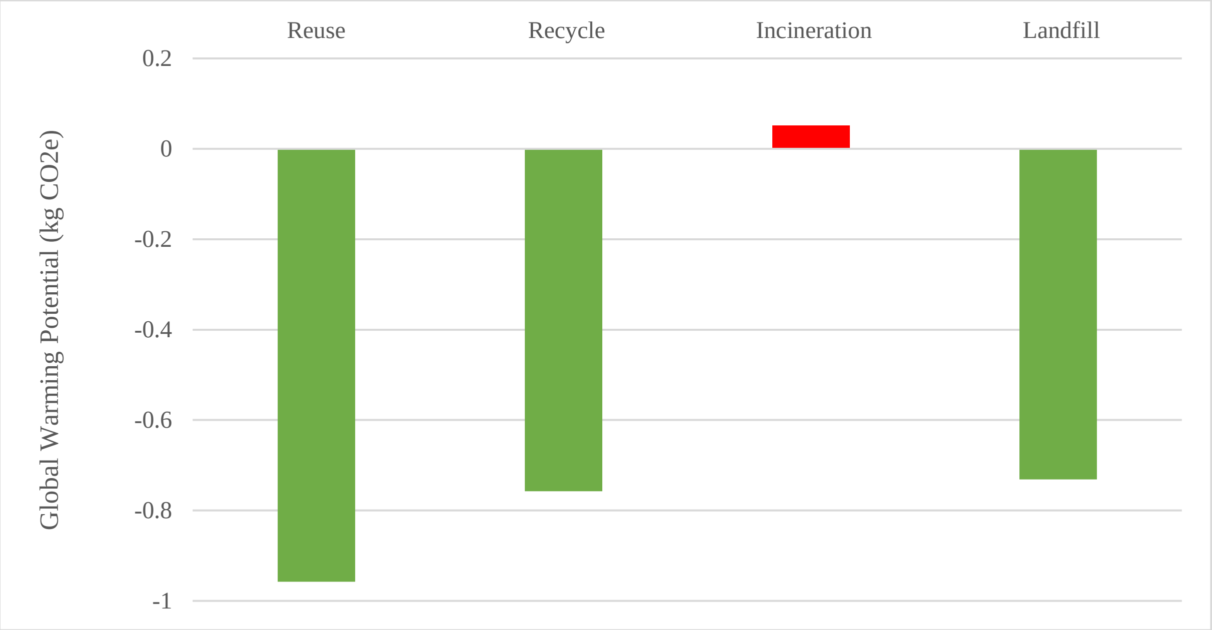

**Figure 9**. Average net climate impacts of the EOL scenarios.

## 2. *Case 1*

The emission profiles constructed for Case 1 reveal differences in GWP and GWMP across the different building types and regions (Figures 10 – 18). The scales of the y-axis increase across building heights, since taller buildings emit and store more carbon.

In these figures, the positive region of the y-axis represents all GHG emissions emitted during each lifetime of MT, starting from the first life in a building and ending with either the reuse, recycle, incinerate or landfill EOL scenario. The first life emissions (shown in red) correspond to the GWP impact of the entire building, rather than just the GWP of the CLT and glulam. This allows for a comprehensive analysis that is more representative of all the emissions associated with building with structural mass timbers. The emissions from other EOL scenarios are also located in the positive region of the graphs, shown in orange, yellow, pink, and brown.

On the negative side of the y-axis, the GWMP is shown as the carbon storage benefit of each application of MT. In the first life in a building, the benefit of temporal carbon storage (i.e., delayed emissions and the corresponding $CO_2e$) is shown in dark green. The other EOL scenario GWMPs are shown on the negative y-axis as well, shown in dark blue, light blue, and light green. Since a portion of the MT was incinerated, biogenic ‘carbon storage loss’ after building demolition at year 80 is also factored in the analysis. The total $CO_2e$ storage in the building during the first lifetime is shown as a horizontal line.

## Pacific Northwest Buildings

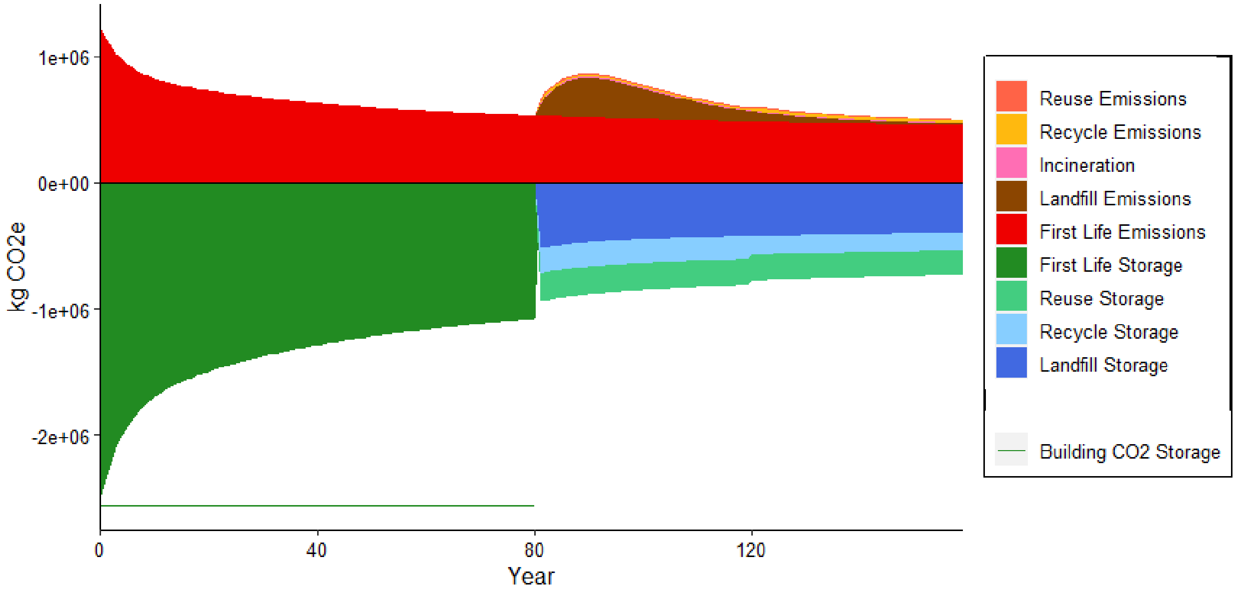

**Figure 10**. Emission profile of the 8-story PNW building in Case 1.

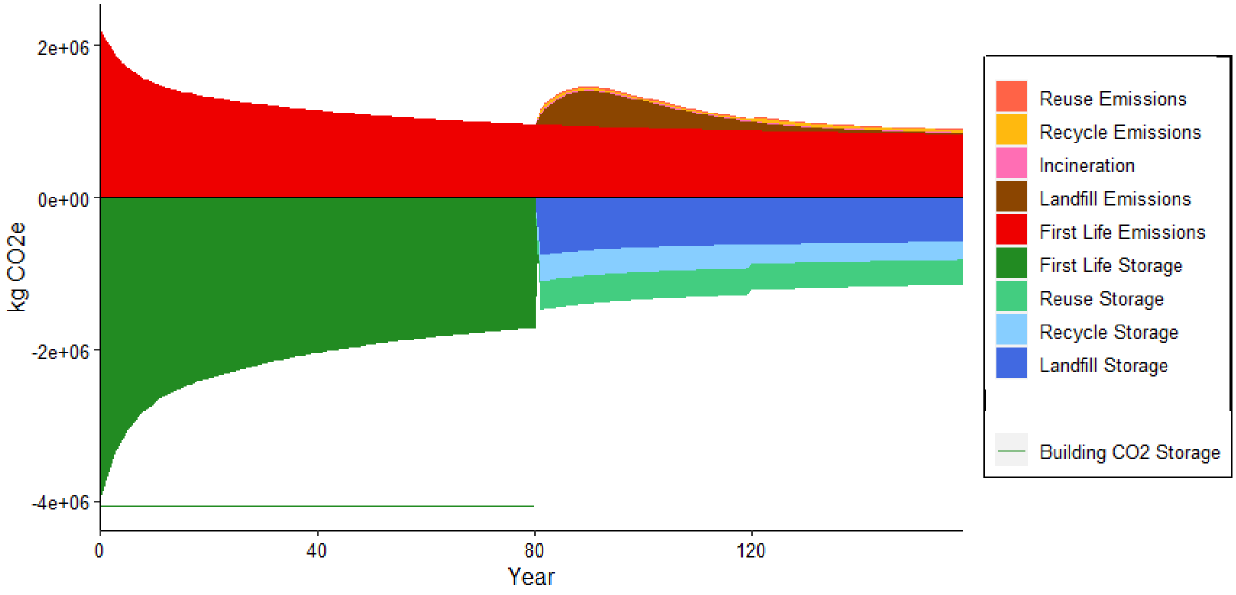

**Figure 11**. Emission profile of the 12-story PNW building in Case 1.

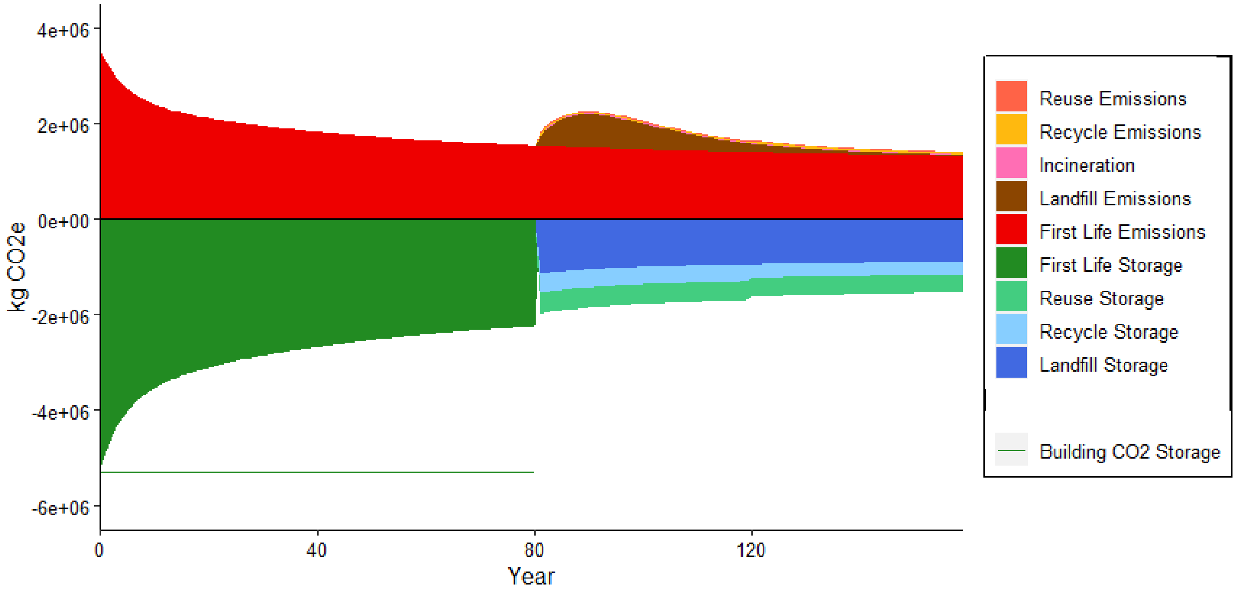

**Figure 12**. Emission profile of the 18-story PNW building in Case 1.

## Northeast Buildings

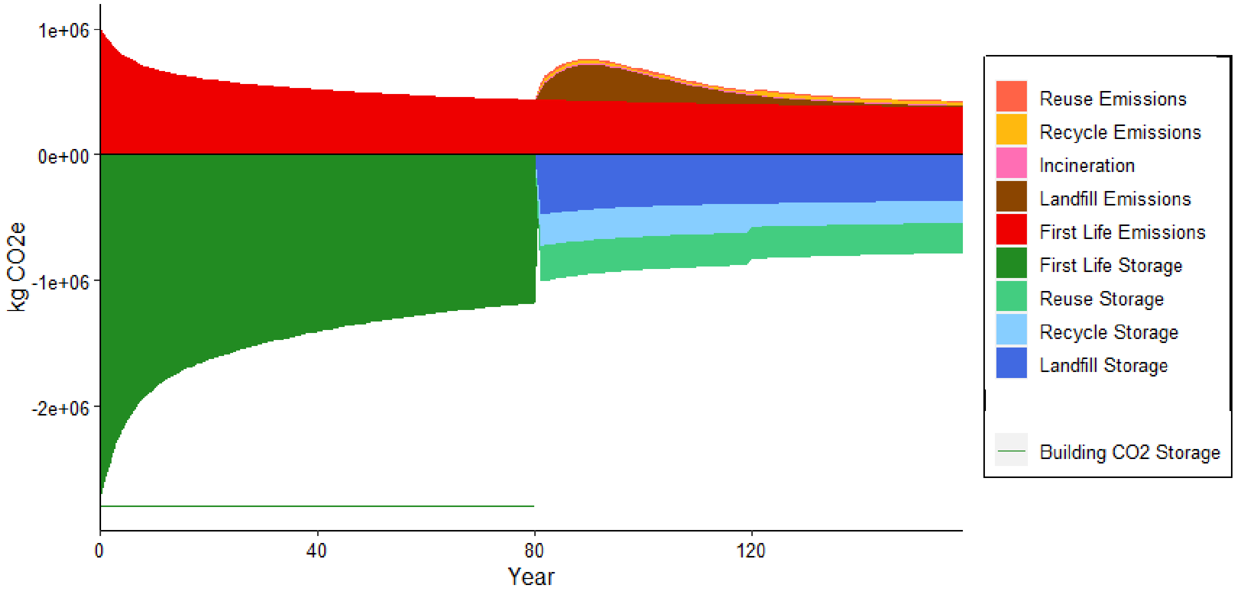

**Figure 13**. Emission profile of the 8-story NE building in Case 1.

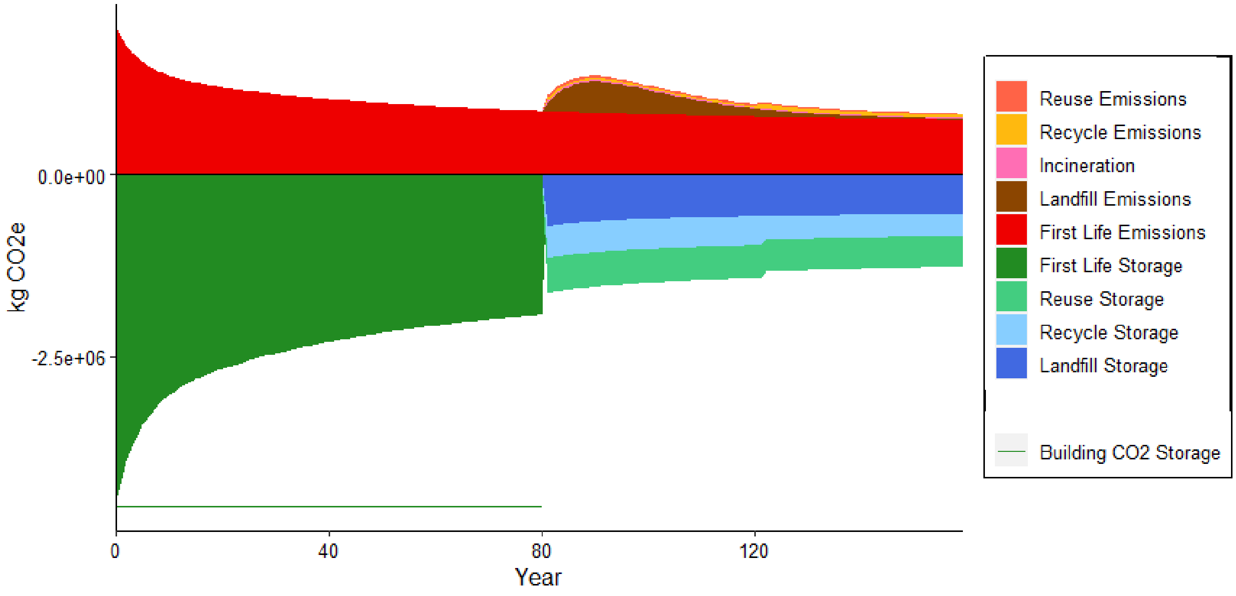

**Figure 14.** Emission profile of the 12-story NE building in Case 1.

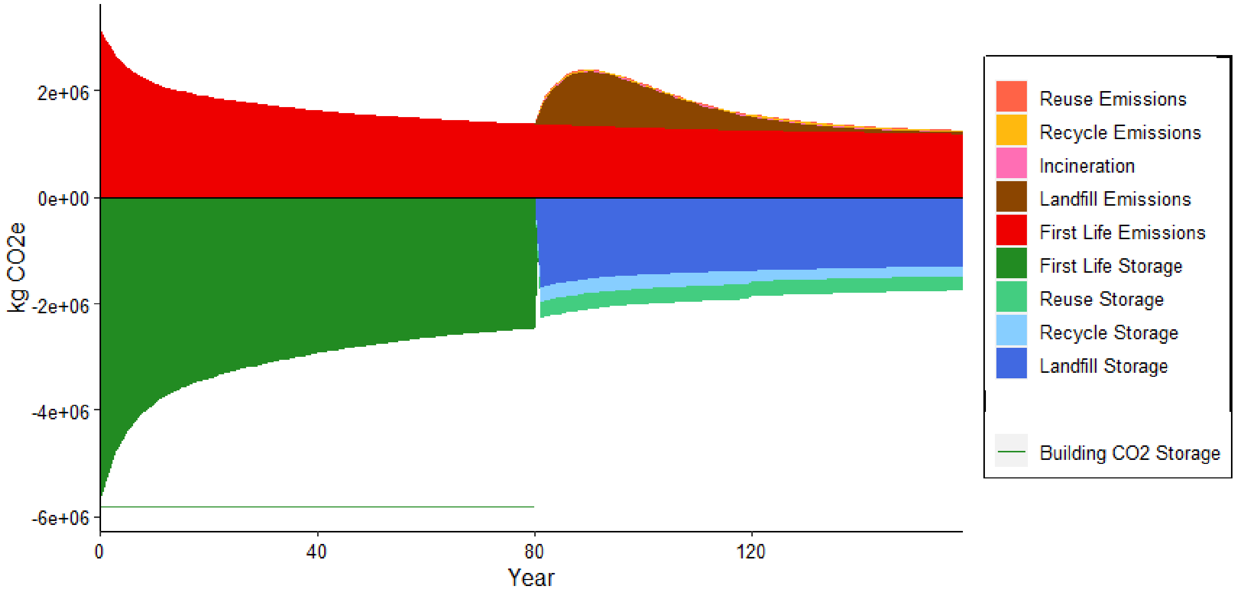

**Figure 15**. Emission profile of the 18-story NE building in Case 1.

## Southeast Buildings

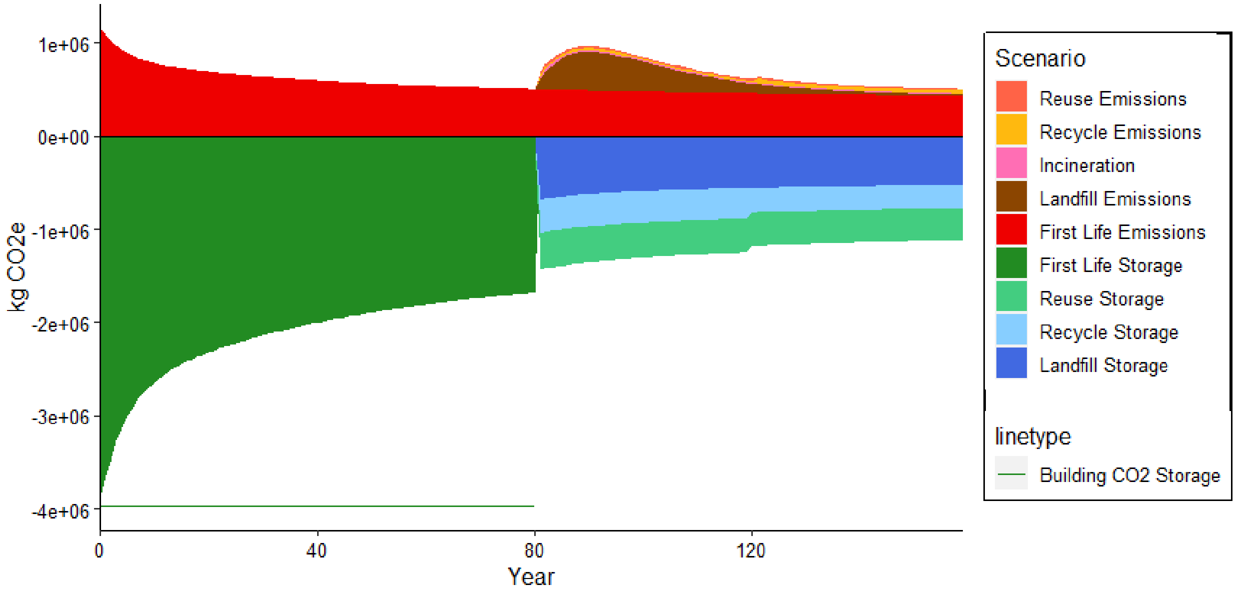

**Figure 16**. Emission profile of the 8-story SE building in Case 1.

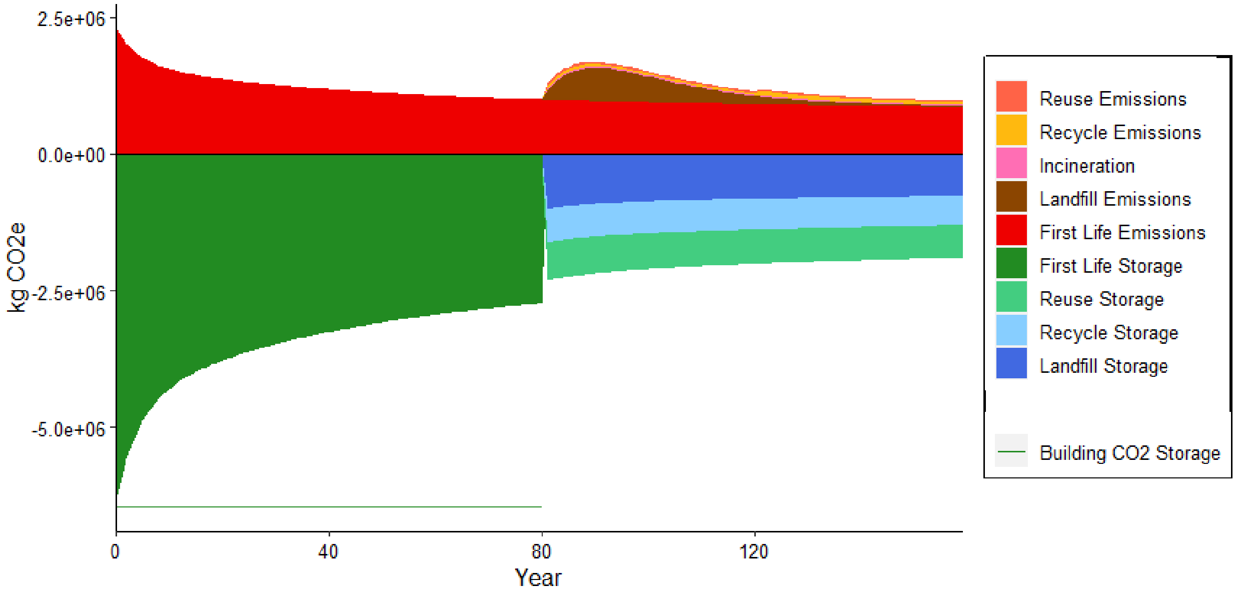

**Figure 17**. Emission profile of the 12-story SE building in Case 1.

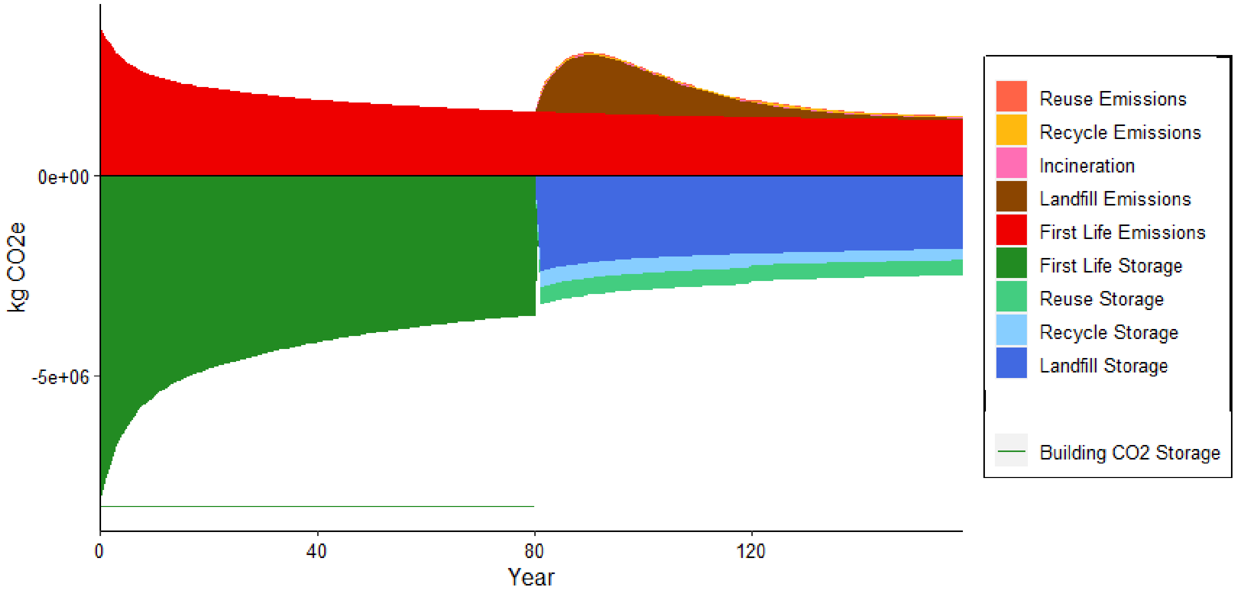

**Figure 18.** Emission profile of the 18-story SE building in Case 1.

### *3. Case 2*

Similar to Case 1, the emission profiles for Case 2 are grouped by region (Figures 19 – 27). Given that Case 2 diverts half the amount of demolition MT to the landfill as compared to Case 1, the emission impacts from other EOL scenarios are more visible on most of these profiles, since more MT is being allocated to the other EOLs. Additionally, since no MT was incinerated in this case, there is less biogenic carbon lost after building demolition.

**Pacific Northwest Buildings**

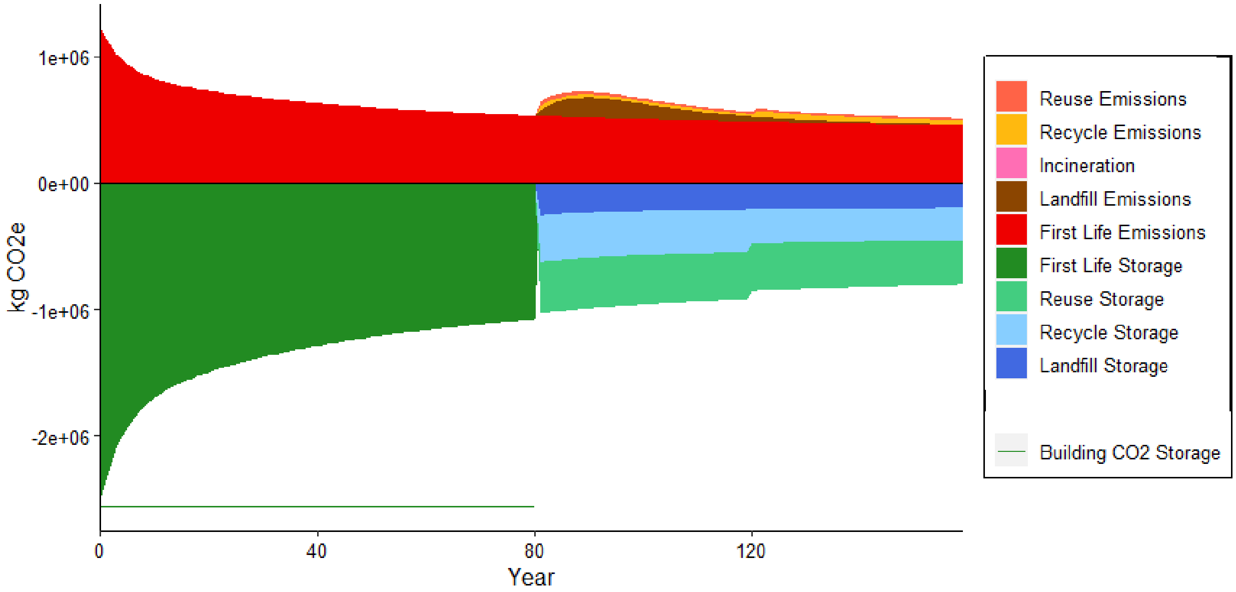

**Figure 19.** Emission profile of the 8-story PNW building in Case 2.

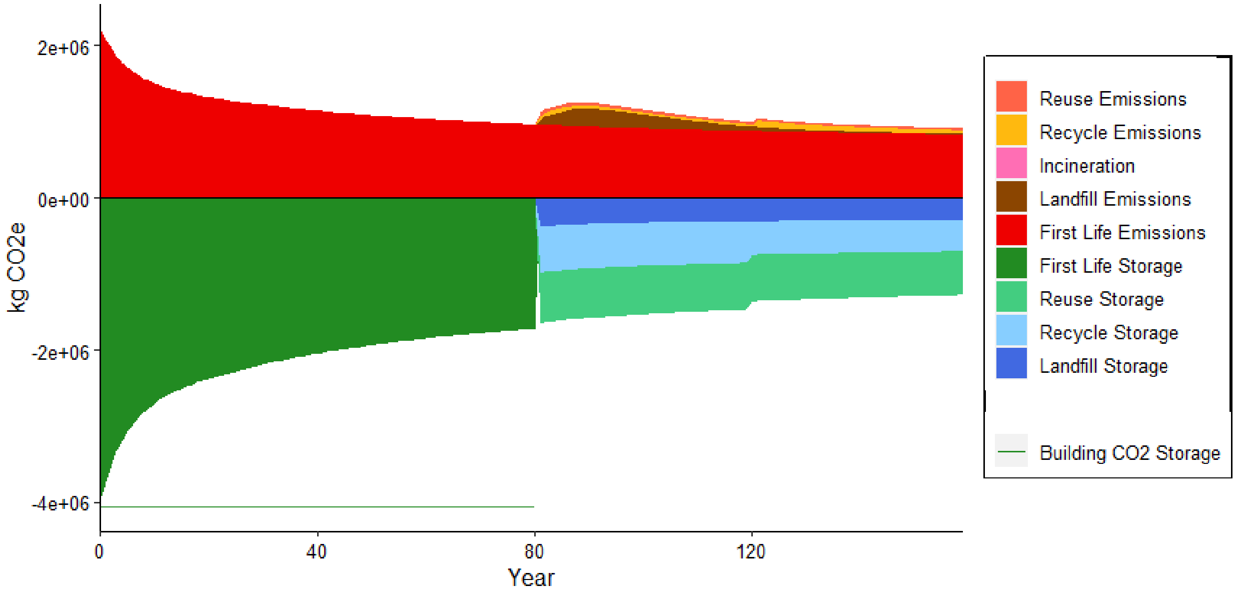

**Figure 20.** Emission profile of the 12-story PNW building in Case 2.

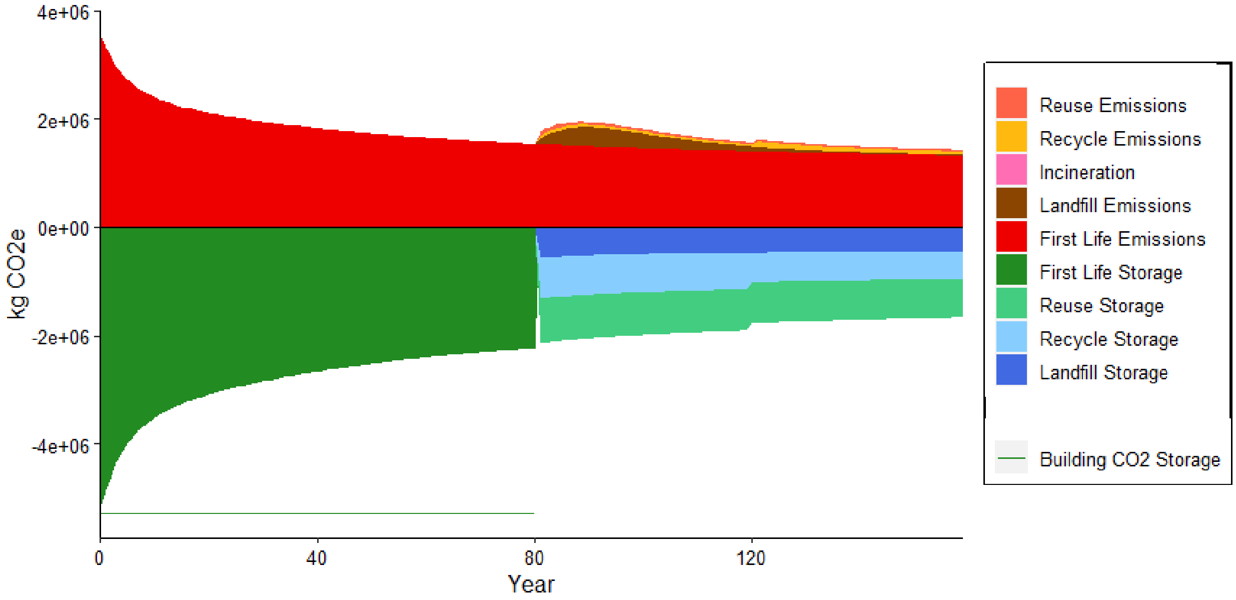

**Figure 21.** Emission profile of the 18-story PNW building in Case 2.

## Northeast Buildings

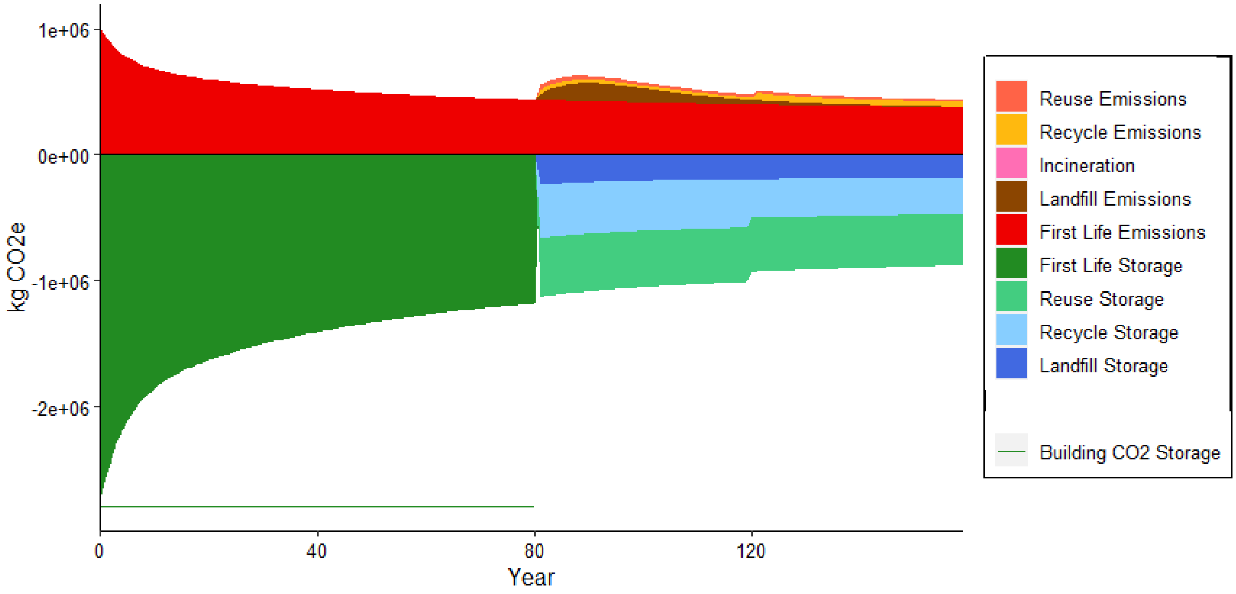

**Figure 22.** Emission profile of the 8-story NE building in Case 2.

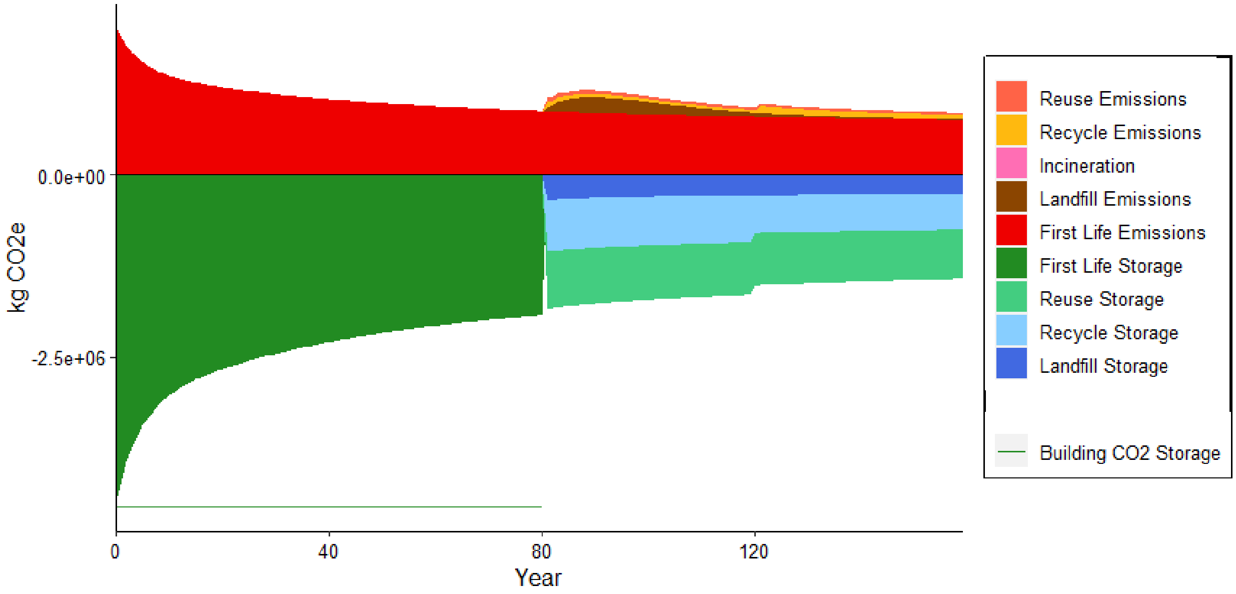

**Figure 23.** Emission profile of the 12-story NE building in Case 2.

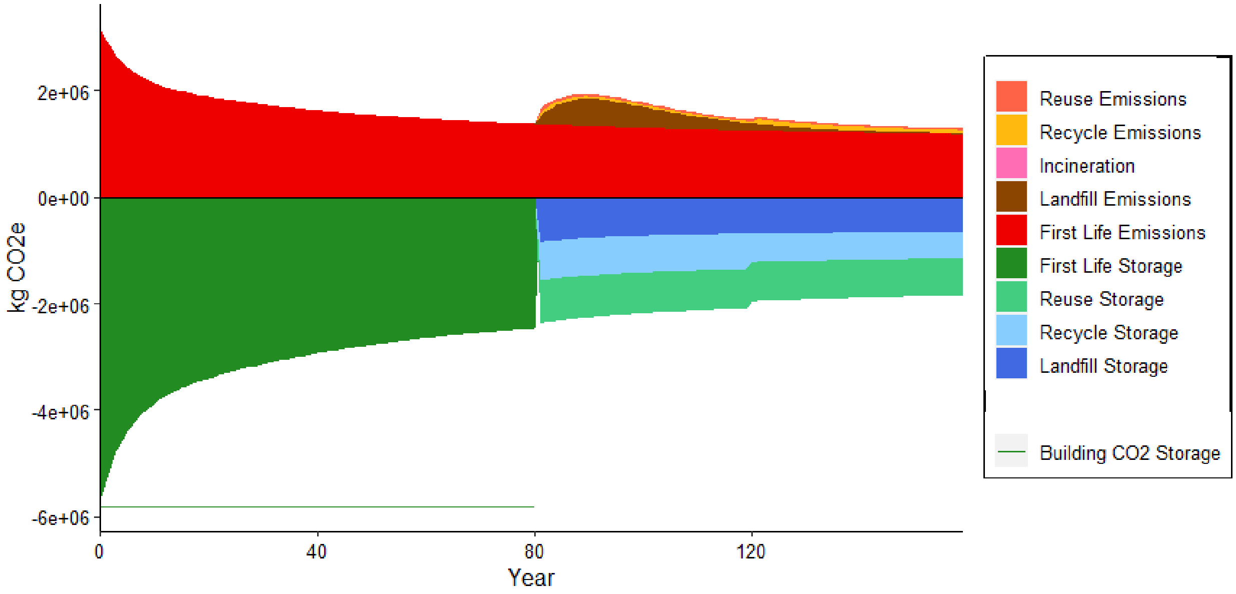

**Figure 24**. Emission profile of the 18-story NE building in Case 2.

## Southeast Buildings

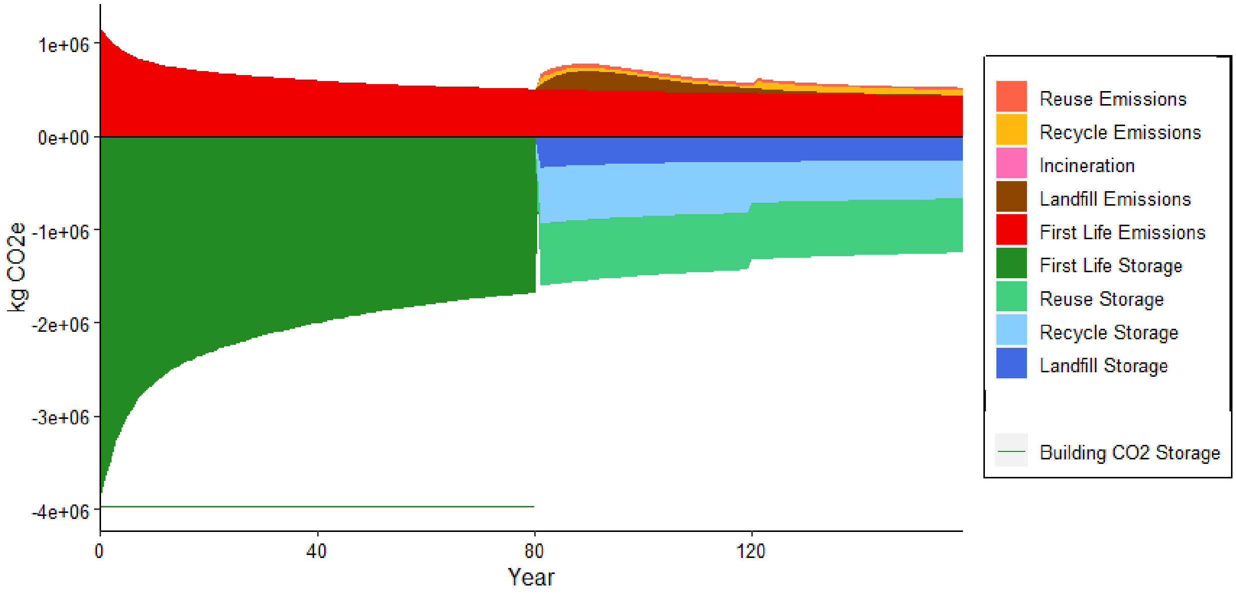

**Figure 25.** Emission profile of the 8-story SE building in Case 2.

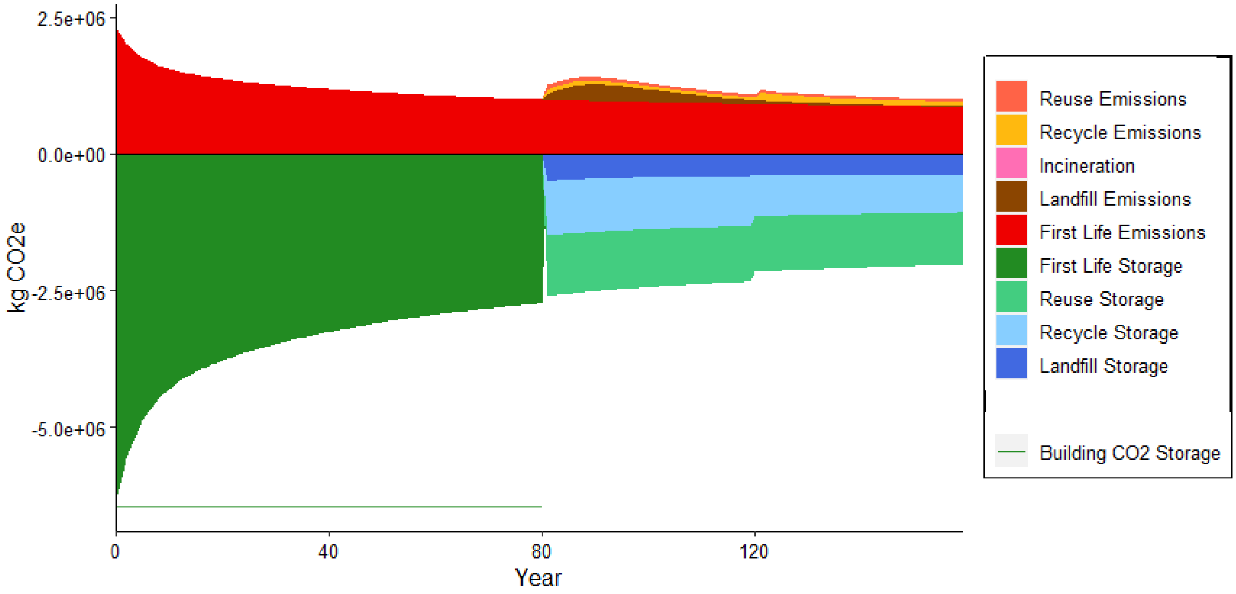

**Figure 26.** Emission profile of the 12-story SE building in Case 2.

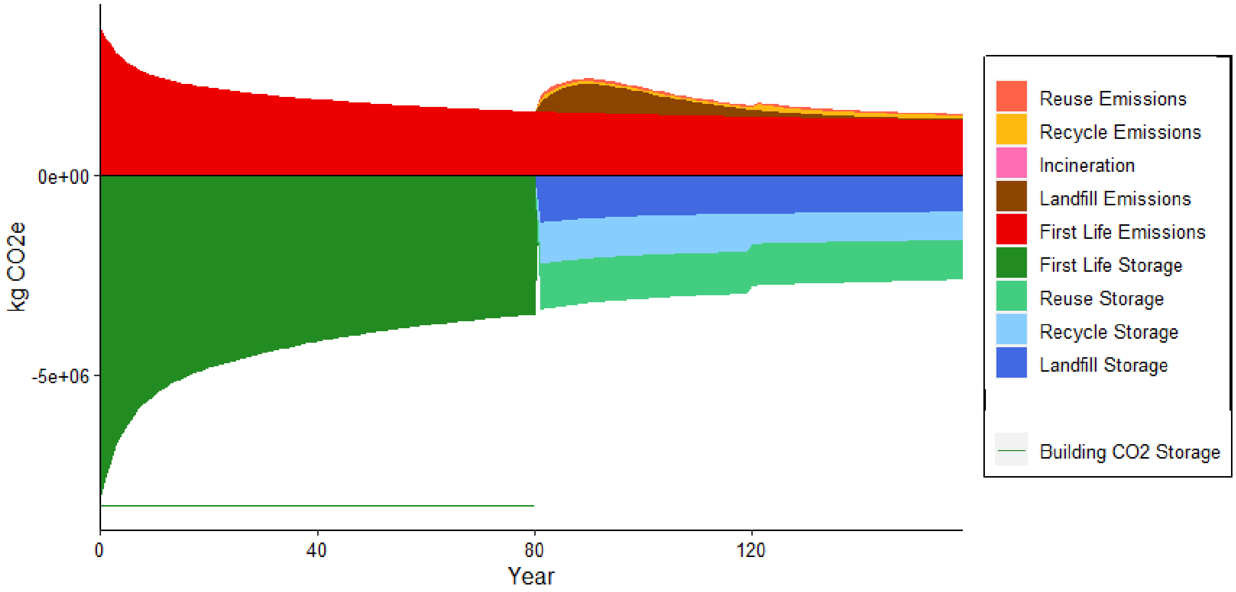

**Figure 27.** Emission profile of the 18-story SE building in Case 2.

### *4. Case Comparison*

To gain a clearer understanding of the differences in GWP and GWMP in each building, the cumulative impacts for each building in Cases 1 and 2 are shown side-by-side (Figure 37). The y-axis scale for this graph is similar to those of the previous emission profiles. Typically, if the portion in green (GWMP) is larger than the portion in red (GWP), this indicates that Case 1's allocation of demolition mass timber after the first life in a building provides a net benefit to the climate. Larger differences between GWP and GWMP suggest greater climate benefits.

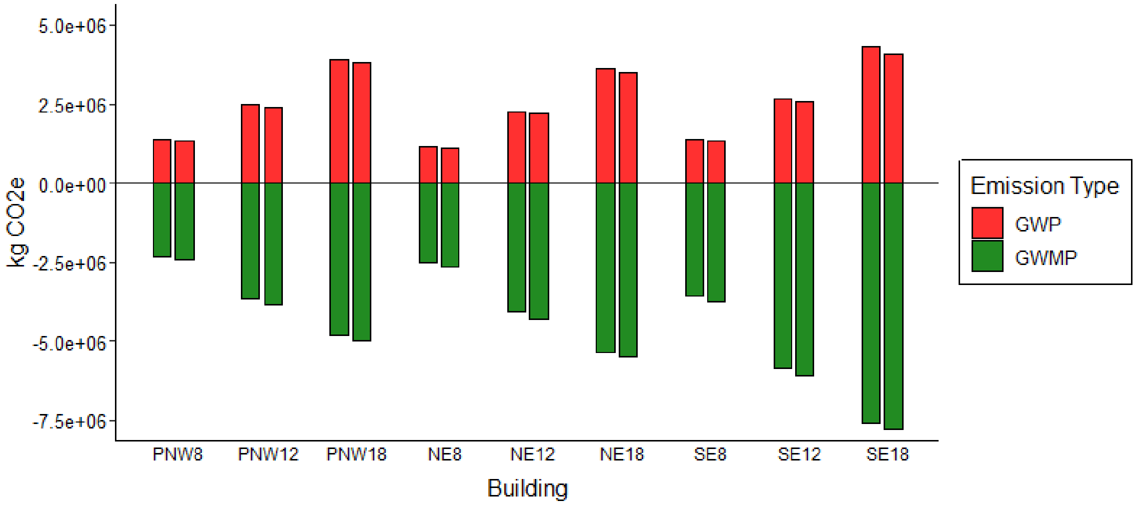

**Figure 28.** GWP and GWMP impacts for each building in Cases 1 and 2. In each cluster of two bars per building, Case 1 is the leftmost bar and Case 2 is the rightmost bar.

The net impact for each building was calculated by averaging the values for the positive emissions and summing it with the averaged values of negative emissions (Figure 38). The net impact of each building per $m^2$ was calculated by dividing the results from Figure 38 by each building's respective floor area (Figure 39). A negative net impact suggests that the total climate benefits of storing carbon in the building outweighed the climate impact of GHG emissions over the 160 years of this study. More negative net impacts indicate a greater difference between the GWP and GWMP of a building (i.e., better benefits to the climate). Lastly, the GWP and GWMP impacts per m$^2$ of each building in the first lifetime are presented (note that the GWMP in this figure is shown as positive) (Figure 40).

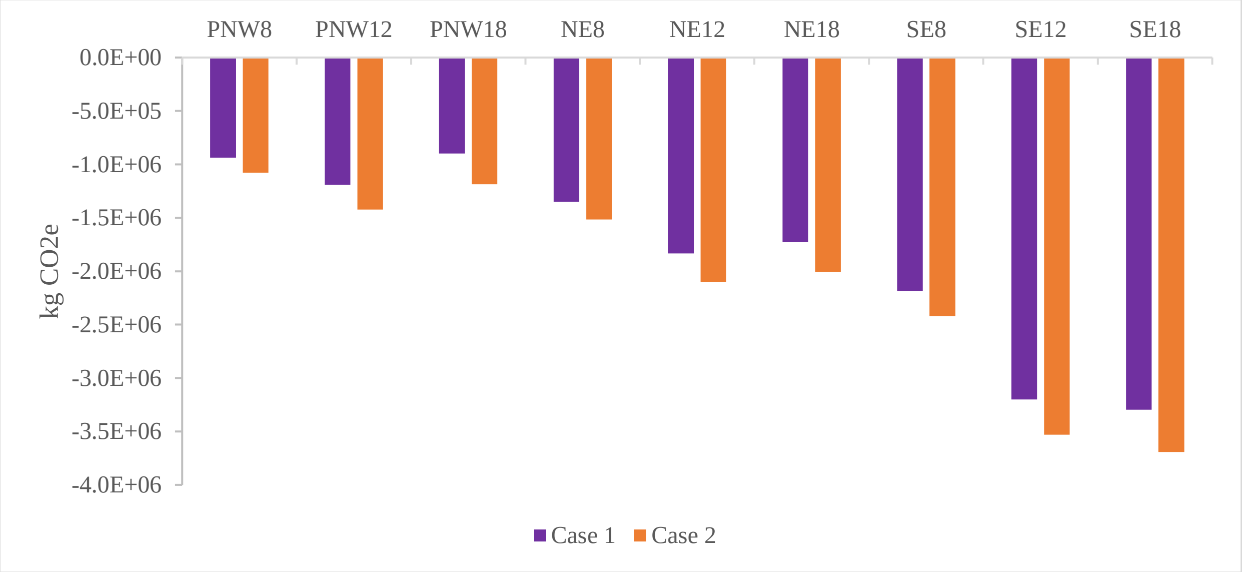

**Figure 29.** Net impact of each building in Cases 1 and 2.

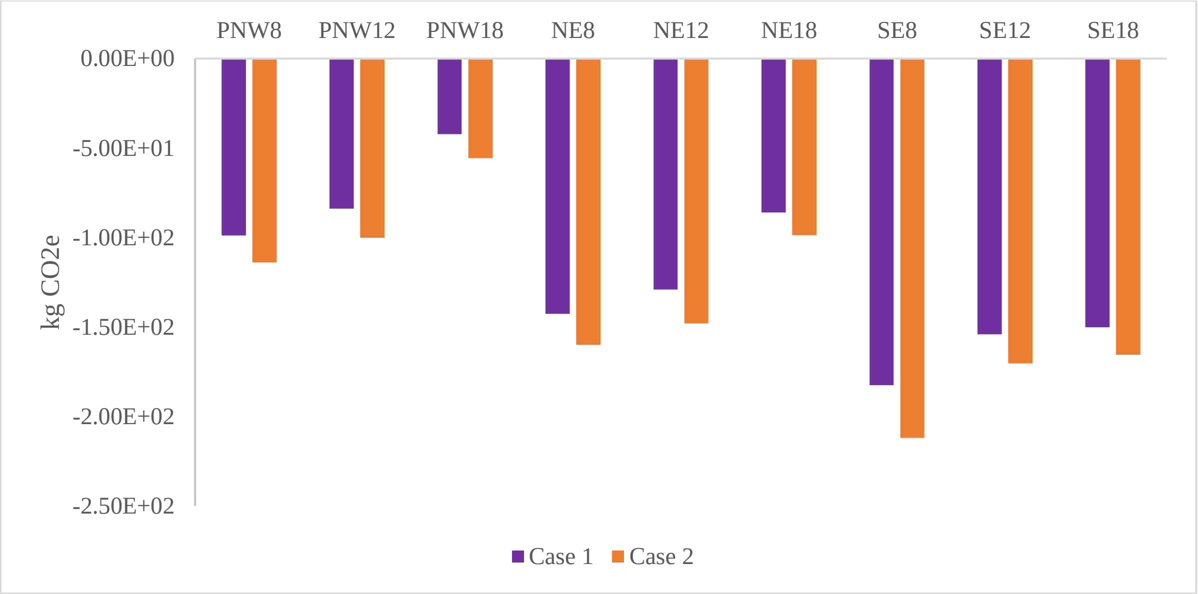

**Figure 30**. Net impact of each building per $m^2$ in Cases 1 and 2.

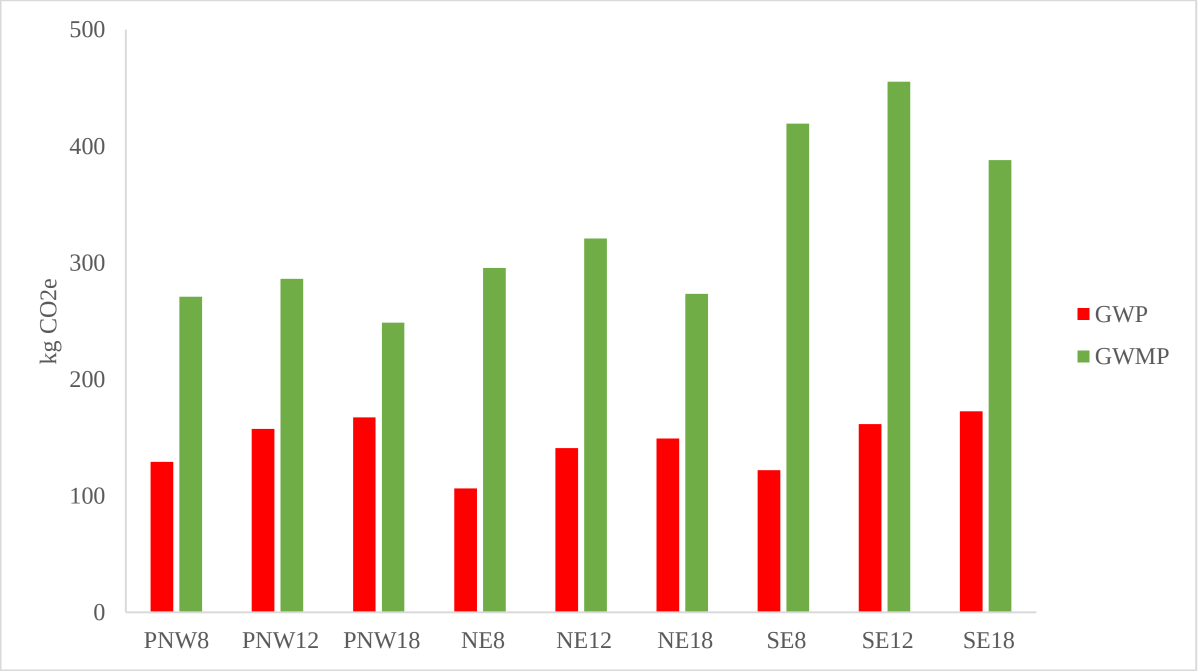

**Figure 31.** GWP and GWMP of each building per $m^2$. GWMP is shown as positive rather than negative for easy side-by-side comparison to GWP.

## C. Substitution Effects

### *1. First Lifetime*

The DFs for MT in buildings vary across regions and building types (Table 3; Figure 41). In the table, the equation is set up in the rows, where the “Timber” row can be subtracted from the “Concrete” row, and the result can be divided by the “WU” (wood use) row to provide the DF. Figure 41 shows a graphical representation of the DFs for easier comparison across different regions. Higher DFs indicate that wood is being used more efficiently in terms of GHG reductions.

**Table 3**. DFs for the 8, 12, and 18-story buildings in the PNW, NE, and SE.

| | **PNW** | | | **NE** | | | **SE** | | |
|---|---|---|---|---|---|---|---|---|---|
| **GHG (kg $CO_2e/m^2$)** | *8-Story* | *12-Story* | *18-Story* | *8-Story* | *12-Story* | *18-Story* | *8-Story* | *12-Story* | *18-Story* |
| Concrete | 226.03 | 281.44 | 238.87 | 213.76 | 267.04 | 207.39 | 202.75 | 253.50 | 220.86 |
| Timber | 129.07 | 157.32 | 167.34 | 106.35 | 141.00 | 149.07 | 121.93 | 161.55 | 172.38 |
| **WU (kg $CO_2e/m^2$)** | 270.69 | 286.12 | 248.55 | 295.48 | 320.70 | 273.32 | 419.39 | 455.18 | 387.94 |
| **DF** | 0.36 | 0.43 | 0.29 | 0.36 | 0.39 | 0.21 | 0.19 | 0.20 | 0.12 |

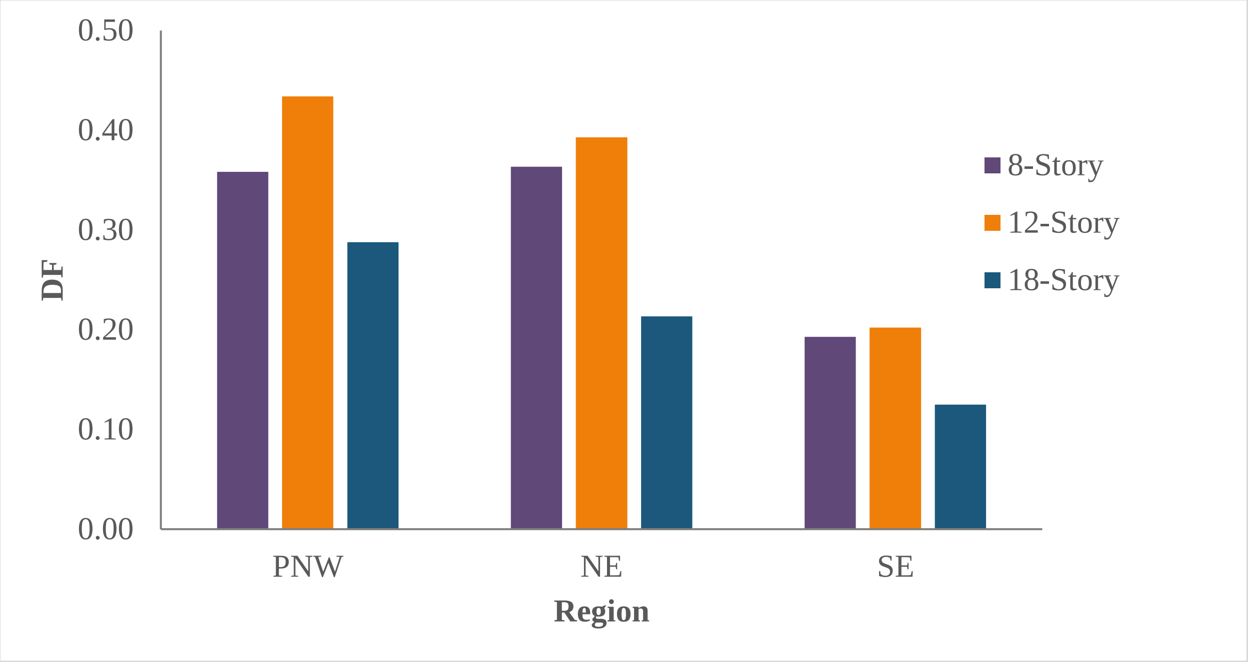

**Figure 32**. Graphical representation of the building DFs.

The analysis of the DFs of individual building elements revealed trends where the use of mass timbers was most effective at displacing GHG emissions (Table 4; Figure 42). Note that some building elements have negative DFs which indicates that substituting concrete with mass timber increased the GWP of the element (i.e., more GHG emissions occurred when mass timber was used than when concrete was used in that element).

**Table 4.** DFs of individual building elements for the 8, 12, and 18-story buildings in the PNW, NE, and SE.

| | **PNW** | | | **NE** | | | **SE** | | |
|---|---|---|---|---|---|---|---|---|---|
| | *8-Story* | *12-Story* | *18-Story* | *8-Story* | *12-Story* | *18-Story* | *8-Story* | *12-Story* | *18-Story* |
| **Columns** | 0.03 | 0.22 | 0.19 | 0.13 | 0.34 | 0.36 | 0.04 | 0.18 | 0.30 |
| **Walls** | 0.61 | 0.56 | -0.69 | 0.34 | 0.25 | -0.41 | 0.09 | 0.04 | -0.41 |
| **Floors** | 0.53 | 0.60 | 0.53 | 0.55 | 0.62 | 0.51 | 0.33 | 0.35 | 0.32 |

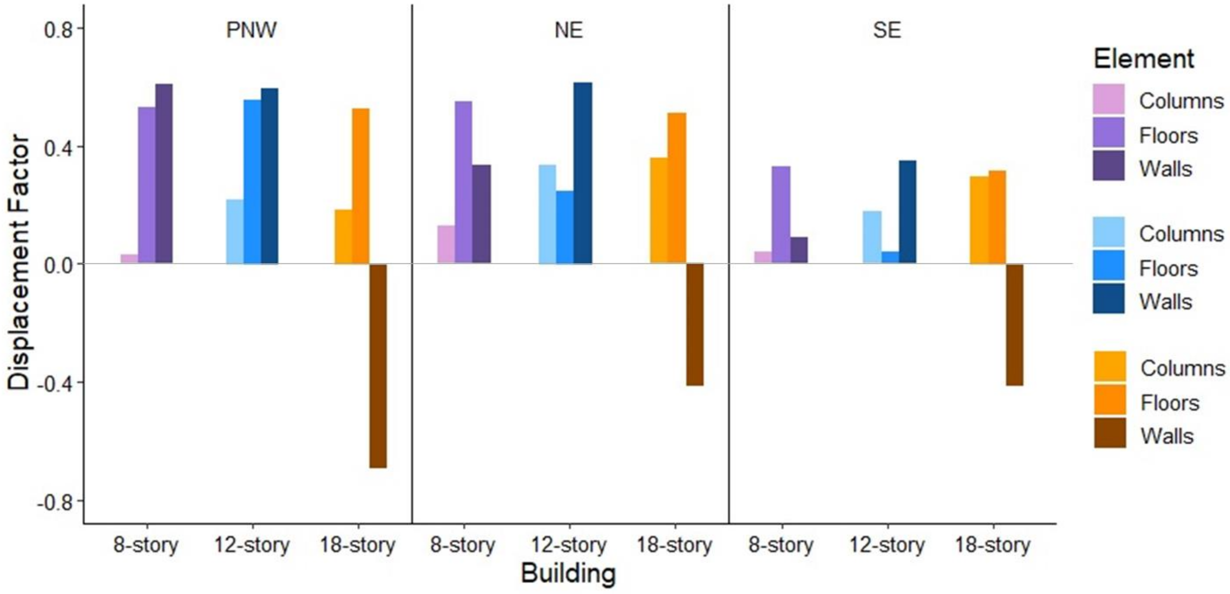

**Figure 33.** Graphical representation of the building element DFs.

### 2. *Second Lifetime*

The DFs from previous studies for the EOL products are presented in Table 5. The DFs for these scenarios are higher than the DFs calculated for the case study buildings. It should be noted that in these studies, the DFs represent the displacement of a single unit of non-wood material per unit of glulam or CLT, rather than the displacement of all non-wood materials in an entire building.

**Table 5.** Displacement factors of the EOL scenarios.

| **EOL Scenario** | **Displacement Factor** | **Source** | **Notes** |
|---|---|---|---|
| Reuse | 0.58 | Suter et al., 2017 | Glulam replacing steel |
|  | 0.8 | Dodoo et al., 2019 | CLT, lumber, glulam, and plywood (replacement not specified) |

|  |  |  |  |
|---|---|---|---|
|  | 1.3 | Knauf et al., 2015 | Softwood based glued timber products (glulam, CLT) replacing steel, concrete, bricks |
|  | 1.3 | Fruehwald et al., 2014 | Glulam and CLT (replacement not specified) |
| Recycle | 0.41 | Suter et al., 2017 | Particleboard replacing glass |
|  | 1.10 | Knauf et al., 2015 | Wood-based panels like particleboard, MDF, and OSB (for walls, ceilings, and roofs) replacing gypsum board, plaster, concrete, and brick type walls |
| Incinerate | 0.62 | Lippke and Puettmann, 2013 | Recovered CDM replacing natural gas |
|  | 2.1 | Dodoo et al., 2019 | CLT, lumber, glulam, and plywood replacing fossil gas |
|  | 3.2 | Dodoo et al., 2019 | CLT, lumber, glulam, and plywood replacing fossil coal |
| Landfill | 1.4 | Dodoo et al., 2019 | CLT, lumber, glulam, and plywood replacing fossil gas |
|  | 2.4 | Dodoo et al., 2019 | CLT, lumber, glulam, and plywood replacing fossil coal |

# IV. Discussion

## A. Emission Profiles

As demonstrated in Figure 9, reuse provided the best net climate impacts of the four EOL scenarios. Recycling provided the second-best impact, followed by landfilling and incineration. The net impact of recycling is marginally better than that of landfilling (a difference of 0.02 kg $CO_2e$ per kg CLT), but refining the model to better match real-world practices for the second instance of recycling may change this. For example, modeling the incineration impacts of 20% of the particleboard created would lower the net impacts of recycling, but modeling landfilling in addition to incineration for the 20% of particleboard might raise the net impacts. However, in this model, the recycling impacts are roughly the same as the landfilling impacts.

Incineration was the only scenario that provided no global warming mitigation benefit. Incinerating MT at the end of MT's first life decreased the total pool of stored carbon, an effect which can be seen in the gap between the areas of first life storage and EOL storage. Additionally, incinerating some of the particleboard created in the recycling scenario at year 120 resulted in more losses in stored carbon. As such, prioritizing reuse for demolition MT and avoiding incineration produced better net climate impacts.

One of the most noticeable differences between the emission profiles of Case 1 compared to the other two cases is the lack of visibility of EOL emission impacts other than landfilling in Case 1. This is caused by the larger allocation of MT to the landfill in Case 1, where the proportion of demolition MT sent to the landfill was much higher than in the other three scenarios. Consequently, the GWMP impacts from reuse and recycle were too small to be distinguishable at the large scale of emissions provided by the first life and landfilling, since landfilling had the highest positive emissions across all EOL scenarios.

When comparing the EOL emission profiles to determine the differences in GWP and GWMP, the GWP impacts for the reuse, recycle, and incinerate scenarios are quite similar (0.066, 0.066, and 0.079 kg $CO_2$e/kg MT, respectively). Landfill GWP impacts, however, are roughly twice as high, which may be a result of the type of emissions generated. Fossil $CO_2$ is the main type of emission for reuse and recycling, $N_2O$ is the main emission for incineration, and $CH_4$ is the primary emission for landfilling. Given the higher radiative efficiency of $CH_4$ as compared to $CO_2$, this is likely a contributing factor to the markedly higher GWP impacts for landfilling on the emission profiles (both in the individual EOL scenarios profiles, and the building profiles).

$N_2O$ has a higher RE than $CH_4$, but the amount of $N_2O$ emissions is negligible compared to the amount of $CH_4$ emissions. Thus, the GWP impacts for reuse, recycle, and incinerate were on too small of a scale to appear clearly on the profiles.

In all nine buildings across the two cases, the negative portions of the graphs were larger than the positive portions: that is, the total benefits to the climate from building with mass timbers outweighed the total global warming impacts from GHG emissions. This makes the mass timber buildings a net sink for carbon during the building's functional life and the second life of its mass timber products. Extending the lifetime of wood products by reusing or recycling them after building demolition allows the wood to mitigate the building's embodied emissions at a larger magnitude than if the wood were burned or landfilled.

In the PNW and NE, the net climate impacts decreased between the 8 and 12-story buildings, but increased for the 18-story building in both cases (Figure 37). This trend is best explained by examining what is occurring on a unit-basis instead of a whole-building basis. When scaling the impacts down to a $m^2$ of each building, the net impacts become less negative (i.e., worse for the climate) with increasing building height (Figure 39). Even though the 18-story buildings contain more mass timbers (and thus, more stored carbon) than the 8 or 12-story buildings, the amount of biogenic carbon stored does not increase proportionally across the three building heights per $m^2$, despite a consistent increase in embodied carbon (Figure 40). In all three regions, the 18-story building contains the *least* amount of biogenic carbon storage per $m^2$ out of the three building heights, in addition to having the most embodied carbon. This is because the building design changes as the height increases: the quantity of MT changes disproportionally relative to the quantity of other materials. In other words, the "rate" of MT use does not increase as much as the "rate" of other material use across the three buildings, which is shown by the trend of decreasing stored carbon per $m^2$ between the 12 and 18-story buildings. Coupling this “unit effect” of decreasing stored carbon with higher embodied carbon results in a climate disadvantage for taller wood buildings compared to shorter ones, particularly if not enough MT is used.

In Figure 38, the only region that did not follow the trend of decreasing whole building net climate benefits between the 12-story and 18-story buildings was the SE. This 18-story building had lower (i.e., better) net benefits than both the 8 and 12-story buildings. This may be due to the density of the wood species used in the SE: the Southern yellow pine used had a density of 510 $kg/m^3$, as compared to the 434 and 466 $kg/m^3$ of the NE and PNW, respectively. As such, the SE 18-story building had *more* carbon stored per $m^2$ of building compared to 18-story buildings in the other regions. This meant that there was a greater potential for carbon storage benefits in the second lifetime. This effect of second lifetime benefits outweighed the “unit effect” of decreasing embodied carbon per $m^2$, thanks to the sheer amount of carbon stored in the SE 18-story building. Indeed, the net impacts per $m^2$ of building in the SE 18-story building were relatively similar to those of the SE 12-story building, a trend not seen in the other regions. This implies that at a certain point, the density of the wood used can push the net climate impacts of a taller building past those of a shorter building. The effect of density also manifests in the trend of better net climate impacts across regions, with the smallest negative impacts occurring in the PNW buildings, and the largest occurring in the SE buildings (Figure 38).

Of the two cases, the buildings in Case 1 had the smallest net negative impacts (i.e., the worst benefits to the climate). This can be attributed to the high proportion of demolition MT allocated to the landfill and incineration relative to the other two cases. Landfilling provided worse net climate benefits than reuse and recycling, while incineration provided an increase in GWP but no benefits from storage. Given that Case 2 allocated half the landfilled MT and all of the incinerated MT to the reuse and recycle scenarios, this case had the best net climate impacts, suggesting that circulating waste MT in the bioeconomy after the first lifetime results in two main benefits: sustainably increasing the wood supply and maximizing climate change mitigation.

Using the standard 100-year GWMP metric may be overestimating the climate impacts of biogenic carbon storage in mass timber products in the short term. Many government entities, industries, and organizations have set emission targets over the next few decades, resulting in carbon neutrality by 2050. Some of these approaches include increasing biogenic carbon storage to cancel out emissions and reach net carbon neutrality, and the common accounting approach is the 100-year GWMP. However, given the demonstrated overestimation of this metric compared to a metric on a longer time horizon, using it may lead to false carbon neutrality if the amount of estimated biogenic carbon storage is less than what is occurring. Adopting a longer time horizon in future studies is critical to properly assess the climate change mitigation potential of mass timber products.

One additional limitation to considering a 100-year metric instead of a 160-year or even a 500-year metric is that it captures less of the whole climate impact since some of the GHGs considered in this study have longer lifespans than the selected time horizon. However, if the time horizon were extended out to 500 years, it would be appropriate to also add in more lifetimes for mass timber instead of only considering two. It is estimated that wood products can be recycled up to three times before the decreasing particle size prevents further recycling, and recycling scenarios could apply to reused mass timber (Höglmeier et al., 2013; Jarre et al., 2020; Campbell, 2018). Carrying out such an approach in future research would improve the accuracy of the climate impact estimations of the reuse and recycle scenarios.

Future research may benefit from adopting a cascading recycling approach to the reuse and recycle treatments, where the products of these scenarios would be recycled at the end of their respective lifetimes up to three times. With this approach, a 500-year time horizon would be more appropriate than the 160-year time horizon considered in this study. Though complex, such an approach would help accurately quantify the carbon storage benefits associated with increasing our available wood supply by maximizing the efficient use of wood products.

The trends of low GWP and high GWMP for reused MT as demonstrated in the individual EOL emission profiles and the differences between Cases 1 and 2 suggest that reusing demolition MT will provide the best carbon benefits in the second lifetime. Extending the scope of the analysis to match the atmospheric lifespan of longer-lived GHGs could strengthen this conclusion in future research. However, another key carbon benefit can be considered alongside the emission profile impacts to strengthen this analysis under the current scope: the substitution effects.

## B. Substitution Effects

### *1. First Lifetime*

#### a) Regional Differences

The buildings in the PNW and NE have notably higher whole building DFs than buildings in the SE, which can be attributed to differences in the density of wood species used in the mass timbers. In the PNW, Douglas fir and western hemlock lumber had a density of 467 kg/m$^3$; in the NE, Eastern spruce and white pine had a density of 434 kg/m$^3$; in the SE, Southern pine had a density of 510 kg/m$^3$. With a higher density species, CLT and glulam are using more wood to achieve similar GHG reductions, which translates into lower DFs and lower efficiency at displacing GHG emissions.

Given this trend between species density and DFs, the NE buildings should have higher DFs than the PNW buildings, but the PNW had the best performance in DFs across all regions. Since the densities of PNW lumber and NE lumber are quite similar, the difference in DFs might be attributed to differences in the design of the buildings. However, the DF discrepancies are best explained by DF trends for the walls.

### b) Walls

For the 8-story buildings, the difference among whole building DFs can be attributed to the use of CLT in the interior walls. Less CLT was used in the interior wall of the PNW buildings than in the NE buildings, due to seismic requirements of the IBC: all demising walls (walls that separate private tenant space from common spaces or other tenants' spaces) used metal studs in the PNW, while demising walls in other regions used CLT. The reduction in GHG emissions for the interior walls was also much larger in the PNW buildings (22 kg $CO_2e/m^2$ more). Thus, it took less CLT to displace more $CO_2e$, making the CLT in the PNW interior walls more efficient at displacement, and giving the walls a higher DF. Furthermore, the DF for the SE 8-story walls was drastically lower than both the PNW and NE, since the wood density (and therefore wood use) was much higher.

The PNW 12-story building also displaced more GHG emissions in the interior walls when compared to the NE (7 kg $CO_2e/m^2$ more); however, the amount of displacement was less drastic than in the 8-story buildings. The use of less CLT in the interior walls of the 8 and 12-story buildings resulted in higher DFs for the PNW region buildings than the NE buildings, despite the higher density of wood species. The benefit of using less CLT in the walls (as seen in the PNW) had a stronger effect on DF than the benefit of using a lower density species (as seen in the NE). Similar to the trend in the 8-story buildings, the SE 12-story walls DF was extremely low due to a large amount of wood use.

Given this trend of achieving higher DFs with lower CLT use, one might expect to see similar results in the 18-story buildings. However, no CLT was used in the interior walls of the PNW 18-story buildings due to the seismic restrictions, and this element had the lowest DF of all elements and regions. Additionally, the walls of the NE 18-story buildings had negative DFs as well, albeit still higher than that of the PNW 18-story walls. All the walls in 18-story buildings were negative because of several factors specific to each region.

In the NE and SE, the use of CLT in the interior walls *increased* GHG emissions compared to the concrete building interior walls. The GWPs of MT interior walls in the NE and SE were higher than those of their concrete counterparts because the use of CLT did not displace concrete- more concrete was used in the MT interior walls because IBC codes require that wood in walls of 18-story buildings must not be visible. While less rebar and insulation were used in the MT buildings, more steel for brace framing and gypsum wallboard was used. Ultimately, not enough materials were displaced to produce a decrease in GHG emissions, and the increase in concrete use increased GHG emissions. However, this increase was smaller than the increase seen in the PNW 18-story walls.

In the PNW, the design of the 18-story MT building resulted in an increased GWP for the interior walls, despite the lack of use of CLT in that element. Slightly less concrete was used in this element in the MT building than in the concrete building, but more gypsum wallboard was used due to the use of CLT elsewhere in the building. Furthermore, the amount of concrete used was higher than in the NE buildings, which explains the higher GHG emissions for the PNW walls. Since the DFs of the exterior and interior walls were combined into a single DF, the impact of higher GHG emissions in the interior walls was added to the GWP impact of the exterior walls. This impact was divided by the amount of CLT in the exterior walls to produce the DF. Using less CLT to achieve *greater* increases in GHG emissions (as compared to the NE) translates into a more negative DF.

### c) Floors

The floors had consistently high DFs across most regions and building sizes. In this element, the reduction in GHG emissions when comparing the MT buildings to the concrete ones can be explained by the large displacement of concrete. An average of 480 kg of concrete per $m^2$ of building was displaced in the PNW building floors, and despite roughly 77 kg of gypcrete/$m^2$ being added, this produced a large reduction in the floor GWP. Similar quantities of concrete were displaced in the other regions, but since the density of the SE MTs was so high, the SE floors had slightly lower DFs.

### d) Columns

Several trends can be observed in the DFs of the columns. Generally, DFs increased with increasing building height. The DFs of the 8-story building columns are near zero in the PNW and SE, yet are considerably higher in the 12 and 18-story buildings. The amount of glulam used in the columns for each building varied across each region.

In the PNW, glulam use increased with increasing building size, ranging between 50 – 60 kg/$m^2$. In the NE, glulam use was around 38 kg/$m^2$ for all sizes, and in the SE, the quantity used ranged between 48 – 52 kg/m$^2$. The lower use of glulam in the NE is matched by the higher DFs for that region.

A possible explanation for the trend of increasing DFs with greater building heights lies in the amount of glulam required to displace the concrete in the columns. In the 8-story buildings, the glulam-to-concrete ratio is 8:1 – 9:1, while in the 12 and 18-story buildings, the ratio is 2:1 – 3:1 (Droog, 2022). In other words, more glulam is required to replace concrete in smaller buildings. As observed in the architectural drawings of the buildings, the concrete columns have different sizes in each building type: 16” x 16” for the 8-story buildings, and 24” x 24” for the 12 and 18-story buildings. Despite this, the size of the glulam beams used is constant across all building types. Thus, in the 8-story buildings, more glulam was used to displace a smaller volume of concrete, resulting in a lower DF.

### *2. Second Lifetime*

Each EOL scenario had a range of DFs presented in the literature. Though each study used the same calculation for DFs, the material substituted varied, creating a range of DFs related to how much GHG emissions were mitigated in each type of material displaced. The DFs of the wood products in reuse and recycle are compared to one another, while the DFs of bioenergy produced in the incinerate and landfill scenarios were separately compared.

For the reuse scenario, the literature provided a range of 0.58 – 1.3. The lower end of the range represents the substitution of steel, while the upper end represents concrete, brick, and steel. Thus, the higher values may be more representative of the substitution taking place with the reused MT, since in the first lifetime CLT and glulam mostly displaced concrete. The values for recycle were 0.41 – 1.1, a slightly lower range of values than reuse. Given that a different product was created from each scenario (CLT/glulam versus particleboard), the product with a longer lifetime and the ability to substitute for more fossil-fuel intensive materials (CLT) should have a higher DF range, which aligns with this result.

For incineration, the DFs range between 0.62 – 3.2. The upper end of this range is roughly 3 and 2.5 times greater than the upper limits of reuse and recycle, and this may be related to differences in the methodology across different studies. With incineration, one study specified the substitution of CLT/glulam/lumber for fossil gas versus fossil coal (DFs of 2.1 and 3.2, respectively), while one study used a different source material (CDM instead of CLT, with a DF of 0.62). Finally, for landfilling, the range of DFs is 1.4 – 2.4. The scenario in this study had landfilled CLT with gas capture for energy replacing fossil gas and coal.

Comparing the differences in ranges across the scenarios can also be done by comparing results from the same studies. One study provided DFs for reuse and recycle, citing DFs of 1.3 and 1.1, respectively (Knauf et al., 2015). Another study showed DFs of 0.8 for reuse, 2.1 – 3.2 for incinerate, and 1.4 – 2.4 for landfill (Dodoo et al., 2019). This suggests that reusing MT results in better DFs than recycling MT. On the bioenergy side, incineration produces better DFs than landfilling. With landfilling, the energy content of the wood decreases during anaerobic decomposition, as microbes digest the material. Furthermore, only a small proportion of the wood's stored carbon is converted to methane, which is captured for energy or electricity generation (WARM, 2020*a*). Thus, only a small portion of wood's energy potential is used for energy generation in landfilling. On the other hand, incineration consumes all of the wood's chemical energy, and the heat generated is used to produce steam in a boiler for electricity generation (Kaza et al., 2018). This higher consumption of wood's chemical energy may explain why incineration energy is more efficient in displacing fossil fuels.

When comparing the four EOL DFs, the bioenergy scenarios (landfill and incinerate) have much higher DFs than the wood panels scenarios (reuse and recycle). However, in terms of climate change mitigation, the latter scenarios outperform the first two considerably. Furthermore, comparing the DFs of completely different types of wood products depends heavily on the biogenic carbon neutrality assumption which is commonly adopted in LCA. Though this research assumes that all biogenic carbon emitted from MT products is carbon-neutral, there has been debate over the validity of that assumption regarding combustion.

Opponents to the carbon-neutrality assumption argue that the instant release of biogenic carbon through combustion creates a carbon debt, in which the climate warming effects of the immediate emission are not instantly counteracted by forest regrowth (Mather-Gratton et al, 2021; Leturq, 2020; Weiguo et al., 2018; Kendall et al., 2009). Since regrowth is a slow, decades-long process, releasing a pulse emission of a GHG into the atmosphere has radiative forcing effects during the time it takes for the forest to eventually recapture the emission. This is argued to create a carbon debt, in which the balance of climate warming effects from emissions and climate mitigating effects of regrowth is thought to be disrupted by creating extra warming effects that are not mitigated. As such, it may not be prudent to directly compare the substitution effects of bioenergy to those of product and building material substitution, given that this approach may fail to account for the extra warming impacts suggested by the carbon debt. One method to adjust the carbon debt suggests using a carbon-cost curve for bioenergy, in which the marginal costs of increasing bioenergy use are constructed by accounting for all GHG effects (Harbel, 2013). Another suggests adopting a time correction factor into life cycle assessment methodologies, such as a $GWP_{bio}$ factor that corrects the GWP provided by LCAs depending on the amount of time a pulse GHG emission stays in the atmosphere (Cherubini et al., 2011). Adopting one of these approaches may result in more accurate substitution effects for scenarios that combust mass timber.

# V. Conclusions

This research demonstrates that mass timber products are a net carbon sink for buildings, and the climate benefits of long-term carbon storage outweigh the climate warming impacts of GHG emissions embodied in a building. Accounting for the second life of these products in a variety of end-of-life scenarios helps document these storage benefits more accurately. When comparing the benefits and emissions associated with each scenario, reuse produces the best net climate benefits in terms of high biogenic carbon storage, and low embodied greenhouse gas emissions. Recycling had the second-best net climate impact due to the continuation of temporal storage benefits from the second instance of recycling. Landfilling had the next-best net impact due to the high $CH_4$ emission generation, while incineration had the worst net impact since there was no biogenic carbon storage.

End-of-life scenario cases that allocated more mass timber to reuse performed best in terms of net climate benefits over the 160 years of this study. A limitation of this study is that it allocated 80% of the particleboard created from the first instance of recycling to the second instance, and the remaining 20% to incineration. This is a simplifying assumption that is not reflective of real practices since the percentages are arbitrary and some portion of the particleboard may be landfilled. This research will be further developed by adding in a cascading recycling approach that divides particleboard into recycle, incinerate or landfill scenarios after the first life of particleboard (i.e., the second life of MT in the recycle scenario).

Comparing the whole-building net climate impacts to the impacts per $m^2$ of building revealed contradictory trends, in which net impacts were better in taller buildings on a whole-building scale, but worse for taller buildings on a $m^2$ basis, due to the 18-story buildings having the highest embodied carbon and the lowest stored carbon per $m^2$. The uncertainty over where to prioritize mass timber placement based on these trends further emphasizes the importance of reusing mass timber products since this can sustainably supply an increased timber demand, which reduces the need to allocate timber to certain building projects over others based on height. The only building which did not follow the whole building net impact trend was the SE 18-story building, which had better net impacts than the shorter buildings due to the high-density wood allowing for more carbon storage benefits in the second life. However, using more dense MT in buildings to gain more carbon storage benefits may result in increased embodied emissions if the MT has longer transportation distances than local sources.

In the first lifetime, substitution effects for mass timbers were high when used in floors, and better in columns for taller buildings and walls for shorter buildings. Since mass timbers in floors were assumed to be landfilled, however, prioritizing the use of mass timber in floors may inhibit EOL options in the second lifetime. When taking the substitution effects of each scenario into account, reuse outperforms recycling, but scenarios that substitute bioenergy for fossil energy (incinerate or landfill) perform best. However, this approach assumes carbon neutrality for the release of all biogenic carbon into the atmosphere, which has been contested when concerning combustion due to the creation of a carbon debt during the time lag in which forest regrowth recaptures the emissions. As such, the greater substitution effects associated with incineration and landfill may not have an accurate accounting of the climate impacts from combustion, but this could be corrected for in future research with time correction factors or carbon-cost curves. This research quantified the carbon balance for MT products in different EOL scenarios and showed that storage benefits could be maximized by reusing and recycling MT, and substitution benefits could be maximized by landfilling or incinerating MT. Limitations to the methodology of this research should be addressed in future research with the adoption of a cascading recycling approach and adjustments for the carbon debt created by incineration and landfilling.

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# VIII. Appendix I

These tables were provided in the Supplementary Material from Puettmann et al., 2021.

**Supplementary 2 (S2)—Bill of Materials**

**Table S4.** Whole-building bill of materials, PNW.

| | | | 8-Story | | 12-Story | | 18-Story | |
|---|---|---|---|---|---|---|---|---|
| **Assembly** | **Material: Name** | **Unit** | **Timber** | **Concrete** | **Timber** | **Concrete** | **Timber** | **Concrete** |
| Columns and Beams | Concrete | m$^3$ | — | 93 | — | 385 | — | 586 |
| | Glulam | m$^3$ | 859 | — | 1376 | — | 2265 | — |
| | Rebar | kg | — | 59,392 | — | 139,608 | — | 285,609 |
| Exterior Walls | Aluminum stud | kg | — | 740 | — | 1562 | — | 2411 |
| | CLT | m$^3$ | 172 | — | 365 | — | 564 | — |
| | 3–5/8" fiberglass mat | m$^2$ | — | 1638 | — | 3479 | — | 5387 |
| | 5/8" gypsum board | m$^2$ | 1638 | 1638 | 3479 | 3479 | 5387 | 5387 |
| | 5" mineral wool | m$^2$ | 1638 | — | 3479 | — | 5387 | — |
| | 1–1/2" polystyrene | m$^2$ | — | 1638 | — | 3479 | — | 5387 |
| Floors | 3/8" acoustic mat | m$^2$ | 8271 | — | 12,095 | — | 18,317 | — |
| | CLT | m$^3$ | 1444 | — | 2112 | — | 3199 | — |
| | Concrete | m$^3$ | 372 | 2293 | — | 2865 | 374 | 4666 |
| | Gypsum concrete | m$^3$ | 420 | — | 614 | 1537 | 931 | — |
| | 3/8" PE vapor barrier | m$^2$ | 1220 | 1214 | 1533 | — | 1227 | 1229 |
| | Rebar | kg | 5401 | 41,697 | — | 54,551 | 5444 | 87,245 |
| Foundation | Concrete | m$^3$ | 458 | 674 | 1402 | 1874 | 602 | 818 |
| | Rebar | kg | 23,981 | 20,366 | 102,676 | 187,233 | 28,755 | 34,696 |
| Interior Walls | CLT | m$^3$ | 461 | — | 801 | — | — | — |
| | Concrete | m$^3$ | — | 516 | — | 961 | 1479 | 1419 |
| | 3–5/8" fiberglass mat | m$^2$ | 3375 | 3511 | 5774 | 5934 | 8506 | 8830 |
| | 5/8" gypsum board | m$^2$ | 29,566 | 24,041 | 84,107 | 40,707 | 148,456 | 60,959 |
| | 5–1/2" mineral wool | m$^2$ | — | — | — | — | — | — |
| | Rebar | kg | — | 73,125 | — | 145,244 | — | 214,477 |
| | Steel stud | kg | 15,756 | 16,302 | 25,350 | 25,974 | 37,674 | 38,844 |
| | Exterior brace Framing | kg | 10,534 | — | 16,272 | — | 24,369 | — |

**Table S5** Whole-building bill of materials, NE.

| **Assembly** | **Material** | | 8-story | | 12-story | | 18-story | |
|---|---|---|---|---|---|---|---|---|
| | | **Unit** | **Timber** | **Concrete** | **Timber** | **Concrete** | **Timber** | **Concrete** |
| **Columns and Beams** | Concrete | m$^3$ | — | 93 | — | 385 | — | 586 |
| | Glulam | m$^3$ | 758 | — | 1207 | — | 1733 | — |
| | Rebar | kg | — | 59,392 | — | 139,608 | — | 285,609 |
| **Exterior Walls** | Aluminum stud | kg | — | 738 | — | 1550 | — | 2400 |
| | CLT | m$^3$ | 172 | — | 364 | — | 564 | — |
| | 3–5/8" fiberglass mat | m$^2$ | — | 1638 | — | 3479 | — | 5387 |
| | 5/8" gypsum board | m$^2$ | 1638 | 1638 | 3479 | 3479 | 5387 | 5387 |
| | 5" mineral wool | m$^2$ | 1638 | — | 3479 | — | 5387 | — |
| | 1–1/2" polystyrene | m$^2$ | — | 1638 | — | 3479 | — | 5387 |
| **Floors** | 3/8" acoustic mat | m$^2$ | 8229 | — | 12,053 | — | 18,277 | — |
| | CLT | m$^3$ | 1437 | — | 2105 | — | 3192 | — |
| | Concrete | m$^3$ | 372 | 2293 | — | 2865 | 370 | 6894 |
| | Gypsum concrete | m$^3$ | 418 | — | 612 | — | 928 | — |
| | 3/8" PE vapor barrier | m$^2$ | 1220 | 1214 | 1533 | 1537 | 1214 | 1229 |
| | Rebar | kg | 5401 | 41,697 | — | 54,551 | 5388 | 87,245 |

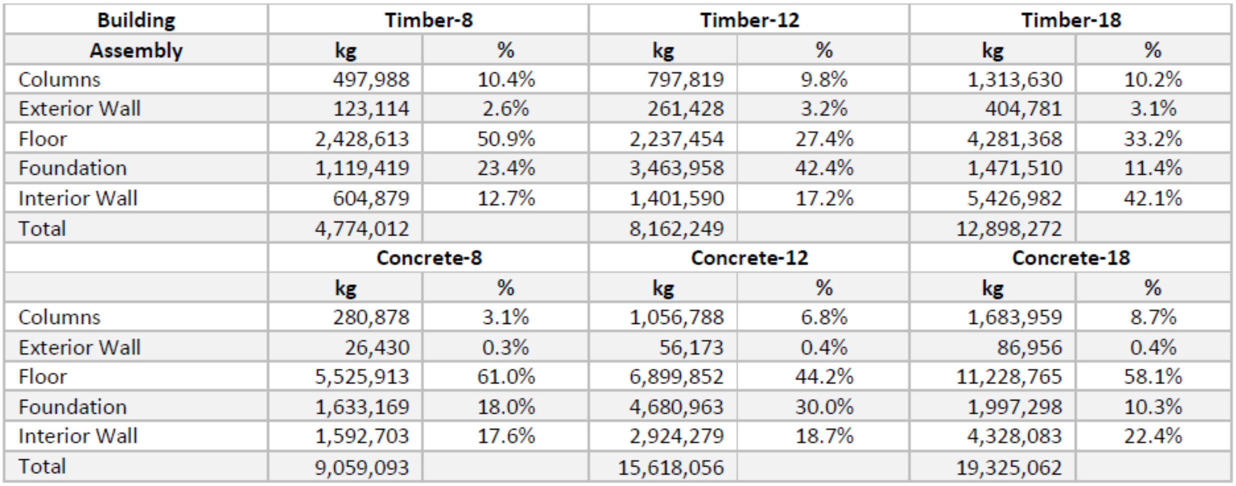
**Table S6.** Whole-building bill of materials, SE.

| Assembly | Material: Name | Unit | 8-Story | | 12-Story | | 18-Story | |
|---|---|---|---|---|---|---|---|---|
| | | | Timber | Concrete | Timber | Concrete | Timber | Concrete |
| **Columns and Beams** | Concrete | $m^3$ | — | 93 | — | 385 | — | 586 |
| | Glulam | $m^3$ | 752 | — | 1207 | — | 1733 | — |
| | Rebar | kg | — | 59,392 | — | 139,608 | — | 386,927 |
| **Exterior Walls** | Aluminum stud | kg | — | 730 | — | 1534 | — | 2375 |
| | CLT | $m^3$ | 172 | — | 364 | — | 564 | — |
| | 3–5/8" fiberglass mat | $m^2$ | — | 1638 | — | 3479 | — | 5387 |
| | 5/8" gypsum board | $m^2$ | 1638 | 1638 | 3479 | 3479 | 5387 | 5387 |
| | 5" mineral wool | $m^2$ | 1638 | — | 3479 | — | 5387 | — |
| | 1–1/2" polystyrene | $m^2$ | — | 1638 | — | 3479 | — | 5387 |
| **Floors** | 3/8" acoustic mat | $m^2$ | 8229 | — | 12,053 | — | 18,277 | — |
| | CLT | $m^3$ | 1437 | — | 2105 | — | 3192 | — |
| | Concrete | $m^3$ | 372 | 2293 | — | 2865 | 370 | 4666 |
| | Gypsum concrete | $m^3$ | 418 | — | 612 | — | 928 | — |
| | 3/8" PE vapor barrier | $m^2$ | 1218 | 1214 | 1533 | 1537 | 18,277 | 1229 |
| | Rebar | kg | 5401 | 41,697 | — | 54,551 | 8364 | 87,245 |
| **Foundation** | Concrete | $m^3$ | 367 | 674 | 1402 | 1874 | 601 | 818 |
| | Rebar | kg | 12,498 | 20,366 | 102,743 | 187,233 | 28,741 | 34,699 |
| **Interior Walls** | CLT | $m^3$ | 1153 | — | 2053 | — | 1835 | — |
| | Concrete | $m^3$ | — | 516 | — | 961 | 1474 | 1419 |
| | 3–5/8" fiberglass mat | $m^2$ | 280 | 323 | 500 | 5934 | 757 | 8830 |
| | 5/8" gypsum board | $m^2$ | 13,724 | 24,041 | 74,381 | 40,707 | 175,872 | 60,959 |
| | 5–1/2" mineral wool | $m^2$ | 3287 | — | 5617 | — | 8317 | — |
| | Rebar | kg | — | 73,125 | — | 145,206 | 202,066 | 214,477 |
| | Steel stud | kg | 8112 | 16,302 | 13,300 | 25,974 | 19,812 | 38,844 |
| | Exterior brace framing | kg | — | — | — | — | — | — |

# IX. Appendix II

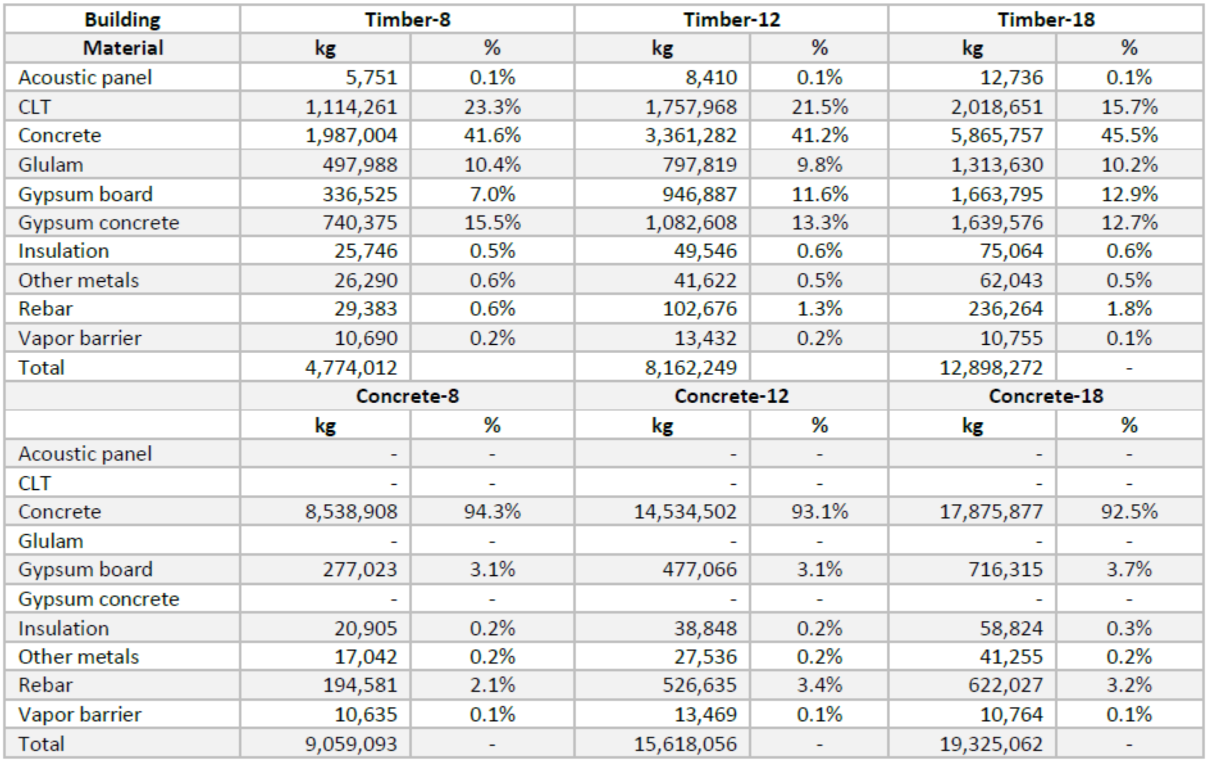
These tables were taken from the unpublished white paper detailing the work of Puettmann et al.'s 2021 whole building LCA (Puettmann et al., n.d.).

**Table 5-2 Whole Building Mass by Assembly, PNW**



| Building | Timber-8 | | Timber-12 | | Timber-18 | |
|---|---|---|---|---|---|---|
| Assembly | kg | % | kg | % | kg | % |
| Columns | 497,988 | 10.4% | 797,819 | 9.8% | 1,313,630 | 10.2% |
| Exterior Wall | 123,114 | 2.6% | 261,428 | 3.2% | 404,781 | 3.1% |
| Floor | 2,428,613 | 50.9% | 2,237,454 | 27.4% | 4,281,368 | 33.2% |
| Foundation | 1,119,419 | 23.4% | 3,463,958 | 42.4% | 1,471,510 | 11.4% |
| Interior Wall | 604,879 | 12.7% | 1,401,590 | 17.2% | 5,426,982 | 42.1% |
| Total | 4,774,012 | | 8,162,249 | | 12,898,272 | |
| | Concrete-8 | | Concrete-12 | | Concrete-18 | |
| | kg | % | kg | % | kg | % |
| Columns | 280,878 | 3.1% | 1,056,788 | 6.8% | 1,683,959 | 8.7% |
| Exterior Wall | 26,430 | 0.3% | 56,173 | 0.4% | 86,956 | 0.4% |
| Floor | 5,525,913 | 61.0% | 6,899,852 | 44.2% | 11,228,765 | 58.1% |
| Foundation | 1,633,169 | 18.0% | 4,680,963 | 30.0% | 1,997,298 | 10.3% |
| Interior Wall | 1,592,703 | 17.6% | 2,924,279 | 18.7% | 4,328,083 | 22.4% |
| Total | 9,059,093 | | 15,618,056 | | 19,325,062 | |

**Table 5-3 Whole Building Mass by Material, PNW**



| Building | Timber-8 | | Timber-12 | | Timber-18 | |
|---|---|---|---|---|---|---|
| Material | kg | % | kg | % | kg | % |
| Acoustic panel | 5,751 | 0.1% | 8,410 | 0.1% | 12,736 | 0.1% |
| CLT | 1,114,261 | 23.3% | 1,757,968 | 21.5% | 2,018,651 | 15.7% |
| Concrete | 1,987,004 | 41.6% | 3,361,282 | 41.2% | 5,865,757 | 45.5% |
| Glulam | 497,988 | 10.4% | 797,819 | 9.8% | 1,313,630 | 10.2% |
| Gypsum board | 336,525 | 7.0% | 946,887 | 11.6% | 1,663,795 | 12.9% |
| Gypsum concrete | 740,375 | 15.5% | 1,082,608 | 13.3% | 1,639,576 | 12.7% |
| Insulation | 25,746 | 0.5% | 49,546 | 0.6% | 75,064 | 0.6% |
| Other metals | 26,290 | 0.6% | 41,622 | 0.5% | 62,043 | 0.5% |
| Rebar | 29,383 | 0.6% | 102,676 | 1.3% | 236,264 | 1.8% |
| Vapor barrier | 10,690 | 0.2% | 13,432 | 0.2% | 10,755 | 0.1% |
| Total | 4,774,012 | | 8,162,249 | | 12,898,272 | - |
| | Concrete-8 | | Concrete-12 | | Concrete-18 | |
| | kg | % | kg | % | kg | % |
| Acoustic panel | - | - | - | - | - | - |
| CLT | - | - | - | - | - | - |
| Concrete | 8,538,908 | 94.3% | 14,534,502 | 93.1% | 17,875,877 | 92.5% |
| Glulam | - | - | - | - | - | - |
| Gypsum board | 277,023 | 3.1% | 477,066 | 3.1% | 716,315 | 3.7% |
| Gypsum concrete | - | - | - | - | - | - |
| Insulation | 20,905 | 0.2% | 38,848 | 0.2% | 58,824 | 0.3% |
| Other metals | 17,042 | 0.2% | 27,536 | 0.2% | 41,255 | 0.2% |
| Rebar | 194,581 | 2.1% | 526,635 | 3.4% | 622,027 | 3.2% |
| Vapor barrier | 10,635 | 0.1% | 13,469 | 0.1% | 10,764 | 0.1% |
| Total | 9,059,093 | - | 15,618,056 | - | 19,325,062 | - |

**Table 5-10 GWP Contribution and Comparison of the Buildings by Assembly (unit: per $m^2$ floor area) (A1-A5), PNW**

| | 8-Story | | | 12-Story | | | 18-Story | | |
|---|---|---|---|---|---|---|---|---|---|
| | Timber | Concrete | Diff. (%) | Timber | Concrete | Diff. (%) | Timber | Concrete | Diff. (%) |
| | | | | A1-A3 (kg $CO_2$ eq/$m^2$ floor) | | | | | |
| Columns | 11.36 | 14.04 | -19% | 12.16 | 26.81 | -55% | 13.29 | 32.64 | -59% |
| Exterior Wall | 5.30 | 5.73 | -8% | 7.51 | 8.26 | -9% | 7.71 | 8.48 | -9% |
| Floor | 46.91 | 112.10 | -58% | 30.80 | 96.05 | -68% | 36.98 | 101.75 | -64% |
| Foundation | 20.01 | 27.05 | -26% | 46.94 | 68.18 | -31% | 12.08 | 16.35 | -26% |
| Interior Wall | 29.87 | 53.61 | -44% | 41.76 | 65.20 | -36% | 76.02 | 64.19 | 18% |
| **Total** | **113.44** | **212.53** | **-47%** | **139.18** | **264.50** | **-47%** | **146.08** | **223.41** | **-35%** |
| | | | | A4 (kg $CO_2$ eq/$m^2$ floor) | | | | | |
| Columns | 2.44 | 0.13 | 1719% | 2.61 | 0.35 | 649% | 2.86 | 0.36 | 686% |
| Exterior Wall | 0.51 | 0.10 | 438% | 0.73 | 0.13 | 438% | 0.75 | 0.15 | 383% |
| Floor | 5.90 | 2.99 | 97% | 5.28 | 2.49 | 112% | 5.48 | 2.65 | 107% |
| Foundation | 0.58 | 0.85 | -32% | 1.19 | 1.60 | -26% | 0.34 | 0.46 | -26% |
| Interior Wall | 2.16 | 1.47 | 46% | 3.00 | 1.71 | 76% | 5.33 | 1.69 | 215% |
| **Total** | **11.59** | **5.54** | **109%** | **12.79** | **6.28** | **104%** | **14.77** | **5.31** | **178%** |
| | | | | A5 (kg $CO_2$ eq/$m^2$ floor) | | | | | |
| Columns | 0.42 | 0.25 | 70% | 0.52 | 0.72 | -28% | 0.66 | 0.88 | -25% |
| Exterior Wall | 0.10 | 0.02 | 331% | 0.17 | 0.04 | 339% | 0.20 | 0.05 | 342% |
| Floor | 2.06 | 4.85 | -58% | 1.47 | 4.71 | -69% | 2.16 | 5.89 | -63% |
| Foundation | 0.95 | 1.43 | -34% | 2.27 | 3.19 | -29% | 0.74 | 1.05 | -29% |
| Interior Wall | 0.51 | 1.40 | -63% | 0.92 | 2.00 | -54% | 2.73 | 2.27 | 20% |
| **Total** | **4.04** | **7.95** | **-49%** | **5.35** | **10.65** | **-50%** | **6.49** | **10.14** | **-36%** |
| | | | | Total A1-A5 (kg CO2 eq/m2 floor) | | | | | |
| Columns | 14.22 | 14.42 | -1% | 15.29 | 27.88 | -45% | 16.81 | 33.89 | -50% |
| Exterior Wall | 5.91 | 5.85 | 1% | 8.41 | 8.43 | 0% | 8.66 | 8.69 | 0% |
| Floor | 54.86 | 119.94 | -54% | 37.55 | 103.25 | -64% | 44.62 | 110.28 | -60% |
| Foundation | 21.54 | 29.33 | -27% | 50.40 | 72.97 | -31% | 13.16 | 17.85 | -26% |
| Interior Wall | 32.54 | 56.49 | -42% | 45.67 | 68.90 | -34% | 84.09 | 68.16 | 23% |
| **Total** | **129.07** | **226.03** | **-43%** | **157.32** | **281.44** | **-44%** | **167.34** | **238.87** | **-30%** |

**Table 5-11 Building material contribution analysis on A1-A5 GWP (kg $CO_2$ eq) per square meter ($m^2$) Timber and concrete buildings, PNW**

| | 8-Story | | | 12-Story | | | 18-Story | | |
|---|---|---|---|---|---|---|---|---|---|
| | Timber | Concrete | Diff. (%) | Timber | Concrete | Diff. (%) | Timber | Concrete | Diff. (%) |
| | | | | Total A1-A5 (kg CO2 eq/$m^2$ floor) | | | | | |
| Acoustic panel | 0.26 | | | 0.50 | | | 0.51 | | |
| CLT | 40.82 | | | 42.97 | | | 33.09 | | |
| Concrete | 32.92 | 166.54 | -80% | 39.01 | 191.79 | -80% | 48.20 | 162.51 | -70% |
| Glulam | 14.22 | | | 15.29 | | | 16.81 | 0.00 | |
| Gypsum board | 12.31 | 10.15 | 21% | 23.21 | 11.71 | 98% | 27.28 | 11.73 | 133% |
| Gypsum concrete | 7.35 | | | 7.23 | | | 7.44 | 0.00 | |
| Insulation | 5.85 | 8.38 | -30% | 7.21 | 10.77 | -33% | 7.19 | 10.90 | -34% |
| Other metals | 7.86 | 6.16 | 28% | 8.33 | 6.90 | 21% | 8.27 | 6.91 | 20% |
| Rebar | 4.87 | 32.19 | -85% | 11.39 | 58.06 | -80% | 17.37 | 45.64 | -62% |
| Vapor barrier | 2.62 | 2.60 | 1% | 2.18 | 2.20 | -1% | 1.17 | 1.17 | 0% |
| **Total** | **129.07** | **226.03** | **-43%** | **157.32** | **281.44** | **-44%** | **167.34** | **238.87** | **-30%** |

### Table 5-13 Whole Building Mass by Assembly, NE

| **Building** | **Timber-8** | | **Timber-12** | | **Timber-18** | |
|---|---|---|---|---|---|---|
| **Assembly** | **kg** | **%** | **kg** | **%** | **kg** | **%** |
| Columns | 356,530 | 8.1% | 568,072 | 7.0% | 815,335 | 6.2% |
| Exterior Wall | 116,949 | 2.7% | 248,335 | 3.0% | 384,517 | 2.9% |
| Floor | 2,332,204 | 52.9% | 2,154,134 | 26.4% | 4,112,569 | 31.2% |
| Foundation | 855,959 | 19.4% | 3,323,465 | 40.7% | 1,410,199 | 10.7% |
| Interior Wall | 748,662 | 17.0% | 1,872,846 | 22.9% | 6,473,949 | 49.1% |
| **Total** | **4,410,304** | | **8,166,852** | | **13,196,569** | |
| **Building** | **Concrete-8** | | **Concrete-12** | | **Concrete-18** | |
| **Assembly** | **kg** | **%** | **kg** | **%** | **kg** | **%** |
| Columns | 272,886 | 3.1% | 1,023,691 | 6.8% | 1,633,500 | 8.8% |
| Exterior Wall | 26,425 | 0.3% | 56,160 | 0.4% | 86,948 | 0.5% |
| Floor | 5,323,313 | 60.9% | 6,653,324 | 44.2% | 10,821,963 | 58.0% |
| Foundation | 1,566,335 | 17.9% | 4,493,047 | 29.8% | 1,915,227 | 10.3% |
| Interior Wall | 1,548,281 | 17.7% | 2,841,543 | 18.9% | 4,205,965 | 22.5% |
| **Total** | **8,737,240** | | **15,067,766** | | **18,663,603** | |

### Table 5-14 Whole Building Mass by Material, NE

| **Building** | **Timber-8** | | **Timber-12** | | **Timber-18** | |
|---|---|---|---|---|---|---|
| **Material** | **kg** | **%** | **kg** | **%** | **kg** | **%** |
| Acoustic panel | 5,722 | 0.1% | 8,380 | 0.1% | 12,709 | 0.1% |
| CLT | 1,381,855 | 31.3% | 2,263,287 | 27.7% | 2,798,359 | 21.2% |
| Concrete | 1,697,965 | 38.5% | 3,220,721 | 39.4% | 5,620,445 | 42.6% |
| Glulam | 356,530 | 8.1% | 568,072 | 7.0% | 815,335 | 6.2% |
| Gypsum board | 165,521 | 3.8% | 842,180 | 10.3% | 1,961,942 | 14.9% |
| Gypsum concrete | 736,604 | 16.7% | 1,078,837 | 13.2% | 1,635,999 | 12.4% |
| Insulation | 29,405 | 0.7% | 56,016 | 0.7% | 85,138 | 0.6% |
| Other metals | 8,112 | 0.2% | 13,182 | 0.2% | 19,812 | 0.2% |
| Rebar | 17,900 | 0.4% | 102,743 | 1.3% | 236,195 | 1.8% |
| Vapor barrier | 10,690 | 0.2% | 13,432 | 0.2% | 10,635 | 0.1% |
| Total | 4,410,304 | 100% | 8,166,852 | 100% | 13,196,569 | 100% |
| **Building** | **Concrete-8** | | **Concrete-12** | | **Concrete-18** | |
| **Material** | **kg** | **%** | **kg** | **%** | **kg** | **%** |
| Acoustic panel | - | - | - | - | - | - |
| CLT | - | - | - | - | - | - |
| Concrete | 8,217,059 | 94.0% | 13,984,264 | 92.8% | 17,214,426 | 92.2% |
| Glulam | - | - | - | - | - | - |
| Gypsum board | 277,020 | 3.2% | 477,064 | 3.2% | 716,318 | 3.8% |
| Gypsum concrete | - | - | - | - | - | - |
| Insulation | 20,905 | 0.2% | 38,848 | 0.3% | 58,825 | 0.3% |
| Other metals | 17,040 | 0.2% | 27,524 | 0.2% | 41,244 | 0.2% |
| Rebar | 194,581 | 2.2% | 526,597 | 3.5% | 622,027 | 3.3% |
| Vapor barrier | 10,635 | 0.1% | 13,469 | 0.1% | 10,764 | 0.1% |
| Total | 8,737,240 | 100% | 15,067,766 | 100% | 18,663,603 | 100% |

## Table 5-21 GWP Contribution and Comparison of the Buildings by Assembly (unit: per $m^2$ floor area) (A1-A5), NE

| | 8-Story | | | 12-Story | | | 18-Story | | |
|---|---|---|---|---|---|---|---|---|---|
| | Timber | Concrete | Diff. (%) | Timber | Concrete | Diff. (%) | Timber | Concrete | Diff. (%) |
| | A1-A3 (kg CO2 eq/$m^2$ floor) | | | | | | | | |
| Columns | 6.48 | 13.81 | -53% | 6.88 | 26.47 | -74% | 6.02 | 29.45 | -80% |
| Exterior Wall | 4.50 | 5.02 | -10% | 6.37 | 7.17 | -11% | 6.02 | 6.76 | -11% |
| Floor | 41.67 | 106.48 | -61% | 23.66 | 91.30 | -74% | 27.86 | 88.32 | -68% |
| Foundation | 14.59 | 26.06 | -44% | 44.94 | 65.55 | -31% | 10.73 | 14.31 | -25% |
| Interior Wall | 23.41 | 52.29 | -55% | 39.57 | 63.55 | -38% | 79.36 | 57.42 | 38% |
| **Total** | **90.66** | **203.65** | **-55%** | **121.42** | **254.03** | **-52%** | **129.99** | **196.26** | **-34%** |
| | A4 (kg CO2 eq/$m^2$ floor) | | | | | | | | |
| Columns | 1.64 | 0.07 | 2320% | 1.74 | 0.15 | 1065% | 1.52 | 0.15 | 886% |
| Exterior Wall | 0.48 | 0.08 | 503% | 0.68 | 0.11 | 503% | 0.64 | 0.11 | 503% |
| Floor | 6.43 | 0.99 | 552% | 6.12 | 0.82 | 644% | 5.69 | 0.79 | 623% |
| Foundation | 0.15 | 0.27 | -45% | 0.40 | 0.55 | -28% | 0.10 | 0.14 | -26% |
| Interior Wall | 3.27 | 1.31 | 150% | 5.29 | 1.50 | 252% | 5.05 | 1.37 | 270% |
| **Total** | **11.96** | **2.71** | **341%** | **14.23** | **3.14** | **353%** | **13.01** | **2.55** | **410%** |
| | A5 (kg CO2 eq/$m^2$ floor) | | | | | | | | |
| Columns | 0.30 | 0.23 | 30% | 0.37 | 0.67 | -45% | 0.37 | 0.75 | -50% |
| Exterior Wall | 0.10 | 0.02 | 325% | 0.16 | 0.04 | 335% | 0.18 | 0.04 | 338% |
| Floor | 1.97 | 4.50 | -56% | 1.41 | 4.35 | -68% | 1.89 | 4.98 | -62% |
| Foundation | 0.73 | 1.33 | -45% | 2.18 | 2.94 | -26% | 0.65 | 0.88 | -26% |
| Interior Wall | 0.63 | 1.31 | -52% | 1.23 | 1.86 | -34% | 2.98 | 1.93 | 54% |
| **Total** | **3.73** | **7.39** | **-49%** | **5.35** | **9.86** | **-46%** | **6.07** | **8.58** | **-29%** |
| | Total A1-A5 (kg CO2 eq/$m^2$ floor) | | | | | | | | |
| Columns | 8.42 | 14.10 | -40% | 8.99 | 27.29 | -67% | 7.92 | 30.36 | -74% |
| Exterior Wall | 5.08 | 5.13 | -1% | 7.21 | 7.32 | -1% | 6.83 | 6.90 | -1% |
| Floor | 50.07 | 111.97 | -55% | 31.19 | 96.48 | -68% | 35.45 | 94.09 | -62% |
| Foundation | 15.47 | 27.66 | -44% | 47.52 | 69.04 | -31% | 11.48 | 15.32 | -25% |
| Interior Wall | 27.31 | 54.90 | -50% | 46.08 | 66.92 | -31% | 87.39 | 60.72 | 44% |
| **Total** | **106.35** | **213.76** | **-50%** | **141.00** | **267.04** | **-47%** | **149.07** | **207.39** | **-28%** |

## Table 5-22 Building material contribution analysis on A1-A5 GWP (kg CO2 eq) per square meter (m2) Timber and concrete buildings, NE

| | 8-Story | | | 12-Story | | | 18-Story | | |
|---|---|---|---|---|---|---|---|---|---|
| | Timber | Concrete | Diff. (%) | Timber | Concrete | Diff. (%) | Timber | Concrete | Diff. (%) |
| | Total A1-A5 (kg $CO_2$ eq/$m^2$ of floor) | | | | | | | | |
| Acoustic panel | 0.26 | | | 0.26 | | | 0.24 | | |
| CLT | 39.81 | | | 43.67 | | | 33.08 | | |
| Concrete | 30.47 | 154.78 | -80% | 36.16 | 178.14 | -80% | 44.44 | 138.10 | -68% |
| Glulam | 8.42 | | | 8.99 | | | 7.92 | | |
| Gypsum board | 6.34 | 10.61 | -40% | 21.60 | 12.23 | 77% | 30.78 | 11.24 | 174% |
| Gypsum concrete | 8.57 | | | 8.47 | | | 7.92 | | |
| Insulation | 4.43 | 8.26 | -46% | 5.61 | 10.57 | -47% | 5.20 | 9.81 | -47% |
| Other metals | 2.53 | 5.34 | -53% | 2.75 | 5.75 | -52% | 2.52 | 5.26 | -52% |
| Rebar | 2.97 | 32.23 | -91% | 11.36 | 58.20 | -80% | 15.93 | 41.94 | -62% |
| Vapor barrier | 2.55 | 2.53 | 1% | 2.13 | 2.14 | 0% | 1.03 | 1.04 | -1% |
| **Total** | **106.35** | **213.76** | **-50%** | **141.00** | **267.04** | **-47%** | **149.07** | **207.39** | **-28%** |

## Table 5-24 Whole Building Mass by Assembly, SE

| **Building** | **Timber-8** | | **Timber-12** | | **Timber-18** | |
|---|---|---|---|---|---|---|
| **Assembly** | **kg** | **%** | **kg** | **%** | **kg** | **%** |
| Columns | 463,324 | 9.6% | 743,728 | 8.4% | 743,728 | 7.6% |
| Exterior Wall | 136,769 | 2.8% | 290,422 | 3.3% | 290,422 | 3.2% |
| Floor | 2,501,442 | 51.7% | 2,397,157 | 27.0% | 2,397,157 | 31.8% |
| Foundation | 851,916 | 17.6% | 3,336,774 | 37.6% | 3,336,774 | 10.0% |
| Interior Wall | 881,996 | 18.2% | 2,109,962 | 23.8% | 2,109,962 | 47.4% |
| **Total** | **4,835,447** | | **8,878,042** | | **14,101,796** | |
| **Building** | **Concrete-8** | | **Concrete-12** | | **Concrete-18** | |
| **Assembly** | **kg** | **%** | **kg** | **%** | **kg** | **%** |
| Columns | 272,611 | 3.1% | 1,027,115 | 6.8% | 1,733,079 | 9.2% |
| Exterior Wall | 26,418 | 0.3% | 56,144 | 0.4% | 86,924 | 0.5% |
| Floor | 5,321,124 | 61.0% | 6,644,934 | 44.1% | 10,812,798 | 57.6% |
| Foundation | 1,559,048 | 17.9% | 4,510,840 | 29.9% | 1,923,001 | 10.3% |
| Interior Wall | 1,546,751 | 17.7% | 2,838,694 | 18.8% | 4,201,758 | 22.4% |
| **Total** | **8,725,952** | | **15,077,728** | | **18,757,561** | |

## Table 5-25 Whole Building Mass by Material, SE

| **Building** | **Timber-8** | | **Timber-12** | | **Timber-18** | |
|---|---|---|---|---|---|---|
| Material | **kg** | **%** | **kg** | **%** | **kg** | **%** |
| Acoustic panel | 5,722 | 0.1% | 8,380 | 0.1% | 12,709 | 0.1% |
| CLT | 1,700,937 | 35.2% | 2,785,395 | 31.4% | 3,443,899 | 24.4% |
| Concrete | 1,697,231 | 35.1% | 3,234,030 | 36.4% | 5,625,077 | 39.9% |
| Glulam | 463,324 | 9.6% | 743,728 | 8.4% | 1,067,448 | 7.6% |
| Gypsum board | 165,521 | 3.4% | 842,180 | 9.5% | 1,961,909 | 13.9% |
| Gypsum concrete | 736,604 | 15.2% | 1,078,837 | 12.2% | 1,635,999 | 11.6% |
| Insulation | 29,405 | 0.6% | 56,016 | 0.6% | 85,138 | 0.6% |
| Other metals | 8,112 | 0.2% | 13,300 | 0.1% | 19,812 | 0.1% |
| Rebar | 18,020 | 0.4% | 102,743 | 1.2% | 239,171 | 1.7% |
| Vapor barrier | 10,690 | 0.2% | 13,432 | 0.2% | 10,635 | 0.1% |
| **Total** | **4,835,567** | | **8,878,042** | | **14,101,796** | **100.0%** |
| **Building** | **Concrete-8** | | **Concrete-12** | | **Concrete-18** | |
| **Material** | **kg** | **%** | **kg** | **%** | **kg** | **%** |
| Acoustic panel | - | - | - | - | - | - |
| CLT | - | - | - | - | - | - |
| Concrete | 8,205,778 | 94.0% | 13,994,241 | 92.8% | 17,207,087 | 91.7% |
| Glulam | - | - | - | - | - | - |
| Gypsum board | 277,020 | 3.2% | 477,064 | 3.2% | 716,318 | 3.8% |
| Gypsum concrete | - | - | - | - | - | - |
| Insulation | 20,905 | 0.2% | 38,848 | 0.3% | 58,825 | 0.3% |
| Other metals | 17,032 | 0.2% | 27,508 | 0.2% | 41,219 | 0.2% |
| Rebar | 194,581 | 2.2% | 526,597 | 3.5% | 723,348 | 3.9% |
| Vapor barrier | 10,635 | 0.1% | 13,469 | 0.1% | 10,764 | 0.1% |
| **Total** | **8,725,952** | | **15,077,728** | | **18,757,561** | |

## Table 5-32 GWP Contribution and Comparison of the Buildings by Assembly (unit: per $m^2$ floor area) (A1-A5), SE

| | 8-Story | | | 12-Story | | | 18-Story | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Timber** | **Concrete** | **Diff. (%)** | **Timber** | **Concrete** | **Diff. (%)** | **Timber** | **Concrete** | **Diff. (%)** |
| | **A1-A3 (kg CO2 eq/$m^2$ floor)** | | | | | | | | |
| Columns | 10.26 | 13.23 | -22% | 10.98 | 25.29 | -57% | 10.51 | 37.95 | -72% |
| Exterior Wall | 5.59 | 4.86 | 15% | 7.92 | 6.93 | 14% | 8.17 | 7.15 | 14% |
| Floor | 48.66 | 101.11 | -52% | 33.67 | 86.33 | -61% | 39.36 | 91.53 | -57% |
| Foundation | 14.29 | 25.56 | -44% | 43.63 | 63.59 | -31% | 11.40 | 14.16 | -20% |
| Interior Wall | 31.18 | 49.71 | -37% | 47.88 | 60.42 | -21% | 88.19 | 59.71 | 48% |
| **Total** | **109.99** | **194.46** | **-43%** | **144.08** | **242.56** | **-41%** | **157.63** | **210.51** | **-25%** |
| | **A4 (kg CO2 eq/$m^2$ floor)** | | | | | | | | |
| Columns | 1.51 | 0.04 | 3991% | 1.61 | 0.08 | 1905% | 1.54 | 0.10 | 1370% |
| Exterior Wall | 0.38 | 0.01 | 3520% | 0.53 | 0.01 | 3525% | 0.55 | 0.02 | 3526% |
| Floor | 3.45 | 0.49 | 611% | 3.29 | 0.40 | 714% | 3.36 | 0.44 | 672% |
| Foundation | 0.08 | 0.14 | -45% | 0.21 | 0.29 | -28% | 0.06 | 0.08 | -26% |
| Interior Wall | 2.53 | 0.25 | 925% | 3.11 | 0.29 | 968% | 2.16 | 0.29 | 647% |
| **Total** | **7.94** | **0.92** | **762%** | **8.75** | **1.08** | **709%** | **7.66** | **0.92** | **731%** |
| | **A5 (kg CO2 eq/$m^2$ floor)** | | | | | | | | |
| Columns | 0.39 | 0.23 | 70% | 0.73 | 0.67 | 9% | 0.54 | 0.87 | -38% |
| Exterior Wall | 0.12 | 0.02 | 412% | 0.29 | 0.04 | 673% | 0.23 | 0.04 | 416% |
| Floor | 2.03 | 4.49 | -55% | 2.35 | 4.35 | -46% | 2.26 | 5.43 | -58% |
| Foundation | 0.72 | 1.32 | -45% | 3.27 | 2.95 | 11% | 0.71 | 0.97 | -26% |
| Interior Wall | 0.75 | 1.31 | -43% | 2.07 | 1.86 | 10% | 3.36 | 2.11 | 59% |
| **Total** | **4.01** | **7.37** | **-46%** | **8.71** | **9.86** | **-12%** | **7.09** | **9.43** | **-25%** |
| | **Total A1-A5 (kg CO2 eq/$m^2$ floor)** | | | | | | | | |
| Columns | 12.16 | 13.49 | -10% | 13.32 | 26.04 | -49% | 12.58 | 38.93 | -68% |
| Exterior Wall | 6.09 | 4.90 | 24% | 8.74 | 6.98 | 25% | 8.95 | 7.21 | 24% |
| Floor | 54.14 | 106.09 | -49% | 39.32 | 91.08 | -57% | 44.98 | 97.40 | -54% |
| Foundation | 15.09 | 27.02 | -44% | 47.11 | 66.83 | -30% | 12.17 | 15.21 | -20% |
| Interior Wall | 34.43 | 51.26 | -33% | 53.07 | 62.57 | -15% | 93.70 | 62.11 | 51% |
| **Total** | **121.93** | **202.75** | **-40%** | **161.55** | **253.50** | **-36%** | **172.38** | **220.86** | **-22%** |

## Table 5-33 Building material contribution analysis on A1-A5 GWP (kg CO2 eq) per square meter (m2) Timber and concrete buildings, SE

| | 8-Story | | | 12-Story | | | 18-Story | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Timber** | **Concrete** | **Diff. (%)** | **Timber** | **Concrete** | **Diff. (%)** | **Timber** | **Concrete** | **Diff. (%)** |
| | **Total A1-A5 (kg $CO_2$ eq/$m^2$ of floor)** | | | | | | | | |
| Acoustic panel | 0.23 | | | 0.41 | | | 0.23 | | |
| CLT | 59.13 | | | 65.16 | | | 53.94 | | |
| Concrete | 26.93 | 147.18 | -82% | 36.51 | 169.29 | -78% | 45.16 | 140.90 | -68% |
| Glulam | 12.16 | | | 11.49 | | | 12.58 | | |
| Gypsum board | 5.31 | 8.89 | -40% | 18.24 | 10.27 | 78% | 27.82 | 10.26 | 171% |
| Gypsum concrete | 5.93 | 0.00 | | 5.61 | | | 6.06 | | |
| Insulation | 4.19 | 7.96 | -47% | 5.44 | 10.29 | -47% | 5.39 | 10.35 | -48% |
| Other metals | 2.50 | 5.33 | -53% | 2.75 | 5.74 | -52% | 2.76 | 5.74 | -52% |
| Rebar | 2.91 | 31.03 | -91% | 10.92 | 56.01 | -81% | 16.98 | 51.31 | -67% |
| Vapor barrier | 2.41 | 2.40 | 1% | 2.05 | 2.02 | 2% | 1.07 | 1.08 | -1% |
| **Total** | **121.70** | **202.79** | **-40%** | **158.58** | **253.63** | **-37%** | **171.99** | **219.64** | **-22%** |