Effects of Cascade Use of Wood and Recycling of Construction Materials on Fossil Greenhouse Gas Emissions of Concrete and Wood-Based Buildings

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Abstract

The construction sector aims to decrease greenhouse gas (GHG) emissions and increase circular use of construction materials. Many nonrenewable construction materials could be recycled more efficiently or replaced with renewable materials, such as wood. Cascading is the sequential use of wood in multiple material applications before incineration. This study estimated how much increased recycling and cascade use of wood could decrease GHG emissions of a concrete building, a cross-laminated timber building, and a modular building based on the use of wood. Furthermore, the study assessed how the increased recycling and cascading would influence the substitution effects of wood construction, i.e., on the avoided fossil-based GHG emissions when preferring wood to nonrenewable alternatives. The GHG emissions of construction materials of the buildings decreased 30 to 35 percent with assumed recycling rates and cascading principles, with the relative decrease being largest for the concrete building. Notably, using wood ash as a cement replacement decreased the GHG emissions of the concrete building the most. The substitution effect of wood construction was slightly reduced because of cascading and recycling. This study considered only fossil-based GHG emissions, and changes in the forest carbon balance were excluded.

The building and construction sector accounts for 36 percent of global energy use and 39 percent of energy-related CO_2 emissions (Global Alliance for Buildings 2019). Additionally, the building and construction sector is responsible for more than 30 percent of the extraction of natural resources and generates 25 percent of the global solid waste (Benachio et al. 2020). The construction sector has a considerable potential to reduce global greenhouse gas (GHG) emissions and support the circular use of natural resources (Illankoon and Vithanage 2023). More attention has recently been given to embodied emissions originating from production of construction materials (Röck et al. 2020). As the energy efficiency of buildings improves, the GHG emissions caused by the production of construction materials are becoming even more relevant in climate change mitigation (Lützkendorf and Balouktsi 2022).

In Finland, 1.6 million tons of construction waste were generated in 2017, representing 13 percent of the national waste load. Most of the construction waste is wood (41 percent), followed by mineral and stone waste (33 percent) and metals (14 percent). The proportion of wood waste is much larger in Finland compared with southern and mid-European countries, where the average proportion is only 5 percent (Peuranen and Hakaste 2014). Recycling nonwood construction materials such as steel and concrete is already a common practice, but plastics, gypsum, and insulation wools could be recycled and reused more efficiently (Korpayev et al. 2023, Jiang et al. 2024). The use of wood has caused lower

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fossil-based embodied emissions compared with concrete and steel, and replacing nonrenewable construction materials with wood is an option to reduce GHG emissions of construction materials (Sathre and O'Connor 2010, Hafner and Schäfer 2017). Wood-based construction materials can be based on the use of virgin wood, but more climate change mitigation could be provided by using recycled wood as well as side and waste streams of forest industries.

In addition to recycling, the term cascading has been used in literature, referring to a broader aspect of resource efficiency, mainly in the context of wood-based products. Several definitions of cascading are available, but generally it is defined as "the efficient utilization of resources by using residues and recycled materials for material use to extend total biomass availability within a given system" (Vis et al. 2016). Thus, it can refer to the improved use of side streams and by-products and also the reuse or recycling of discarded products at the end of their life cycle. According to the European Union (EU) waste hierarchy principle, materials should be kept in circulation for as long as possible before eventual energy recovery or disposal, with extended service life and reuse over recycling preferred (European Commission 2021). Also, recycling can be divided into downcycling (recycling with decreasing material quality), closed-loop recycling (recycling with unchanging material quality), and upcycling (recycling with increasing quality; Vis et al. 2016).

Cascade use can decrease the GHG emissions of construction materials (Onuaguluchi and Banthia 2016, Bais-Moleman et al. 2018, Arceo et al. 2023). Yet, as the literature review by Thonemann and Schumann (2018) concludes, the environmental effect of wood cascading remains unclear. It is estimated that an increased cascade use of wood products may reduce the total GHG emissions of Germany by 0.19 percent (Budzinski et al. 2020). Overall, the benefit of material cascading over energy recovery depends largely on the transportation distance of waste to heat and power plants, whereas, e.g., sorting and decontamination, processes have been found to play a minor role (Risse et al. 2019). In forested countries with long transport distances, strict requirements on material recycling may lead to even worse environmental effects than energy use (Vis et al. 2016).

Research has focused on value-chain material flow analysis and indirect land-use effect analysis (e.g., Höglmeier et al. 2013, Suominen et al. 2017). However, a limited number of studies have investigated the cascading effects at the product- and end-use levels (Risse et al. 2019, Llana et al. 2022). This could be because of the obstacles in wider market uptake, e.g., quality and availability of collected waste wood caused by contamination, source separation, legislation and standards, automatic detection and sorting of mixed waste, cost aspects (Vis et al. 2016). Yet, several cascading pathways are also available in the context of building products and construction.

Substitution effects describe how much the use of wood decreases or increases GHG emissions as compared with a nonwood alternative, typically including only fossil emissions taking place in the technosystem (excluding carbon balance in forest ecosystems; Myllyviita et al. 2021). Although the manufacturing of wooden construction materials causes relatively low fossil GHG emissions, studies suggest that substitution effects are not large enough to compensate for the short-term reduction in a forest carbon sink because of increased use of wood as building materials (e.g., Smyth et al. [2014], [2016], Valade et al. [2018], Schulte et al. [2022], Niemi et al. [2025]). The substitution effects of wood use are also expected to be further reduced in the future because of the decarbonization of the energy sector and increased recycling of mineral-based construction materials (Geng et al. 2019, Myllyviita et al. 2022). However, these studies did not consider how cascade use of wood materials would influence the substitution effects of wood-based construction.

In most countries, wood-based by-products and discarded construction wood are abundantly available (Mantau 2012). Thus, they could be used as raw materials for construction products instead of using discarded wood directly for energy production. Moreover, with cascading, it may be possible to avoid the use of virgin wood, resulting in a reduction in the net GHG emission indirectly due to avoiding additional wood harvesting (Hossain and Poon 2018), although only if the recycled and virgin products are perfect substitutes, i.e., can be used interchangeably (Zink et al. 2016).

This study assesses how the cascade use of wood-based construction materials and recycling of renewable construction materials could affect the GHG emissions of three alternative building types (one concrete, two wood based). Specifically, the following research questions are addressed.

- How much can the embodied GHG emissions of each building type be reduced using recycled building products and wood by-products to substitute conventional building components?
- How much is the substitution result (avoided fossil emissions) affected because of cascading and recycling when concrete buildings are substituted for wood-based buildings?

Material and Methods

Building types

Three alternative six-story buildings constructed in Sweden were used as a reference to estimate how increased material cascade use of wood and recycling of fossil construction materials would influence the GHG emissions of construction materials (Tettey et al. 2019). Life-cycle inventories of construction materials for the alternative buildings were obtained from Tettey et al. (2019; Table 1).

In Tettey et al. (2019), one of the buildings was based on a prefabricated concrete frame (concrete building); the other two buildings were based on the use of wood. The external walls of the concrete building were made of a 150-mm-layer of expanded polystyrene (EPS) insulation sandwiched between 100-mm and 230-mm prefabricated concrete wall panels. The framing of the cross-laminated timber (CLT) building and the intermediate and ceiling floors have CLT panel elements as the main structural components. The modular building is based on the use of individual light-frame timber volumetric elements, delivered for assembly on the construction site. The three reference buildings had six stories with a total heated floor area of 1,686 m^2 divided into 24 apartments with one to three rooms. The buildings were functionally equivalent regarding floor area and energy efficiency and designed to meet the Swedish passive house criteria. More details on the alternative buildings are available in Tettey et al. (2019).

Table 1.—Raw materials for the three assessed buildings (tons per building; Tettey et al. 2019).

Construction material	Building type: Concrete	CLT[a]	Modular
Concrete	2,838.0	229.1	229.1
Steel	95.2	12.6	14.2
Lumber	50.9	127.4	153.5
Particleboard	20.8	0	22.8
Plywood	3	20.9	29
CLT	0	175.7	0
Glue-laminated timber (glulam)	0	40.3	7.8
Stone wool insulation	11.1	31.7	10.6
Glass wool insulation	0	0	23.6
EPS insulation[b]	13.6	4.5	4.5
Plasterboard	22.6	109.7	116.1

[a] CLT = cross-laminated timber.
[b] EPS = expanded polystyrene.

Measures to reduce the GHG emissions of construction materials

The GHG emissions of all construction materials were estimated in the referenced state and in an increased recycling scenario. In the increased recycling scenario, it is assumed that both wood-based and nonrenewable construction materials are based on efficient use of recycled raw materials. Also, nonrenewable construction materials were assumed to be replaced with wood, if applicable. Scientific literature was reviewed to obtain insights on potential recycling and cascading regimes; viable recycling regimes were applied when calculating the GHG emissions of building in an increased recycling scenario (see the "Non-renewable construction materials" and "Wood-based raw materials" sections; Table 2). Each cascade or substitution strategy could be applied in each building type, but the overall effect may vary for the different buildings because of different shares of building products per building. The system boundary was gate-to-gate, i.e., the GHG emissions for recycling of nonrenewable construction materials and cascade use of wood included emissions caused by recycling and transportation.

For the referenced situation, i.e., without cascading and recycling options, the GHG emissions of construction materials were obtained from the Finnish Environmental Institute (2023) database for construction (Table 3). The estimates of loss factors (i.e., share of material losses during cutting, installation, other on-site processes) were also included. Loss factors were 3 percent for EPS, steel, and insulation materials; 10 percent for wood and CLT; and 5 percent for the remainder of the construction materials. It was then estimated how much the GHG emissions of the construction materials would decrease because of increased cascading and recycling. The research literature was reviewed to find estimates on how recycled raw materials could replace existing nonwood and wood-based construction materials. For the construction materials without increased recycling assumptions, it was assumed that the GHG emissions would not change from the referenced situation (Table 3). Finally, the GHG emissions of the three buildings were aggregated by multiplying the mass of required construction material with the GHG emissions of a construction material. The GHG emissions of the building were aggregated using GHG

Table 2.—Emission reduction strategies for mineral and wood-based construction products considered in the analysis.

	Non-renewable raw materials	Wood-based raw materials
Recycling	Concrete Gypsum boards	Particleboard from recovered sawn wood Glulam from recovered sawn wood CLT from recovered sawn wood[a]
Substitution via residues or by-products	Cement replaced with wood ash Mineral insulation replaced with wood fiber insulation EPS replaced with nanocellulose	

[a] CLT = cross-laminated timber; EPS = expanded polystyrene.

emissions of the construction materials in the referenced state and then applying increased recycling and cascading assumptions.

Nonrenewable construction materials.—Most of the steel is already being recycled (80% to 90 percent), thus, the options for further increasing the recycling rate of steel are limited. Although concrete construction and demolition waste is typically recycled and used as road sub-bases and civil engineering projects, it is not yet a common practice to use recycled concrete as a raw material in a new building (Kuoribo et al. 2024).

Gypsum boards are used especially in wood-based buildings to ensure fire safety. Wood-based buildings include a substantial proportion of gypsum boards (Table 1), so the production emissions of gypsum boards generate a significant proportion of the GHG emissions of a wood-based building. However, the gypsum boards can be made of fully

Table 3.—Greenhouse gas emissions of construction materials in the reference state and after increased recycling and cascade use of wood.

GHG emissions (kg CO_2 eq./kg) of construction materials[a]	Reference	Increased recycling and cascading
Concrete	0.18[b]	0.11[c]
Steel	2.53[b]	—
Wood	0.14[b]	—
Particleboard	0.39[b]	0.37[d]
Plywood	0.30[b]	—
CLT	0.12[b]	0.11[e]
Glulam	0.11[b]	0.08[f]
Rock wool	1.17[b]	0.24[g]
Glass wool	1.17[b]	0.24[g]
EPS	2.90[b]	1.18[h]
Gypsum	0.28[1]	0.15[i]

[a] CLT = cross-laminated timber; EPS = expanded polystyrene; GHG = greenhouse gas.
[b] Finnish Environmental Institute (2023).
[c] Vu et al. (2019), Tosti et al. (2018).
[d] Hossain and Poon (2018).
[e] Llana et al. (2022).
[f] Risse et al. (2019).
[g] Ruuska (2013), Termex (2020); insulation, demolition, and transport emissions.
[h] Lavoine and Bergström (2017).
[i] Pedreño-Rojas et al. (2020), Gyproc (2024); demolition and transport emissions only.

recycled gypsum. Recycling gypsum can deliver about 40 to 45 percent GHG savings when compared with natural gypsum manufacturing (Pedreño-Rojas et al. 2020).

Wood-based raw materials.—Particleboard can be made of recycled wood (e.g., Merrild and Christensen 2009). First, wood waste is shredded, and foreign objects are removed to produce wood chips. Although the use of recycled wood as a raw material for particleboard production has become a common practice in the EU, direct virgin raw material replacement may be unrealistic in the countries where production is already based on secondary raw materials, such as industrial residues. Finland, for instance, has a relatively small production volume of particleboard, and the production is fully based on wood chips and sawdust originating from the wood industry (Suominen et al. 2017). However, in this study the anticipated GHG reduction was estimated on the basis of whether the production of particleboard would be determined by the use of recycled wood. Hossain and Poon (2018) estimated that 295 kg CO_2 equivalents GHG emissions are associated with the production of m^3 of particleboard with recycled wood waste (share of waste wood 50%), whereas 313 kg CO_2 equivalents GHG emissions are associated with the same amount of particleboard production from virgin wood. Thus, the use of waste wood rather than virgin wood could decrease the GHG emissions of particleboard by 6 percent (Table 3).

Glue-laminated timber (glulam) can be made of recycled sawn wood (i.e., beams, boards, laths; Risse et al. 2019). The recycling process includes sorting and removal of impurities, mechanical cleaning of surfaces, and sawing pieces into boards (Risse et al. 2019). The emissions caused by the production of glulam from waste wood were 80 kg CO_2 equivalents/0.679 m^3 of glulam, whereas glulam made of virgin wood generated emissions of 105 kg CO_2 equivalents/0.679 m^3 of glulam (Risse et al. 2019). Thus, glulam based on the use of recycled wood is assumed to generate 25 percent fewer emissions than glulam based on the use of virgin wood (Table 3).

Llana et al. (2022) estimated that CLT that includes 50 percent reclaimed timber has equal structural properties as CLT comprising 100 percent of virgin timber. The manufacturing process is similar to a process in which 100 percent of raw material is new timber, so the manufacturing emissions are similar. Thus, it was assumed that the manufacturing emissions of CLT based on recycled timber were the same as the manufacturing emissions of CLT based on virgin timber with a gate-to-gate system boundary.

Currently, the reuse of structural timber is not a widespread approach, primarily because of the lack of demand for salvaged materials and prohibitive building regulations but also the absence of design standards and concerns related to quality of reclaimed timber (Cristescu et al. 2020, Niu et al. 2021). In this study, all structural timber was assumed to be made of virgin raw materials; no reused sawn wood was used. Production of plywood is also based on virgin raw materials, and no substitute materials were assumed for those.

The emissions caused by harvesting and transportation were extracted from the GHG emissions of recycled wooden construction materials. However, the emissions avoided are minimal because emissions of harvesting and transportation cover only 0.011 tons of CO_2 eq. per ton of wood (Metsäteho 2021).

Substitution of building components.—The concrete industry plays a significant role in climate change mitigation because it emits 7 percent of the total CO_2 emission globally (Mohd Hanifa et al. 2023). Various ways to decrease GHG emissions of concrete have been described. One of the most discussed options is to replace some of the cement with wood ash (e.g., Siddique 2012, Vu et al. 2019). It is estimated that 1.5 million tons of ash are generated annually as a by-product of energy combustion in Finland. Wood ash has been used as fertilizer and in earthworks, but it also has the potential to be used as a raw material in concrete production. Wood ash is not covered by current usage recommendations in industrial standards, but research suggests it could be used in place of coal ash to replace some of the cement in concrete (Teker Ercan et al. 2023). Blending wood ash may lower the cost of cement manufacture, and availability of wood ash should be satisfactory; however, its use in industrial scale may be constrained by relatively high variance in its quality, depending on the biomass type used in power plants and combustion technology (Štirmer et al. 2018, Kannan and Raja Priya 2021).

Strength properties of concrete mixtures decrease marginally with increase in wood ash contents, but wood ash can be used for making precast products and structural grade concrete (Siddique 2012). According to Teker Ercan et al. (2023), an optimal replacement rate of Portland cement with wood ash is 10 to 20 percent to yield environmental gains without compromising strength properties. A 20 percent replacement rate has been estimated to reduce fossil emissions by 16 percent (Teixeira et al. 2015). In this study, the decrease in emissions was estimated using an assumption on use of ash 30 percent by weight, decreasing emissions of concrete by 40 percent (Tosti et al. 2018).

Mineral insulation materials can be replaced with renewable insulation comprising certain types of newspaper (Ruuska 2013). In the manufacturing process, boric minerals are added to the insulation mix to provide protection against fire and decay (Ruuska 2013). It has been estimated that fiber insulation would have the same functionality as mineral insulation materials (Ruuska 2013). The GHG emissions of fiber insulation material is only 0.234 kg CO_2 eq./kg, which is less than 10 percent of the GHG emissions of glass wool or of EPS (Ruuska 2013, Schulte et al. 2021). In addition to replacing glass wool with newspaper-based insulation, it was assumed that EPS was replaced with nanocellulose. Lavoine and Bergström (2017) suggest that nanocellulose-based foams could replace standard commercial EPS foams with a 50 percent reduction in thickness needed to reach the passive house standard. When assuming similar densities for both materials, the conclusion is that 1 kg of EPS can be replaced with 0.5 kg of nanocellulose foam. The GHG emissions of nanocellulose foam is only 0.57 kg CO_2 eq./0.5 kg, and it can be used to replace 1 kg of EPS with GHG emissions of 2.9 kg (Lavoine and Bergström 2017).

Aggregating displacement factors

Substitution effects were quantified by displacement factors (DFs), which describe how much a wood-based product decreases or increases the net GHG emissions per unit of wood used (Sathre and O'Connor 2010). Only fossil GHG emissions in the technosystem were considered, whereas biogenic emissions and removals associated with forest ecosystems and the temporary carbon storage in wood products were excluded. Considering the latter would require dynamic modeling of biogenic carbon emissions and removals in the forest ecosystems and product pools over time against a counterfactual scenario (Myllyviita et al. 2021), which is beyond the scope of the current paper providing point estimates of fossil GHG footprints.

The DFs were estimated for replacing the concrete building with the CLT or modular building (Table 1). DFs can be aggregated for construction materials, e.g., steel (Knauf et al. 2015, Simonsen et al. 2023). However, it is vital to ensure functional equivalency, so in most cases it is advisable to define DFs at the level of a building. For example, it varies regarding how much wood is required to replace a kilogram of steel in a building, or the use of wood may have effects on other construction materials required in a building (Myllyviita et al. 2021).

DFs were aggregated in the referenced state when no increased recycling or cascade use of wood was assumed. Then, DFs were aggregated with increased recycling assumptions. The DFs were aggregated for each building type according to Sathre and O'Connor (2010):

$$DF = \frac{GHG\ nonwood - GHG\ wood}{Cwood - Cnonwood}$$

where GHG nonwood and GHG wood include aggregated GHG emissions (as tons of carbon) of the required construction materials, and Cwood and Cnonwood include biogenic carbon contained in the respective building types. GHG nonwood and GHG wood were aggregated by multiplying the required raw materials with the GHG emissions of the raw materials (Table 1). Cwood and Cnonwood were summed up, including all wood-based raw material in a building with an assumption that the carbon content of wood-based raw materials was 50 percent. The carbon content of wood ash can vary in the range of 5 to 30 percent (Campbell 1990); in this study, the carbon content of ash was set as 20 percent. Cascading increases the shares of both Cwood and Cnonwood DFs.

Results

GHG emissions of concrete and wood-based buildings

The GHG emissions of the construction materials of the concrete building design were in the referenced state (without assumption of increased recycling and cascade use of wood) 835 tons of CO_2 eq., i.e., approximately four times larger than those of the CLT (211 tons of CO_2 eq.) and modular building (209 tons of CO_2 eq.; Table 4). Most of the GHG emissions of the concrete building were, as expected, caused by concrete (61%) and steel (29%; Figs. 1a and 1b). Insulation materials were the major source of the GHG emissions of the CLT and the modular buildings (20%), followed by concrete (20%), steel (15%), and gypsum (16%).

The GHG emissions of all three buildings decreased when increased recycling of construction materials and cascade use of wood were assumed. The relative decrease was highest for the modular building (54%) followed by the CLT building (51%). Although the relative decrease was smallest for the concrete building (38%), the absolute decrease was highest with 226 tons of CO_2 eq. Most of the decrease (80%) was achieved by the addition of ash to concrete. Also, the GHG emissions of wood-based buildings decreased due to the addition of ash to concrete; however, the decrease was much smaller (i.e., 7% of the total GHG emissions of the building because of the lower amount of concrete used in wood-based buildings). Using newspaper as an insulation material instead of mineral insulation materials decreased the GHG emissions of wood-based buildings by 20 percent. The recycling of gypsum decreased the GHG emissions of wood-based buildings by 7 percent. Producing particleboard from recycled wood decreased the GHG emissions of the modular building by 4 percent.

Displacement factors

The DFs for alternative building types before cascading were 1.17 tC/tC (tons of carbon per tons wood (as carbon) used construction) for the CLT building and 2.46 tC/tC for the modular building (Table 5). Thus, compared with the concrete building design, the modular building design avoided fossil emissions more efficiently than the CLT

Table 4.—Greenhouse gas emissions of raw materials of alternative buildings as kg CO_2 equivalents.

	Emissions per raw material in the reference state (share of the total emissions)			Emissions per raw material with increased recycling (share of the total emissions)		
	Building type			Building type		
Raw material	Concrete	CLT[a]	Modular	Concrete	CLT	Modular
Concrete	511,938 (61%)	40,894 (19%)	40,894 (19%)	430,028 (61%)	34,351 (23%)	34,351 (24%)
Steel	245,140 (29%)	32,445 (15%)	36,565 (17%)	245,140 (35%)	32,445 (22%)	36,565 (26%)
Wood	7,839 (1%)	19,620 (9%)	23,639 (11%)	7,279 (1%)	18,218 (12 %)	21,951 (15%)
Particleboard	8,518 (1%)	0	9,337 (5%)	8,028 (1%)	0	8,800 (6%)
Plywood	945 (less than 0%)	6,584 (3%)	9,135 (4%)	945 (less than 1%)	6,584 (4%)	9,135 (6%)
CLT	0	23,192 (11%)	0	0	23,192 (16%)	0
Glulam	0	4,655 (2%)	901 (<1%)	0	3,103 (2%)	601 (<1%)
Rock wool	13,200 (2%)	38,040 (18%)	12,720 (6%)	2,798 (<1%)	8,063 (6%)	2,696 (2%)
Glass wool	0	0	28,320 (14%)	0	0	6,003 (4%)
EPS	40,623 (5%)	13,442 (6%)	13,442 (6%)	8,010 (1%)	2,651 (2%)	2,651 (2%)
Gypsum	6,644 (1%)	32,252 (15%)	34,133 (16%)	3,844 (1%)	18,659 (13%)	19,747 (14%)
Sum	834,847	211,123	209,086	706,072	147,266	142,499

[a] CLT = cross-laminated timber; EPS = expanded polystyrene.

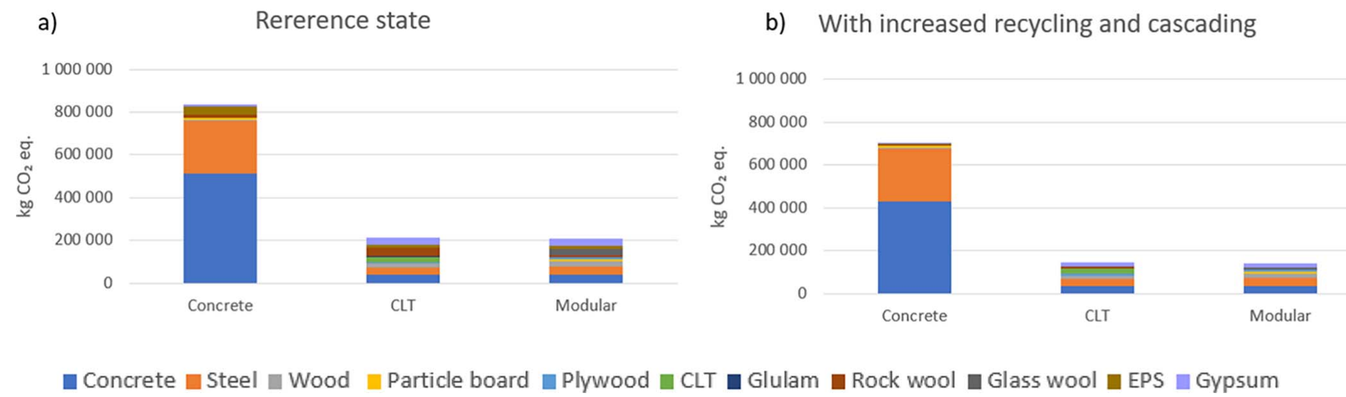

Figure 1.—(a), (b) Greenhouse gas emissions of the buildings.

building design. When increased recycling and cascade use of construction materials was assumed, the GHG emissions of the three buildings decreased, affecting the DFs as well. The DFs of the CLT and the modular building slightly decreased, i.e., the increased recycling and cascade use of construction materials reduced the substitution effect of wood construction regardless of the building design. With increased recycling and cascading assumptions, the DFs for the CLT and modular building were 0.95 tC/tC and 2.26 tC/tC, respectively.

Discussion

Circular use of construction materials and cascade use of wood decreases fossil-based GHG emissions of concrete and wood-based buildings

In the reference situation, the construction materials of the concrete building generated more fossil-based GHG emissions than those of the two alternative wood-based buildings. When the increased recycling and cascade use of wood was assumed, the fossil-based GHG emissions of the construction materials of all three building types decreased 30 to 35 percent. The anticipated emission reductions are likely to be even larger if decarbonization of the energy sector occurs (Myllyviita et al. 2022, Arceo et al. 2023). The absolute fossil-based GHG emission decrease was three times higher for the concrete building than for the wood-based buildings, although the relative decreases were not markedly different between the three buildings. A similar reduction in the embodied carbon intensity was detected by Zhang et al. (2023), who considered a cascading strategy of substituting low-carbon materials, optimizing material use, and using local materials. The review by Zhu and Feng (2024) revealed a slightly larger (50%) reduction in fossil-based GHG emissions through wood material reuse and recycling.

Table 5.—Displacement factors (as tC/tC) for alternative building types with and without increased recycling.

	CLT building replacing concrete building[a]	Modular building replacing concrete building
Reference	1.17 tC/tC	2.46 tC/tC
With increased recycling and cascading	1.18 tC/tC	2.26 tC/tC

[a] CLT = cross-laminated timber.

Although cascade use of wood-based construction materials is assumed to reduce fossil-based GHG emissions of wood-based buildings, it is crucial to acknowledge that cascading can also decrease emissions of concrete buildings. Using wood ash in cement production can decrease the emissions of concrete, reducing the overall fossil-based GHG emissions of the concrete building. This study, however, was based on that assumption that 30 percent of concrete can be replaced with ash, generating an emission reduction of 40 percent. This is a highly optimistic estimation and assumes that the quality of concrete is not deteriorating because of the use of ash. Recycling nonrenewable construction materials can decrease fossil-based GHG emissions of wood-based construction. Using recycled gypsum as a raw material for gypsum boards decreases the fossil-based GHG emissions of wood-based buildings. Also, insulation materials could be replaced with a renewable alternative, both in wood-based and mineral construction (e.g., Schulte et al. 2021). The other selected recycling options considered in this study had only a minor effect on the fossil-based GHG emissions of the three alternative buildings.

The substitution effects of wood use in buildings were slightly decreased when increased recycling of the construction materials was assumed, i.e., in the future there may be less fossil-based GHG emissions to be avoided with wood-based construction if the rate of recycling increases. Although this assessment was based on only three alternative building types and the results should not be generalized to wood construction as a whole, these conclusions can be expected to hold for most building type comparisons if the difference in wood use and concrete use intensity of the buildings being compared is high enough. Substitution effects also are likely to be affected by other factors not considered in this study, e.g., decarbonization of the energy sector, carbon capture and storage (Brunet-Navarro et al. 2021).

Limitations and needs for further research

In this study, only fossil-based GHG emissions were considered; however, when it comes to wooden materials, the consideration of biomass carbon significantly influences the overall GHG balances. This is because tree harvesting temporarily reduces the amount of carbon in forests (Soimakallio et al. 2022). This reduction is often greater than the combined effect of avoided fossil-based GHG emissions from material or energy substitution and carbon sequestration into harvested wood products (Niemi et al. 2025). Therefore, including the effects of tree harvesting on forest carbon balances may result in increasing atmospheric CO_2 concentration over 100 years compared with no increase in wood construction if the extra demand leads to additional harvest. Consequently, these factors should not be equated with the overall GHG emission reduction when replacing one building type with another. However, when virgin wood is replaced with recycled wood, fewer trees could be harvested, enabling more carbon stored in forests. Quantifying the magnitude of this effect would require dynamic modeling of distinct scenarios (Helin et al. 2013, Soimakallio et al. 2025).

According to Helin et al. (2016), avoiding tree harvesting in a year results in a reduced global warming potential over 100 years (GWP-100), which is comparable to avoiding 0.8 to 0.9 units of fossil carbon emission in the same year for each unit of carbon harvested less from forests. This figure should be multiplied by 1.7 to 2.0 to achieve the effect (1.4 to 1.8 tC/tC) attributable to wood materials from virgin wood because roughly one-half of the carbon content of saw logs is converted into wood materials and one-fifth is required for internal energy in producing wood materials, whereas the remainder is available for external energy or materials. Cascading and recycling of wooden materials do not influence HWP (harvested wood product) stocks when replacing materials from virgin wood because they would have provided the same HWP function if they had been produced and used.

The benefits of substituting recycled wood for virgin wood are partly offset by the reduced wood available for energy recovery, an effect not considered in this paper. According to Niemi et al. (2025), the range for substitution credits for energy recovery is approximately 0.3 to 1.0 tC/tC. Consequently, the exclusion of biomass carbon is a more significant factor than the exclusion of energy recovery, implying that the overall benefits of recycling wood could be higher than assessed in this paper.

Recycling of discarded construction materials is focused on downcycling regimes, i.e., they are used for an application of less value than the original purpose of the material (Allwood 2014). However, the switch toward a high-quality recycling scheme appears to provide superior environmental benefits (Di Maria et al. 2018). Although many construction elements are technically reusable, they result in being recycled by crushing or melting (Gobbo et al. 2024). The obstacles prohibiting the reuse of construction materials should be tackled by improving communication between different actors in the value chain and by adjusting legislation to favor reuse (Knoth et al. 2022).

The recycling of concrete and metals is already quite efficient, so the cascade use of wood is a plausible option for further increasing the proportion of recycled construction materials. In this study, it was assumed that structural timber was made of virgin wood, although using recycled wood is possible to some extent. Few studies have estimated the potential to recycle and reuse structural timber. Di Ruocco et al. (2023) estimated the potential of reusable structural building components based on two case study buildings. According to the authors, the quantity of reusable materials of structural building components as new structural building components varied from 40 to 54 percent, whereas the quantity of structural materials based on scrap to be used as structural components varied from 4 to 5 percent. Several limitations are related to the cascade use of wood such as cost-effectiveness, scale, quality, cleanliness, geographical location, legislation, and European Union's target to increase the share of renewable (Kanerva 2015). The greatest cascading opportunities are found in preparing wooden packages and furniture for reuse (Kanerva 2015).

Data availability limits assessing the potential effects of recycling and reuse of building materials. Therefore, an approach based on building typology is commonly used in material intensity studies (also used in this study; Arceo et al. 2023). Applying the building typology approach to a few buildings, which are commonly situated in a narrow geographical area or cover only a short temporal period, is used to represent all buildings in a certain area. Transferring building typologies and material intensities to other locations is the current most practical approach, but it contains uncertainty based on differences, e.g., in local construction methods, availability of materials, climate, building codes, and zoning regulations. Therefore, larger scale efforts to estimate building material intensity to cover more locations and building types should be made so that in the future, studies relying on typology transfer can better quantify the associated uncertainty (Arceo et al. 2023).

Conclusions

The cascade use of wood and recycling of construction materials are promising options for reducing the GHG emissions of both wood-based and mineral construction materials. The results of this study show that the GHG emissions of both wood-based buildings and the concrete building would decrease (30% to 35%), because of increased recycling and cascading. Although the cascade use of wood is typically connected to wood-based construction, cascading can in some cases decrease the GHG emissions of concrete buildings more than those of wood-based buildings, e.g., when displacing cement with wood ash.

In this study, the fossil GHG emissions of the construction materials of the two wood-based buildings were much smaller than those of the concrete building. The substitution effects of wood construction, however, slightly decreased because of increased recycling and cascading, implying that in the future, the avoided fossil GHG emissions via wood use could be slightly smaller, given increased recycling and cascade use of wood. Although the case study was mostly based on Finnish datasets, the results are applicable to other Nordic countries and, to some extent, other Northern regions as well.

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