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ScienceDirect

Energy Procedia 96 (2016) 112 – 123

Energy Procedia

SBE16 Tallinn and Helsinki Conference; Build Green and Renovate Deep, 5-7 October 2016, Tallinn and Helsinki

High-Rise Timber Buildings as a Climate Change Mitigation Measure - A Comparative LCA of Structural System Alternatives

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Abstract

This paper reports on a study examining the potential of reducing greenhouse gas (GHG) emissions from the building sector by substituting multi-storey steel and concrete building structures with timber structures. Life cycle assessment (LCA) is applied to compare the climate change impact (CC) of a reinforced concrete (RC) benchmark structure to the CC of an alternative timber structure for four buildings ranging from 3 to 21 storeys. The timber structures are dimensioned to meet the same load criteria as the benchmark structures. The LCA comprises three calculation approaches differing in analysis perspective, allocation methods, and modelling of biogenic CO_2 and carbonation of concrete. Irrespective of the assumptions made, the timber structures cause lower CC than the RC structures. By applying attributional LCA, the timber structures are found to cause a CC that is 34-84 % lower than the RC structures. The large span is due to different building heights and methodological assumptions. The CC saving per m^2 floor area obtained by substituting a RC structure with a timber structure decrease slightly with building height up to 12 storeys, but increase from 12 to 21 storeys. From a consequential LCA perspective, constructing timber structures can result in avoided GHG emissions, indicated by a negative CC. Compared to the RC structures, this equal savings greater than 100 %.

Keywords: High-rise buildings, timber buildings, LCA, climate change mitigation, CLT

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doi:10.1016/j.egypro.2016.09.112

1. Introduction

In their fifth assessment report [1], the Intergovernmental Panel on Climate Change (IPCC) confirms that there is a 95% probability that human influence is the dominant cause of climate change. The temperature increase needs to be stabilised below 2°C relative to pre-industrial levels in order to prevent severe and irreversible impacts on the climate system. Reaching this target requires an urgent and fundamental departure from business as usual. Alongside reducing anthropogenic greenhouse gas (GHG) emissions to maintain global warming below 2°C, several counteracting trends need to be handled: Rapid population growth, extensive migration to cities and increased levels of wealth for billions of people in developing countries. UN Habitat estimates that 3 billion people will need a new home in the next 20 years [2]. In 2010 buildings accounted for 35% of total global energy use, and 19% of energy-related GHG emissions [3]. This energy use and related emissions may double or potentially triple by 2050 if business as usual is practiced to meet our demands. Consequently, reducing the energy use and climate change impacts of buildings is seen as a critical climate change mitigation measure by the IPCC.

The last decades have seen extensive efforts to increase the efficiency of building operations, to reduce the related energy use and GHG emissions. With reduced energy consumption and GHG emissions in the use phase, the relative contribution from building materials increase. In new energy-efficient buildings, the embodied energy use related to construction, transport and production of building materials and demolition can constitute 40-50 % of the total life cycle energy consumption [4, 5]. The embodied GHG emissions can be even more significant than the embodied energy use [6], due to the hitherto stricter regulations governing renewable energy use in building operation, than in building materials production. Embodied GHG emissions can constitute more than 50-60 % of the total life cycle GHG emissions for modern buildings. EU's revised Directive on Energy Performance of Buildings (EPBD2) states that all buildings shall be built as "nearly zero energy buildings" by 2020. In buildings where the operational energy use is to a large extent balanced by renewable energy production on the building site, embodied energy will account for up to 100 % of net energy consumption. The next step in reducing building sector GHG emissions is thus to minimise energy use related to production and transport of building materials.

The combination of population growth and GHG emission reduction targets stimulates construction of more densely concentrated urban areas with high-rise buildings. Dense cities allow for increased public transportation and less car travel. In addition, denser cities with multi-unit apartment buildings have a reduced energy need for residential heating due to a lower building surface to volume ratio and more shared walls [7, 8]. However, constructing taller comes with a "structural premium": taller buildings require stronger structures, and have greater use of materials per floor area [9]. As an effect, high-rise buildings have higher embodied energy use and GHG emissions per m^2 floor area compared to low-rise buildings. This have been described in the literature as the "energy premium" and the "CO_2 premium" for building height [10-14]. Thus, choosing environmental friendly construction materials is especially important for taller buildings.

Structural systems for high-rise buildings have traditionally consisted of steel and concrete. Production of these materials is energy and emission intensive, and accounts for a great portion of total GHG emissions from materials production in the building sector. Timber building materials prove to cause considerably lower climate change impact (CC) than materials of steel and concrete [15-20]. The interest in multi-storey and high-rise timber buildings has consequently grown around the world, and several structural systems for high-rise timber buildings have been proposed [21-23].

The purpose of this study is to assess the potential of reducing GHG emissions from the structural systems of multi-storey buildings by substituting structures of reinforced concrete (RC) with timber structures. Life cycle assessment (LCA) is applied to compare the CC of a RC structure with a corresponding timber structure, for building heights of 3, 7, 12 and 21 storeys. The CC per m^2 gross floor area (GFA) is plotted as a function of building height for both structural alternatives, to investigate the relation between building height and GHG saving potential. Different methodological approaches are applied in order to get a holistic picture of the CC of the different structural alternatives.

2. Theoretical framework - The climate change impact of building materials

2.1. Timber

Timber materials are often referred to as being «carbon neutral», due to the feature of biomass as a temporary carbon storage. The CO_2 released from biomass due to decay or incineration is referred to as biogenic CO_2 emissions, and was once removed from the atmosphere by the biomass through photosynthesis. However, if the global biomass stock is reduced due to timber production, the biospheric pool of stored carbon will be reduced. This would not result in carbon neutrality, but cause an increased atmospheric CO_2 concentration. Hence, an important prerequisite for climate friendly timber materials is a sustainable harvest where the biospheric carbon pool is maintained.

As long as the biospheric carbon pool is kept constant, the biogenic CO_2 fluxes absorbed from and released to the atmosphere that are initiated from timber production cancel each other out. However, even if a timber product is carbon flux neutral when it comes to biogenic CO_2, GHG emissions will occur during felling, logging and manufacturing of timber products. In addition, *carbon flux* neutral does not necessarily mean *climate change* neutral. While the net CO_2 emission may be zero, the net effect on the radiative forcing can be either positive or negative, depending on the time difference between CO_2 release into and sequestration from the atmosphere [24, 25]. If the release of biogenic CO_2 occurs before the same amount is again sequestered by replanted trees, the related harvest will have caused a temporary increased radiative forcing in the atmosphere. Conversely, if timber production cause sequestration of biogenic CO_2 prior to the corresponding release, the timber products can cause a temporary reduction of the radiative forcing in the atmosphere. When timber is used in long-lived products like building structures, this can be achieved if the rotation period of the tree species used is short enough compared to the lifetime of the building structures.

How to account for biogenic CO_2 emissions in LCA is widely debated. The currently common LCA practice is to assume that biogenic CO_2 emissions are climate change neutral. This practice underestimates the benefit from storing carbon in long-lived products, but overestimates the benefit from short-lived products like biofuel incinerated shortly after harvest [24, 25]

Guest et al. [25] propose a method for calculating the global warming potential (GWP) of biogenic CO_2 emissions from different biomass products, denoted GWP_{bio}. The GWP_{bio} factors are calculated as a function of storage period in the biomass product and the rotation period of the three species used. The temporary perturbation of the atmospheric CO_2 concentration is taken into account by combining the decay function of a pulse emission of CO_2 occurring at the end-of-life (EOL) of the biomass product, with the growth-rate function for the relevant biomass species. The Bern IRF function is used to model the decay of the released CO_2 to the atmosphere. Results show that the GWP_{bio} decrease with shorter rotation periods and longer storage periods, since then atmospheric CO_2 equivalent to the biogenic CO_2 pulse spends shorter time in the atmosphere. If the storage period is too short compared to the rotation period, then the GWP_{bio} has a positive value, meaning that it causes a temporary increased atmospheric CO_2 concentration within the time horizon. However, since a sustainable harvest is assumed, the GWP_{bio} is less than 1 in all cases, showing that it is a better option than fossil CO_2 emissions. The results also show that even if only carbon sequestration occurs within the time horizon, due to a storage period that exceeds the rotation period, the GWP_{bio} values never reach -1. This illustrates an important aspect of including interactions with the global carbon cycle: Due to the carbon exchange mechanisms between the atmosphere and other carbon sinks, the actual CC cannot be found by simply summing all the CO_2 fluxes going to and from the atmosphere within the time horizon. Removing CO_2 from the atmosphere will reduce the rate of carbon uptake by the oceans and terrestrial biosphere, in order to obtain a new equilibrium.

2.2. Concrete and steel

Production of cement is the major source of the energy use and CO_2 emissions related to concrete manufacturing. About 50 % of these emissions stem from fossil fuel combustion, while the rest are caused by release of CO_2 during the calcination of limestone. When exposed to air, concrete will over time absorb some of the CO_2 emitted during the calcination process. This process is termed carbonation and is a very slow process, where CO_2 is re-bound to the calcium compounds in the hardened cement. Carbonation occurs during the entire lifecycle of concrete, and the rate of the reaction depends on several factors, such as the amount of pure clinker in the concrete, density of the concrete and the surface area of the concrete exposed to air. The carbonation rate will be far higher for exposed concrete surfaces that are in direct contact with CO_2 and water than for the interior of the concrete [26].

Demolished concrete, if not landfilled, is usually crushed into recycled aggregate and later used in road construction, as filling in drainage works or reused in production of new concrete. Recycled aggregate is usually stored for 2-16 weeks at the crushing plant before it is used. During this period, the rate of carbonation is substantially higher than during the lifetime of the building [27]. When the crushed concrete is taken into use, the carbonation rate is slowed down again.

Reduction of the environmental impact of concrete is usually related to the clinker production. Since the emissions stemming from the calcination process cannot be avoided, the amount of clinker in the cement has to be reduced. Limestone can be replaced by pozzolans like fly ash, blast-furnace slag or silica dust [28]. Pozzolans can also be added separately to the concrete mix, replacing some of the cement.

Production of steel is causing a great share of the CO_2 emissions in the manufacturing sector, about 27 % [29]. Virgin steel production requires large quantities of coal. Using recycled steel helps reducing the coking coal needed from reduction of iron ore, and is thus widely adopted in steel manufacturing. Most steel construction materials are recovered at the EOL of the building life cycle and used as scrap for production of new steel products. About 85 % of all scrap from construction steel was recycled in 2013 on a global scale [30]. However, since recycled steel is desired for steel production, the current availability of steel scrap is not high enough to meet the demand [31]. This is due to a constant increase in the steel production; since the availability of scrap is dependent on steel production in the past, it cannot follow the demand until the steel production has been stabilised for a certain period. Most of the resent increase in steel production has taken place in fast developing countries like China, where no steel scrap has been available. As long as there is a lack of steel scrap, using scrap in steel production will cause production of virgin steel somewhere else where the scrap could have been used. Thus, it can be argued that the benefit of steel recycling should be given to the producer of steel which make scrap available, rather to the user of scrap.

3. Methods

3.1. The building structures

Material quantity data for the benchmark structures of 3, 7 and 12 storeys are adopted from Ayensu and Jensen [32], and is based on a shearwall framing system in reinforced concrete (RC). Foundations are not included in the original material quantity data, but are added in the current study. For all three structures, a concrete strength of approximately 30 MPa is assumed. Resulting material quantities are summarised in Table 2.

Specifications for the benchmark structure of 21 storeys are based on the hotel part of the building Scandic Lerkendal in Trondheim, Norway. Slabs, columns and structural walls of RC make up the structural system, which includes a basement. The foundations consist of a foundation slab and 400 friction piles of concrete. The building information model (BIM) of the building is used as the data source for material quantities. The average concrete strength for the entire structure is estimated to be 45 MPa by the supplier of the structural system. The amounts of reinforcing steel per m^3 of concrete are based on environmental product declarations (EPD) of precast concrete products delivered by the supplier of the structural system [33-35].

All timber structures are dimensioned to meet the same loading conditions as the benchmark structures. The structures are also designed with the same footprint areas and building heights. The program Sofistik is used to model the loads [36]. The timber structures up to 12 storeys are modelled with a column/beam frame of glue-laminated timber (glulam) combined with mass timber elements of cross-laminated timber (CLT). CLT is used in slabs, shear walls and core walls around the elevator shaft and stairs. The 21-storey timber structure consist of slabs and walls of CLT, glulam beams, and a glulam trusses along the façade. A concrete basement is added to achieve the required wind load resistance. The foundations consist of a 600 mm concrete slab and 120 RC friction piles.

The structures are compared on the basis of load bearing capacity, meaning that only materials needed in the load bearing structure and in the foundations are included in the study. Thus, any extra materials for heat insulation, sound insulation etc. is out of the scope of this study. Flanking sound in timber structures may lead to some extra sound insulation in timber structures compared to concrete structures. However, the embodied GHG emissions for this sound insulation will most likely be small compared to the embodied GHG emissions for the load bearing structures.

Table 1. Building specifications

	3	7	12	21
Location	USA	USA	USA	Trondheim, Norway
Design wind speed	67 m/s	67 m/s	67 m/s	26 m/s
Live load	2.4 kN/m2	2.4 kN/m2	2.4 kN/m2	2-3 kN/m2
Storey height	3.66 m	3.66 m	3.66 m	3.4 m
Building height	12 m	26.5 m	44.8 m	76 m
Gross floor area	2613 m2	6097 m2	10542 m2	11823 m2

Table 2. Material quantity data

Material	RC structures				Timber structures			
	3	7	12	21	3	7	12	21
Concrete C25/30 (m^3)	925	2031	3436	0	23	174	261	718
Concrete C35/45 (m^3)	0	0	0	7186	0	0	0	0
Rebar steel (t)	51	105	186	955	2	24	36	93
Glulam (m^3)	0	0	0	0	78	125	206	234
CLT (m^3)	0	0	0	0	513	1410	2792	4639

3.2. LCA methodology

LCA is a standardised method used to quantify environmental impacts of a product´s life cycle from the extraction of resources, through raw material production, manufacture, use and up to EOL disposal and recycling. The ISO standards provide a framework [37] and rules for calculation [38]. The software tool SimaPro v7 is used to calculate the life cycle resource consumption and emissions of the building materials. Inventory data has been collected from several sources including the Ecoinvent v.3.2 database [39], EPDs, information from manufacturers and other studies. The goal of the LCA study is to compare the environmental impact of RC structures and timber structures, given different sets of assumptions and scenarios. The functional unit is defined to be a building structural system including foundations with a certain load bearing capacity and a given number of storeys, with a 60-year lifetime. Since only the building structures are assessed, and the goal is to compare two material choices, the system boundaries are set to cradle-to-gate. This corresponds to A1-A3 as defined in the standard NS-EN 15643-2 [40]. In a consequential approach, the avoided impacts due to recycling or reuse of materials after EOL are also accounted for (stage D). The impact category assessed is the climate change impact (CC), calculated with the ReCiPe method using the hierarchal perspective [41]. This perspective is based on the most common policy principles regarding time frame (100 years) and impacts considered.

In the current study, three calculation approaches are applied, differing in analysis perspective, handling of biogenic CO_2-emissions, allocation rules and accounting for recycling benefits. For all three approaches, material emission factors are calculated and multiplied with the corresponding material quantities to obtain the total CC for each building structure. Approach 1 follows common EPD practice as given by related standards [42-45]. Approach 2 differ in allocation methods and includes GWP_{bio} factors from Guest, Cherubini and Strømman [25] and carbonation of concrete during the building lifetime. In approaches 1 and 2, all generic data is modelled with the Ecoinvent system model "Recycled content", with allocation by partitioning in multi-output processes and cut-off allocation in recycling chains. Approach 3 is a consequential approach, where impacts from reuse and recycling and carbonation of concrete after EOL are included. Generic processes applied in this approach are based on the consequential system model in Ecoinvent, with substitution by system expansion instead of allocation. All emission factors in approaches 1 and 2 are calculated with a Nordic electricity mix (0.139 kg CO_2-eq/kWh). In the consequential approach, a marginal electricity mix has to be used. It is assumed that in a Nordic market, the marginal mix is a European mix (0.476 kg CO_2-eq/kWh).

The emission factors for both mixes are based on statistics from Eurostat and Entso-e, 2007-2011 [46, 47]. A sensitivity analysis is conducted in approaches 1 and 2 where European or American electricity mixes are used. The emission factor for the American electricity mix (1.1 kg CO_2-eq/kWh) is taken from Ecoinvent. All approaches are summarised in Table 3.

Table 3. Overview of the calculation approaches

	Approach 1	Approach 2	Approach 3
Analysis perspective	Attributional	Attributional	Consequential
Carbonation of concrete	Not included	During building lifetime	Lifetime & after EOL
GWP_{bio}: materials & biofuels	0 & 0	-0.06 & 0.44	-0.06 & 0.44
Ecoinvent system model	Recycled content	Recycled content	Consequential
Allocation in production of wooden products	Partitioning, economy	Partitioning, mass	Substitution
Allocation of coal incineration to fly ash	No	Partitioning, economy	No
Allocation of benefits from steel recycling	To the user of scrap	To the user of scrap	To the producer of scrap
Electricity mix	Nordic	Nordic	EU
System boundaries	A1-A3	A1-A3	A1-A3 + D

3.3. Assumptions for the different building materials

The timber is assumed to stem from a sustainable harvest where the biospheric carbon pool is kept constant. The LCI data for the timber materials are based on data from Norwegian forestry and timber producers, collected and quantified in the Norwegian MIKADO project [48]. The project used average data for spruce and pine collected from several forestry production chains and sawmills, and specific data for a Norwegian producer of mass timber. Most of the emissions in the forestry supply chain stem from fossil fuel use by harvester machines and the transport trucks. In the rest of the supply chain up to factory gate, electricity use is the main contributor to resource use and emissions.

In the current study, several allocation methods are applied in multi-output processes in the timber production chain. In approach 1, allocation methods are based on product category rules (PCR) for building materials [43]. Economic partitioning is applied to allocate impacts between residues and timber products. Mass allocation is applied between different timber products of which the difference in economic value is low. In approach 2, mass allocation is applied in all cases. Since approach 3 is a consequential approach, substitution is used. It is assumed that 90 % of all residues except cellulose fibres are incinerated to replace natural gas. After deconstruction of the building, 90 % of the timber materials are assumed to be incinerated with heat recovery to replace natural gas.

Biogenic CO_2 emissions are treated climate change neutral in approach 1. In approaches 2 and 3, a GWP_{bio} factor of -0.06 is applied to the biogenic CO_2 emissions from the timber materials, corresponding to a rotation period of 100 years and a storage period of 60 years [25]. In addition, a GWP_{bio} factor of 0.44 is applied to all biogenic emissions stemming from incineration of biofuel. This corresponds to a 100-year rotation period and no storage, assuming that the biofuel is incinerated shortly after harvest. The factor is applied to all bioenergy used as input in the timber production, and to the emissions occurring when residues from the timber production is incinerated to replace natural gas. Even though the system boundaries are set to cradle-to-gate, the biogenic CO_2 emissions from incineration of timber materials at EOL are accounted for; by applying the GWP_{bio} factor to the CO_2 content of the timber materials, both the uptake and the release of biogenic CO_2 is included in the resulting CC. Excluding the release of the biogenic CO_2 emissions would give a biased result, indicating that the timber materials are causing a permanent CO_2 removal.

In modelling the emission factors for steel and concrete, three different production scenarios are applied, due to a large variety in production technologies. The scenarios are shown in Table 4. The concrete emission factors are based on processes in the Ecoinvent library, and modified according to electricity mix and fly ash content. The carbonation uptake is calculated according to Pommer and Pade [49]. The carbonation uptake is dependent on cement content in the concrete mix, exposure and geometry of the concrete structure, and is therefore calculated or each of the structures. After deconstruction, 90 % of the concrete is assumed to be crushed into aggregate. The remaining 10 % is lost during the recovery and recycling process. The aggregate is assumed to be exposed to air for 4 months, before it replaces natural gravel in new concrete production or as filling in belowground applications. The increased carbonation during the 4-month exposure period is accounted for in stage D. This stage also contains avoided impacts from extraction of natural gravel and impacts from crushing of concrete into gravel size. These impacts are calculated according to Wahlström et al [50], excluding transport between the crushing facility to the final utilization site due to uncertain data. The impact of crushing concrete into aggregate is almost as high as the impact of extracting gravel, hence the net benefit is very small.

Table 4. Overview of the production technology scenarios applied for steel and concrete emission factors

	PA Reference scenario	PB Worst-case scenario	PC Best-case scenario
Concrete	5 % fly ash	no fly ash	30 % fly ash
Rebar steel	80 % scrap content	16 % scrap content	100 % scrap content

Table 5. Material emission factors for concrete and steel applied in the current study, by calculation approach and production technology scenario. The carbonation uptake displayed yields for the 12-storey structure for C25/C30 and the 21-storey structure for C35/C45. *Contribution from fly ash* shows the resulting emissions from allocating impacts from burning of coal to the fly ash.

Contribution to CC		Approach 1			Approach 2			Approach 3		
		PA	PB	PC	PA	PB	PC	PA	PB	PC
Concrete C25/30 (kg CO_2-eq/m^3)										
A1-A3	Excluding fly ash emissions	291	383	207	291	383	207	293	377	203
	Contribution from fly ash	0	0	0	7	0	44	0	0	0
	Carbonation through lifetime	0	0	0	-26	-34	-16	-26	-34	-16
D	Carbonation after crushing	0	0	0	0	0	0	-35	-46	-21
	Net benefit from recycling	0	0	0	0	0	0	-0,07	-0,07	-0,07
Total		291	383	207	272	349	235	231	297	167
Concrete C35/45 (kg CO_2-eq/m^3)										
A1-A3	Excluding fly ash emissions	326	433	228	326	433	228	343	444	239
	Contribution from fly ash	0	0	0	8	0	51	0	0	0
	Carbonation through lifetime	0	0	0	-22	-29	-14	-22	-29	-14
D	Carbonation after crushing	0	0	0	0	0	0	-45	-59	-27
	Net benefit from recycling	0	0	0	0	0	0	0	0	0
Total		326	433	228	312	404	265	276	356	199
Rebar steel (kg CO_2-eq/kg)										
A1-A3		0.89	2.21	0.48	0.89	2.21	0.48	2.97	2.97	2.97
D		0	0	0	0	0	0	-0.65	-0.65	-0.65
Total		0.89	2.21	0.48	0.89	2.21	0.48	2.32	2.32	2.32

The steel emission factors are modelled with Ecoinvent processes and modified according to scrap content and electricity mix. Rebar steel is commonly produced with a large share of steel scrap, and thus 80 % and 100 % scrap is assumed in the reference and the best-case scenario, respectively. The worst-case scenario is based on a global average rebar steel product from Ecoinvent with 16 % scrap. In approach 3, the availability of steel scrap is taken into account. Since there is a current lack of steel scrap, the benefit from recycling is allocated to the producer of steel as a benefit obtained after EOL (stage D). It is assumed that whenever a steel product is demanded, this result in production of some virgin steel, i.e. the global steel production mix is maintained. The recycled content in all scenarios is consequently assumed equal to the share of scrap in the global production mix. At EOL, it is assumed that 90 % of the steel is recycled and replaces the global average steel mix in 2076. According to Pauliuk et al. [31], the global mix in 2016 and 2076 respectively, contains approximately 30 % and 60 % steel scrap. Where the steel scrap is used is not important in a consequential approach, and thus equal emission factors are obtained for all production scenarios.

Table 6. Material emission factors for glulam and CLT. *Biogenic CO_2 materials*: Biogenic CO_2 emissions from incineration of building materials at EOL. *Biogenic CO_2 bioenergy*: Biogenic CO_2 emissions from bioenergy used in the production chain for the timber products. *NG replaced by residues*: The natural gas replaced by incineration of residues from felling, logging and manufacturing. *Incineration of residues:* Biogenic CO_2 emissions from incineration of the residues to replace the natural gas. *NG replaced by materials*: The natural gas replaced by incineration of the timber materials at EOL.

Contribution to CC	Glulam (kg CO_2-eq/m^3)			CLT (kg CO_2-eq/m^3)		
	Approach 1	Approach 2	Approach 3	Approach 1	Approach 2	Approach 3
Biogenic CO_2 materials	0	-44	-44	0	-47	-47
Biogenic CO_2 bioenergy	0	113	105	0	121	112
Fossil fuels	91	87	131	104	99	147
NG replaced by residues	0	0	-322	0	0	-343
Incineration of residues	0	0	118	0	0	125
NG replaced by materials	0	0	-596	0	0	-634
Total	91	156	-608	104	173	-640

4. Findings

Table 7 shows the resulting CC per gross floor area (GFA) for the benchmark structures and the timber structures. For all analysis perspectives and production technology scenarios, the timber structures cause a substantially lower CC than the benchmark structures. The smallest difference between timber and concrete occurs for the 12-storey structures constructed with the best-case concrete and steel materials, when approach 2 is applied. Still, the CC in this case is 34 % lower for the timber structure. In approach 1, substituting a RC structure with a timber structure will on average cause a 70 % lower CC, based on all scenarios and building heights. This average saving is smaller in approach 2 due to the inclusion of GWP_{bio} factors: 56 %. In approach 3, the CC for all timber structures is negative, due to the avoided emissions from replacement of natural gas by incineration of bioenergy and timber materials. This leads to savings greater than 100 % compared to the RC structures.

Fig. 1 illustrates the CC/GFA of all structures in the reference scenario as a function of building height (A), and the saving of CC/GFA obtained by constructing a timber structure instead of a RC structure in each case (B). For the benchmark structures, the CC/GFA decrease slightly by building height up to 12 storeys, due to a decrease of structural materials per GFA. From 12 to 20 storeys the use of structural materials per GFA increase rapidly, and the CO_2 premium emerge. For the timber structures, the CO_2 premium is somewhat evident already from 3 storeys in approaches 1 and 2. However, the CO_2 premium from 12 to 21 storeys is substantially lower for the timber structures than the concrete structures. This cause the GHG saving potential to decrease from 3 to 12 storeys, but increase from 12 to 21 storeys. In approach 3, the opposite of a CO_2 premium occur for the timber structures: the CC/GFA decrease with building height. In the consequential perspective, greater use of timber materials per m^2 floor area is equivalent to a greater amount of avoided GHG emissions due to substitution of natural gas by biofuel from timber waste.

The CO_2 premiums for the two structural alternatives is dependent on the structural premiums, and reflect how the structural material quantities per m^2 increase or decrease with building height. In addition, the material choices affect the steepness of the CO_2 premium curves; materials with more GHG emissions lead to steeper curves. Consequently, there are two reasons for why the timber structure outperform the concrete structure with respect to the CC: Firstly, the timber structure consists of materials with lower emission factors. Secondly, the structural premium for the timber structure is smaller from 12 to 21 storeys. However, the material emission factors are of greatest importance.

Table 7. CC per m^2 GFA for all structures in reinforced concrete (RC) and timber (T). The saving shows the GHG emissions saved if a timber structure is constructed instead of a RC structure, relative to the emissions caused by the RC structure.

	Storeys	CC/GFA (kg CO_2-eq/m^2)								
		Reference scenario			Worst-case scenario			Best-case scenario		
		RC	T	Saving	RC	T	Saving	RC	T	Saving
App. 1	3	120.5	26.3	-78 %	179.1	27.9	-84 %	82.8	25.3	-69 %
	7	112.3	37.8	-66 %	165.8	45.7	-72 %	77.3	33.8	-56 %
	12	111.6	40.0	-64 %	165.3	46.8	-72 %	76.7	36.4	-52 %
	21	270.1	67.3	-75 %	441.8	83.2	-81 %	177.7	59.0	-67 %
App. 2	3	114.7	41.6	-64 %	168.1	43.1	-74 %	93.2	41.0	-56 %
	7	105.8	54.6	-48 %	154.1	62.1	-60 %	86.5	51.9	-40 %
	12	105.4	59.3	-44 %	154.1	65.8	-57 %	85.9	56.9	-34 %
	21	261.7	94.7	-64 %	424.1	109.7	-74 %	200.4	89.1	-56 %
App. 3	3	127.9	-140.3	-210 %	151.1	-139.7	-193 %	104.8	-140.9	-234 %
	7	117.0	-144.7	-224 %	138.5	-142.8	-203 %	95.4	-146.5	-254 %
	12	117.3	-169.1	-244 %	139.0	-167.4	-220 %	96.0	-170.7	-278 %
	21	355.2	-230.8	-165 %	403.8	-226.8	-156 %	308.2	-234.8	-176 %

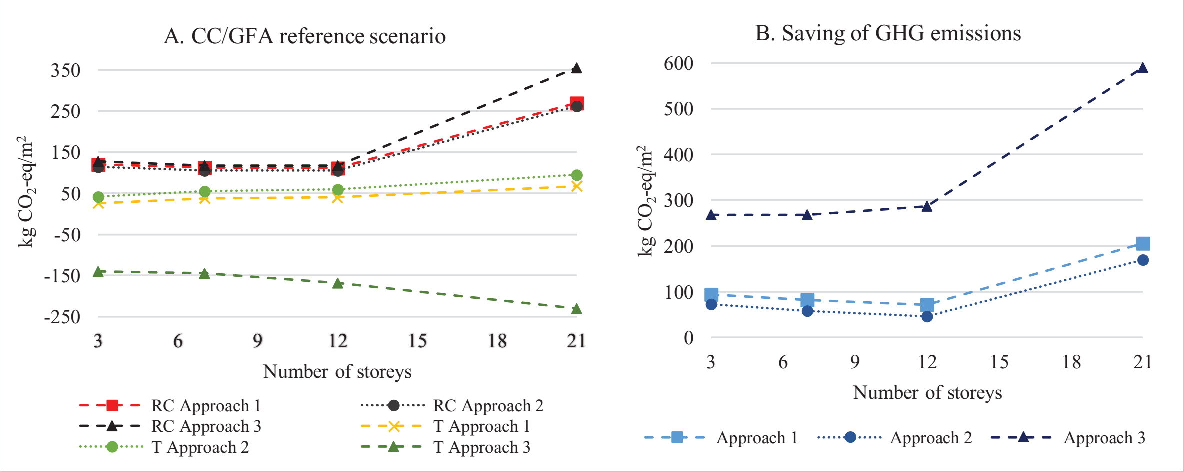

Fig. 1. A: Comparison of CC per m^2 GFA for reinforced concrete (RC) and timber (T), by building height and calculation approach for the reference scenario. B: absolute saving of CC/GFA by substituting RC structure by a timber structure for the reference scenario.

Figure 2 and 3 shows the total CC for the 21-storey timber and the 21-storey RC structures, respectively. The CC is broken down into contribution from the different parts of the supply chains, according to the divisions shown in Table 5 and 6. Negative values means that GHG emissions are avoided as a result of activities related to the structures.

For the timber structures, the biogenic CO_2 emissions from incineration of biofuels increase the CC substantially when the GWP_{bio} factor is applied. This increase is larger than the decrease caused by the negative GWP_{bio} factor for the timber materials, resulting in a net increase of the CC from A1-A3 of about 40 %. In approach 3, the avoided emissions from replacement of natural gas by incineration of bioenergy and timber materials are larger than the emissions from the production of materials for the timber structure, resulting in a net negative CC. When it comes to stage D, the total net avoided GHG emissions for the concrete structure are considerably smaller than the net avoided GHG emissions for the timber structures. Hence, the climate change mitigation potential of substituting concrete structures with timber structures is larger seen from a consequential analysis perspective.

It is important to note that the dimensioning wind load is far greater for the buildings up to 12 storeys than for the

21-storey building. If all structures were dimensioned for the same wind load, the building structures up to 12 storeys would require less materials. Hence, the difference in CC between the buildings up to 12 storeys and the 21-storey building would most likely be higher.

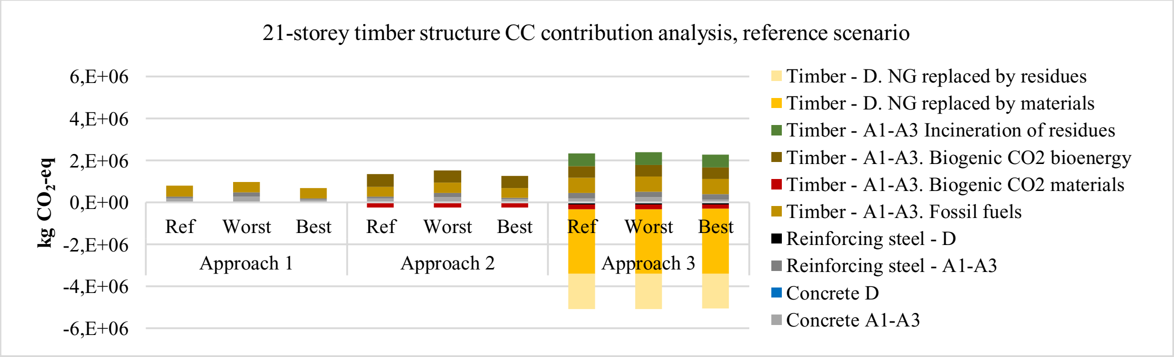

Fig. 2. The resulting CC for the 21-storey timber structure, by contribution from the different stages in the life cycle.

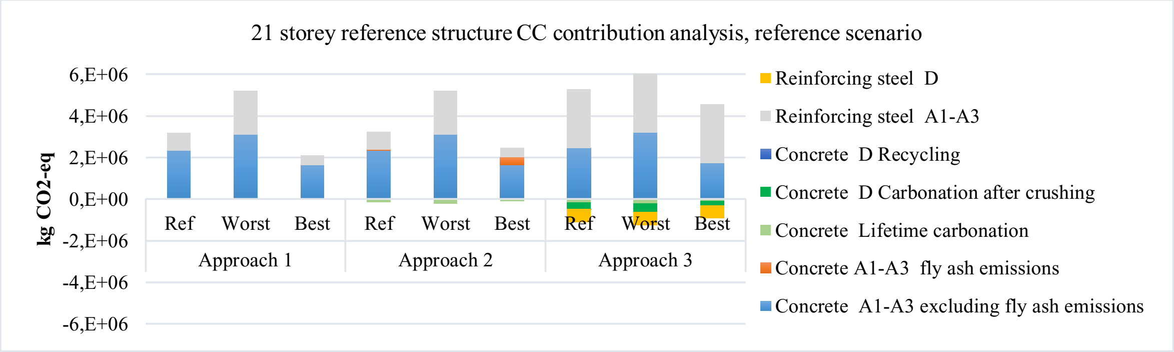

Fig. 3. The resulting CC for the 21-storey RC structure, by contribution from the different stages in the life cycle.

All emissions are calculated with a Nordic electricity mix in approaches 1 and 2, and a European mix in approach 3. This is done to isolate the effects of the methodological choices. However, the climate change impact for the building structures will vary considerably with the electricity mix used in the production of the materials. Thus, the climate change impact of each structure is also calculated with European and American electricity mixes in approaches 1 and 2, and with American mix in approach 3. When the EU mix is applied, the CC saving obtained by substituting a RC structure with a timber structure decrease on average by 9 % in approach 1, and 8 % in approach 2. Still, the average saving is a 61 % lower CC in approach 1 and 48 % lower in approach 2. When the American electricity mix is used, the saving potential decreases by 16 % on average in both approaches 1 and 2, still leaving a saving potential of 45 % in approach 1 and 31 % in approach 2. For one case, the calculated CC is 6 % higher for the timber structure than the concrete structure: for the 12-storey buildings when approach 2 and the best case scenario for production of concrete and steel is applied. However, when the benefits from reuse and recycling is included in approach 3, the timber structures are outperforming the concrete structures for all cases, also for the 12-storey building. With the American electricity mix, substituting a concrete structure with a timber structure can still save 2 times the emissions caused by the concrete structure.

5. Discussion

The results obtained in this study yield for theoretical building structures dimensioned on a conceptual level. Environmental impacts of structural systems can vary substantially according to structural detailing and geographical location. The location will both determine the load resistance criteria for the structures and the production technologies and thus emission factors for the building materials. Since the structures analysed in the current study are dimensioned for different locations, the relations obtained for CC/GFA as a function of building height are not suitable to generate a general function, but are rather meant to show the trends. Further research should include LCAs of specific as-built multi-storey timber buildings to get more certain data.

The findings analysed are representative for a Nordic market, or material production technologies corresponding to a Nordic electricity mix. The sensitivity analysis reveal that with European or American average electricity mixes, the CC will in general be higher for all structures. The timber structures are more affected by higher emission factors for the electricity mix, due to a larger share of electricity used as input compared to the steel and concrete. However, there are still large potentials in saving GHG emissions by substituting steel and concrete structures with timber structures.

6. Conclusion

LCA is used to compare the climate change impact of reinforced concrete structures to corresponding timber structures in a Nordic market, for building heights of 3, 7, 12 and 21 storeys. The CC is calculated with three different calculation approaches. The relation between building height and the potential of reducing GHG emissions by substituting RC structures with timber structures is examined by comparing the CO_2 premium for building height for the two structural alternatives. The results show that constructing building structures with timber materials instead of steel and concrete can reduce the CC of the building sector, with the underlying assumption of sustainable harvest. If 90 % of timber production residues and timber material waste is incinerated with heat recovery to replace natural gas, the consequence of constructing a timber structural system is a negative CC. The timber structures can cause from -140 to -235 kg CO_2-eq/m^2 floor area in a consequential analysis perspective, depending on building height. The absolute saving of GHG emissions in this analysis perspective range from 246 to 634 kg CO_2-eq/m^2. If the benefits of reuse and recycling are excluded, and the structures are analysed with an attributional approach, the timber structures cause from 34 % to 84 % lower CC than the RC structures, depending on building height and production technologies applied. The absolute CC reduction obtained by substituting a RC structure with a timber structure per m^2 decrease with building height from 3 to 12 storeys, but increase with building height from 12 to 21 storeys, except from in the consequential approach where it increase all the way. Despite the methodological differences, the timber structures cause lower CC than the benchmark structures for all structures, in all approaches and scenarios.

Acknowledgements

The structural dimensioning of the timber structures has been conducted by structural engineer Mia Nilsson from Asplan Viak AS. The authors would also like to acknowledge the valuable expertise, inputs and guidance from Dr.-Ing Sigurdur Gunnarsson, Mie S. Fuglseth, Oddbjørn Dahlstrøm and Christian Solli.

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