Carbon dioxide balance of wood substitution: comparing concrete- and wood-framed buildings

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Abstract

In this study a method is suggested to compare the net carbon dioxide (CO_2) emission from the construction of concrete- and wood-framed buildings. The method is then applied to two buildings in Sweden and Finland constructed with wood frames, compared with functionally equivalent buildings constructed with concrete frames. Carbon accounting includes emissions due to fossil fuel use in the production of building materials, the replacement of fossil fuels by biomass residues from logging, wood processing, construction and demolition, carbon stock changes in forests and buildings, and cement process reactions. The results show that wood-framed construction requires less energy, and emits less CO_2 to the atmosphere, than concrete-framed construction. The lifecycle emission difference between the wood- and concrete-framed buildings ranged from 30 to 133 kg C per m^2 of floor area. Hence, a net reduction of CO_2 emission can be obtained by increasing the proportion of wood-based building materials, relative to concrete materials. The benefits would be greatest if the biomass residues resulting from the production of the wood building materials were fully used in energy supply systems.

Keywords

carbon dioxide, building materials, wood, concrete, forest industry, greenhouse gas balance, biomass, biofuels

1. Introduction

The growing concentration of atmospheric carbon dioxide (CO_2), contributing to global climatic change, is a long-term and large-scale problem (Houghton et al. 1996; IPCC 2001). Strategies to address this issue include reducing fossil fuel emissions and increasing carbon sinks. Forests and forest products can play an important role both as means to reduce emissions and to increase sinks. Forest sector activities can influence carbon fluxes directly by storing carbon in forests or forest products and by substituting fossil fuels with bioenergy, or indirectly by using wood products in place of more greenhouse gas-intensive materials like steel, aluminium and concrete (Schlamadinger and Marland 1996). Although fossil CO_2 emission also occurs during the lifecycle of wood fuels and materials, substituting wood in place of other materials reduces emission, compared to the baseline of using other materials. In this study we integrate the direct and indirect effects of substituting wood in place of concrete by evaluating the carbon stock changes and fossil fuels used in material production and use, as well as incorporating the byproducts of wood materials, such as logging, processing, construction and demolition residues, into energy supply systems to replace fossil fuels.

Increasing the use of wood material in construction is a potential option for reducing net CO_2 emission because of the relatively low energy needed to manufacture wood products compared with alternative materials, the storage of carbon in wood building materials, and the increased availability of biofuels from wood byproducts. Using biomass for direct substitution of fossil fuels or fossil fuel-intensive materials is an important means of reducing greenhouse gas emissions as it provides permanent and cumulative reduction in CO_2 emission, whereas sequestration or conservation of carbon is typically limited or temporary (Schlamadinger and Marland 1996). The relation between bioenergy and an increased use of construction wood is complex, and its analysis is important for our understanding of the net CO_2 emission reduction from substituting wood in place of other materials.

The potential supply of wood raw material for substitution in Europe is large. Wood harvested in Europe in the mid 1990s was about 60% of the net growth increment of European forests, leaving an unused increment of about 300 $Mm^3\ y^{-1}$ over bark (UNECE/FAO 2000). In Finland and Sweden the figures are 20.2 $Mm^3\ y^{-1}$ (73%) and 28.1 $Mm^3\ y^{-1}$ (71%), respectively. Furthermore, continuation of the current harvesting levels would change the age class structure towards older age classes and the growth increment would decline in the long run (Nabuurs et al. 2002). If harvesting levels are increased, age class structure would change towards younger age classes and growth increment would increase. This would further increase the substitution potential. Intensification of forest management on at least part of the forest area through, e.g. fertilization or choice of tree species, would further increase the increment and the substitution potential, within ecological constraints (Börjesson et al. 1997). However, the substitution potential is not directly proportional to the growth increment. The benefit derived from fuel and material substitution is also related to the wood quality and the kind of products and services that can be obtained from the harvested wood. In principle, greater emission reduction can be obtained if the lifecycle of a wood product is extended by cascading, in which both material *and* fuel substitution are utilized (Dornburg 2004).

Maximization of wood substitution can also conflict with attempts to optimize the use of forests and forest products for carbon sequestration. Normally, the maximization of (time-averaged) carbon stocks in a system composed of managed forest ecosystems and solid wood products leads to a longer forest rotation period with lower biomass production and lower substitution potential. The relation between rotation period and maximal carbon stock is complex, however, and prolonging the rotation period can in some cases lead to smaller soil carbon stocks (Liski et al. 2001). In any case, carbon sequestration is a limited option because it can reduce the net CO_2 emission only as long as the carbon stocks in a forest area are increasing. Saturation of biomass stocks will eventually take place, and the stock level must then be preserved to avoid any release of stored carbon. The same conditions apply to stocks of wood products. Substitution, on the other hand, is a sustainable option that can be utilized continuously, leading to permanent and cumulative emission reductions.

In this study, the linkage between wood building materials, bioenergy systems, and net CO_2 emission is explicitly considered. Previous studies have examined the CO_2 emission of building material production (e.g. Buchanan and Honey 1994), and others have explored the potential for substitution of fossil fuel by biomass fuels (e.g. Gustavsson et al. 1995). Few studies have directly considered the relation between wood building production and bioenergy systems, and its impact on carbon flows. Fossdal (1995) included sawmill residues used for kiln drying of lumber in his study of emissions from building material production. CO_2 emission of wood building materials calculated by Buchanan and Levine (1999) assumed a percentage of process energy input to have been supplied by wood residues. Koch (1992) showed wood structural systems to use less energy and emit less CO_2 than alternative materials, based on a 1976 study that included heat energy values of sawmill residues. The Consortium for Research on Renewable Industrial Materials (CORRIM) found concrete- and steel-framed houses to use 16 and 17% more total energy, respectively, than equivalent wood-framed houses. Because much of the energy for the wood-framed house is produced internally from wood processing, the concrete- and steel-framed houses used 2.5 and 2.8 times more non-bioenergy, respectively. CO_2 emission was lower for the wood-framed houses due to C storage in wood products and reduced use of fossil fuels (Lippke et al. 2004). Scharai-Rad and Welling (2002) considered the utilization of demolition wood to replace fossil fuels, and found environmental performance, including net greenhouse gas emissions, of buildings to be more favourable as the volume of recovered wood increased.

Börjesson and Gustavsson (2000) found net CO_2 emission to be lower for wood-framed buildings than for concrete buildings, when considering forest and sawmill residues as well as demolition waste as substitutes for fossil fuel. Pingoud and Perälä (2000) estimated the maximum wood substitution potential in new building construction in Finland. The total amount of materials used during one year in 11 main building parts in new construction of 9 main building types was estimated. An expert judgement was performed, where the commercial potential for increased wood use in each building part was assessed. The results indicated that nearly twice as much wood material could have been used in Finland in 1990 compared to the amount that was actually used. With each kg of additional wood material used, the use of masonry materials could have been reduced by 3.6 kg and the use of metals reduced by 0.1 kg. Such a substitution, including the displacement of fossil fuels by wood residues from sawmills and construction sites, would have reduced fossil CO_2 emission by about 1 Tg or 1.8% of total Finnish CO_2 emission in 1990. Furthermore, sawn wood typically requires less processing energy than other wood products such as paper and panels (Pingoud 2001; Pingoud and Lehtilä 2002). From a climate change mitigation perspective it would thus be beneficial to choose the less energy-intensive wood products to fulfil a given service demand, although demand for the various products has so far been largely independent of CO_2 implications.

2. Accounting of net CO_2 emission

Here we suggest a method to estimate the net CO_2 emission from the construction of wood- and concrete-framed buildings. We then apply the method to buildings in Sweden and Finland. We include the use of fossil fuels in the production of the building materials, the substitution of fossil fuels by biomass fuels, changes in biomass carbon stocks in forests and building materials, and chemical reactions in the production and use of cement. Carbon fluxes are quantified at Year 0 when the materials are produced and the buildings constructed. Fluxes that occur gradually during the assumed 100-year life span of the buildings are also calculated, as are fluxes related to the demolition of the buildings at Year 100. The total fluxes occurring from Years 0 to 100 are then summed to yield the total net CO_2 flux during the building lifecycle. We do not distinguish between CO_2 emissions that occur at different times.

A basic task in the substitution analysis is to define a functional unit to allow objective comparison of the energy inputs and CO_2 outputs of alternative scenarios. In this study the reference entity is the physical enclosure provided by a multi-storey apartment building over its lifespan. We consider one wood-framed building known as *Wälludden*, which was constructed in Växjo, Sweden, and another wood-framed building built in the *Viikki* ecological area of Helsinki, Finland. The lifespan of the buildings is assumed to be 100 years, based on Nordic conditions. Buildings are typically renovated after about 50 years and can then be used for another 50 years. The primary energy use in renovation is assumed to be the same regardless of the building frame material used (Cole and Kernan 1996).

When distinguishing between buildings with frames made of wood and concrete, it must be recognized that a structural frame of a certain material does not imply that the entire building is constructed of that material. Wood-framed buildings contain substantial amounts of concrete (e.g. in foundations), and concrete-framed buildings contain substantial amounts of wood (e.g. in roof framing, doors and windows). In addition, wood-framed buildings may require large amounts of plasterboard to cover the wooden framing. The objective of material substitution is not therefore to completely replace one material with another, but to favour the use of one material over another in cases where either material could practically be used. Because different materials fulfil various architectural and engineering requirements to differing degrees, studies of the energy and environmental impact of material substitution must examine the functional unit from a system perspective.

We compare the two wood-framed buildings described above to hypothetical buildings of identical size and functionality constructed with concrete frames. We define the baseline as the net CO_2 emission from the concrete-framed versions of the buildings. The fossil-fuel substitution impact is the difference in net CO_2 emissions between the wood-framed building and the concrete building over their lifecycles, resulting from fossil fuel used for material production and biomass used to replace fossil fuel. The biological carbon sequestration impact is the difference between the carbon stocks in the wood-framed building and the concrete-framed building (see Section 2.4). The benefit from carbon sequestration occurs only once, when a wood-framed building first replaces a concrete-framed one, and continues as long as the wood-frame building is replaced by a new building with identical carbon content. Substitution impact benefits occur when the wood-framed building first replaces the concrete-framed one, and then every time the old wood-framed building is replaced by a new wood-framed building instead of a concrete-framed one.

To consider the effect of forest management on the carbon balance of the baseline concrete-frame building, we include the same amount of forestland within the system boundaries regardless of the frame material. That area is determined by the forestland required to produce the lumber, plywood and particleboard used in construction of the wood-framed building. Because the concrete-framed building uses less wood, some of the forest is not needed for material production. We call this area "surplus forest" and we consider two alternative scenarios for it. In one scenario, the surplus forest is harvested at Year 0 and used to replace fossil fuels. In the other scenario, the surplus forest is left untouched and allowed to remain standing during the lifecycle of the building. These are further discussed in Section 2.4.

2.1 Energy demand and supply for material production

The energy demands of building material production, and the characteristics of the system used to supply the required energy, largely determine the CO_2 emission from the production of the material. Different physical processes can be used to produce the same material, each with unique requirements and effects on the environment. The efficiency of industrial technologies has generally improved over time resulting in differences in energy requirements and emissions between materials processed by state-of-the-art technologies and those made in older factories. Variation is also seen geographically, as technological innovations diffuse across countries and regions. For example, Richter (1998) has shown a large variability in cumulative energy demand for wood-based products in different studies, and Josa and colleagues (2004) have shown a large range of energy use and CO_2 emission in cement production in the European Union.

The data used in this study to calculate the final-use energy needed to produce building materials are primarily based on a study by Fossdal (1995). These relatively recent Norwegian data are internally consistent and geographically close to Finland and Sweden, although some data could be country specific. We modified Fossdal's data to include the energy required to crush aggregate for concrete, and we assumed the energy used for plywood manufacture (not included in Fossdal's study) is equal to that of particleboard manufacture. The end-use energy data are divided into the use of electricity, fossil fuels and biofuels. This breakdown gives flexibility when studying the effects of variation of electricity supply systems and replacement of fossil fuels. We calculate the total primary energy use for the production of materials by taking into account the efficiencies of fuel cycles and conversion and distribution systems. Hence the entire energy chain is considered in the analysis, from the natural resources to the produced electricity, heat and transportation fuels, including the extraction, transportation, distribution and refining of fuels. We assume the end-use fossil fuel used in material production to be oil, with a specific carbon emission of 22 kg C/GJ (Gustavsson et al. 1995). The fuel-cycle efficiency, when considering energy inputs and losses along the fuel chain from natural resource to combustion, is assumed to be 94.5% (Fossdal 1995).

The net flow of CO_2 to the atmosphere resulting from building construction is affected by the supply system used to provide electrical energy for the production processes. Several types of electrical energy production systems exist with significant variations in associated greenhouse gas emissions, and the systems evolve over time. The geographical scale of analysis is important, particularly if the power production systems vary between countries and the national electricity markets are integrated, as is the situation in Europe. About half of the electricity produced in the European Union (EU-15 countries) in 2001 was based on fossil fuels, 33% on nuclear power, 13% on hydropower and 1.5% on biomass. In Sweden, about 4% was based on fossil fuels, 45% on nuclear power, 49% on hydropower and 2% on biomass. In Finland, about 40% was based on fossil fuels, 31% on nuclear power, 18% on hydropower and 11% on biomass (European Commission 2003).

New investments in energy systems will further influence the power production and should be evaluated in terms of the total lifetime of the investments. This is a complex issue. The energy plants that are currently being constructed may be used until 2040 or even longer. Stand-alone coal-fired power plants, which are currently the dominant marginal electricity production method in northern Europe, are likely to be replaced during that period. Decarbonisation and CO_2 sequestration in large-scale, fossil fuel-fired plants may be important issues in greenhouse gas emission reduction during such a long period (Herzog et al. 2000; Moomaw and Moreira 2001). Natural gas-fired power plants have a high conversion efficiency, which in combination with the low carbon content of the fuel, means that such plants have significantly lower CO_2 emission than coal-fired plants. Hence, from a greenhouse gas perspective natural gas-fired, stand-alone power plants, perhaps combined with CO_2 capture and storage, may be used for marginal electricity production in the future, depending on the development of technology and the need to reduce greenhouse gas emissions. From an energy diversity and security point of view, however, coal-fired power plants might be used in the coming 40-50 years for marginal electricity production in Europe.

In this study we examine two different scenarios, using coal-fired and natural gas-fired condensing plants for electricity generation. The coal-fired plant represents current marginal production in northern Europe while the natural gas- or coal-fired plants represent possible future situations. The end-use efficiencies of coal-fired and natural gas-fired condensing plants are assumed to be 40% and 50%, respectively. Electricity distribution loss is assumed to be 2%. Specific full-fuel-cycle CO_2 emission from fossil fuel used for electricity generation is assumed to be 18 and 30 g C/MJ for natural gas and coal, respectively (Gustavsson et al. 1995). Calculations of primary energy for electricity generation assume fuel cycle efficiencies of 90% for coal and 95% for natural gas.

Adalberth (2000) found building assembly activities to use less than 10% of the energy used to manufacture the materials of the Wälludden building. Scheuer et al. (2003) assumed construction energy use to equal 5% of the embodied energy of the construction materials used. Cole (1999) also showed that the overall contribution of the on-site construction phase of the building's lifecycle is small in relation to the total energy use and emissions. Here, we assume the energy requirement for and carbon emission resulting from the on-site construction of the buildings do not differ between the concrete- and wood-framed versions, and we do not included them in the analysis.

The energy use in operating the buildings and the related emission of greenhouse gases are not included in this analysis. These parameters are not expected to differ significantly between buildings constructed with a wood frame and with a concrete frame. Adalberth (2000) has calculated the difference to be less than 1% for the Wälludden building. The energy use in operating the building is clearly dominant over the energy use in the production of building materials, hence lowering the operating energy is important. The Wälludden building was constructed according to the Swedish building code, which requires energy-efficient buildings. Still, the energy use in operation of the building could be reduced by e.g. heat recovery of exhaust air and improved thermal performance of windows (Adalberth 2000).

2.2 Substitution of fossil fuels

We assume that logging and processing residues and wood-based construction and demolition waste are used to replace fossil fuels. Several issues concerned with methodology and assumptions arise when comparing fossil- and bioenergy-based systems (Gustavsson et al. 2000). What type of fossil system would be replaced, and what type of bioenergy system would be used to replace the fossil system? More broadly speaking, how should fossil- and bioenergy-based systems be compared? The choice of systems influences the results and must therefore be made bearing in mind the geographical boundaries and time perspective of the study, which determine the prerequisites for the technologies that should be included in the analysis. Using an existing, old fossil fuel-based system as the reference system may favour wood fuel-based systems, while the optimal solution might be a combination of modern fossil and wood fuel-based energy systems. When considering new investments in supply systems, for example as a result of increasing energy demands or the need to replace existing supply systems, a resource- and cost-efficient supply system with a minimum of greenhouse gas emissions might be the logical fossil fuel-based reference system (Schlamadinger et al. 1997).

Here we use a simplified approach. The energy conversion efficiency is assumed to be unchanged when coal is replaced by biomass, and 4% lower when natural gas is replaced by biomass. These are average values for various conversion technologies, and we make no distinction between thermal, electrical and cogeneration use of fuels (Gustavsson and Johansson 1994). The CO_2 that would have been emitted by the replaced fossil fuels is then calculated for the entire fossil fuel cycle, including end-use emission as well as from energy used for fuel extraction, conversion and distribution. Fossil fuel emissions replaced by logging and sawmill residues and building construction waste are assigned to Year 0 accounts, and those replaced by demolition waste are assigned to Year 100 accounts.

To determine the link between wood used as construction material in the buildings and the availability of biomass as an energy source, we developed a relation based on tree growth characteristics and the material conversion efficiencies of harvesting and processing practices. First, the masses of the different wood-based products used in the finished buildings (lumber, plywood and particleboard) are adjusted to include the waste generated during construction, here assumed to be 10% for all wood products. Wood losses occurring between the primary wood processor and the construction site, for example in secondary wood processing industries that manufacture doors and windows, are not included in this analysis. These losses, described in Sections 3 and 5, may be significant and will be integrated into this model in the future. Next, the wood product masses are adjusted for their assumed water content (15%) and the proportion of wood in the finished product (100% for lumber, 90% for plywood and particleboard). Then, the amount of roundwood under bark needed to produce these amounts of products is calculated, based on a breakdown between end product and mill residue of 49% end product, 51% chips and sawdust. We assume particleboard is produced from residue from lumber production.

The amount of living tree biomass corresponding to the required roundwood volume is calculated using biomass expansion factors (BEF) that distribute total tree biomass between stem, bark, foliage, stump and roots (Lehtonen et al. 2004). The BEFs for 100-year old trees of the two most prevalent Nordic softwood trees, Scots pine and Norway spruce, are averaged to yield 53% of the biomass in stemwood under bark, 5% in bark, 20% in foliage and branches, and 22% in the stumps and roots.

Of this total amount of biomass, part can be practically recovered for energy generation. This is shown schematically in Figure 1, and the recovery percentages and the assumed moisture content and heat values of the biofuels are shown in Table 1. Characteristics of additional biofuel assumed available when surplus forest from concrete-framed buildings is harvested for biofuel are also shown. The available bioenergy is obtained by multiplying the recoverable biomass by its respective heat value. To account for the biomass energy used internally in the lumber production process for kiln-drying, a deduction in available energy is made of 2.07 MJ per kg of lumber used in the buildings (Fossdal 1995). We assume that wood-based construction materials recovered during demolition at the end of the buildings' lifecycle are used for energy. To account for practical on-site limitations of wood recovery during demolition, we assume that 90% of lumber, plywood and particleboard is recoverable. This recovery percentage is likely to be achieved and perhaps exceeded in the future as the value of wood as an energy source is more widely recognized, and as more buildings become designed and constructed in ways that facilitate deconstruction to allow greater recycling and reuse of building materials.

The recovery and transportation of biomass fuels require an energy input. We quantified this energy as a percentage of the heat energy content of the biomass recovered, as shown in Table 1. Calculations of CO_2 emissions resulting from this activity are based on the use of diesel fuel over the entire fuel cycle.

Figure 1. Schematic flow chart of wood materials during the building lifecycle

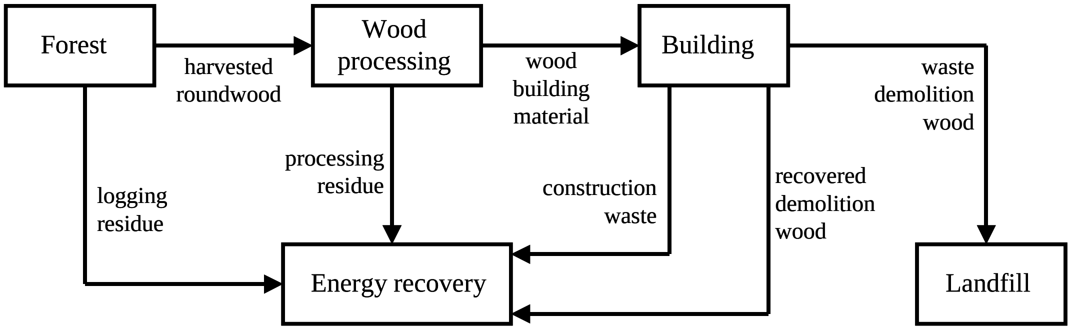


Table 1. Amounts and properties of recovered biofuels. Energy for recovery and transport is expressed as percent of heat value of biofuel recovered.

Source	Recovery (%)	Moisture Content (%)	Heat Value (MJ/kg dry biomass)	Recovery/transport energy [a] (% of heat value)
Wood Product Production				
Roots and stumps	0	-	-	-
Branches, foliage, tops	70	60	15.3	5
Bark	100	60	15.3	1
Processing residues	100 [b]	50	16.6	1[c]
Construction waste	100	15	18.6	1
Demolition wood	90	15	18.6	1
Surplus Forest for Bioenergy				
Roots and stumps	0	-	-	-
Bark	100	60	15.3	3[d]
Stemwood	100	60	15.3	3[d]
Branches, foliage, tops	70	60	15.3	5

[a] Based on Börjesson (1996) and authors' estimates

[b] Includes processing residues not used for process energy (see Table 3) or particleboard raw material (see Table 4)

[c] Energy used to harvest and transport logs to sawmill is included in specific energy use data for wood products (Fossdal 1995)

[d] Includes chipping

2.3 Net CO_2 emission from cement reactions

CO_2 is released during the manufacture of Portland cement, when calcium carbonate is heated and broken down into calcium oxide and CO_2. Cement production is the largest source of non-energy-related industrial emission of CO_2. Approximately 0.5 tonnes of CO_2 is released for each tonne of cement produced (IPCC 1996). Some of this CO_2 is later taken up again by the cement over a time scale of years to centuries due to carbonation. In this chemical reaction, calcium hydroxide in the hydrated cement reacts with atmospheric CO_2 to form calcium carbonate and water (Illston and Domone 2001). Carbonation is generally considered to be an undesirable effect, because it lowers the pH of the cement matrix, which may lead to corrosion of the steel reinforcement and spalling of the concrete. It is, however, not entirely detrimental, because the carbonation process increases the strength and reduces the porosity of the concrete in the carbonated zone. In this study, data for the initial release of CO_2 during cement production are based on Fossdal (1995). We then assume that 8% of this amount is re-fixed by carbonation of the concrete material during the 100-year lifecycle of the buildings (Gajda 2001).

2.4 Carbon stock change and carbon sequestration in wood products

Changes in biomass carbon stock are considered in terms of the wood biomass in the materials of the wood-framed buildings, and the total forest biomass needed to produce these end-use products. At Year 0, the amount of wood in the building materials is subtracted from the total forest biomass required to produce these materials, to yield the net carbon stock change. This assumes that all biomass that is not sequestered in the buildings is either burned or decays during Year 0. This is not strictly true, as some forest residue, e.g. roots and stumps, may require many years for decomposition and some fraction may be sequestered as soil organic carbon for long periods. We assume that the timing of decomposition does not affect the validity of the life-cycle emission results, and that the amount of long-term sequestered carbon is negligible.

We assume that at Year 100 the forest that was harvested at Year 0 has completely re-grown, consistent with Nordic forestry practice using an average 100-year rotation period. We thus assume that all the carbon released during the initial harvest will have been re-fixed by forest regrowth by the end of the building's lifecycle. Meanwhile, the carbon that had been locked up in the wood building materials is assumed to be released at demolition at Year 100 through burning and decomposition. Thus, the net carbon stock is unchanged between the beginning and end of the lifecycle: the forest that is cut at Year 0 re-grows by Year 100, and carbon stored in wooden building materials at Year 0 is released at Year 100.

In the calculations of carbon stock changes of concrete-framed building construction we take into account the surplus forestland. As the area of forestland needed to produce the wood products for the wood-framed building was included in the system boundaries of each comparison, some surplus forest biomass remains unused when the building frame is made of concrete. We considered two alternative scenarios for the surplus forest. In one scenario, it is assumed to remain untouched. The forest is assumed to be 100 years old when the buildings are constructed (Year 0), and the biomass in the untouched forest continues growing during the next 100 years until the end of the building's lifecycle. We assume the carbon stock of that portion of the forest increases by either 0% or 50% between Years 0 and 100 (as the trees increased in age from 100 years to 200 years old). The increase in forest biomass is accounted in the carbon stock at Year 100. Forest growth from age 100 to 200 will depend on many factors, including species composition. Norway spruce trees may not survive to age 200, so the biomass of forests composed primarily of this species will increase little during this period (Isomäki 2004). Scots pine trees can continue growing to age 200, so the biomass of these forests will continue to increase. We address this variability by considering biomass increase of either 0% or 50% in untouched forests from age 100 to age 200. However, regardless of the biomass increase during the building lifecycle, and in the absence of natural or anthropogenic disturbances such as insects or fires, eventually the carbon stock in the forest stand will reach equilibrium where natural death and decomposition equals new growth. Hence, the biomass continuously accumulated during tree growth will be lost through decay or combustion.

In the other scenario, we assume that the surplus biomass is harvested at Year 0 and used to replace fossil fuels. The forest re-grows over the following 100 years, and the net carbon stock is unchanged between the beginning and end of the lifecycle, as described above. This scenario illustrates the potential carbon balance impact of harvesting surplus forest for use as fuel, although using stemwood from long-rotation forestry is typically not used for energy purposes due to economic considerations.

Our assumption of equal forest area being available for both the wood- and concrete-framed buildings, and the resulting consideration of surplus forest of the concrete-framed building, serve to quantify the carbon balances of the buildings under different forest management strategies. The actual use of forest land will depend on the competing demands for the various products and services that forest can provide. This study addresses the carbon balance impact of several micro-level factors: whether an individual building is built of wood or concrete, and the alternative uses for the forest if the building is built of concrete instead of wood. On a macro-level, additional study is needed to determine the aggregate impact of a large-scale increase in forest biomass demand, not only for building material but also for fuel, paper, carbon storage and ecological services.

As noted above, the change in carbon stock of wooden construction materials is zero over the lifecycle of the building, thus having no net effect on atmospheric carbon balance. However, a carbon sequestration effect could occur if a permanent change were made from concrete- to wood-framed construction. This would be the case if a concrete building, representing the baseline, were replaced by a wood-framed one, which after demolition is always replaced by a new wood-framed building with a similar carbon stock. This would result in a permanent step change in carbon stock (i.e. carbon sequestration) compared with the baseline, at the point in time when concrete is replaced by wood.

3. The Wälludden and Viikki buildings

The Wälludden project is a 4-story building containing 16 apartments, with a total usable floor area of 1190 m^2. It is one of the first multi-story buildings constructed in Sweden after the building code was changed in 1994 to allow wooden-framed buildings higher than two floors (Bengtson 2003). The foundation consists of concrete slabs. Two-thirds of the facade is plastered with stucco, while the facades of the stairwells and the window surrounds consist of wood panelling. The outer walls consist of three layers, including plaster-compatible mineral wool panels, 120 mm thick timber studs with mineral wool between the studs, and a wiring and plumbing installation layer consisting of 70 mm thick timber studs and mineral wool. The floor frame is made of light timber joists, consisting of several layers to provide a total thickness of 420 mm. All rooms except the bathrooms have parquet floors. The amount of construction materials required to make the Wälludden building with a wood-frame and a concrete-frame is based on Adalberth (2000, 2002).

The Viikki building is a 4-story apartment block built in 1997 in the ecological building area of Viikki in Helsinki, Finland. The building considered in this study contains 21 apartments with a total usable floor area of 1175 m^2. It has prefabricated load-bearing wooden wall framing, with facade materials of mostly sawn wood products with 150 mm mineral wool insulation. The internal wall cladding is mainly plasterboard. The foundation is constructed of hollow core slabs, base beams and pile footings, all in concrete. Flights of stairs include potstone slabs and glue-laminated boards. The intermediate floor framing is made of plywood and sawn wood balks with mineral wool insulation, covered by parquet except in bathrooms. The total floor thickness is 400 mm. Roof structures are sawn wood, plywood and steel sheet with 222 mm mineral wool insulation. This wood-framed building was compared with a similar, but hypothetical, building constructed conventionally in concrete. The concrete building includes concrete sandwich elements and hollow core slabs. VTT Building and Transport calculated the building materials required in the equivalent concrete building (Perälä 2004).

Some parts of the Viikki building are assumed to be identical in both the wood and the reference concrete building, and are therefore not included in the material comparison. These materials include wooden windows, doors, fittings, and HVAC systems. These building parts represent a minor portion of the total amount of materials used in the Viikki building, and have no impact on comparisons between the wood framed building and its concrete reference. Material input calculations for the Wälludden building include all materials, including parts identical in both the wood-framed and concrete-framed versions. Therefore, comparisons of net CO_2 emission should not be made between the Wälludden and the Viikki buildings, but instead between the wood-frame and concrete-frame version of each building. The calculated amounts of materials used in each version of the Wälludden and Viikki buildings are shown in Table 2.

Table 2. Comparison of materials (tonnes of air-dry material) contained in the studied buildings. The data for the Viikki building exclude wooden windows, doors, fittings and HVAC systems, which are assumed to be identical in the wood- and concrete-framed building.

Material	Wälludden		Viikki	
	Wood frame	Concrete frame	Wood frame	Concrete frame
Lumber	59	33	103	23
Particleboard	18	17	27	9
Plywood	21	20	15	0
Concrete	223	1,352	190	2,014
Blocks	4	4	0	0
Mortar	24	23	0.1	0.1
Plasterboard	89	25	139	22
Steel	16	25	19	16
Copper/Zinc	0.6	0.6	0	0
Insulation	21	25	23	9
Macadam	315	315	15	0
Glass	4	4	0	0
Paper	2	2	0.1	0
Plastic	2	2	2	2
Putty/Fillers	4	4	11	14
Paint	1	1	8	0.4
Ceramic tiles	1	1	0	0
Porcelain	0.6	0.6	0	0
Appliances	3	3	0	0

To account for waste material generated during construction of the buildings, the material amounts in the finished buildings (Table 2) were increased on a percentage basis. The amount of building waste typically varies between materials, and also varies between construction sites. Björklund and Tillman (1997) provide a survey of building waste percentages typical of Swedish construction sites. We base our waste percentage values on their figures, assuming 1.5% concrete waste, 7% insulation waste, 10% plasterboard and wood waste, and 15% steel reinforcement waste. For all other materials we assume 5% waste, except macadam and sanitary ware for which we assume 0% waste. Our calculations consider the recovery of wood waste for use as a substitute for fossil fuels, described in Section 2.2. Transportation, disposal or recycling of non-wood waste materials is not considered in this study. The waste percentages we assume are representative of material waste generated on the building site during construction. Additional waste can also be produced at secondary material processing industries that provide manufactured products to the building site, such as doors, windows and glue-laminated beams. Further work is required to quantify this waste and assess its impact on greenhouse gas balances.

4. Results

4.1 Energy balances of buildings

Based on total material mass inputs for the buildings, and specific energy demand data for the manufacture and transportation of building materials based primarily on Fossdal (1995), we calculated the total final-use energy needed to provide the building materials. We then calculated total primary energy use for the building materials (Table 3) by taking into account efficiencies of fuel cycle, conversion and distribution systems. The additional materials needed due to construction waste are reflected in these figures, and in all subsequent calculations. Biofuels shown are those used internally in the lumber production process for kiln drying. Calculations of CO_2

emissions from the production of building materials are based on energy use figures summarized in Table 3.

Table 3. Primary energy use (GJ) for production and transportation of building materials for the Wälludden and Viikki buildings with wood and concrete frames, divided into end-use electricity, end-use fossil fuels, and end-use biofuels.

	Final-use	Distribution	Conversion	Fuel Cycle	Total
Wälludden					
Wood-frame					**2330**
Electricity	311	6	476	79	873
Fossil Fuel	1251	0	0	69	1320
Biofuel	137	0	0	0	137
Concrete-frame					**2972**
Electricity	408	8	624	104	1144
Fossil Fuel	1661	0	0	91	1752
Biofuel	76	0	0	0	76
Viikki					
Wood-frame					**2907**
Electricity	383	8	586	98	1075
Fossil Fuel	1512	0	0	83	1595
Biofuel	237	0	0	0	237
Concrete-frame					**3205**
Electricity	372	8	569	95	1043
Fossil Fuel	2000	0	0	110	2110
Biofuel	52	0	0	0	52

The production of biofuels derived from forest harvesting, wood-product manufacture, building construction and the later demolition of the buildings is shown in Table 4. For comparison, the heat value of the lumber residue used to make particleboard is also shown. More biofuels are available from residues of the wood-framed building materials than from the concrete-framed building materials. Use of the surplus forest for bioenergy makes the total biofuel amounts approximately the same for the two buildings. The amount of wood processing residue used to make particleboard is small in relation to the total amount of biofuel available for all the buildings.

Table 4. Production of biofuels (GJ) derived from wood product manufacture and demolition of the Wälludden and Viikki buildings with wooden frames, the corresponding buildings with concrete frames when the surplus forest (SF) is untouched, and with concrete frames when the surplus forest is used for bioenergy. For comparison, the heat value of wood processing residue used to make particleboard is also shown.

	Wälludden			Viikki		
	Wooden-frame	Concrete-frame (SF-untouched)	Concrete-frame (SF-bioenergy)	Wooden-frame	Concrete-frame (SF-untouched)	Concrete-frame (SF-bioenergy)
Forest residues	593	383	1474 [a]	876	172	3821 [a]
Processing residues	1113	649	649	1606	255	255
Construction waste	171	122	122	250	55	55
Demolition waste	1480	1037	1037	2187	483	483
Total biofuels	3357	2191	3282	4918	964	4614
Particleboard	289	281	281	428	146	146

[a] including stemwood from the surplus forest

4.2 Net CO_2 emission at Year 0

The net CO_2 emission at Year 0 takes into account activities that occur when the buildings are first constructed. These include emissions from fossil fuel used for the production of the materials, process reactions from cement manufacture, substitution of fossil fuel by forest and sawmill residues and construction waste, and carbon stock changes due to the cutting of the forest and construction of the buildings. We calculated net CO_2 emissions for the wood-framed buildings, and for the concrete-framed buildings assuming that the surplus forest land is untouched or used for bioenergy. We assumed that electricity for material production is generated by either coal- or natural gas-fired condensing plants, and that biomass fuel replaces either coal or natural gas. Net CO_2 emission is positive in all scenarios, because of the large emission from forest harvesting and fossil fuel use in material production (Table 5). The total net CO_2 emission at Year 0 is slightly more favourable when the Wälludden building is built with a wood frame, and when the Viikki building is built with a concrete frame and the surplus forest is left untouched. This difference results from the different proportional use of concrete and wood in the two buildings, which may result from different building practices, architectural and engineering traditions, etc. The net CO_2 emission at Year 0 is highest for both buildings when built of concrete and the surplus forest is used for bioenergy.

If electricity is generated by natural gas-fired condensing plants, and biomass fuels are assumed to replace natural gas instead of coal, the effect of fossil fuel substitution and the emission from material production are lower because natural gas is less carbon intensive than coal. However, the pattern of differences between the buildings, and the relative ranking of Year 0 net CO_2 emissions between the different scenarios, are the same as when coal is considered as the fossil fuel.

Table 5. Net emissions of CO_2 (expressed in tonnes of C) for the Wälludden and Viikki buildings constructed with wooden frames, and with concrete frames where surplus forest is either untouched or is harvested for bioenergy. Either coal or natural gas (NG) is used to generate electricity for material production, and is the fossil fuel replaced by recovered biofuel. Year 0 is when the building is constructed. Building lifecycle begins in Year 0 and continues for 100 years thereafter. Negative entries represent avoided net emission to the atmosphere.

			Wälludden						Vikkii			
	Wooden-frame		Concrete-frame (SF-untouched)		Concrete-frame (SF-bioenergy)		Wooden-frame		Concrete-frame (SF-untouched)		Concrete-frame (SF-bioenergy)	
	coal	NG	coal	NG	coal	NG	coal	NG	coal	NG	coal	NG
Year 0												
Fossil fuel for material production	51.3	39.0	67.7	51.5	67.7	51.5	62.6	47.3	72.4	57.7	72.4	57.7
Cement reactions	4.3	4.3	22.7	22.7	22.7	22.7	3.1	3.1	33.0	33.0	33.0	33.0
Replacement of fossil fuel by biomass	-56.7	-32.2	-34.8	-19.8	-67.9	-38.5	-82.5	-46.9	-14.5	-8.3	-125.1	-70.7
Forest stock change	144.3	144.3	93.1	93.1	144.3	144.3	212.9	212.9	41.7	41.7	212.9	212.9
Building stock change	-40.3	-40.3	-28.2	-28.2	-28.2	-28.2	-59.5	-59.5	-13.1	-13.1	-13.1	-13.1
Total	103.0	115.1	120.5	119.3	138.7	151.8	136.7	157.0	119.4	110.9	180.2	219.7
Lifecycle (Years 0-100)												
Fossil fuel for material production	51.3	39.0	67.7	51.5	67.7	51.5	62.6	47.3	72.4	57.7	72.4	57.7
Cement reactions	4.0	4.0	21.0	21.0	21.0	21.0	2.9	2.9	30.4	30.4	30.4	30.4
Replacement of fossil fuel by biomass	-101.2	-57.7	-66.0	-37.7	-99.1	-56.3	-148.3	-84.6	-29.1	-16.6	-139.6	-79.0
Forest stock change	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Building stock change	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	-45.9	-14.8	22.7	34.8	-10.3	16.2	-82.8	-34.4	73.8	71.5	-36.7	9.0

4.3 Net CO_2 emission for 100-year lifecycle

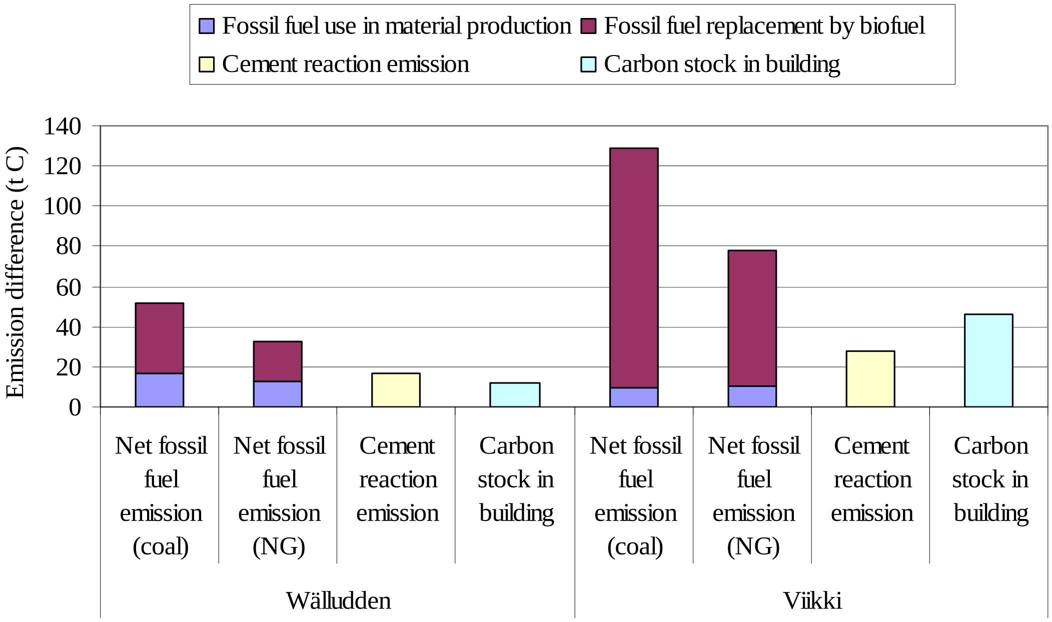
Net CO_2 emission for the 100-year lifecycle of the buildings includes all the emissions from Year 0, plus other emissions and carbon stock changes occurring during the rest of the building's lifecycle. This includes re-growth of the forest, uptake of CO_2 by cement carbonation reactions, demolition of the buildings, and substitution of fossil fuel by wood-based demolition waste.

The wood-framed buildings have the lowest lifecycle carbon emissions, with net carbon emissions of –46 to –83 tonnes when electricity is generated by coal-fired condensing plants and biomass fuels replace coal (Table 5). When natural gas is the fossil fuel considered, the wood-framed buildings have lifecycle net emissions of –15 to –35 t C. The concrete-framed buildings where the surplus forest is untouched, assuming 0% growth of the surplus forest during the building lifecycle, have much lower substitution of fossil fuel, and high fossil fuel use in the manufacture of materials. Per square meter of usable floor area, the difference between the wood- and concrete-framed buildings is 58 kg C/m^2 and 133 kg C/m^2 for the Wälludden and Viikki buildings, respectively, when coal is the fossil fuel considered. If surplus forest is used for bioenergy the concrete-framed buildings have negative net emissions. The substitution of fossil fuel has a similar pattern to that of the wood-framed buildings, but more fossil fuel is used in manufacturing the concrete materials so their lifecycle net CO_2 emission is less negative than for the wood-framed buildings. The difference between the wood- and concrete-framed buildings is 30 kg C/m^2 and 39 kg C/m^2 for the Wälludden and Viikki buildings, respectively, when coal is the fossil fuel considered. If the surplus forest is untouched and increases in biomass by 50% during the 100-year lifecycle, the uptake of carbon by forest biomass will result in net lifecycle C emissions of –3 and –12 tonnes for the concrete-framed versions of the Wälludden and Viikki buildings, respectively.

The ranking of the different scenarios is the same in both the Wälludden and Viikki buildings, with the wood-frame building having the lowest net lifecycle CO_2 emission, followed by the concrete-frame building when surplus forest is used for bioenergy, while the concrete-frame building with untouched surplus forest has the highest net lifecycle CO_2 emission. The differences in values that exist between the Wälludden and Viikki buildings result from the different absolute quantities of materials used, and from the different proportions of materials used in each building. These variations are introduced by the different architectural and engineering designs of the buildings. In addition, the material accounting used in this study included all materials used in the Wälludden building, but ignored some materials in the Viikki building that did not differ between the wood- and concrete-framed versions.

In Figure 2 the emission differences between the wood-framed and concrete-frame versions of the buildings are shown. Differences in emissions due to fossil fuel use, fossil fuel replacement by biofuel, and cement process reactions are compared to the carbon sequestration in wood building materials as defined in section 2.4. The carbon stock change is 18% and 30% of the substitution impacts from fossil fuel and cement reaction of the Wälludden and Viikki buildings, respectively, assuming coal is used for electricity generation for material production and if recovered biofuels replace coal. The corresponding figures using natural gas are 24% and 44%.

Figure 2. Differences between the wood- and concrete-framed versions of the buildings in net fossil fuel emission (assuming either coal or natural gas is used for electricity generation for material production and if recovered biofuels replace either coal or natural gas), cement process reaction emissions, and carbon stock in wood building materials. Surplus forest in concrete-framed case is not included.



5. Uncertainties

The change in net CO_2 emission due to the substitution of construction materials will depend on the magnitudes and interactions of a number of variables. Some of these variables have not been precisely measured and others vary with place, time and process technology, so aspects of uncertainty are inevitable in such an analysis and must therefore be recognized.

Each type of building constructed is unique, and is made of a mix of materials of varying qualities and quantities. Different architectural and engineering solutions can achieve the same or similar function using different material mixes and building designs, and hence with different primary energy uses and net CO_2 emission. What is of critical interest then is not the exact results specific to these two buildings, which may not be identical to any other building to be constructed, but instead an appreciation of the advantages that can be gained as wood is increasingly used instead of concrete in building design.

Primary energy use in material production processes will also vary. Different physical processes can be used to produce the same material, and the efficiency of many industrial processes has improved over time. Different production technology is used both within and between different geographic regions. Nevertheless, Gustavsson and Sathre (2005) varied numerous parameters representing process efficiency of both wood and concrete production, and found wood construction to consistently use less energy and emit less CO_2 than concrete materials.

Because electricity is a major form of end-use energy in building material production, the carbon intensity of the method of generating electricity will affect the net CO_2 emission of the construction. Likewise, the carbon intensity of the fossil fuel assumed to be replaced by the biomass by-products of wood building materials will affect the outcome of a substitution analysis. However, while the characteristics of the reference fossil system affect the absolute extent of the emission reduction, the wood-frame construction gives lower net CO_2 emission than the concrete-frame scenarios regardless of which fossil fuel is replaced.

The reduction in net CO_2 emission will depend in part on the percentage of total biomass residue that is recovered for energy production. Sources of biofuels include logging, processing, construction and demolition residues. Utilization of logging residues is subject to ecological constraints involving nutrient cycling and organic matter content of soils, but can make a significantly contribution to energy supply (Lundborg 1998; Börjesson et al. 1997). It also requires the logistical capability to efficiently collect and transport the residues, which is currently being developed in several countries including Sweden and Finland. The use of sawmill residue is more widespread, and our assumption of 100% utilization of bark, chips and sawdust is valid for wood processing industries in Scandinavia. The amount of construction waste depends on a variety of factors including the design of the building, the size and quality of materials supplied to the construction site, and the craftsmanship of the construction personnel. Additional waste material can be produced by secondary material processing industries that provide manufactured products to the building site. Utilization of wood-based demolition waste has the potential to increase (Thormark 2001), particularly if greater attention is paid during building design and construction to facilitate disassembly, thus allowing greater reuse and recycling of materials (Kibert et al. 2002). Policy measures including landfill dumping fees and regulations can also affect the amount of wood that is recovered from building demolition sites and reused. Energy recovery from non-reusable wood is expected to increase, because it is not resource-efficient to landfill combustible wood while at the same time extracting and burning fossil fuels.

The decomposition dynamics of unburned biomass is subject to uncertainty. Roots and stumps remain in the forest after harvesting, and some demolition wood might not be recovered and instead be deposited in landfills. The rate and type of decomposition of unburned biomass, and the effect on greenhouse gas balances, are influenced by many factors and cannot be precisely modelled (IPCC 2000; Micales and Skog 1997). Some wood biomass deposited in landfills may form a permanent carbon stock, for example the lignin fraction of wood under anaerobic conditions. Other wood fractions under the same conditions can produce methane, a gas with higher radiative efficiency but shorter lifetime than carbon dioxide. However, as the percentage of demolition wood that is recovered for energy increases, this issue will become less significant. Roots and stumps comprise 22% of the total forest biomass modelled in this study, thus their decomposition may affect the final greenhouse gas balance. However there should be little difference between the balances of the wood- and concrete-framed buildings, particularly if the surplus forest is harvested for bioenergy.

6. Conclusions and discussion

In this study we suggest a method to compare the net CO_2 emission from the construction of concrete- and wood-framed buildings. Using this method we investigated the primary energy use and net CO_2 emission for two buildings in Sweden and Finland, made with wood frames compared with functionally equivalent buildings made with concrete frames. The results show that the production of materials for wood-framed construction requires less energy, and emits less CO_2 to the atmosphere, than the production of materials for concrete construction.

This study shows the importance that fossil fuel substitution has on total net CO_2 emission. Over the lifecycle of wood-framed buildings, the substitution potential of logging, processing, construction and demolition residues is greater than the fossil energy inputs to material production, leading to negative net CO_2 emission. The advantage of wood over concrete construction depends strongly on the percentage of biomass residues recovered for fossil fuel substitution. More logging residues might be removed from the forest, subject to ecological constraints involving nutrient cycling and organic matter content of soils. This action may cause decreased soil carbon stock, however, adding another dynamic element to the long-term carbon balance. More wood-based construction waste might be recovered during building demolition, particularly if greater attention is paid during building design and construction to facilitate disassembly, allowing greater reuse and recycling of materials. The heat energy value of the raw material used for particleboard production is small compared with the total heat energy in all recovered biofuels, suggesting that there is no significant trade-off between material and energy uses of wood-product residues. The magnitude of the difference in carbon balance between wood- and concrete-framed buildings will vary with the carbon intensity of the fossil fuel considered. The relative advantage of wood over concrete construction is greater when coal is replaced than when a less carbon-intensive fuel is replaced.

Uncertainties remain in accurately determining the primary energy use in building material production, and how that use varies with time, place, and process technology. Further uncertainties exist regarding the time dynamics of biomass growth and decomposition in forests, and how this may affect the results of this study. Nevertheless, we do not expect these uncertainties to affect the fundamental conclusions of this study.

The carbon stock of wood products in the building is of minor importance to the lifecycle net CO_2 emission. During a building's life span the stock could be significant, but over the complete lifecycle the change in carbon stock will be zero. If the total stock of wood-framed buildings is expanding the carbon stock in the buildings will increase as long as more wood is added through new constructions than is taken away due to demolition of buildings. Hence, the permanence of the carbon stock in buildings depends on the difference between the increase in the amount of wood in new construction and the decrease in the amount of wood from demolished buildings. The only significant (permanent) stock change occurs when there is a change from concrete construction to wood construction, and to preserve this stock change in the future a wood-framed building must always be replaced by another wood-framed building with a similar carbon stock.

This study suggests that a net reduction of CO_2 emission can be obtained by increasing the proportion of wood-based materials used in building construction, relative to concrete materials. On a marginal scale this emission reduction can likely be achieved at zero cost, because wood-framed buildings are economically competitive with apartment buildings (Persson 1998) and single family houses (Lippke 2004) made with concrete frames. An important topic for future development is to better understand how wood-framed buildings can be most effectively designed and constructed so as to minimize net CO_2 emission, within the technical restrictions imposed by architectural and engineering requirements and the economic constraints of competitiveness with other materials.

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