A state-of-the-art review of energy and climate effects of wood product substitution

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Summary

In this report we address multiple aspects of wood substitution, which can be defined as "any use of wood that replaces other inputs of production in providing equivalent service or function." We focus on wood product substitution, or the use of wood to replace other materials such as concrete, steel or bricks, rather than wood fuel substitution. We briefly describe the historical uses of wood in the context of sustainable material cycles, and we suggest that wood material may increase in relative importance in the future, due to environmental concerns and the exhaustion of non-renewable raw materials and fuels. We conduct a comprehensive literature survey of previous studies on wood substitution, including fundamental research and case study analyses, as well as reviews and syntheses of previous works. We provide a brief synopsis of each item of literature. We then describe the methodological issues involved in wood substitution analysis, including the definition of functional units and the establishment of effective system boundaries in terms of activities, time, and space. We report on a meta-analysis of greenhouse gas displacement factors of wood substitution, in which 20 separate studies were analyzed and compared to determine the range of efficiency with which using wood instead of other materials can reduce net greenhouse gas emissions. Finally, we report the results of an analysis of large-scale wood substitution, in which we estimate the greenhouse gas emission reduction and energy use reduction resulting from a full substitution of wood-based materials in both single-family houses and multi-family apartment buildings at the country level (Sweden) and the regional level (EU-25).

1. Introduction

1.1 What is wood product substitution?

Wood substitution can be defined as "any use of wood that replaces other inputs of production in providing equivalent service or function" (Gustavsson et al., 2006a; pg. 1098). Wood can replace fossil fuels in providing energy services (wood fuel substitution), or wood can replace other materials in providing a physical function (wood product substitution). The mechanical and chemical properties of wood make it suitable for use as both a product and a fuel, and wood can thus be "cascaded" by using it in one or more product applications, followed by the recovery of its available energy by using it as a fuel (Sathre and Gustavsson, 2006). In this report, we focus on wood product substitution, or the use of wood to replace other materials such as concrete, steel or bricks.

1.2 Background: the sustainable material cycle of wood

Wood has long been a primary source of energy and material for human society (Perlin, 1989). Until recent centuries, wood had been the most important fuel for cooking, heating and industry, and an important raw material for construction, agriculture, crafts, shipbuilding etc. The renewable nature of wood, and its integral place in the global carbon cycle, allowed its continuing use indefinitely. Forest trees captured and stored solar energy flows, gathered periodically for human use, without perturbing the stability of the climate system.

Sustainable forest management practices were developed in some regions of the world, ensuring a continuing supply of wood for energy and material uses. In other regions, the use of wood outstripped locally available supply, in some cases due to a lack of attention paid to forest regeneration activities. The local scarcity of wood in several areas of western Europe provided an impetus to develop innovative technologies to use coal (Clow and Clow, 1956), eventually leading to fossil-dependent economies of scale that gave preference to fossil fuels even in cases where wood was abundant (Flinn, 1959). Over the last several centuries, many previous uses of wood have been replaced by non-renewable fossil fuels such as coal, oil and natural gas, and materials such as concrete, metals and plastics (Gustavsson et al., 2006a).

Schulz (1993) suggested that the substitution of wood by other materials and energy sources, which is continuing even today, will be reversed and a new phase of increased wood use will begin due to environmental reasons and the exhaustion of certain non-renewable raw materials and fuels (Figure 1.1). The future development of wood use is difficult to predict, but the realisation of the importance of climate change mitigation, coupled with the implementation of suitable policy instruments, could motivate a significant increase in the use of wood use (Gustavsson et al., 2006a).

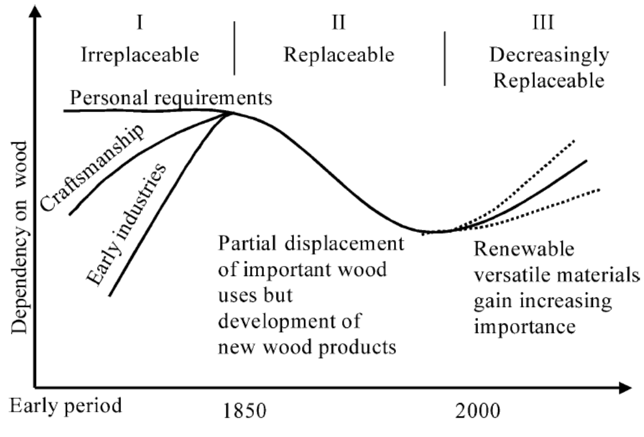

Figure 1.1. Three Phases Theory of the history of wood utilisation. (Source: Gustavsson et al. 2006a, from Schulz 1993)

The role of wood material in a transition to a society based primarily on renewable resources needs to be considered in a long-term context. The period of historic decline in relative significance of wood product use has been a time of unprecedented growth in overall material supply and demand, made possible by the exploitation of both primary forests and exhaustible fossil fuels. The challenge we face now is qualitatively different—to transition to a sustainable society that recognizes limits to global energy and material flows. It appears that the solar-driven material cycle of wood can play a significant role in this transition.

Forest products will likely play an increasingly important role in the energy and material economy of Sweden. Biofuels provided about 19% of Sweden's energy supply in 2007, and is expected to become more important in the future (Swedish Energy Agency, 2008). Wood material is widely used for constructing single-family homes in Sweden, and there is growing interest in increasing the use of wood construction material in other types of buildings such as apartments and industrial structures (Näringsdepartementet, 2004). Although it is possible to increase the production rates of forests and plantations through more intensive management, wood resources are nevertheless finite. It is thus necessary that the available wood resources are used wisely and efficiently. As the effects of sustainable forestry and efficient wood use on energy security and climate stability become better understood, wood product substitution is seen as an increasingly significant contributor towards sustainable development.

1.3 The role of wood material in greenhouse gas balances

Several mechanisms have been identified by which wood product substitution affects GHG balances. These mechanisms include: the fossil energy used to manufacture wood products compared with alternative materials; the avoidance of industrial process carbon emissions such as in cement manufacturing; the physical storage of carbon in forests and wood materials; the use of wood by-products as biofuel to replace fossil fuels; and the possible carbon sequestration in, and methane emissions from, wood products deposited in landfills. The effects of each of these mechanisms are summarized below:

Less fossil fuel consumption in manufacturing: The manufacturing of wood products typically requires less total energy, and in particular less fossil energy, than the manufacturing of most alternative materials. "Cradle to gate" analyses of material production, including the acquisition of raw materials (e.g., mining or forest management), transportation, and processing into usable products, show that wood products need less production energy than a functionally equivalent amount of metals, concrete, or bricks. Furthermore, much of the energy used in wood processing is thermal energy used for drying, for which wood processing residues are commonly used. Thus, the fossil carbon emission from wood product manufacturing is generally much lower than that of non-wood products. Composite wood products, while making more efficient use of roundwood raw materials, require a relatively higher use of fossil energy than do solid wood products. This energy, used for production of resins and additives as well as for the mechanical processing of wood fibres, is still commonly less than that needed for non-wood products.

Avoided process emissions: Using wood products in place of cement-based products avoids the industrial process carbon emissions from cement manufacturing. CO_2 emissions are inherent to cement production, due to chemical reactions (calcination) during the transformation of raw materials into cement clinker. Avoided process emissions can be a significant part of the GHG benefits of wood products when wood is used in place of concrete and other cement-based materials. While avoided calcination reaction emissions are well quantified, there is some uncertainty regarding the net effect of cement process emissions, due to CO_2 uptake by carbonation reaction. Carbonation is a slow reaction that occurs over the life cycle of cement products, and involves reabsorption of CO_2 from the atmosphere. Nevertheless, as carbonation uptake is less than calcination emission, there is still a net GHG benefit when substituting wood in place of cement products.

Carbon storage in products: Wood material is composed of about 50% carbon by dry weight, this carbon having been drawn from the CO_2 removed from atmosphere by the growing tree. In other words, wood products provide a physical storage of carbon that was previously in the atmosphere as a greenhouse gas. The climatic significance of carbon storage in wood products depends on the dynamics of the products pool as a whole, i.e., whether the total quantity of stored carbon is increasing, decreasing, or is stable. Atmospheric carbon concentration is affected by *changes* in the size of the wood product pool, rather than by the size of the pool itself. In the short to medium term, significant climate benefits can result from increasing the total stock of carbon in wood products, by using more wood products or using longer-lived wood products. In the long term as the stock of products stabilizes at a higher level, wood products provide a stable pool of carbon as long as new wood entering the pool is balanced by old wood leaving the pool. Some wood substitution studies have covered a relatively short time frame, and have considered carbon storage to be equivalent to avoided emissions. Other studies have considered the long-term carbon dynamics of wood products, and show that the substitution effect of avoiding fossil emissions is ultimately much more significant than the carbon stored in wood products.

Carbon storage in the forest: The life cycle of wood products begins with the growth of trees, so the consideration of carbon flows in forest ecosystems is essential to accurately understanding the climate impacts of wood product use. Without exception, all of the wood substitution studies reviewed here have assumed as boundary conditions that the forests that produce the wood are managed sustainably. Over a complete rotation period of sustainable (yield) forestry, the carbon content in tree biomass remains unchanged, by definition. Forest soils often store more carbon than forest biomass, and several studies suggest that soil carbon stock in managed forests maintains a dynamic equilibrium level over multiple rotations. This discussion of wood production in *managed* forests must be distinguished from the carbon balance effects of harvesting *primary* forests. Conversion of primary (old-growth) forests to secondary, managed forests results in a loss of stored carbon from both biomass and soils, before the carbon stocks in forest biomass again reach dynamic equilibrium. The level of the new equilibrium depends on soil characteristics, forest management intensity, and other factors. Afforestation, or the creation of forests on previously non-forested land, generally increases the carbon stock in biomass and soil as well as producing wood for product substitution.

Avoided fossil fuel emissions due to biomass substitution: The wood contained in a finished forest product is only a part of the total biomass flow associated with the product. Substantial biomass residues are generated during forest thinning and harvest operations, and during primary and secondary wood processing. At the end of its service life, unless it is recycled for additional material use, the wood product itself becomes combustible residue. These by-products can be used as biofuel to replace fossil fuels, thus avoiding fossil carbon emissions. The CO_2 emitted during the direct combustion of sustainably-produced biofuel is balanced by CO_2 uptake in regrowing forests. However, the quantification of GHG benefits due to the use of residues from the wood product value chain is not straightforward. Issues addressed by the studies reviewed here include the varying carbon intensity of the fossil fuel replaced, leakage (i.e., a unit of additional biofuel does not necessarily lead to a unit reduction of fossil fuel use), soil carbon reduction due to removal of harvesting residues, and uncertainties about how post-use wood products will be handled by future waste management systems. Nevertheless, studies indicate that the recovery and combustion of the biomass by-products associated with wood products is the single most significant contributor to the life cycle GHG benefits of wood product use.

Carbon dynamics in landfills: Carbon dynamics in landfills are recognized to be quite variable, and can have a significant impact on the GHG balance of wood products. A fraction of the carbon in landfilled wood products will likely remain in (semi)permanent storage, providing climate benefits. However, another fraction may decompose into methane, which has much higher global warming potential (GWP) than CO_2. The few instances of negative displacement factors (i.e. wood use giving greater GHG emission than non-wood use) found in this review are largely the result of methane emissions from landfilled wood. However, methane gas from landfills can be partially recovered and used as a biofuel to replace fossil fuels. Thus, the landfilling option for post-use wood products carries great uncertainties, and could result in climate benefits (partial sequestration in landfills, and partial production of methane biofuel) or climate impact (emission of methane to the atmosphere).

2. Literature survey

Numerous authors have described their research into the energy and climate impacts of material substitution. Here we briefly summarize these contributions in chronological order, first focussing on case studies and fundamental research, and then describing previous efforts at synthesising multiple data.

2.1 Analyses of wood substitution: case studies and fundamental research

Boyd et al. (1976, summarized in 1977) conducted a pioneering study of energy aspects of the US forest sector. The study included detailed material balances for the production of a variety of structural products made of solid and composite wood. The authors calculated the labour, capital depreciation, mechanical energy and heat energy needed to produce a unit weight of each product. The system boundaries included forestry activities, harvest and transport of roundwood, processing into products, and transport to building sites. The study found that the energy needs of the forest product industries are potentially fulfilled by biofuel residues produced during wood product manufacture. A comparison of the energy needed to produce wood-based construction elements showed that 2 to 10 times more energy was needed to make comparable elements with non-wood materials.

Koch (1992) analyzed the energy and GHG implications of a proposed decrease in forest harvest in the northwest USA, and the resulting reduced use of forest products. He discusses the potential societal responses to a reduced availability of new wood products from the region, such as forgoing the services provided by the products, increasing the recycling rate of post-use products, and increasing the import of roundwood or wood products from other countries. He concludes that the most likely response will be an increased use of non-wood materials to provide the services that the wood products would have provided. Using energy use data from Boyd et al. (1976), he calculates the energy and CO_2 emission implications of substitution steel, concrete, brick, and other non-wood materials in place of wood products. The scenario with the greatest harvest reduction gives an increased energy use of about 140 million barrels of oil per year and an increased GHG emission of 61.6 tons CO_2 per year.

Buchanan and Honey (1994) compared several different building types made with wood, steel and reinforced concrete, quantifying the energy used and carbon emitted during production of the buildings. The production of wood buildings was consistently found to use less energy and have lower CO_2 emissions. At both the level of individual building elements as well as when comparing entire buildings, using wooden materials instead of other materials resulted in lower net carbon emission in all cases. The paper contains an appendix with data specific to New Zealand on the energy use and carbon emissions for producing a variety of materials, based on both average and marginal carbon intensity of electricity.

Künniger and Richter (1995) compared the environmental impacts caused over the life cycle of utility poles made of preservative-treated wood, reinforced concrete, and tubular steel. The wood poles were found to have significantly lower global warming potential than the poles made of other materials. The wood poles also had lower impacts in most other environmental categories, but showed higher levels of ecotoxicity due to the preservative treatment.

Suzuki et al. (1995) used a top-down methodology employing input/output tables of the Japanese economy to compare buildings made of wood, reinforced concrete, and steel. They found construction of the wood buildings to have substantially lower energy use and CO_2 emissions than the other buildings. However, due to methodological issues (non-equivalent functional unit) the quantitative results of the concrete buildings should not be directly compared with those of the wood and steel buildings.

Cole and Kernan (1996) studied the life cycle energy use of a three-storey office building with a wood, steel, or concrete structural frame, finding that the wood building had the lowest energy use. Construction of the structural system of the concrete structure required up to 1.39 times more energy, and the steel structure up to 1.82 times more energy, than the wood structure. In a life cycle perspective, including building operation energy and recurring maintenance energy over the full lifespan, the difference between the structural systems became much less significant. Energy efficiency measures taken to reduce operation energy increase the relative importance of the lower energy use for producing wood structural systems.

Schlamadinger and Marland (1996) conducted a theoretical analysis of system-wide carbon flows associated with biomass production and use, the avoided carbon emissions due to fuel and material substitutions dominate over carbon storage in biomass and products, in the long term. Carbon stocks eventually reach equilibrium, but substitution benefits are continuing and cumulative. The displacement factor, or avoided emissions per unit of wood use, is an important parameter in carbon mitigation efficiency of the biomass system.

Björklund and Tillman (1997) conducted a life cycle assessment of buildings made with wood or concrete frames. The energy use and CO_2 emission was clearly lower for construction of the wood buildings. Impacts during the operation phase dominate over those of the construction phase, making the life cycle differences less pronounced. The authors also assessed other environmental impact categories of the buildings, including resource use, air pollution emissions, water pollution emission, and waste generation. The overall environmental impact of the buildings was assessed using 3 LCA assessment methods. The wood versions of both buildings were consistently found to have substantially lower environmental impacts during the construction phase than the concrete versions. For the apartment building, environmental impact during the operation phase was also calculated, and was approximately the same for all three materials. Because the impact during the operation phase was greater than the impact during the construction phase, the reduced impacts of the wooden material became less pronounced when seen in a life cycle perspective.

Jönsson et al. (1997) conducted a life cycle assessment of flooring materials made of solid wood, linoleum, and vinyl. The energy use and CO_2 emission is clearly lower for the wood flooring. Per m^2 of flooring per year of service, the wood flooring uses 1.6 MJ of energy, the linoleum uses 2.3 MJ, and the vinyl flooring uses 2.8 MJ. Fossil fuel use was very much lower for the wood flooring than for the other materials. Per m^2 of flooring per year of service, the wood flooring emits 0.011 kg CO_2, the linoleum emits 0.064 kg CO_2, and the vinyl flooring emits 0.21 kg CO_2. The study also assessed other environmental impact categories of the flooring materials, including resource use, environmental toxin emissions, air pollution emissions, and waste generation. The overall environmental impact of the flooring was assessed using 3 different assessment methods. The wood flooring was consistently found to have lower overall environmental impacts than the other materials.

Skog and Nicholson (1998) estimated the use of wood and paper products in the US from 1910 to 2040, and analyzed the fate of the carbon contained in the products. Historical data from 1910 to mid-1960s show a decrease in forest product use, partly due to decreasing fuelwood use. After the mid-1960s it has increased, and is projected to continue increasing to 2040. A significant amount of carbon is accumulating in landfills, and the authors expect it to remain in long-term sequestration. Burning of forest products for energy purposes (including byproducts and post-service-life products) is increasing, while emissions without energy recovery are expected to remain low.

Buchanan and Levine (1999) compared several different building types made with wood, steel and reinforced concrete, quantifying the energy used and carbon emitted during production of the buildings. They found the production of wood buildings to consistently use less energy and have lower CO_2 emissions than buildings made of other materials. They calculated displacement factors for the various construction alternatives, defined as the ratio of decreased carbon emission to increased carbon storage in wood construction material. The displacement factors ranged from 1.05 to 15 kg C emission avoided per kg C additional wood material, depending on the building systems compared.

Cole (1999) studied the energy use and GHG emission due to the on-site construction of structural assemblies. He found that steel structures had the lowest energy use and emissions, followed by wood structures, and concrete structures had much higher energy use and emission. Transportation of construction workers to and from the building site caused a large share of the energy use and emissions for many of the structural assemblies studied. When worker transportation is included, the share of construction energy to total initial embodied energy is 2-5% for steel assemblies, 6-16% for wood assemblies, and 11-25% of concrete assemblies.

Börjesson and Gustavsson (2000) assessed the energy and GHG balances in a life cycle perspective, from resource extraction to demolition, of a 4-storey apartment building, built with either a wood-frame or concrete frame. The authors observe the need for a long time perspective when considering GHG balances, due to long-term processes like forest growth, cement carbonation, decomposition of landfilled wood, etc. They conducted analyses over the 100 year lifespan of the building (coinciding with the rotation period of the forest), and over a period of 300 years encompassing 3 consecutive forest rotations and building lifespans. They found that the wood building has lower emissions than concrete in almost all scenarios. The GHG performance of the wood material was highly affected by methane emission from landfilled wood, as well as the time period used in the analysis. If wood is not landfilled or if methane gas is collected, wood construction consistently has lower GHG emission than concrete. Using forests for building material production, rather than carbon storage, becomes increasingly advantageous as the time perspective lengthens.

Hillier and Murphy (2000) conducted a life cycle analysis of preservative treated wooden poles compared to poles made of steel, concrete, or fibreglass. The main focus of the study was the severity and management of the toxicological impacts of the preservative treatments, in relation to the other impacts caused by the wood and non-wood materials. The wood poles consistently had lower global warming potential (GWP) than the other materials. Toxicity impacts of the wooden poles were relatively high due to the preservative treatment, unless the poles were burned in a controlled manner with ash and energy recovery.

Pingoud and Perälä (2000) analyzed the potential for wood substitution in the Finnish construction sector, finding that the use of wood-based products could increase by almost 70%. The carbon stock in wood products would then have been 0.37 Mt C larger. An additional 1.5 Mt C forest biomass would have to be harvested to provide the raw materials. Each kg of additional wood product used could result in a 3.6 kg reduction in the use of masonry products and 0.12 kg reduction in metals use. On a national level, the primary energy used for material production would decrease from 8.8 TWh to 7.7 TWh, and the CO_2 emission from fossil fuel use and process emissions would decrease by 0.165 Mt C. Additional amounts of biofuel would be produced in association with the additional production of wood construction materials. If this biofuel were used to replace light fuel oil, 0.24 Mt C of fossil carbon emission would be avoided. If all above-ground wood biomass were used as biofuel, including wood products after demolition, 1.5 Mt C of fossil carbon emission could be avoided.

Glover et al. (2002) reviewed several earlier studies of the energy needed to produce building materials and houses made of wood, steel, and concrete. They also made supplemental calculations of the uncertainty of energy use in construction, using the ranges of material production energy found in their review. They conclude that wood-based construction is generally less energy intensive than concrete or steel construction. This study is relevant to the question of climate impacts of building construction due to the link between fossil energy use and GHG emission. However, it may underestimate the climate advantage of wood construction because it does not consider calcinations emissions of cement production and the use of climate-neutral bioenergy in the wood products industry.

Scharai-Rad and Welling (2002) analyzed buildings and building components made of wood and non-wood materials, and found that production of the wood alternatives consistently used less energy and emitted less GHG than non-wood materials. The recovery of energy from demolition wood at the end of the product life cycle further improved the energy and GHG performance of the wood alternatives.

Wood also generally performed better on other environmental impact indices (acidification, eutrophication, and photochemical ozone creation).

Sedjo (2002) used LCA data from Künniger and Richter (1995) to calculate that converting from wood utility poles to steel poles in the US would cause in increased emission of 163 Tg CO_2eq. Of this amount, 100 Tg is due to the increased emission of producing steel poles instead of wooden poles, and 63 Tg is due to the release of carbon currently stored in wooden poles.

Petersen and Solberg (2002, 2003, 2004) conducted a series of studies on the energy use, GHG emission, and economic costs of several wood products compared to non-wood alternatives. The authors calculate a "discounted global warming potential" that gives different importance to GHG emissions that occur at different times. The discount rates used by the authors range from 0% to 8%. The 0% discount rate corresponds to the commonly-used assumption that all emissions have equal weight independent of when they occur. Using discount rates greater than zero result in less significance placed on future emissions, thus the various alternatives for end-of-service-life management of the materials become less important.

Petersen and Solberg (2002) compared roof beams made of steel and glue-laminated wood, finding that manufacturing the steel beams uses two to three times more energy and six to twelve times more fossil fuels than manufacturing glulam beams. In the "most likely scenario," steel beam manufacturing causes five times more GHG emission than manufacture of glulam beams. The authors calculate that 0.24-0.31 metric tons CO_2eq emission is likely to be avoided per m^3 of sawn wood used to make glulam beams. Petersen and Solberg (2003) compared flooring material made of natural stone and solid oak wood. Manufacturing the wooden floor requires 1.6 times more energy, but produced only one-third of the GHG emission, compared to manufacturing the stone floor. The authors calculate that 0.4 metric tons CO_2eq emission is likely to be avoided per m^3 of wood materials in the wooden floor. In both studies, the post-use management of the wood material has a significant effect on life-cycle GHG emissions: burning the wood to substitute fossil fuels significantly decreases net GHG emissions, and landfilling results in increased GHG (methane) emissions.

Petersen and Solberg (2004) compared flooring made of solid oak wood, linoleum, vinyl, polyamide carpet, and wool carpet. The methodology is similar to the same authors' earlier articles, with some significant changes including assuming no GHG emissions from landfilled materials, and an alternative scenario with expanded system boundaries to include carbon flows in the forest trees both before and after harvest.. The wooden floor results in less life-cycle GHG emissions than the other materials. Depending on the material replaced, the authors calculate that 0.5 to 8.4 t CO_2eq emission is likely to be avoided per m^3 of wood materials in the wooden floor.

Bowyer et al. (2005), summarized by Lippke et al. (2004), reported on the CORRIM research project whose goals were to create a database of environmental performance measures of the life cycle of wood and non-wood construction materials, to develop an analytical framework for evaluating the environmental and economic impacts of alternative building materials, and to diffuse the resulting information to interested parties. The research team collected data on the inputs and outputs associated with the production of a range of wood-based construction materials in the USA. They analyzed 2 case-study houses made with wood frames and non-wood frames, finding that the wood construction resulted in about 16% lower total energy use and 28% less GHG. The wood-framed versions also performed better than, or similar to, the non-wood versions in other environmental performance indices (air emissions, water emissions, and solid waste). In a life cycle perspective, energy use and emissions from building construction were relatively small compared to energy use and emissions from building operation. Dynamic modeling of carbon flows shows that intensified forest management provides lower net CO_2 emissions, due to increased potential for material and fuel substitution, with the effect becoming more pronounced as the time horizon becomes longer.

Perez-Garcia et al. (2005b) studied the carbon dynamics of forests, wood products, and material and energy substitution, over a time horizon of 165 years. Four management regimes of varying intensity are modeled, with harvest rotation periods of 45, 80 and 120 years as well as a no-harvest scenario. CORRIM data (Bowyer et al. 2005) on wood vs. non-wood building construction were used to estimate the effects of material substitution on net carbon flows, taking into account avoided emissions of fossil carbon when less energy-intensive materials are used. They found that the system-wide net carbon emission is lowest when forests are managed more intensively for production of wood products. Although shorter harvest rotations reduce average carbon stock in forests, this reduction is more than compensated for by increased carbon storage in wood products, and by decreased emissions from avoided non-wood products. The authors observe that meaningful analyses of the carbon emission impacts of forestry must extend beyond the forest land itself, and include the impacts of the usage of forest products.

Gustavsson et al. (2006b) compared the energy use and CO_2 emission of apartment buildings made with wood or concrete frames. The accounting of CO_2 emissions included fossil emissions from the production and transport of material, calcination emissions from cement manufacture, atmospheric carbon fixed during tree growth and released during wood combustion or decay, and avoided fossil emissions due to the use of biofuels instead of fossil fuels. The wood-framed buildings were found to have lower energy use and emission. More energy is available from biomass residues from logging, processing, construction, and demolition than is used to produce the wood buildings. Because of reduced fossil and process emissions during material production, and the substitution of fossil fuels by biomass residues, the wood buildings had lower lifecycle net CO_2 emissions than the concrete buildings. Per m^3 of additional wood product used to make a wood building instead of a concrete building, lifecycle net emission was reduced by 0.68 to 1.14 tC.

Gustavsson and Sathre (2006) studied the variability of energy use and CO_2 emission of buildings with wood or concrete frames. The authors calculated the life cycle “energy balance” and “CO_2 balance” of a case study 4-storey apartment building made with a wood frame and a reinforced concrete frame. They varied a number of system parameters including clinker production efficiency, blending of cement, crushing of aggregate, recycling of steel, lumber drying efficiency, material transportation distance, carbon intensity of fossil fuel, recovery of logging, sawmill, construction and demolition residues for biofuel, and growth and exploitation of surplus forest not needed for wood material production. The wood buildings were consistently found to have lower energy use and CO_2 emission. Recovery of biomass residues, particularly demolition wood, had the single greatest effect on the energy and carbon balances of both the wood and concrete buildings. Land use issues and concrete production parameters also had significant effects. In all cases but one (a combination of parameters giving the worst performance of the wood building), the wood building had lower energy use and net CO_2 emissions than the concrete building.

Lippke and Edmonds (2006) analyzed potential changes in construction systems to increase wood product content. They compared four types of cold-climate wall construction, two types of warm-climate wall construction, and four types of floor construction. Each construction option uses a different mix of wood-based and non-wood materials. The function, including thermal efficiency, of each subassembly is identical, allowing comparison. They found that increasing the use of wood-based products in place of non-wood products improves the building’s environmental performance. Wood-based construction systems used from 25% to 76% of the fossil fuel that is used for equivalent non-wood systems, and emitted from 14% to 69% of the greenhouse gases. Increasing the use of biofuels in wood processing industries further reduces GHG emissions.

Eriksson et al. (2007) conducted a broad system analysis of the carbon stocks and flows associated with forest management and forest product usage. They model forest growth under 3 management regimes to determine the carbon stocks in trees and soil, the production levels of harvestable biomass, and the fossil emissions associated with each regime. The harvested biomass was assumed used to replace fossil fuels and non-wood construction materials. They found that net carbon emissions were lowest when forests were managed intensively to produce construction materials. The substitution effect of using wood instead of non-wood materials had the greatest single impact on the overall carbon balance. Removing harvest residues for use as biofuel led to avoided fossil emissions that were about 10 times greater than the reduced soil carbon stock. The authors discuss the forest management regimes in comparison to an option of non-management and non-use of forest land. They observe that in the long term, the carbon stock in unmanaged forest biomass and forest soil will reach a dynamic equilibrium, where carbon stock increases due to tree growth will be balanced by decreases due to respiration and decomposition. Because no forest products are produced, other non-wood materials and fossil fuels will be used instead, resulting in relatively greater net carbon emissions. Because the substitution benefits of forest products are cumulative, while the carbon sink in forest biomass and soils is limited, the managed use of forests becomes more attractive as the time horizon lengthens.

Gerilla et al. (2007) compared the energy use and atmospheric emissions over the life cycle of houses made of wood or reinforced concrete. They use a top-down model using data from input-output tables for the Japanese economy, unit prices of the various materials, and assumptions about lifespan and maintenance needs. Life cycle CO_2 emission was lower for the wood building than for the concrete building. For both building types, 79% of the total emissions occurred during the operation phase, 12% during the construction phase, and less than 9% was due to maintenance. Emission of NO_x, SO_x and suspended particulate matter were also lower for the wooden building than for the concrete building.

Sathre (2007) developed and applied a methodology to compare the life cycle energy use and carbon emission associated with wood and non-wood construction. Two case-study multi-storey apartment buildings are analyzed. Significantly less energy is used, and less CO_2 is emitted, over the life cycle of the wood materials. The most important single factor affecting the energy and carbon balances is the use of biomass by-products from the wood product chain as biofuel to replace fossil fuels. Carbon stock changes in forests and wood materials are less significant over the building life cycle and forest rotation period. In the long term, the active and sustainable management of forests, including their use as a source for wood products and biofuels, allows the greatest potential for reducing net CO_2 emission.

Upton et al. (2007) quantified and discussed the “carbon profile,” or net effect on atmospheric carbon levels, of the Canadian forest sector. The authors distinguish between GHG *emissions*, carbon *sequestration*, and *avoided* GHG emissions associated with the forest products industry. Between 1990 and 2005, it appears that the carbon profile has improved substantially.

Valsta (2007) concluded that the optimal use of forests for climate change mitigation depends on two factors: the GHG benefits obtained by using forest products, and the change in carbon storage in forest ecosystems. GHG benefits are higher when wood is used as a material (e.g. building construction) than when used as biofuel. The economic value of carbon storage depends heavily on the discount rate that is chosen. For typical parameter values applied to managed secondary forests (not old-growth forests), it is climatically advantageous to harvest the forests and use the wood in place of other materials.

2.2 Reviews and syntheses of previous works

Brunklaus and Baumann (2002) reviewed six studies that analyze various aspects of environmental performance of building materials. The studies are reviewed in terms of their coverage of environmental impacts in a life cycle perspective, the suitability of their functional comparisons between wood and non-wood materials, the appropriateness of their input data, and other methodological issues that affect the validity of their results. Four of the studies are from Sweden, and two are from Germany. Two studies analyze complete apartment buildings, two analyze single-family houses, and two analyze structural systems. The authors find methodological irregularities with several of the studies, including non-equivalent functional units, lack of transparency, and inconsistent input data. One of the studies focuses only on toxicological impacts. That study concludes that there is no inherent impact difference between wood and non-wood construction, the impact arising from paints, solvents, putties, etc. that are used regardless of the primary construction material. Of the other five studies, four conclude that during the construction phase, wood material has slightly or significantly less environmental impact than non-wood material. Most of the studies find that over the entire life cycle, the advantages that wood may have during the construction phase are overwhelmed by the impacts occurring during the operations phase. Thus, most of the studies conclude that in a life cycle perspective, there is no significant difference in environmental impacts between wood-based and non-wood-based construction. The authors conclude that efficiency improvements in the building operation phase (space heating, electricity, water heating) are more important than building material choice, to achieve reductions in life cycle energy use and CO_2 emissions. In specific response to external arguments that wood construction is more environmentally friendly, the authors say that: the advantage of wood being a renewable resource depends on the sustainability of forestry practices; the advantage of energy recovery from post-use wood products depends on the waste handling and energy supply systems that will exist at the time of future demolition; the advantage of reduced CO_2 emission depends on carbon storage in forests and wood products, and on the relative CO_2 emissions of alternative energy supplies.

Eriksson (2003, summarized in 2004) reviewed and summarized 12 life cycle assessments that compare the energy use and GHG emission of wood structures to that of steel or concrete structures. The studies are not completely comparable with each other, because some compare complete buildings and others compare only the structural differences between the wood and non-wood constructions. However, the author selects eight studies with “reasonably comparable” differences between the wood and non-wood options, although the absolute numbers for energy use and GHG emissions should not be compared. The author calculated the energy use difference and GHG emission difference between each of the wood and non-wood buildings, per m^2 of floor area. All the energy use differences except one are positive, meaning that the wood buildings use less energy than the non-wood buildings. The one case with a negative difference results from a methodological inconsistency in which the feedstock energy value of the wood raw material is counted as an energy use, but the heat content in the same material at the end of the building life cycle is not credited as an energy source. The GHG emission difference between the wood and non-wood buildings is positive in every study, meaning that the wood buildings result in less GHG emission than the non-wood buildings. The differences range from 60 to 400 kg CO_2eq per m^2 floor area, with most being in the range of 150 to 200 kg CO_2eq per m^2. The author states, “Thus the conclusion for GWP is even clearer; Regardless of system boundary conditions applied in the different studies, a building with a primary wood structure will give a lower GWP than the alternatives.” The author discusses the system boundaries used in the different studies, in particular the varying inclusion of raw material feedstock energy and recovery of heat energy from post-use wood. He concludes that it is more appropriate to not include the feedstock energy of the wood material (because it is harvested for use as a structural material, and would not economically be harvested for use as biofuel), and to include the energy content of the post-use wood (because it is a resource that is available at the end of the building’s service life).

Taylor and van Langenberg (2003) reviewed and summarized over 20 studies that compare the environmental performance of wood products to that of non-wood products. Although the focus of the study is the use of wood in furniture manufacture, the authors find few studies specifically comparing wood and non-wood furniture. Therefore, the authors review studies of television cabinets, flooring materials, window frames, building elements, and complete buildings. In all cases, the performance of the wood products in terms of GHG impacts was better than that of the non-wood products to which they were compared. Wood materials also had relatively lower environmental impact than non-wood materials in other categories such as waste generation, toxicity, photochemical ozone, acidification, and eutrophication. The authors observe that the wood content in furniture results in very low environmental impact, but the presence of other materials like finishes, adhesives, and metal or plastic trim, even in small quantities, can significantly increase the environmental impact of the furniture.

Franklin Associates (2004) reviewed and synthesized LCA literature to determine the methods used to characterize carbon sequestration or landfill emission from forest products in their use and post-use phases. The report identifies 66 LCA studies of wood and paper products. Most of these studies do not track carbon throughout the life cycle of the products. Some consider the fixation of atmospheric carbon into tree biomass through photosynthesis. Most studies do not consider the fate of carbon in products at the end of their service life, for example sequestration in, or methane emission from, landfills. Where biomass carbon is included it is usually, but not always, considered to be "global warming neutral." The authors conduct an in-depth review of 13 of the studies. Issues to which the authors pay particular attention are: system boundaries and data sources; types of paper and wood products covered by the study; time-in-use (i.e. service life) of each product type; effects of recycling on effective service life; fixation of atmospheric carbon during tree growth; amount and duration of carbon sequestration in landfills; amount and timing of methane generated from landfills; amount and timing of CO_2 generated from landfills; and assumptions about collection and burning of landfill methane. In these 13 studies there was very little uniformity in the methodology and assumptions regarding the fate of carbon during the life cycle of the products. The studies covered a diverse range of forest product (various types and grades of paper and wood products), though even different studies of the same types of products used different methodologies and assumptions. The system boundaries of the studies varied substantially, including the treatment (or not) of carbon sequestration during forest growth. Treatment of carbon flows in landfills was very diverse. The studies generally used simplified assumptions that were not backed up by empirical data, for example that all organic matter decays in landfills, or that no organic matter decays in landfills. Some studies offered several different scenarios, or uncertainty analyses, to show the significance of the assumptions made. The report does not specifically address other options for end-of-life management of forest products besides landfilling, for example reuse or burning with energy recovery. The authors note that several of the reviewed studies do consider these options, though there is no discussion in the report of which end-of-life management option is most beneficial from a climate change mitigation perspective. There is also no analysis or discussion of suitable system boundaries regarding forest growth and regrowth.

Reid et al. (2004) conducted a multi-disciplinary analysis of the use of wood products for climate change mitigation. It includes an overview of the role of forests in the global carbon cycle, and discusses potential strategies for using forests for climate change mitigation. These include reducing deforestation to preserve existing carbon stocks in forests, increasing forest area to sequester additional carbon, and storing additional carbon in wood products. The authors review trends in wood markets, on a global level and a European level. They also discuss wood products in the context of broader concerns about sustainable development, and the role of sustainable forest management in terms of economic, social and environmental sustainability. The authors discuss barriers to more widespread use of wood instead of other materials, such as perceived issues with fire safety and durability, and the lack of knowledge and experience of architects and builders about wood engineering and construction. One chapter discusses the comparative GHG impacts of wood and non-wood materials. The authors briefly review six life cycle assessments of wood products, most of which were conducted in European countries. The authors present data on the CO_2eq emissions associated with a range of building materials, such as concrete, bricks, sawn lumber, and particleboard, expressed per kg and per m^3 of material. They also present similar emission data on various packaging materials, such as cardboard, glass, plastics, steel and aluminum, expressed per kg of material. The wood-based materials are seen to have significantly lower GHG emission than the non-wood materials. Unfortunately, the authors do not relate the data to comparable functional units, so no results-oriented conclusions can be drawn from the data. Indeed, the authors fail to mention that data on GHG emission per unit mass or volume is insufficient to compare the relative impacts of different materials, because often different amounts of each material will be required to fulfil the same function.

Petersen and Solberg (2005) reviewed 12 studies conducted in Norway or Sweden that analyze the environmental impact of wood product use compared to non-wood product use. The products include building frames, beams, walls, flooring material, and railroad ties. All the studies use life cycle analysis methodology, but with varying system boundaries. All the studies include raw material extraction and processing, but the remaining life cycle stages are included in only some of the studies. Some studies consider end-use electricity, while others consider primary energy used to produce electricity. The studies vary in their treatment of end-of-life material management. Thus, the authors note that the results of the studies should not be directly compared with each other. All of the studies show that wood has less net GHG emission than the comparable non-wood products, as long as the wood is not landfilled after use. The management of the wood at the end of its service life has a significant impact on the GHG emission. The studies show that wood has lower energy consumption, emission of SO_2, waste generation, and use of non-renewable resources. Preservative-treated wood can have high toxicological impacts. Of the 12 studies reviewed, the authors select nine studies that include sufficient data to calculate the GHG emission avoided per m^3 of wood. The calculated displacement factors of the nine studies average 0.66, ranging from a low of -0.88 (due to methane emission from landfilled wood) to a high of 3.02. Few of the studies considered the relative economic costs of the wood and non-wood alternatives. The few studies that considered economics found the wood alternatives to have equal or slightly lower costs than the non-wood alternatives. The authors feel that economic analysis should be combined with life cycle environmental analysis, to produce information on material substitution that is more policy-relevant.

Ekvall (2006) reviewed the analytical methodology used, and the results obtained, by eight research groups that have studied the environmental impacts of using different types of building frame materials. The focus of the review is on CO_2 emissions over the life cycle of the buildings. The results of most of the studies reviewed have shown that wood framed construction leads to lower CO_2 emission. The significance of the emission difference varies between studies. Some studies have concluded that in a life cycle perspective, the difference in emissions attributable to the frame material is insignificant in relation to the much larger emissions due to the operation of the building. The operation phase of the building life cycle is not affected by the choice of frame material, in the studies reviewed. The author finds that broad system aspects associated with the choice of frame material can have a significant impact on CO_2 emissions. These aspects include the effects of harvest on forest carbon dynamics, the use of wood residues (including the post-use building material) as a biofuel to replace fossil fuel, and the fate of the non-harvested forest in case non-wood materials are used in construction. In this broad system perspective, the use of wood-frame construction has a significant potential to reduce CO_2 emission. There can be a large difference between the potential and the actual CO_2 emission benefits of using wood materials instead of non-wood materials. There are inherent uncertainties involved in life cycle analyses involving future actions (e.g. the fate of materials from buildings demolished decades in the future). At the present time, it is uncertain whether future demolition materials will be landfilled or burned with energy recovery, and if the latter, what type of energy source will be replaced by the recovered demolition material. Other types of uncertainties regarding the CO_2 emission impact of choice of frame material are: whether recycled steel replaces ore-based or scrap-based steel; how waste-handling systems will develop in the future; how changes in demand for wood material affects forest management; how energy systems develop in the future, and the role of combustible waste in future energy systems. Because of the various uncertainties involved in the analysis, the author believes that there is no single objective answer quantifying the CO_2 emission benefit of wood-frame construction. Instead, he suggests that an analytical methodology be developed with the input of academic researchers and representatives from diverse industries, including the wood products and concrete industries. Such an analysis, in spite of the inherent uncertainties involved, would provide a robust basis for policy decisions.

Gustavsson, et al. (2006a) conducted an interdisciplinary study of the current and potential use of wood material substitution for GHG mitigation, based on perspectives from engineering, natural sciences, and social sciences. The authors consider wood substitution to mean "increasing the transformation of forest biomass into wood products in order to replace products emitting more GHGs per functional unit." The focus of the study is on using wood instead of other materials, but the use of wood instead of fossil fuels is also considered due to the characteristics of wood and its multiple uses over its life cycle. The authors briefly describe the history of wood use, from its preindustrial use at the predominant fuel and material, to its declining use as other industrial materials and fossil fuels largely replaced wood. They suggest that wood use may again increase in relative importance, due to future scarcity of non-renewable materials and fuels. The various material uses of wood are reviewed, as well as the non-wood materials that compete with wood for different uses. The authors note that the share of one- or two-family houses built with wood-based construction ranges from <20% in UK, Germany and France, to >80% in USA, Canada and the Nordic countries. The share of window frames made of wood ranges from <30% in southern Europe, to >60% in the Nordic countries. The authors offer several reasons for the wide variation in wood product use, including building standards, building traditions, perceived concerns about wood performance and about forest sustainability, and a lack of knowledge of wood among architects and engineers. The authors quote studies estimating that carbon sequestration in wood products is on the order of 0.026 to 0.139 GtC per year, and substitution benefits are on the order of 0.25 GtC per year. They believe that there is significant potential for decreasing GHG emissions by increasing the use of wood products. They distinguish between different potentials for GHG mitigation, which are (from highest to lowest): physical, technological, socioeconomic, economic, and market potential. The authors describe the general approach to quantifying GHG benefits of wood substitution, based on a comparison of the life cycle emissions of functionally equivalent products. They provide data from three case studies, including two apartment buildings in Sweden and Finland made with either wood or concrete frames, and roof beams in Norway made of glue-laminated wood or steel. Recommendations are given regarding knowledge gaps that should be filled to allow more efficient GHG mitigation through wood substitution. Recommendations include: a need for studies that integrate material and energy substitution; optimize wood substitution in terms of GHG emission and costs; understand the sources and extent of variation; a need for implementation studies, including adoption, diffusion, and econometric studies; dissemination of practical information to construction professionals, legislators, and consumers.

Werner and Richter (2007) reviewed and summarized life cycle assessments conducted in the last 20 years that compare the environmental performance of wood products to that of non-wood products. Based on a preliminary review of over 40 assessments, they conduct a more in-depth assessment of 13 studies that are quantitative, transparent, and with no obvious methodological flaws. The studies analyzed a range of wood products including door and window frames, insulation materials, flooring materials, wall construction, railway sleepers, utility poles, and complete buildings. In all cases but one, the performance of the wood products in terms of GHG impacts was “positive” or “very positive” in relation to the non-wood products to which they were compared. The one case in which wood material was found to have higher GHG impact than other materials was wood flooring, which was assumed to be landfilled after its service life, with high methane emissions. Wood materials also had generally favorable performance in other environmental impact categories. In particular, wood products had lower total energy use, lower non-renewable energy use, and lower quantities of solid waste. Preservative-treated wood products had relatively high toxicological and/or photosmog impact. Incineration of wood products, while providing a source of biofuel, can cause acidification and eutrophication impact. Composite wood products, while making more efficient use of roundwood raw materials, require a relatively higher use of fossil energy than solid wood products. The energy is needed for production of resins and additives, as well as for the processing of wood fibers and manufacture of the finished products.The authors observe that the results of comparative life cycle analyses can be very sensitive to allocation procedures used to model recycling or multi-output processes, and to assumptions related to end-of-life scenarios (e.g. landfilling or thermal energy recovery).

Sathre and O’Connor (2008) reviewed existing scientific literature to summarize consensus findings, or range of findings, addressing the net life cycle greenhouse gas footprint of wood construction products. They reviewed 48 international studies for findings on fossil energy used in wood manufacturing compared to alternatives, the avoidance of industrial process carbon emissions as with cement manufacturing, the storage of carbon in forests and forest products, the use of wood by-products as a biofuel replacement for fossil fuels, and carbon storage and emission due to forest products in landfills. Data from 20 of the reviewed studies were then used in a meta-analysis of displacement factors, that is, the quantification of greenhouse gas emission avoided per functional unit of wood used in place of other materials. All of the studies reviewed found that the production of wood-based materials results in less greenhouse gas emission than the production of alternatives. Over the complete life cycle of wood products, the great majority of studies also found lower total emission for wood products. End-of-life management of wood products is the single most significant variable for the full life cycle carbon profile of wood products. The few studies with scenarios in which the greenhouse gas emission of wood products is greater than of alternatives addressed worst-case wood disposal options. The overall consensus provides a clear carbon rationale for increasing wood substitution in place of other products, assuming forests are sustainably managed and that wood waste and by-products are used responsibly

3. Methodological issues in wood substitution analysis

3.1 Analytical challenges of wood product substitution

Although sophisticated tools for the analysis of life cycle environmental impacts of many goods and services have been developed over the last several decades (e.g. ISO, 2006), there are additional challenges in analysing forest products (Perez-Garcia et al., 2005a) and building materials (Kotaji et al., 2003). There are several reasons for the increased complexity of the environmental analysis of *forest products* compared to that of most other products: a much longer time frame is involved, including the time for forest growth and the long lifespan of some wooden products; a range of useful products are obtained at different points in time, including forest thinnings during the time of forest growth, primary products and by-products at the time of forest harvest, and combustible residues at the end of the product lifespan; a broad array of joint products can be obtained from a tree (e.g. saw, veneer, and pulp logs) and a stand (e.g. different uses from different species in a mixed forest stand); and the unique relationship between forest development and environmental services, including climate stability (Perez-Garcia et al., 2005a). The variety of time dynamics of greenhouse gas flows of wood product substitution is illustrated in Figure 3.1. Fluxes of energy and carbon go on at many different scales and patterns, impeding the simple characterization of the effects of substitution. Furthermore, the life cycle analysis of *building materials* is also more complex than that of many other products due to: the long lifespan of most buildings, with impacts occurring at different times during the life cycle; the possible changes in form or function during the lifespan of the building; the multitude of different actors, including designers, builders and users, that influence the life cycle impacts of the building; and the lack of standardisation of building design and construction, making each building unique (Kotaji et al., 2003).

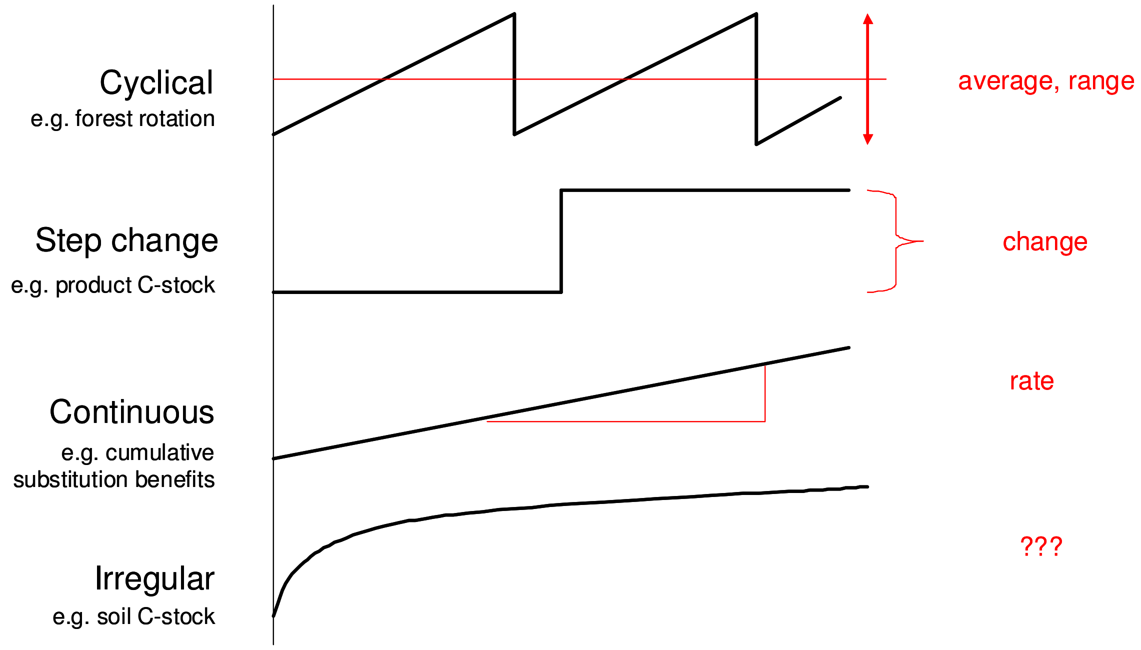

Figure 3.1. Examples of time dynamics of greenhouse gas flows of wood product substitution analysis, and the parameters by which such flows can be characterized.

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3.2 Modelling approaches

Analysis of wood product substitution can use either of two different, but complementary, modelling approaches to system analysis: bottom-up and top-down methods. Bottom-up models start from a detailed understanding of the fundamental elements and processes of the system, and then generate aggregate system behaviour by simulating the relations between the individual entities of the system. A process-based analysis, for example, begins with mass and energy balances of the final production process, and works backward to determine the energy and material needs of each contributing input. As the analysis expands to include higher-order indirect inputs, the contribution of additional factors becomes less significant and more cumbersome to determine. System boundaries of the analysis are drawn at an appropriate level, beyond which the energy and material flows are ignored. While giving detailed information on the particular process studied, this method allows truncation error outside of the system boundaries.

Top-down models, on the other hand, begin with an overall description of aggregate performance of the system, and proceed to subdivide the system to understand its functioning. An input-output analysis, for example, uses macro-economic data on monetary transactions between industrial sectors, including flows of commercial energy. Data on energy and material purchases by particular industrial sectors are coupled with information on physical production, yielding average values for the energy and material balances of the materials produced. Truncation error is avoided because contributions from the entire economy are considered, by definition accounting for 100% of commercial material and energy flows. However, this method has limited detail of particular processes because the data are highly aggregated. It does not account for non-commercial energy sources such as biomass residue used internally in wood production processes. Furthermore, because it is based on statistical data of historical or current production, it has limited relevance to innovative technologies that are now being developed for future implementation.

Bottom-up models have the advantage of greater detail in system parameters, but may lack completeness if some parts of the system are excluded from the model. Top-down models include the entire system, but may suffer from limitations in understanding the relations between the elements in the system and how they can be modified to achieve desired objectives. Top-down models appear particularly unsuited for energy and carbon balance analysis of forest industries, where a large part of the energy and carbon flows occur outside the realm of macro-level statistical compilations. For example, a significant part of the energy used in forest product industries is derived from biomass residues generated internally, and the dynamics of biological carbon stocks and flows, and their complex interactions with fossil carbon emission, are inadequately described from the top down.

3.3 Functional unit

A comparative analysis of wood-based materials relative to non-wood materials requires the definition of a reference entity or “functional unit” to allow objective comparison of the materials. A functional unit is a measure of the required properties of the studied system, providing a reference to which input and output flows can be related. These inputs and outputs, which vary between the different products compared, are the reference flows which determine the environmental impacts. The reference flows are the specific outcomes of fulfilling the abstract functional unit in different ways (Weidema, 2004). Energy and CO_2 analysis of wood substitution in construction can be compared on a variety of functional units: material mass or volume, building component, complete building, or services provided by the built environment. The functional unit applies to the buildings and materials, not to the energy use or the CO_2 emissions which are the result of the functional unit being fulfilled.

A commonly used unit by which impacts are calculated is a unit mass of individual materials. For example, industrial process analyses commonly determine the primary energy required to manufacture a kg or tonne of material. This information can be useful input for a more elaborate analysis, but by itself is incomplete because the function of different materials cannot be directly compared. One tonne of lumber, for example, does not fulfil the same function as one tonne of steel. Similar analysis on the basis of unit volume of material suffers the same shortcoming. A more useful functional unit is to compare performance on the basis of the function provided by building components. That is, building components that provide the same function (e.g. structural support, or wall sheathing), made of either wood-based or non-wood materials, can be compared (Sathre and Gustavsson, 2006).

Nevertheless, a particular material may fulfil more than one function (e.g. structural support and thermal insulation), and a given building function may be fulfilled by a combination of materials. Changing one material may impact on other functions in various ways, for example sound transmission, fire protection, and the overall weight of the building and the required foundation design. Thus, a more comprehensive analysis is at the building level (Kotaji et al., 2003), alternately using wood-based or non-wood materials. This can be based on a generic hypothetical building (Björklund and Tillman, 1997), or a case study of completed buildings (Gustavsson et al., 2006b; Lippke et al., 2004). The functional unit can be defined so that all the options have the same impacts during the operation phase, potentially simplifying the analysis (see Section 3.4.1.2).

The choice of allocation procedure can have a significant effect on the results of a comparative analysis of wood and non-wood products (Jungmeier et al., 2002). Allocation is the process of attributing impacts or benefits to a particular part of a process that results in multiple outputs. This is particularly important for wood materials, because multiple co-products are produced from the same raw material, and wood products themselves can be used as biofuel at the end of their service life as a material product. Allocation is a subjective procedure, and depends in part on the perspectives and values of the analyst (Werner et al., 2007). However, allocation can often be avoided, e.g. by system expansion by adding additional functions to the functional unit so the systems compared have identical functions (Gustavsson and Karlsson, 2006). For example, the secondary function of wood as an energy source can be compared to an alternative of providing the same energy with fossil fuels.

To facilitate comparison among different case studies, performance can be measured on the basis of the services provided by the building, rather than the building itself. For example, if the primary service provided by a building is protection against the climatic elements, comparison can be made on the basis of m^2 or m^3 of climate-controlled floor area or interior space. This can allow comparison between buildings of different size, although it may be difficult to distinguish between differences due to the scale effect of the buildings (e.g. inherent differences between single family and multi-family buildings, or single storey and multi-storey buildings) and the differences due to the building material choice.

Building codes can be used as a measure of function of a building, thus different buildings that each fulfil building codes for e.g., thermal efficiency or fire resistance, might be considered to be functionally equivalent in this regard. However, building codes are minimum standards that must be reached, and a building that perform significantly better than the code requirements may erroneously be considered equivalent to a building that simply meets the code. Therefore, caution should be taken when building codes are used as a measure of building function.

When analysing at the level of entire buildings, it should be recognised that a structural frame of a certain material does not imply that the entire building is constructed of that material. The objective of material substitution is therefore not 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. As some wood is generally used in all buildings, the focus of analysis is on the amount of *additional* wood that is used, and the resulting decrease in non-wood materials that are required. The functional unit is always described as a demand side variable, i.e. the building or product used. However, land use issues and sustainability concepts involving substitution may also be revealed from a supply side perspective such as the unit of forest that produces such functional units.

3.4 System boundaries

Defining system boundaries is a necessary part of analyzing the impacts of wood product substitution. System boundaries delineate what is included in the analysis, and what is disregarded. Boundaries should be established broad enough to capture the significant impacts of interest, but not so broad as to make the analysis too unwieldy. System boundaries can be identified in terms of procedural, temporal, or spatial characteristics. Although these are not truly independent, we discuss them here separately. An activity always has spatial and temporal boundaries; and without an activity, spatial and temporal boundaries have no significance. There exists a range of mechanisms by which wood product substitution affects energy use and CO_2 emission, and system boundaries should be established to ensure that the significant effects of these mechanisms are included in the analysis.

3.4.1 System boundaries: Activities

Procedural system boundaries define which physical activities or processes are considered in the analysis. These can include, for example, production of the materials, operation of the building, recovery and use of co-products, and post-use material management. Supply of energy has a strong impact on primary energy use and net CO_2 balance, and is discussed in depth in a separate section.

3.4.1.1 Production phase

The first stage of a building material life cycle is the acquisition of materials. Raw materials are extracted from their natural state (e.g. by mining of minerals or harvesting of primary forests) or are cultivated (e.g. timber production in managed forests). The materials may then go through one or several stages of processing and re-processing. Processing operations may involve resizing, separation of different components, combining with other materials, and changing of chemical structure. Primary and secondary processing may occur at the same location, or may require transport from one processing facility to another. The burdens of building the processing infrastructure that produce the products are usually excluded from life cycle studies, under the assumption of a long life span that allocates these burdens over so many products so as to have a negligible impact.

Processing energy
Energy is required to manufacture both wood products and non-wood products. A “cradle to gate” analysis of material production includes the acquisition of raw materials, transport, and processing into usable products. The type of end use energy varies, and could include electricity, biofuels, and various types of fossil fuels. Primary energy required to provide the different types of end use energy, and the resulting CO_2 emissions, can be determined through consideration of fuel cycle, conversion, and distribution losses (see Section 3.4.1.5).

Different physical processes can be used to produce the same material, each process 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. Data on industrial energy use can also vary depending on the methodology used to obtain the data. System boundaries of an energy analysis can range from a restrictive analysis of direct energy and material flows of a particular process, to an expansive analysis including energy and material flows of entire industrial chains and society as a whole. Data may be direct measurements of a particular machine or factory, or may be aggregated for an entire industrial sector. Figure 3.2 shows the primary energy used for production of materials for wood- and concrete-framed versions of a building, using specific energy use data from three different European process analyses. These results suggest that in spite of absolute differences between the analyses (due to varying system boundaries, regional differences, etc.), the *relative* energy use of wood vs. non-wood materials is more consistent (Gustavsson and Sathre, 2004).

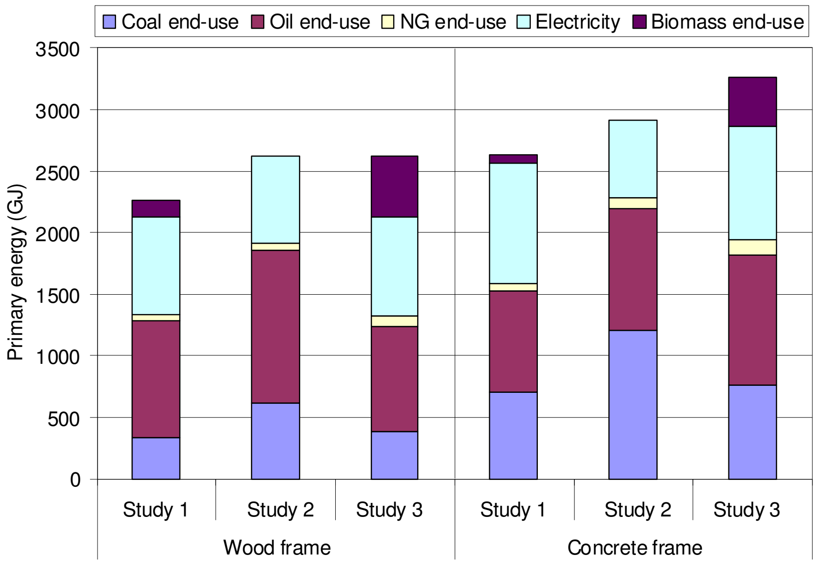

Figure 3.2. Primary energy used for production of materials for wood- and concrete-framed versions of a building, using specific energy use data from three different process analyses. Study 1 is Fossdal (1995), Study 2 is Worrell et al. (1994) and Study 3 is Björklund and Tillman (1997). (Figure adapted from Gustavsson and Sathre, 2004)

Raw material supply

For those materials extracted directly from natural deposits, for example mineral ores, an appropriate system boundary for the calculation of energy and carbon balances begins at the point of extraction. For biological materials that are cultivated, for example wood from sustainably managed forests, the analysis includes the technological (i.e. human directed) energy used for biomass production. This includes the fossil fuels used for the management of forest land and for the transport and processing of wood materials. Gross solar energy intercepted by the plants for photosynthesis and growth is generally not included in the energy balance (IFIAS, 1974), unless the specific objectives of the analysis requires it. Carbon balances of biological materials include the carbon fluxes that occur during the life cycle of the plants.

There is an inherent variability in the quality of forest biomass, thus the different types of biomass (e.g. sawlogs, pulpwood, forest residues) are not completely comparable or substitutable. For example, any biomass can be burned to produce heat, but not all biomass can be made into structural lumber. Sawlogs can be used for a full range of processes including lumber production, pulp manufacture, and heating, but the uses of forest residues are more limited. Similarly, the characteristics of wood (durability, dimensional stability, bending properties, grain structure, colour etc.) determine the range of appropriate uses, e.g. for building construction, furniture manufacturing, pulp and paper. Thus, in an analysis involving forest production, it is important to distinguish between various types of forest biomass.

Cement process reactions

Manufacture of cement-based products result in industrial process carbon emissions. CO_2 emissions are inherent to the cement production process, due to chemical reactions (calcination) during the transformation of raw materials into cement clinker. Process emissions can be a significant part of the GHG emissions from manufacturing concrete and other cement-based materials. While calcination reaction emissions are well quantified, there is some uncertainty regarding the net effect of cement process emissions, due to subsequent CO_2 uptake by carbonation reaction. This slow reaction occurs over the life cycle of cement products, and reabsorbs from 8% to 57% of the CO_2 that was initially emitted (Dodoo et al., 2009). Nevertheless, as carbonation uptake is less than calcination emission, process reaction emissions can be a significant part of the GHG emissions of cement products, and should be included in the analysis.

3.4.1.2 Operation phase

The operation phase generally contributes the greatest share of life cycle energy use and CO_2 emissions of a building. As the emphasis of a wood substitution study is on the energy and carbon balances of building materials, the impacts from *operating* the buildings are of interest only to the extent that they are affected by the choice of material. Numerous studies have analysed wood and non-wood building versions that are designed to be thermally equivalent. The functional unit of the comparative analysis is chosen so as to give the same services, resulting in no differences in the operation impacts. Some studies do not include impacts that occur during the operation phase, reasoning that the impacts are the same in both building versions, thus do not affect the relative environmental impacts of the wood and non-wood building (e.g. Gustavsson et al., 2006b; Upton et al., 2008). Adalberth (2000) compared apartment buildings constructed with a wood frame and a concrete frame, and calculated the difference in operation energy between them to be less than 1%. Cole and Kernan (1996) found the difference in operating energy between wood and concrete framed office buildings in Canada to be negligible, and Lippke et al. (2004) compared wood houses with steel and concrete houses having identical thermal properties, and found no difference in operation energy. In such cases, adding the operational energy use would increase the total primary energy use for both the wood and non-wood alternative, but the difference between them would remain the same. The thermal mass of building materials may in some cases affect the heating or cooling energy requirements of a building, depending on climate, building size, configuration, and orientation.

Major efforts have been made to reduce the energy used for building operation, e.g. by improved insulation, reduced air leakage through the house envelope and by heat recovery from ventilation air. Such measures result in lower space heating demand, but increased material use and hence increased energy demands for production and construction. Gustavsson and Joelsson (2009) conducted an integrated analysis of the linkage between construction energy input and operational energy input. This type of analysis permits the optimisation of primary energy use over the entire building life cycle. Connections, trade-offs and synergies between different phases of the life cycle need to be identified to allow an optimisation of building construction and operation practices to reduce environmental impacts. In analyses of cost-effectiveness, the full life cycle building costs including external costs need to be considered.

3.4.1.3 Co-products

Biomass flows over the life cycle of a wood-based building material are shown schematically in Figure 3.3. In addition to the principal flows of roundwood and finished wood materials, there are numerous co-product flows. Co-products are materials or products of some value that are produced simultaneously with the main product. The harvesting of trees, and their processing into wood products, generates considerable biomass residues that can be used as biofuel. Residues are generated during primary processing when logs are reduced to lumber, as well as in secondary processing industries that provide manufactured products such as doors, windows and glue-laminated beams. Some residues from wood processing are also used as a raw material for particleboard or other composite wood products.

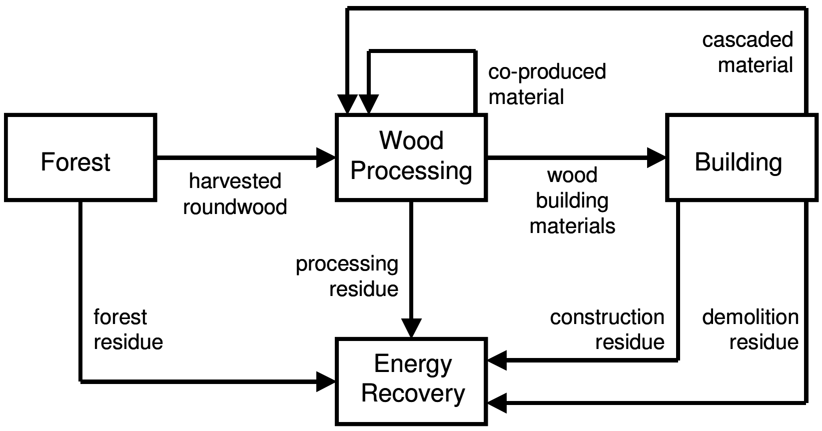

Figure 3.3. Schematic diagram of forest biomass flows over the life cycle of a wood-based building material.

Recovered woody material can be either burned as biofuel, or used as input for further processing into other wood products. Such reprocessing of wood materials at the end of the building life cycle can have significant effects on the energy and carbon balances of the material (Sathre and Gustavsson, 2006). Various alternative uses for recovered wood lumber are possible, including re-use as lumber, and re-processing into particleboard or pulp. Such optimisation of end-of-life product recovery and recycling systems may become increasingly important in the future, to gain additional value from the wood as a material, before it is burned to recover its feedstock energy. In such a future scenario, the "design for disassembly" of buildings would become more prevalent to facilitate the removal of wood products with minimal damage, to maintain their potential for further re-use as a material (Kibert, 2003).

Co-products of non-wood industrial processes, including fossil fuel fly ash and blast furnace slag, can be used as cement binders. Construction cement made of a blend of clinker and other additives is becoming more commonly used (Gartner, 2004). When cement is made with a blend of clinker and co-products of other industrial processes, total energy use is reduced because less clinker must be produced. CO_2 emissions are reduced in 2 ways: less fossil energy is needed for the production of the lower quantity of clinker, and lower clinker production means less CO_2 emissions from the chemical reaction of limestone calcination. Another useful co-product is gypsum, which can be obtained from coal flue gas desulfurization.

3.4.1.4 Post-use material management

An analysis that covers the entire life cycle of a material must consider the fate of the material at the end of its service life. The final stage in the life cycle of a building is the demolition or disassembly of the building followed by the reuse, recycling or disposal of the materials. The energy used directly for demolition of buildings is generally small (1-3%) in relation to the energy used for material production and building assembly (Cole and Kernan, 1996). The percentage of demolition materials that is recoverable is variable, and depends on the practical limitations linked to the building design and whether material recovery is facilitated. Also, systematic recovery of demolition wood is not yet practiced in some areas, and demolition wood is instead landfilled. Methods for accounting the climate effects of recycling materials are still at an early stage of development, particularly in the context of potential policy instruments for climate change mitigation.

Further use of recovered wood material, such as reusing as lumber, reprocessing as particleboard, or pulping to form paper products, can improve the environmental performance of the material. Sathre and Gustavsson (2006) compared energy and carbon balances of products made of recovered wood to the balances of products obtained from virgin wood fibre or from non-wood material. They found that several mechanisms affect the energy and carbon balances of recovery wood, including direct effects due to different properties and logistics of virgin and recovered materials, substitution effects due to the reduced demand for non-wood materials when wood is reused, and land use effects due to alternative possible land uses when less timber harvest is needed because of wood recovery. They concluded that land use effects, e.g. the potential for carbon sequestration or forest biofuel production on the land no longer needed for timber production, have the greatest impact on energy and carbon balances. Substitution effects are next most important, while direct effects are relatively minor.

In cases where material reuse of recovered wood is not practical, recovery of energy by burning the wood is a resource-efficient post-use option. The use of recovered demolition wood as a biofuel directly affects the energy balance of the material. The use of the biofuel to replace fossil fuels, thus avoiding fossil carbon emissions, also affects the carbon balance. Methodological issues regarding the use of biofuels to replace fossil fuels are discussed further in Section 3.4.1.5.

European studies have often concluded that burning wood waste to replace fossil fuel is the best post-use management option (see e.g. Scharai-Rad and Welling, 2002; Börjesson and Gustavsson, 2000). North American studies have generally considered landfilling as a more suitable option (see e.g. Upton et al., 2008). Carbon dynamics in landfills are quite variable, and can have a significant impact on the GHG balance of wood products. A fraction of the carbon in landfilled wood products will remain in semi-permanent storage, providing climate benefits. However, another fraction may decompose into methane, which has much higher global warming potential than CO_2. However, methane gas from landfills can be partially recovered and used as a biofuel to replace fossil fuels. Thus, the landfilling option for post-use wood products carries great uncertainties, and could result in some climate benefit due to partial sequestration in landfills and partial production of methane biofuel, or severe climate impact due to emission of methane to the atmosphere. There is a lack of consistency in the methods and assumptions used to track carbon during the life cycle of wood products (Franklin Associates, 2004). Particularly in regards to carbon sequestration and methane generation in landfills, a wide variety of methods and assumptions have been used in previous studies, leading to different and potentially contradictory conclusions.

The energy and climate performance of non-wood materials can also be significantly affected by post-use management. Production of steel products from recycled steel scrap requires less primary energy, and emits less CO_2, than production of steel from ore. Post-use management of concrete can also lead to reduced net CO_2 emissions, by promoting increased carbonation uptake of CO_2 by e.g., crushing the concrete and leaving it exposed to air. Nevertheless, wood material has relatively more opportunity to improve its energetic and climatic performance, due to its dual role of both material and fuel (Dodoo et al., 2009).

3.4.1.5 Energy supply system

Fossil fuel use

During the life cycle of building materials, fossil fuels are used for extracting, processing, and transporting various raw, finished and residual materials. In a bottom-up analysis, calculation of total fossil fuel use begins with data on material quantities, and specific end-use energy for various production processes broken down by energy carrier. Based on this total end-use energy, total primary energy use can be calculated, taking into account “upstream” energy used over the entire fuel cycle, including extraction, transportation, processing, conversion and distribution of the energy carriers (IFIAS, 1974).

The use of fossil fuels produces CO_2 emissions in quantities that depend on the carbon intensity and fuel-cycle characteristics of the fuel. Specific CO_2 emission values are applied to end-use quantities of fossil fuels to give total emissions. To ensure accurate reporting, specific emission values must include emissions occurring over the entire fuel cycle, including the end-use combustion of the fuels as well as from fuel extraction, conversion and distribution (Gustavsson et al., 2006b). Nevertheless, uncertainties arise in accounting for fossil fuel emissions, due to methodological differences, heterogeneity of fuels, and imprecision in measuring (Marland, 2008).

In cases where the type of fossil fuel is known, e.g. end-use fuels used for material production in well documented industrial processes, the CO_2 intensity of that fuel is used in carbon balance calculations.

In cases where there is some uncertainty as to the appropriate choice of fossil fuel, e.g. the fossil fuel that is used to produce marginal electricity or that is replaced by biomass residues (see Section 3.4.1.5), a "reference fossil fuel" can be employed to determine the significance of the carbon intensity of the fossil fuel that may be used (Sathre, 2007). Coal and fossil gas are two reasonable reference fossil fuels, representing the high and low ends, respectively, of the range of carbon intensity (kg C emitted per GJ heat energy released) of fossil fuels, thus indicating the range of uncertainty introduced by the fossil fuel used.

Electricity supply
The primary energy use and CO_2 emissions during a material life cycle are affected by the supply system used to provide electrical energy for the various processes. Various types of electrical energy production systems exist, with significant variations in associated primary energy use and GHG emissions. Values for *average* or *marginal* primary energy efficiency and CO_2 emissions from electricity production could be used in a substitution analysis. However, average data would inadequately capture the effect of changes to the system brought about by an increased use of wood material. This is because changes in electricity supply do not occur at the average level, but at the *marginal* level (Sjödin and Grönkvist, 2004). A decrease in electricity use, for example through reduced energy use in material processing industries, will cause a decrease in production of electricity from marginal sources. Likewise, an increase in electricity supply, for example from increased use of biomass-fired combined heat and power plants using residues from the forest products industry, will also decrease the existing marginal electricity production. When analysing incremental changes in material use, it is thus appropriate to use data on marginal electricity production that will be influenced by material substitution, rather than data on average electricity production.

Depending on the magnitude of the material substitution that occurs, i.e. whether the substitution occurs on the level of an individual building construction or a society-wide transition toward a bio-based economy, an analysis of the dynamics of the electricity supply system might be needed to understand marginal changes that may occur at differing scales of substitution. Furthermore, electrical supply systems continue to evolve over time. In the years and decades to come, the marginal electricity production will be affected by the evolution and development of the energy system as a whole (Sjödin and Grönkvist, 2004). New investments in electricity production will be largely determined by relative costs and policy incentives. Existing coal-fired condensing plants, which are currently the dominant marginal electricity production method in northern Europe, will eventually be replaced. The electricity plants that are currently being constructed will likely be used until 2040 or even longer. Decarbonisation and CO_2 sequestration in large-scale, fossil fuel-fired plants may become commercialised over this time period, driven by the need for GHG emissions reduction. The production capacity of biomass, wind power and other renewable sources is likely to increase in the future. The identification of marginal electricity production depends on numerous factors including the time frame of analysis, the future development of technology, the need for and incentives to reduce carbon emissions, and the development of alternative sources such as nuclear and renewables. Over the coming decades in northern Europe, the marginal electricity production would appear to be from coal-fired power plants, or less likely from fossil gas-fired power plants.

Replacement of fossil fuel by biomass residues
Biomass residues from the wood products chain can be used as biofuel to replace fossil fuels, thus affecting the energy and CO_2 balances. The net carbon emissions reduction of fossil fuels substitution should be based on the full fuel-cycle emissions of the avoided fossil fuel, the difference in energy conversion efficiency between the fossil fuel and the biofuel, and take into account the emission from fossil fuels used for recovery and transport of the biofuel. The actual combustion of biofuel obtained from sustainably managed forests is generally assumed to have zero net emission. Important methodological issues when comparing fossil- and bioenergy-based systems are the type of fossil system to be replaced, and the type of bioenergy system used to replace it (Gustavsson et al., 2006b). Because the fossil fuel that will be replaced by biofuel use may not be known with certainty, it is worthwhile to conduct the analysis with more than one reference fossil fuel to determine the significance of this uncertainty (see Section 3.4.1.5).

The carbon balance effect of fossil fuel substitution will depend on the extent of biomass residue recovery. Recovery and utilisation of forest residue is becoming more common. In particular, residue from clear-cut areas is increasingly recovered, with efficient logistical systems to collect and transport the residue currently being developed (Eriksson and Gustavsson, 2009). Recovery of forest thinning residue is less common, due to its dispersed nature making efficient and economic collection more problematic. Recovery of stumps is a potentially significant source of biofuel. The use of wood processing residue is quite widespread. Some byproducts are not directly used as biofuel but instead for pulp or particleboard production, though eventually these materials also can be used for energy purposes. The recovery of wood-based construction waste for use as biofuel is becoming more widespread, with source separation of different types of construction wastes occurring on many construction sites. Utilisation of wood-based demolition waste has a significant impact on the energy balance of wood construction, and has the potential to increase. Recovered wood that is contaminated with paint or preservative treatment can often be incinerated under suitable combustion conditions with flue gas cleaning and ash disposal. Policy measures, including landfill dumping fees and regulations, affect the amount of wood that is recovered from building demolition sites. Greater reuse and recycling of materials is possible, particularly if more attention is paid during building design and construction to facilitate disassembly (Kibert, 2003).

Biofuel is generally assumed to replace fossil fuel that otherwise would have been used. However, in economies where energy and/or material use is supply-limited, the availability of an additional unit of biofuel may not lead to a unit reduction in fossil fuel use, due to equilibrating effects in the wider economy. In this case, an additional unit of biomass fuel or material may not *displace* the use of fossil fuel or non-wood material, but instead be used in addition to it. This so-called “leakage” results in the actual climate benefit of using wood products being somewhat lower than the potential benefits, but will increase the services delivered to society.

3.4.2 System boundaries: Temporal

The time at which energy and carbon flows occur can affect the outcome of wood substitution analyses, depending on the system boundaries and assumptions used. Important temporal aspects of the wood life cycle include the dynamics of forest growth including regeneration and saturation, the duration of carbon storage in products, the temporal pattern of fossil fuel use, the availability of residue biofuels at different times, and the time dynamics of cement process reactions. The available data are generally based on current practices and technology, although the full time scope of wood substitution extends both back in time (e.g. when currently mature forests were established) and forward in time (e.g. to the end-of-life of wood products). It may be appropriate to make assumptions about previous practices or forecasts of future technologies, though such projections must be made transparently.

3.4.2.1 Forest growth

Consideration of forest dynamics is an essential part of an analysis of energy and carbon balances of wood products. The life cycle of a wood product begins with the germination of the tree seed, and continues through the growth and harvest of the tree and the manufacture and use of the resulting product. The carbon flux is time-dependent, as the plants grow and accumulate carbon in their tissues, and affects soil carbon content due to the root development and detritus-fall of the plants. This requires an analytical approach that captures the time dynamics of the plant growth, with explicit consideration of temporal scope of the analysis (Schlamadinger et al., 1997). Material inputs to the system include CO_2, water and nutrients, while the wood is an internal flow within the system boundary (Yaro, 1997). The accumulated carbon stock is tracked through the life of the tree, and through the life cycle of the wood product, until the carbon is eventually released again to the atmosphere through combustion or decay. Energy flows begin with the accumulation of solar energy in tree biomass, through to its eventual release when the biomass is burned or decomposes.

The harvest of forest biomass is a discrete event that occurs in the context of a dynamic process of forest growth and regrowth. Depending on biogeographical factors, the rotation period of forest stands ranges from decades to over a century, during which time the trees gradually accumulate carbon in their tissues. Following harvest of the forest stand, assuming no change in land use, the regeneration of the trees initiates another cycle of carbon accumulation. There appears to be a dilemma between short-term climate mitigation efforts involving carbon sequestration in forests and long-term sustainability goals of forests as renewable sources of material and energy, because the harvest of a tree containing a unit of carbon does not result in the immediate avoidance of a unit of fossil carbon. Depending on tree characteristics and the efficiency with which it is processed and used, the avoided fossil carbon emissions will equal perhaps half of the carbon in the tree (authors' calculations based on Sathre and O'Connor, 2008). Approximately a quarter of the tree's carbon will remain in temporary storage during the life span of the wood product, and can be used for additional fossil fuel substitution at the end of the product life. A fraction of the tree biomass will remain in the forest in roots, etc., and slowly decompose and release carbon. Nevertheless, some net CO_2 emission will occur after harvest, until the regrowing forest accumulates additional carbon. As the forest grows, the net CO_2 emissions become negative. The time elapsing between stand harvest and negative net emissions depends on the forest growth rate, which varies with climate, management intensity, etc.

If instead the forest stand were not harvested, it would eventually reach a dynamic equilibrium, with the amount of carbon taken up by new growth balanced by the carbon released by respiration in living trees and decay of dead trees. Carbon storage in forest soils changes at a slower rate, thus buffering the changes in total forest ecosystem carbon stock (Eriksson et al., 2007).

3.4.2.2 Product duration

A part of the carbon that is taken from the atmosphere during the growth of a forest stand remains sequestered during the service life of a wood product. About 50% of the dry weight of wood is carbon. The longer a particular wood fibre is used or reused as a material, the longer those particular carbon atoms will remain out of the atmosphere. Eventually, however, and in the absence of long-term sequestration in e.g. landfills, all the carbon will be emitted through combustion or decomposition. As part of a dynamic biogeochemical cycle, carbon storage in wood products is an inherently transient phenomenon, though some long-lived wood products may store carbon for centuries.

Over the life cycle of a building, there is no change in carbon stock in the building itself. Before the building is built it contains no carbon stock, and after the building is demolished it contains no carbon stock. Combustion of wood-based demolition material ensures that 100% of the carbon stock is oxidised and re-enters the atmosphere as CO_2. If the demolition material is used as biofuel to replace coal, the avoided fossil carbon emissions are roughly equivalent to the carbon stored in the wood material during the building lifespan (Gustavsson et al., 2006b). If the material is landfilled, there may be a fraction of carbon remaining in semi-permanent storage, with the remainder emitted as CO_2 or methane (see Section 3.4.1.4).

On a larger scale, a carbon sequestration effect occurs if the total stock of wood products is increasing. This could occur as a result of general economic growth, whereby more products of all kinds are produced and possessed, or through a societal transition from non-wood to wood-based products. If the total stock of carbon in wood products is increasing, carbon storage in products contributes to reducing atmospheric CO_2 concentration. The carbon stock in wood products would increase if a change were made from non-wood to wood-based construction. This would occur if non-wood buildings, representing the baseline, are replaced by wood-framed ones, which after demolition are always replaced by new wood-framed buildings with a similar carbon stock. This would result in a step change in carbon stock compared to the baseline, at the point in time when the non-wood material is replaced by wood. The permanence of the carbon stock in buildings depends on the difference between the amount of wood added to new construction and the amount of wood removed from demolished buildings (Gustavsson et al., 2006b). The stock of wood products will stabilise if the rate of wood entering the wood products reservoir is equal to the rate at which used wood is oxidised and releases its stored carbon to the atmosphere. At this point, the storage of carbon in wood products has no net effect on the atmospheric CO_2 concentration. This is in contrast to the substitution effect that occurs each time a new wood product is used instead of a non-wood product, which results in permanent and cumulative avoidance of carbon emissions.

3.4.2.3 Fossil fuel use

Fossil fuels are used at different times over the life cycle of a building, as discussed in Section 3.4.1. Fuels are used to extract, process and transport materials used to construct the building. Fuels are used to operate the building, and are later used to dismantle the building. The use of these fossil fuel results in carbon emissions occurring at different times throughout the life cycle of the material.

3.4.2.4 Biomass residue availability

Over the life cycle of a wood-based material, biomass residues will become available at different times. Thinning residues may be generated at different times during the growth phase of the forest. Later, forest residues are created when the forest stand is harvested, processing residues are available when the roundwood is transformed into wood products, and construction site residues are left when the building is assembled. Later still, demolition residues are produced at the end of the building life cycle. The use of these residues to replace fossil fuel results in reduced fossil carbon emissions at different times in the life cycle of the material.

3.4.2.5 Cement process reactions

As discussed in Section 3.4.1.1, chemical reactions affecting the net carbon balance occur continuously throughout the life cycle of cement-based materials. CO_2 emissions occur due to calcination at the time the cement is manufactured, and CO_2 uptake occurs due to carbonation throughout the life cycle of the cement product. The rate of CO_2 absorption by carbonation depends on several factors including the exposed uncoated surface area of the concrete, the composition of the cement used to make the concrete, and the relative humidity and temperature of the environment (Gajda and Miller, 2000). Roughly one-third to two-thirds of the initial calcination emission will eventually be taken up by carbonation reaction, depending on exposure duration and conditions during and after the product lifespan (Dodoo et al., 2009).

3.4.3 System boundaries: Spatial

3.4.3.1 Land use modelling approaches

Careful definition of spatial boundaries and the general consideration of how land is used are important issues when comparing wood and non-wood materials. The use of wood-based materials instead of non-wood materials uses greater quantities of biomass, requiring the use of more land area or intensified forest management (Börjesson and Gustavsson, 2000). A fundamental difference between biomaterials and mineral materials is the regenerative ability of land, subject to appropriate management, to continue to produce the biomaterials during successive rotation periods in perpetuity, via biological processes. Although some materials like metals can be recycled successively, and all materials are naturally recycled over geological time spans, only biomaterials can be indefinitely regenerated on a time scale of use to society. This regeneration is driven by the energy of the sun through the process of photosynthesis, which accumulates the flow resource of solar energy into the replenishable fund resource of plant biomass (Swan, 1998). Land area for the capture of solar radiation is essential to this process, thus a consideration of the use of land and its productive capacity is an essential element of a comparative analysis of wood material use.

A major challenge when comparing wood materials with non-wood materials is to compare the differences in land use needs between the two materials. Sathre (2007) explored four different analytical approaches to treat this issue. The first was to assume that an equal area of land is available to both the wood-based and non-wood-based product, and analyse the carbon balance impacts of various usage options for any land not used for material production. Assumptions on alternative land use may be based on a plausible market response, considering supply and demand for forest biomass and forest-related environmental services over different time scales. For example, a reduction in demand for timber may result in a decreased harvest, leading to an increase in forest carbon stock, or alternatively the trees may be harvested and used for the next lower-valued product.

The second approach was to model the biomass production from a unit area of land under different management options, and analyse the carbon balance impacts of using the produced biomass for various purposes. A third approach was to increase the intensity of use of the biomass resources through material cascading, or multiple reuse of wood fibre in applications that require successively lower quality of material, in effect gaining more functional service from the output of a given land area, or alternatively getting the same function from a smaller land area.

A fourth approach was to assume that the incremental wood material is produced though more intensive use of forest land, or from land that had not been previously used for wood production. The annual harvest of some forest land is much lower than the annual potential harvest. For example, 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/yr (UNECE/FAO, 2000). Continuation of these harvesting levels would change the age class structure towards older age classes and the growth increment would decline in the long run. If harvesting levels are increased, age class structure would change towards younger age classes and growth increment would increase, further increasing the substitution potential.

3.4.3.2 Forest management intensity

Forest management produces a multiplicative effect whereby energy inputs used for forest management are leveraged into a greater energetic output in terms of biomass harvest. A continuum of forest management intensities is possible, from an intense regime to the non-management and non-use of forests. At least three effects on carbon balance can be distinguished if a forest is not managed. First, the forest biomass would continue growing until the stand is mature. At this point a dynamic balance would be reached, where natural mortality equals growth and the long-term average carbon stock remains near-constant. Second, the soil carbon stock would behave in a similar way, i.e. continue to grow at a successively lower rate until a near steady-state situation is reached (Lal, 2005). Third, no forest products would be produced and other, more carbon-intensive, materials and fuels would be used instead, resulting in increased net CO_2 emissions.

The carbon stocks of forest biomass and soil are affected by forest management regimes, including rotation length, thinning, fertilisation, and harvest (Eriksson et al., 2007). Intensification of forest management would increase the growth increment and the substitution potential. Transition to a management regime involving a longer or shorter rotation length would result in a temporary decrease or increase, respectively, in the harvest levels, as individual stands are harvested later or earlier than they otherwise would have been harvested.

A fundamental basis of wood substitution studies is that the forest land must be managed sustainably, in such a way that the land use can be continued indefinitely. Essential elements of sustainable land use include the maintenance of levels of soil nutrients and organic matter, the efficient use of available water supplies, and the protection of natural biotic diversity (Reijnders, 2006).

4. Displacement factors of wood product substitution: a meta-analysis

4.1 Introduction to greenhouse gas displacement factors

A displacement factor of wood product substitution is a measure of the amount of GHG emission avoided when wood is used instead of some other material. It is an index of the efficiency with which the use of biomass reduces net GHG emission, and quantifies the amount of emission reduction achieved per unit of wood use. If the use of non-wood materials in a particular application results in a given amount of GHG emission, while using wood materials to fulfil the same application results in a different amount of emission, then the displacement factor is calculated as the difference in emission divided by the amount of additional wood used. A higher displacement factor indicates that more GHG emission is avoided per unit of wood used. A negative displacement factor means that emission is greater when using the wood product.

Of the 48 studies on the GHG impacts of wood products reviewed by Sathre and O'Connor (2008), it was determined that 20 studies contained sufficient information to calculate the displacement factor of at least one wood product substituted in place of a non-wood product. The studies were restricted to analyses of wood material substitution, i.e., the use of wood instead of non-wood materials like metals, minerals and plastics. Studies of the GHG impacts of wood used exclusively as biofuels were not considered, although many of the studies reviewed also included the fuel substitution effects of biofuels from wood processing residues or post-use wood products.

Schlamadinger and Marland (1996) defined two displacement factors, one for biofuels that substitute directly in place of fossil fuels, and another for wood products whose production requires less fossil fuel than substituted products. Their analysis did not consider other potential substitution benefits not related to fossil fuel use, such as avoided process emissions or carbon sequestration in landfills. In the present meta-analysis, due to the diversity of the studies analyzed, a single displacement factor that incorporates all the GHG emission reductions reported in each study is calculated. Depending on the system boundaries of the study, these may include fossil fuel emissions from material production and transport, process emissions such as cement reactions, fossil emissions avoided due to using biomass by-products and post-use wood products as biofuel, carbon stock dynamics in forests and wood products, and carbon sequestration and methane emissions of landfilled wood materials.

4.2 Methods

In this meta-analysis we calculate displacement factors in units of tC of emission reduction per tC in wood product. The displacement factors could also be calculated in other units, e.g., emission reduction per t of wood product, or per m^3 of wood product, or per m^3 of roundwood, or per hectare of forest land. The inverse of the displacement factor could also be used to express the "biomass cost," or the amount of wood required to achieve a unit of GHG emission reduction (Gustavsson et al., 2007). Here we use the units of tC emission reduction per tC in wood products, as these units appear to be the most transparent and comparable. In addition, because both emission reduction and wood use are expressed in the same unit (tC), the displacement factor is an elegant indicator of the "multiplicative" effect of using wood products for GHG mitigation.

Specifically, we calculate the displacement factor (*DF*) as:

$$DF = \frac{GHG_{non-wood} - GHG_{wood}}{WU_{wood} - WU_{non-wood}}$$

where $GHG_{non-wood}$ and GHG_{wood} are the GHG emissions resulting from the use of the non-wood and the wood alternatives, respectively, expressed in mass units of carbon (C) corresponding to the $CO2_{eq}$ of the emissions, and WU_{wood} and $WU_{non-wood}$ are the amounts of wood used in the wood and non-wood alternatives, respectively, expressed in mass units of C contained in the wood. $WU_{non-wood}$ is non-zero in some applications, e.g., concrete-framed buildings with roof structures, doors or window frames made of wood. *WU* includes only the wood contained in the end-use products, although the GHG benefits of some studies also take into account the impacts of other associated biomass flows such as harvest and processing residues.

The data available in some of the studies allow the calculation of a single displacement factor, with no indication of the range of variability. Other studies report data on several scenarios or assumptions, which allow the calculation of high and low estimates of the displacement factors.

The parameters of wood product use and reduced emissions for each of the 20 studies are given in detail by Sathre and O'Connor (2009). To calculate the displacement factors in consistent units, both parameters are then converted to mass units of carbon (C). Carbon content of GHG emissions is calculated as 12/44 CO_2eq. Carbon content of wood is assumed to be 50% of oven dry weight. Unless otherwise specified in the source documents, calculations have been made assuming a wood density of 500 kg oven-dry matter per m^3, and a moisture content of 15% (mass of water per mass of oven-dry wood).

4.3 Results and discussion

The calculated displacement factors are listed in Table 4.1. The displacement factors average 2.0, and range from a low of -2.3 to a high of 15.0. The wide range of displacement factors is due to the

Table 4.1. Low, middle, and high estimates of displacement factors of wood product substitution (tC emission reduction per tC of additional wood products used) based on data from various studies.

Reference	Application	Low	Middle	High
Börjesson and Gustavsson, 2000	Apartment building	-2.33	4.21	7.48
Buchanan and Levine, 1999	Hostel building		1.05	
" "	Office building	1.13	1.17	1.20
" "	Industrial building		1.60	
" "	House	-0.55	3.57	15.0
Eriksson, 2003	European construction sector	1.36	1.66	1.95
Eriksson et al., 2007	Construction materials	4.43	5.97	7.50
Gustavsson et al., 2006	Apartment building 1	1.94	3.76	5.58
" "	Apartment building 2	0.37	1.82	3.27
Gustavsson and Sathre, 2006	Apartment building	-0.10	2.30	7.33
Jönsson et al., 1997	Solid wood flooring	0.01	0.21	0.32
Koch, 1992	Mixture of wood products		2.20	
Künniger and Richter, 1995	Utility pole (treated roundwood)	0.58	2.47	4.36
" "	Utility pole (glulam)	0.14	1.98	3.82
" "	400V transmission line	1.53	2.73	3.92
" "	20 kV transmission line	1.03	3.39	5.75
Lippke et al., 2004	House	0.92	1.57	2.21
Petersen and Solberg, 2002	Roof beams	-0.76	0.40	1.27
Petersen and Solberg, 2003	Wood flooring	-0.76	0.36	1.15
Petersen and Solberg, 2004	Wood flooring	0.08	1.72	12.9
Petersen and Solberg, 2005	Review of Scandinavian studies	-0.88	0.66	3.02
Pingoud and Perälä, 2000	Finnish construction sector	0.45	1.09	4.05
Scharai-Rad and Welling, 2002	House 1	0.32	0.64	0.96
" "	House 2	2.25	2.76	3.27
" "	3-storey building	1.46	2.26	3.06
" "	Warehouse	0.66	1.21	1.77
" "	Window frame	2.74	4.15	5.56
Sedjo, 2002	Utility poles		1.59	
Upton et al., 2008	House 1	-0.01	0.40	2.16
" "	House 2	2.74	2.84	6.62
Valsta, 2007	Literature survey	1.00	2.00	3.00
Werner et al., 2005	Swiss construction sector		1.60	
Averages		**0.7**	**2.0**	**4.4**

inclusion of "extreme" scenarios in some of the studies, and differences in system boundaries between studies. The few cases of negative displacement factors, in which the greenhouse gas emission of wood products are greater than that of alternatives, are the result of worst-case wood disposal options that are unrealistic in current practice. The middle estimates of the displacement factors range from 0.2 to 6.0, with most lying in the range of 1.0 to 3.0. The average of the low estimates is 0.7, and average of the high estimates is 4.4. The average middle estimate, with a value of 2.0, can be viewed as a reasonable estimate of the GHG mitigation efficiency of wood product use, over a range of product substitutions and analytical methodologies.

The results of this meta-analysis can be compared to the displacement factor when wood is used directly as biofuel to replace fossil fuel instead of being used as a material. In this case, the displacement factor will range from less than 0.5 up to about 1.0, depending largely on the type of fossil fuel replaced and the relative combustion efficiencies.

A displacement factor is valid only for wood used *in place of* other, more carbon-intensive materials. The displacement factors calculated here should not be misinterpreted to suggest that a GHG emission reduction will result from each and every piece of wood used, regardless of how it is used. The use of wood in applications for which wood is typically used will not result in a GHG emission reduction, except to the extent that emission would have been greater *if* non-wood materials were used instead. Thus, depending on the context, a displacement factor can be a measure of either the GHG that is avoided because something is made of wood when it could have otherwise been made of non-wood materials, or of the potential reduction in GHG emission if something made of non-wood materials were instead made of wood. Effective GHG displacement can also occur if wood from sustainably managed forests is used in place of unsustainably harvested wood.

Displacement factors can be considered within two different contexts. In a scenario where wood is widely used in an application, for example single-family housing in North America, then there may be an interest in how much carbon emissions would *increase* if the houses were instead constructed of concrete or steel. Alternatively, in a scenario where non-wood materials are dominant, for example apartment buildings in Europe, the calculation of interest is how much carbon emissions would *decrease* if there were a widespread switch to wood.

Variability is inherent in the determination of displacement factors. Each study shows a unique result, which varies with physical factors like the type of forestry and wood product, the type of non-wood material it is compared against, and the post-use fate of the wood. It also varies with the analytical methodology and assumptions used in the analysis, which adds additional uncertainty. The studies cover a wide range of wood product types and materials substituted, and use data specific to different geographic regions. Some studies include only the production phase of the product life cycle, while others take into account the entire life cycle and consider land use issues and various post-use management options. The studies vary in scale, from micro-level studies of individual building elements, to meso-level studies of complete buildings, to macro-level studies covering wood product usage in a country or region.

The analytical rigour of the studies varied, with some using well-developed methods and well-justified assumptions, while others used less-complete models and data sources. Some studies incorporated established life cycle assessment (LCA) protocols, although there exist additional methodological challenges when comprehensively analyzing the GHG impacts of wood product use (Perez-Garcia et al., 2005). This heterogeneity of study methodologies and assumptions brings advantages and disadvantages to the meta-analysis. While making inter-study comparisons more difficult, it adds to the robustness of the overall results by showing displacement factors for a range of different product substitutions and analytical methodologies. Due to the diversity of the studies, the quantitative values of the displacement factors calculated in this meta-analysis should not be compared with each other. Instead, they should be seen generally to represent the range of expected GHG performance of wood product substitution, depending on the specific products compared and analytical methods employed.

Not all of the studies examined here are completely independent analyses; some data are shared between more than one study. For example, Sedjo (2002) uses GHG emission data from Künniger and Richter (1995), and Lippke et al. (2004) and Upton et al. (2008) analyze the same buildings. Nevertheless, each study offers some new perspective on the issue, by analyzing the data with differing system boundaries or methodological assumptions.

Policies that provide incentives to use wood in place of other, GHG-intensive materials may have additional beneficial climate effects beyond those quantified by displacement factors. A greater global demand for wood products may increase the value of productive forest land, relative to its conversion to other uses, and thereby reduce the rate of deforestation in the tropics (Aulisi et al., 2008). This potential effect is not considered here.

4.4 Displacement factor conclusions

In this analysis we integrate data from 20 different studies in a meta-analysis of the displacement factors of wood products substituted in place of non-wood materials. Calculated in consistent units of metric tons of carbon (tC) of emission reduction per tC in wood product, the displacement factors range from a low of -2.3 to a high of 15.0, with most lying in the range of 1.0 to 3.0. The average displacement factor value is 2.0, meaning that for each tC in wood products substituted in place of non-wood products, there occurs an average GHG emission reduction of approximately 2 tC. Expressed in other units, this average value corresponds to roughly 3.7 t CO_2eq emission reduction per t of dry wood used, or 1.8 t CO_2eq emission reduction per m^3 of wood product.

There is some uncertainty associated with the results of each individual study, and of the meta-analysis as a whole. The studies cover a wide range of wood product types and materials substituted, use data specific to different geographic regions, and employ different methodological techniques and assumptions. Collectively, however, the 20 studies provide a consensus that wood product substitution reduces GHG emission. The positive sign of the "base-case" displacement factor of each study shows that under normal conditions, using wood products results in less GHG emission than using functionally equivalent non-wood products. Post-use management of wood products appears to be the single most significant source of variability in the GHG impacts of the wood product life cycle. The few cases of negative displacement factors are the result of worst-case wood disposal options that are unrealistic in current practice.

The range of displacement factors among the various studies suggests that some types of wood product substitution provide greater GHG reduction than others. The limited sample size of this meta-analysis, and the inconsistencies between the studies, do not allow us to draw firm conclusions regarding specific wood uses to maximize GHG benefits. Additional research should be conducted to determine which types of wood products or building systems should replace which non-wood products to produce the highest possible displacement factor.

By quantifying the range of GHG benefits of wood substitution, this meta-analysis provides a clear GHG rationale for using wood products in place of non-wood materials, provided that forests are sustainably managed and that wood residues are used responsibly. An effective overall strategy to mitigate climate change and transition to a carbon-neutral economy should therefore include the sustainable management of forest land for the continuing production and efficient use of wood products.

5. Wood substitution at larger scale: Swedish and European cases

In this section we present the results of an analysis of substitution effects of 4 case-study buildings, scaled up to macro-level at the national scale (Sweden) and regional scale (Europe).

5.1 Issues in large-scale wood substitution analysis

Wood substitution can be analysed on different levels: micro-level studies, focusing on individual products, processes or decision-making entities; meso-level studies, focusing on certain industries or sectors of the economy; and macro-level studies, focusing on macroeconomic and landscape implications of wood substitution (Gustavsson et al., 2006a). Studies at each level have their own advantages and limitations. Results from studies at different levels can complement each other, thus providing a richer picture of the complex issue of wood substitution than studies using a single approach only.

As the analysis is scaled up from the micro to macro level, a different set of issues is involved. The aggregate use of forest land will depend on the competing demands for the various products and services that the forest can provide, and the alternative materials available. This will differ between a marginal change in product use (i.e. the consideration of a single product substitution) and a structural change in society's production and consumption patterns. On a macro-level, methods are needed to determine the aggregate impact of large-scale changes in forest biomass supply or demand, not only for building materials, but also for fuel, paper, carbon storage and ecological services.

An analysis that integrates the dynamics of forest processes and economic markets is needed to identify interdependencies. For instance, increased carbon sequestration in forest biomass reduces the quantities of biomass available for energy and material substitution. Other interdependencies are transmitted by the price mechanism such that increased use of wooden construction material will tend to increase timber prices, resulting in more intensive forest management. The long time scales further complicates comparisons of strategies; whereas wood fuel can substitute for fossil fuel today, the use of wood in construction will affect energy use in different sectors immediately and fossil fuel substitution when the building is eventually demolished in the future.

Carbon dynamics differ substantially as the scale increases from the forest stand level to the landscape level. At the landscape level, the total carbon balance at any time is the aggregate of the balances of a multitude of stands, each at a different stage of its rotation. The maximum carbon stock at the landscape level is thus lower than the maximum at the stand level, because not all the individual stands will hold the maximum stock at the same time (Kurz et al., 1998). A substitution analysis on the micro-level can analyse wood flows in terms of their relation with the production of an individual stand, while a macro-level analysis must consider flows on the landscape level.

Larger-scale analysis may seek to understand the spatial distribution of the GHG benefits of material substitution. The forest growth, wood processing, material use, and waste disposal may occur at different sites, and possibly different countries. The inter-European and intercontinental trade in wood-based products and fuels is increasing, and there is a large potential for exporting prefabricated wooden buildings, or lumber to be used for wood construction, from forest-rich countries in northern Europe to other regions that predominately use brick or concrete construction. This process would be encouraged by the wider establishment of economic policy instruments for climate change mitigation, e.g. taxation of carbon emission and fossil fuel use, which economically favour less carbon-intensive materials such as wood (Sathre and Gustavsson, 2007). By exporting biomass to be used in applications that result in high CO_2 emission or energy use reductions per unit of biomass, the total CO_2 emission reduction from the available supply of biomass could by increased. For example, the total number of new buildings built per year in Nordic countries is small in relation to the total quantities of biomass potentially available. If the export potential was ignored, the additional biomass would then be used for other uses with lower efficiency of emission reduction, or would be left in the forest. However, if additional biomass were exported and used instead of non-wood buildings in other countries, the higher emission reduction per unit of biomass could be gained by a larger share of the biomass, thus resulting in a greater overall emission reduction globally.

5.2 Previous substitution analyses at a large scale

Several authors have analyzed wood substitution at the national or regional level.

Buchanan and Levine (1999) analysed the energy and carbon implications of increased wood use in New Zealand construction. They calculate that a 17% increase in wood use could result in a 20% reduction in both energy use and carbon emission from building material production. This would be a 1.8% decrease in New Zealand's total carbon emission. The authors also make a scenario analysis of increased wood use on a global level, with similar results.

Pingoud and Perälä (2000) analysed the potential for wood substitution in the Finnish construction sector. The authors compared the total amount of new building construction to a scenario in which the same buildings were built in a way that maximized wood use, finding that the use of wood-based products could increase by almost 70%.

Eriksson (2003) estimated the GHG emission reduction potential of using wood construction material on a European scale. Based on an annual production of 1.8 million housing units, 95% of which are made of non-wood materials, and an average size of 100 m^2/unit, and a GHG emission reduction of 200 to 300 kg CO_2eq/ m^2, the total reduction would be about 35 to 50 Mt CO_2eq per year. This is about 0.9 to 1.3% of total annual European emissions. This would require an additional annual use of 35 million m^3 of sawn softwood, compared to current use of roughly 100 million m^3 per year.

Werner et al. (2005) conducted a scenario analysis of the GHG impacts of increased use of wood products on a national level in Switzerland, based on the substitution effect of using wood in place of non-wood products. They estimated that a 30% increase in wood use would lead to 0.60 Mt of avoided CO_2 emission per year due to reduced fossil fuel use for material production. An additional reduction of 0.36 Mt of CO_2 emissions per year would be achieved by using wood residues to substitute fossil fuel. The GHG benefit of increased carbon storage in products becomes less significant over time, as the carbon stock stabilizes while the substitution effects continue to provide cumulative GHG benefits. They found that much of the wood substitutes in place of heavy, nationally-produced materials such as concrete and brick, resulting in decreased emissions in Switzerland. Other wood use substitutes in place of e.g. steel products manufactured outside of Switzerland, leading to decreased emissions in other countries. Some product substitutions resulted in increased emissions within Switzerland, but decreased net global emissions.

Upton et al. (2006, summarized in 2008) conducted a national-scale analysis of housing construction in the US. Beginning with substitution data of individual case study houses built with wood frames instead of steel or concrete, the authors expand the analysis to 1.5 million houses each year for the next 100 years. They linked the case study data on construction materials in the houses to "upstream" issues like forest growth dynamics and land use issues, and "downstream" issues like disposal of the demolition materials. On a national-scale, building with wood instead of steel or concrete reduces net GHG emission by 9.6 Mt CO_2eq/yr and reduces net energy use by 132 PJ/yr. Issues that affect the results include the time horizon of the study, and the fate of the forest land if it is not used for wood production.

Eriksson et al. (2009) developed four wood construction scenarios depicting wood consumption up to the year 2030 for the European construction sector. The roundwood demand in each year was distributed among supplying countries by a partial equilibrium model for the forest sector that encompasses forestry, wood-using industries, and markets for roundwood and forest products. Resulting data on harvest volumes or timber prices were then used in a forest regional model for

Sweden, where harvest levels were derived by assuming that forest owners maximize their net present value over an infinite horizon with current prices. More detailed analysis of the management implications was performed with a stand model, an individual-tree, distance-independent growth and mortality model that finds optimal steady state stand management programs (planting density, timing and form of thinning and time of final harvest).

5.3 Spatial variation in wood use intensity

The level of wood use in building construction varies significantly between countries. Table 5.1 shows that the share of wood for constructing one- and two-family houses is relatively high in Nordic countries and in North America, but is rather low elsewhere in Europe.

Table 5.1 Share of wood construction in one and two family house construction in selected countries or regions.

Country	Share of wood construction
USA[1]	90-94%
Canada[1]	76-85%
Nordic countries[1]	80-85%
Scotland[2]	60%
UK[3]	20%
Germany[1]	10%
The Netherlands[4]	6-7%
France[2]	4%

Source: Gustavsson et al., 2006a, based on [1] HAF, 2000; [2] Reid et al., 2004; [3] Toratti, 2001; [4] van de Kuilen, 2001.

Wood is commonly used in Nordic countries for single-family houses, but is less common in multi-storey apartment buildings. In contrast, wood is commonly used in North America for construction of both single-family as well as multi-family houses. In recent years, wood has shown signs of increased market penetration in many European countries. For example, in Germany the amount of timber used for construction of one- and two-family houses increased somewhat from 8% in 1993 to 11% in 2000 (see Figure 5.1). There are large differences between regions within the country and between different types of buildings. The share of timber-framed one- and two-family houses is significantly higher in the eastern part of Germany (15%). Only 2% of all multi-family houses in Germany are built of wood. (Statistisches Bundesamt, 2002).

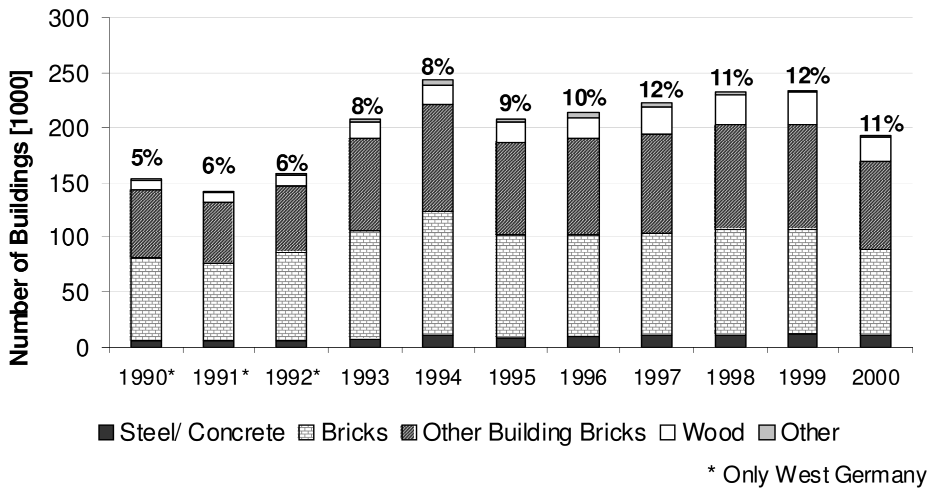

Figure 5.1 Market share of different materials used in construction of small residential houses in Germany, 1990-2000 (Source: Gustavsson et al. 2006a, based on Statistisches Bundesamt 2002). The percentage figures refer to the share of wood material.

Wood use per capita varies significantly among countries, cultures, and environments. Table 5.2 shows apparent consumption (production+imports-exports) of sawn softwood in various European countries in 2006. There is a large range in annual wood consumption, with a region-wide average of 0.17 m^3 per capita per year, but encompassing a range from 0.01 m^3 per capita in Bosnia-Herzegovina to 1.3 m^3 per capita in Estonia.

Table 5.2 Apparent annual consumption of sawn softwood in European countries in 2006. (Source: Eriksson et al., 2009, based on FAOSTAT data)

Country	1,000 m^3	m^3 per 1,000 inhabitants
Europe	102,025	169.3
Albania	55	17.5
Austria	5,212	640.3
Belgium	2,178	209.1
Bosnia and Herzegovina	61	14.1
Bulgaria	144	18.5
Croatia	393	88.5
Cyprus	102	137.6
Czech Republic	3,242	317.8
Denmark	2,111	390.8
Estonia	1,717	1,268.5
Finland	4,948	946.6
France	10,241	165.9
Germany	20,187	244.7
Greece	862	78.0
Hungary	823	81.5
Iceland	91	309.3
Ireland	1,569	386.9
Israel	334	49.1
Italy	7,296	125.7
Latvia	1,641	709.4
Lithuania	916	266.5
Luxembourg	123	271.9
Malta	10	25.8
Netherlands	2,384	146.5
Norway	2,872	625.6
Poland	2,803	73.4
Portugal	675	64.3
Romania	1,027	47.4
Serbia	510	50.2
Slovakia	724	134.6
Slovenia	109	54.6
Spain	5,335	130.0
Sweden	4,848	539.0
Switzerland	1,698	229.0
The fYR of Macedonia	277	139.1
Turkey	4,772	66.0
United Kingdom	9,735	163.4
EU25	89,791	196.3

5.4 Wood construction scenarios

We employ scenarios of increased use of wood material in the construction of single-family houses and multi-family apartment buildings, at a national scale (Sweden) and a regional scale (Europe). The scenarios are based on data on numbers of dwellings constructed annually in the various countries, coupled with informed estimates of current level of wood-based construction in each country and potential for substitution with wood-based materials. The scenarios for increased wood use are compared with a projected *baseline* of continued use of the current mix of building materials. The number of buildings constructed annually is the same in the baseline and the scenarios. We assume a constant annual level of new building construction. The number of new buildings that is assumed to be constructed annually is based on the average number of new dwellings constructed annually from 1980 to 2004 (to 2007 in the Swedish analysis). Figure 5.2 shows the number of new dwellings, both as small houses (1 or 2 family residences) and as larger multi-family residences, built in Sweden each year from 1980 to 2007 (Statistics Sweden, 2009). The numbers vary significantly from year to year, based on economic cycles, demographic changes, etc. Over this period, the average number of dwellings constructed annually in 1-2 family buildings is about 14500 dwellings per year. The average number of dwellings constructed annually in multi-family buildings is about 17250 dwellings per year. We use these numbers in our projections for future construction in Sweden.

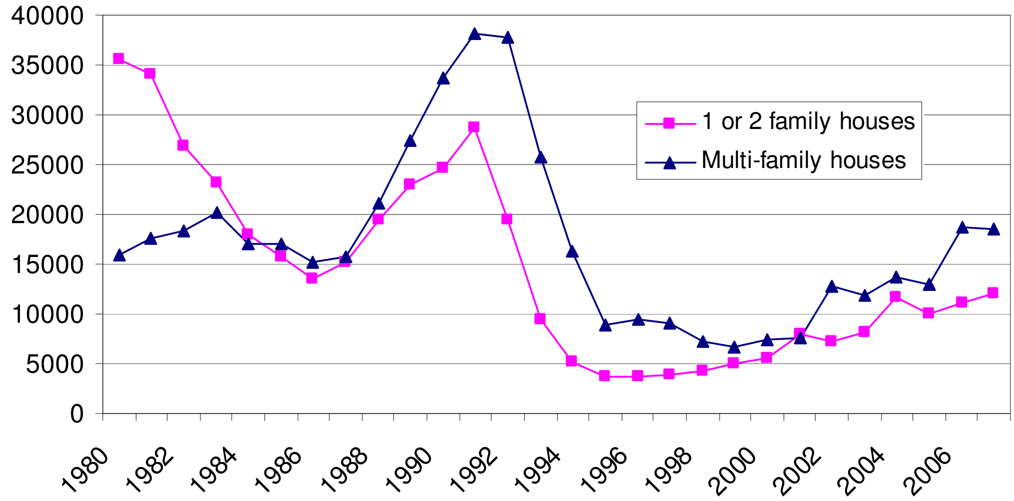

Figure 5.2. Number of new dwellings in completed buildings in Sweden, 1980-2007 (Source: Statistics Sweden, 2009).

Table 5.3 shows the average number of new dwellings constructed annually in each of the EU-25 countries (except Malta, for which data were not available). These figures are based on the average numbers of new dwellings constructed in single-family houses and in multi-family apartment buildings during each of the 5-year periods from 1980 to 2004 (Federcasa, 2006). Some data points were unavailable in this reference, particularly the breakdown between single-family houses and multi-family buildings during the earlier time periods, and in these cases we extrapolated trends from later data that were available. The data for Sweden in Federcasa (2006) showed a greater average number of single family houses constructed in Sweden (16,400 dwellings per year) than did the data from Statistics Sweden (2009) described above (14,500 dwellings per year), and we used the more recent country-specific data from Statistics Sweden (2009). This difference may be due to the difference in categories between the two references, as Federcasa (2006) distinguishes between "single-family dwellings" and "multi-family dwellings," whereas Statistics Sweden (2009) distinguishes between "1- and 2-family dwellings" and "multi-family dwellings."

Because of the difference in floor area between the 4 case-study buildings, as well as the difference in dwelling floor area between countries, we based our calculations upon dwelling area, rather that number of dwellings. Table 5.3 shows average floor area of new dwellings constructed in each of the countries (Federcasa, 2006), which we used in our calculations. The data on average floor area does not distinguish between dwellings in single-family and multi-family buildings, thus in this analysis we assume the same floor area for each type of dwelling. In the national scale analysis of wood substitution in Sweden, however, we differentiate between floor area of 1- and 2-family dwellings and multi-family dwellings based on data from Statistics Sweden (2009) showing an average floor area for 1- and 2-family residence of 108 m^2 and an average floor area for multi-family residence of 67 m^2.

Table 5.3 Number and floor area of new construction of single-family and multi-family dwellings in various European countries, and assumed potential for substituting wood in place of non-wood materials in new construction.

Country	Average floor area of new dwellings (m^2)	Average new dwellings constructed per year (x 1000)		Assumed percent of new construction currently made with wood framing		Annual wood substitution potential (1000 m^2 floor area)	
		Single-family	Multi-family	Single-family	Multi-family	Single-family	Multi-family
Austria	101.1	25.6	26.2	5%	5%	2460	2514
Belgium	105.0	27.1	14.3	5%	5%	2704	1430
Cyprus	197.6	3.6	3.6	5%	5%	668	668
Czech Republic	100.7	24.7	19.0	5%	5%	2358	1822
Denmark	107.0	14.1	8.6	85%	5%	227	878
Estonia	89.1	0.5	6.1	5%	5%	45	515
Finland	90.2	15.4	26.9	85%	5%	208	2304
France	111.0	213.6	142.4	5%	5%	22519	15021
Germany	113.9	166.1	259.1	10%	5%	17027	28039
Greece	124.6	39.2	65.3	5%	5%	4644	7728
Hungary	94.1	25.1	24.2	5%	5%	2241	2165
Ireland	105.0	30.9	7.9	5%	5%	3083	784
Italy	76.5	98.7	120.6	5%	5%	7171	8764
Latvia	92.1	1.0	3.2	5%	5%	87	280
Lithuania	106.2	3.0	12.6	5%	5%	304	1274
Luxembourg	120.2	1.1	1.0	5%	5%	124	112
Netherlands	115.5	69.0	23.6	5%	5%	7572	2585
Poland	107.5	47.0	87.0	5%	5%	4799	8884
Portugal	88.9	25.3	43.1	5%	5%	2138	3641
Slovakia	131.7	22.7	19.2	5%	5%	2838	2404
Slovenia	108.7	4.9	3.9	5%	5%	505	406
Spain	100.6	95.8	240.2	5%	5%	9156	22956
Sweden	94.0	14.5	17.2	85%	5%	231	1546
United Kingdom	82.7	105.4	105.4	20%	5%	6974	8282

Table 5.3 also shows the assumed percent of new construction currently made with wood framing in each of the countries. This is a rough estimate based on discussion in Gustavsson et al. (2006a) and Nordic Timber Council (2002), supplemented by data in Table 4.1. There is significant uncertainty in these estimates of wood-based construction in different European countries, although it is generally acknowledged that very few multi-family buildings are made with wood structures in Europe, and there is much variation between countries in single-family construction, with Nordic countries having a high percentage of wood frame houses and most other counties having a much lower percentage. We base this analysis on the assumption of a full market penetration in each country, such that all new dwellings are made with wood frames, replacing non-wood material that traditionally would have been used.

Based on the information described above, we estimated the total floor area of new dwellings that could be built in each country of wood instead of non-wood materials, broken down by small buildings (1 or 2 families) and large buildings (multi-family apartment buildings).

5.5 Case study buildings

To determine the energy and climate effects of wood substitution, we calculated GHG and energy displacement factors based on published case studies buildings made of wood and of non-wood materials. The GHG displacement factor for each has the units of tC emission reduction per m^2 of dwelling, and the energy displacement factor has the units of GJ energy use reduction per m^2 of dwelling. Each building is compared to a reference building of identical size and functionality, but constructed primarily of non-wood materials. The case studies cover two multi-storey apartment buildings in Sweden (SWE) and Finland (FIN) built with wood frames instead of concrete frames (Gustavsson et al., 2006b). The case studies also cover two single-family houses in the USA, one in the city of Minneapolis (MIN) built with a wood frame instead of steel frame, and one in the city of Atlanta (ATL) built with a wood frame instead of concrete frame (Lippke et al., 2004). The single-family buildings were designed as part of the CORRIM project, and are made to American codes and conform to American building methods. Some differences may exist between these single-family buildings and typical European single family houses (e.g. more masonry (brick or stone) instead of concrete or steel alternative of the CORRIM buildings. We use these American case-study buildings because of a lack of complete and reliable data comparing European single-family houses made of wood and non-wood materials.

Based on a list of materials comprising each wood and non-wood building, we calculated the reduction in primary energy use and net CO_2 emission over the building lifecycle, based on the methodology described by Gustavsson et al. (2006b). The CO_2 reduction takes into account emissions from fossil fuel combustion for material processing and logistics, the reduction of emissions due to replacing fossil fuel with biomass residues, and the avoided emissions due to cement process reactions. The forestry practices and building materials production are based on Swedish conditions. We use specific energy use data from Björlund and Tillman (1997) for the production of concrete, steel, lumber, particleboard, insulation and plasterboard, and we use data from Fossdal (1995) for all other materials. We assume the production of plywood, laminated veneer lumber (LVL) and oriented strand board (OSB) uses the same energy per mass of product as production of particleboard.

As we consider all biomass flows associated with the building construction to be part of the system, the biomass residues from the harvest, processing and demolition that are available for use outside of the production process are assumed to be used as biofuel to replace fossil fuel. 10% of the wood products delivered to the construction site is assumed to be construction waste. Further, 100% of wood residue from wood processing plants, 100% of construction site waste, 90% of demolition wood, and 70% of harvest slash (foliage, branches and treetops) is assumed to be used as bioenergy. Note that we assume here that the wood residues from sawmilling are only used as biofuel and not, for instance, as raw material for pulp. If these residues were used in the pulp industry less fossil fuel could be directly replaced, reducing the estimated emission benefits. The reference fossil fuel is either coal or fossil gas, meaning that the biofuel replaces coal or fossil gas fuel, and electricity used for material production comes from coal- or fossil gas-fired condensing plants. The GHG emission reduction will depend on which marginal fuel is used in electricity generation and energy production in general. Coal is the marginal fuel at present (Sjödin and Grönkvist, 2004), but fossil gas could be a future marginal production option. The emission reductions are higher when coal is the marginal fuel, due to its higher emission factor – i.e. the relative benefits from biofuels is higher when coal is replaced.

Some parts of the FIN, MIN, and ATL buildings are assumed to be identical in both the wood and the non-wood versions of the buildings, and are therefore not included in the material comparison. In the FIN building these materials include wooden windows, doors, fittings, and HVAC systems, and in the MIN and ATL buildings the roofing materials are not included. These building parts represent a minor portion of the total amount of materials used in the buildings, and have minimal impact on comparisons between the wood-framed and non-wood buildings. Material input calculations for the SWE building include all materials, including parts identical in both the wood-framed and concrete-framed versions. Therefore, comparisons of energy use and CO_2 emission should not be made between the 4 case-study buildings, but instead between the wood-frame and non-wood version of each building.

5.5.1 Multi-family apartment buildings (SWE and FIN)

Building SWE uses data from a case study of the Wälludden building constructed in Växjö, Sweden (Gustavsson et al., 2006b). This is a 4-story building containing 16 apartments and 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.

Building FIN uses data from a case study of a 4-story apartment block built in 1997 in the ecological building area of Viikki in Helsinki, Finland (Gustavsson et al., 2006b). 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.

Table 5.4 Comparison of material quantities (tonnes of air-dry material) contained in the case-study buildings SWE and FIN. Source: (Gustavsson et al., 2006b)

Material	SWE		FIN	
	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

Wood material usage for the apartment buildings is compared to reference buildings in which reinforced concrete is used as the frame material. Calculations are based on an analysis of the case-study apartment buildings constructed using wood structural framing, compared to a functionally equivalent building constructed with a reinforced concrete frame (Gustavsson et al., 2006b). The comparison is made on a building level, and all materials composing the two buildings are included in the calculations. The amount of construction materials in the finished buildings with wood- and concrete-frames is shown in Table 5.4.

5.5.2 Single-family buildings (MIN and ATL)

The Minneapolis building (MIN) is a single-family house with two-stories plus a basement, with a total floor area of 192 m^2 (Kasal and Huelman, 2004). It was designed alternatively with wood or steel framing members. In the wood version, all framing members were solid wood with a nominal thickness of 2 inches, with the exception that the floor joists were composite I-joists. Wood-based composites (plywood and oriented strandboard) were used as sheathing and pre-engineered wood roof trusses were used as a roof system. The foundation was designed as 12-inch thick concrete masonry block walls. The above grade exterior wall composition of the wood frame building was as follows (from inside to outside): 1/2 inch gypsum sheetrock, nominal 2x6 inch wood studs 16 inch on center, fiberglass batt insulation, 7/16 inch OSB sheathing, housewrap, and vinyl siding. The steel-stud alternative had the following composition: 1/2 inch gypsum, 6 mil poly vapor retarder, nominal 2x4 inch cold rolled C-channel steel studs 16 inch on center, fiberglass batt insulation (R-13), 7/16 inch OSB, 1-1/2 inch polystyrene foam panel (R-7.5), and vinyl siding. A complete listing of materials is given in Table 5.5.

Table 5.5. Comparison of material quantities contained in the case-study buildings MIN and ATL. (Source: Kasal and Huelman, 2004)

		MIN		ATL	
Material	unit	Steel	Wood	Concrete	Wood
Concrete, 20 Mpa (flyash av)	m^3	21.9	21.9	31.8	31.8
Concrete blocks	each	2327	2327	1668	0
Mortar	m^3	7.4	7.4	5.4	0
Nails	tonnes	0.15	0.2	0.12	0.13
Welded wire mesh/ Ladder wire	tonnes	0.13	0.13	0.18	0.18
Screws, nuts, and bolts	tonnes	0.13	0	0	0
Wide flange sections	tonnes	0.43	0.43	0	0
Rebar, rod, light sections	tonnes	1.01	1.01	1.23	0.18
Hollow structural steel	tonnes	0.1	0.1	0	0
Galvanized sheet	tonnes	0.14	0.27	0.24	0.24
Galvanized studs	tonnes	5.13	0	0	0
Small dimension kd softwood lumber	Mbfm	1.75	7.99	6	6.45
Softwood plywood	msf (3/8 inch basis)	2.82	3.45	0	0
OSB oriented strand board	msf (3/8 inch basis)	5.6	5.32	3.12	5.09
LVL laminated veneer lumber	yd^3	0	1	0	0
Large dimension kd softwood lumber	mbfm	0.35	0.35	0	0
Batt, fiberglass	m^2 (25 mm)	1144	1519	468	468
Extruded polystyrene	m^2 (25 mm)	308	0	0	0
Blown cellulose	m^2 (25 mm)	1761	1761	2100	2100
Polyethylene, 6 mil	m^2	610	610	583	583
Gypsum boards, 1/2 inch regular	m^2	670	670	379	379
Gypsum boards, 5/8 inch regular	m^2	137	137	240	240
Joint compound	tonnes	0.81	0.81	0.62	0.62
Paper tape	tonnes	0.01	0.01	0.01	0.01
Paint, water-based latex	liter	0	0	15.51	0
Stucco over porous surface	m^2	0	0	144.16	0
Aluminium	tonnes	0.16	0.16	0.08	0.1
Vinyl	m^2	703	721	327	467

Shingles, organic felt, 25 year	m^2	131	131	229	229
Felt, #15 organic	m^2	1260	1260	249	719
EPDM membrane	kg	56.0	56.0	37.7	37.7
Low E silver argon filled glazing	m^2	46.8	46.8	31.3	31.3

The Atlanta building (ATL) is a single-storey house with a floor area of 200 m^2 (Kasal and Huelman, 2004). The foundation design is a slab-on-grade. It was designed alternatively with wood framing or with concrete block walls. The building envelope of the wood-framed alternative was: (from inside to outside): 1/2 inch gypsum sheet rock, nominal 2x4 inch wood studs 16 inch on center, fiberglass batt insulation, 7/16 inch OSB sheathing, housewrap, and vinyl siding. The concrete wall composition was: 1/2 inch gypsum sheetrock, 6 mil polyethylene vapor barrier, nominal 2x4 inch wood studs 24 inch on center, fiberglass batt insulation (R-13), concrete block (CMU) (8x8x16 inch blocks), and 2 layers of stucco finish. A complete listing of materials is given in Table 5.5.

5.6 Results

Table 5.6 shows the primary energy use for production of materials for the wood and non-wood versions of the case-study buildings. In each case except the FIN building, the production primary energy is greater for the wood-framed building than the non-wood-framed building. The FIN building uses a significant amount of biofuel to produce the large quantities of wood products in the building, and if this is excluded the fossil-based primary energy is lower for the wood-framed building than for the concrete-framed building.

Table 5.6. Primary energy use (GJ/m^2) for production of materials for wood and non-wood versions of the case-study buildings, broken down by end-use energy carrier.

Building	Coal end-use	Oil end-use	Fossil gas end-use	Biomass end-use	Electricity	Total
SWE						
Wood-frame	339	706	54	322	675	2096
Concrete-frame	671	871	85	251	767	2645
FIN						
Wood-frame	407	935	70	481	933	2826
Concrete-frame	883	1045	60	106	712	2807
MIN						
Wood-frame	222	1076	5	223	770	2297
Steel-frame	465	1103	110	151	937	2766
ATL						
Wood-frame	227	607	3	132	466	1436
Concrete-frame	227	714	3	99	466	1509

Table 5.7 shows the net energy available from recovery of biomass residues from forestry, wood processing, construction site, and demolition site, for wood and non-wood versions of the case-study buildings. Fossil energy used to recover and transport the residues has been deducted from the values shown. The processing residues show the net amount of residues available after composite wood products in the buildings are made from residues from the production of solid wood products. Two buildings, the MIN steel-frame version and the ATL wood-frame version, use relatively much composite wood products and little solid wood products, thus they show negative residues available from wood processing because additional biomass must be supplied to produce the composite wood products. Production of the ATL building produces the same amount of available biomass residues whether it is built with a wood-frame or concrete-frame, and the other 3 case study buildings produce more biomass residues when they are built with wood-frame.

Table 5.7. Energy (GJ/m^2) available from recovery of biomass residues from forestry, wood processing, construction site, and demolition site, for wood and non-wood versions of the case-study buildings. The values shown are net energy, after deducting fossil energy used to recover and transport the residues.

Building	Forest	Processing	Construction	Demolition	Total
SWE					
Wood-frame	499	408	138	1097	2142
Concrete-frame	322	109	97	769	1296
FIN					
Wood-frame	818	762	227	1800	3607
Concrete-frame	160	75	50	397	683
MIN					
Wood-frame	274	17	89	707	1087
Steel-frame	107	-246	49	390	300
ATL					
Wood-frame	153	-65	57	448	593
Concrete-frame	143	47	46	364	599

Tables 5.8 and 5.9 show the total annual emission reduction and energy use reduction if wood-based construction were used in all multi-family and single family buildings in Sweden and in EU-25, respectively. The total emission reduction varies significantly with the building design; the multi-family buildings give greater emission reduction than the single-family buildings. Within each of those building categories, the FIN design has higher reduction than the SWE design, and the MIN design has more reduction than the ATL design. Energy use reduction shows the same pattern in variation between building design that is seen in emission reduction. In all cases, emission reduction is greater if the reference fossil fuel is coal rather than fossil gas, though reference fossil fuel has little effect on energy use reduction.

Table 5.8. Total annual emission reduction and energy use reduction, and additional roundwood requirement, for full market substitution of multi-family and single family buildings in Sweden.

Building	Emission reduction (t C)		Energy use reduction (PJ)		Additional roundwood needed (million m^3 ob)
	Coal	Fossil gas	Coal	Fossil gas	
Multi-family building					
SWE	64 200	49 600	1.62	1.60	0.108
FIN	147 500	104 300	3.67	3.72	0.403
Single-family building					
MIN	9 600	6 300	0.32	0.31	0.022
ATL	1 200	1 100	0.024	0.024	0.001

Table 5.9. Total annual emission reduction and energy use reduction, and additional roundwood requirement, for full market substitution of multi-family and single family buildings in the EU-25.

Building	Emission reduction (t C)		Energy use reduction (PJ)		Additional roundwood needed (million m^3 ob)
	Coal	Fossil gas	Coal	Fossil gas	
Multi-family building					
SWE	7 366 000	5 691 000	186	184	12.4
FIN	16 921 000	11 961 000	421	427	46.2
Single-family building					
MIN	4 076 000	2 693 000	135	132	9.4
ATL	520 000	481 000	10.3	10.3	0.60

The total emission and energy use reduction calculated here can be compared to total emission and energy use in Sweden and Europe. Total greenhouse gas emissions in 2006 in Europe (EU-27) were 1403 million t Ceq, while those in Sweden were 17.9 million t Ceq (European Environment Agency, 2008). The GHG reduction effect of full substitution in Sweden thus ranges from a low of 0.006% of total Swedish emissions (ATL building, fossil gas reference fuel) to a high of 0.82% of total Swedish emissions (FIN building, coal reference fuel). At the level of Europe, the GHG reduction effect of full substitution ranges from a low of 0.03% of total EU-27 emissions (ATL building, fossil gas reference fuel) to a high of 1.2% of total EU-27 emissions (FIN building, coal reference fuel).

Total primary energy use in 2005 in Europe (EU-27) was about 75800 PJ (Eurostat, 2007), while that in Sweden was about 2240 PJ (Swedish Energy Agency, 2007). The energy use reduction effect of full substitution in Sweden thus ranges from a low of 0.001% of total Swedish energy use (ATL building) to a high of 0.16% of total Swedish energy use (FIN building). At the level of Europe, the energy use reduction effect of full substitution ranges from a low of 0.01% of total EU-27 energy use (ATL building) to a high of 0.56% of total EU-27 energy use (FIN building).

Tables 5.8 and 5.9 also show the additional quantities of roundwood that would be required to achieve full wood substitution in Sweden and the EU-25, respectively. This quantity also varies significantly between the building designs. The efficiency of using forest resources to reduce GHG emission and energy use is shown in Table 5.10. The ATL building design, although achieving the least total reduction, also uses the least amount of additional biomass, and thus gives the greatest reduction of emission and energy use per unit of additional roundwood. The SWE building gives the next highest efficiency of biomass use. The FIN building, which gives the greatest total reduction in both emissions and energy use but achieves this reduction by using a much greater quantity of biomass, has the lowest efficiency of using forest resources to reduce emissions and energy use.

Table 5.10. Emission reduction and energy use reduction per unit of additional roundwood in the wood-frmaed version of the case-study buildings.

Building	Emission reduction per additional roundwood (1000 tC/Mm^3)		Energy use reduction per additional roundwood (PJ/Mm^3)	
	Coal	Fossil gas	Coal	Fossil gas
Multi-family building				
SWE	592	458	15.0	14.8
FIN	366	259	9.1	9.2
Single-family building				
MIN	434	287	14.4	14.0
ATL	864	800	17.1	17.1

5.7 Uncertainties

Production energy data were not available for all materials, particularly for the MIN and ATL buildings, so in these cases data for similar materials are used. For example, the fibreglass, polystyrene and cellulose insulations were assumed to use the same production energy as an equivalent amount of mineral wool insulation, and stucco coating was assumed to use the same production energy as an equivalent weight of mortar. Although estimates of production energy data can be obtained for some of these materials, it is preferable to use consistent data from process analyses to avoid introducing errors due to inconsistent system boundaries and other methodological issues. The quantities of these materials affected by this simplification are minor in comparison to the total materials quantity.

As described above, some parts of some of the buildings are assumed to be identical in both the wood and the non-wood versions of the buildings, and are therefore not included in the material comparison. Therefore, comparisons of energy use and CO_2 emission should not be made between the 4 case-study buildings, but instead between the wood-frame and non-wood version of each building.

The most recent comprehensive analyses of energy use in building material production in Europe date from the mid-1990s. 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. There is a need for updating and improving the quality of data available on energy use and environmental impacts in the Swedish building materials industry.

Various factors influence the specific energy use for material production, including cement clinker production efficiency, blending of cement, crushing of aggregate, recycling of steel, lumber drying efficiency, and material transport distance (Gustavsson and Sathre, 2006). There is geographical variation, as technological innovations diffuse across countries and regions. For example, Richter (1998) showed variability in cumulative energy demand for wood-based products in different studies, and Josa et al. (2004) showed a range of energy use and CO_2 emission in cement production in the European Union. Swedish industries are generally considered to be relatively efficient, compared to the global average, but there is nevertheless a potential to increase the efficiency of manufacturing processes.

Swedish forests are generally considered to be sustainably managed, thus the decrease in biological carbon stock in tree biomass that occurs at the time of harvest will be restored as the forest re-grows and accumulates atmospheric carbon through the process of photosynthesis. Carbon storage in forest soils changes at a slower rate, thus moderating the changes in total forest ecosystem carbon stock. Intensified forest management has been shown to increase soil carbon stock, in spite of removal of additional biomass from the ecosystem, due to the increased growth rate and increased litter fall (Eriksson et al., 2007). Although forest dynamics are not explicitly considered in this analysis, an essential boundary condition is that the forests producing the wood for the building are sustainably managed, thus over the complete life cycle there should be minimal net change in carbon stock.

6. Conclusions

In this report we have endeavoured to present the state-of-the-art regarding energy and climate effects of wood product substitution, which is the use of wood to replace other materials such as concrete, steel or bricks. In a brief description of the historical uses of wood in the context of sustainable material cycles, we suggest that wood material may increase in relative importance in the future, due to environmental concerns and the exhaustion of non-renewable raw materials and fuels. Although the future development of wood is difficult to predict, the realisation of the importance of climate change mitigation, coupled with the implementation of suitable policy instruments, could motivate a significant increase in the use of wood use.

We have conducted a comprehensive literature survey of previous studies on wood substitution, including fundamental research and case study analyses as well as reviews and syntheses of previous works. Based on these studies, we have identified several mechanisms by which wood product substitution affects GHG balances. These mechanisms include: the fossil energy used to manufacture wood products compared with alternative materials; the avoidance of industrial process carbon emissions such as in cement manufacturing; the physical storage of carbon in forests and wood materials; the use of wood by-products as biofuel to replace fossil fuels; and the possible carbon sequestration in, and methane emissions from, wood products deposited in landfills.

We have discussed the methodological issues involved in wood substitution analysis, including the definition of a functional unit. The functional unit can be defined at the level of building component, building section, complete building, or services provided by the built environment. Energy use or GHG emission per unit of mass or volume of material can be an important input for a more comprehensive analysis, but by itself is inadequate because equal masses or volumes of different materials do not fulfil the same function. Analysis at the level of a complete building or building service is needed. Other important methodological issues include the establishment of effective system boundaries in terms of activities, time, and space. Activity-based boundaries include life cycle processes such as material production, product operation, and post-use material management. Numerous co-products are associated with the life cycle of wood products, and their analytical treatment can bring significantly uncertainty to the results. Temporal system boundaries include such aspects of the wood life cycle as the dynamics of forest growth including regeneration and saturation, the availability of residue biofuels at different times, and the duration of carbon storage in products. The establishment of spatial boundaries can be problematic, because use of wood-based materials instead of non-wood materials requires the use of more land area to grow the biomass.

We report on a meta-analysis of greenhouse gas displacement factors of wood substitution, in which 20 separate studies were analyzed and compared to determine the range of efficiency with which using wood instead of other materials can reduce net greenhouse gas emissions. Calculated in consistent units of metric tons of carbon (tC) of emission reduction per tC in wood product, the displacement factors range from a low of -2.3 to a high of 15.0, with most lying in the range of 1.0 to 3.0. The average displacement factor value is 2.0, meaning that for each tC in wood products substituted in place of non-wood products, there occurs an average GHG emission reduction of approximately 2 tC.

We also report the results of a simplified analysis of large-scale wood substitution, in which we estimate the greenhouse gas emission reduction and energy use reduction resulting from a full substitution of wood-based materials in both single-family houses and multi-family apartment buildings at the country level (Sweden) and the regional level (EU-25). The design of the wood-based buildings, and the type of reference non-wood buildings that they are compared against, have a strong effect on the energy and emission reduction resulting from the substitution. At the level of Sweden, we estimate that full scale substitution of multi-family buildings can reduce total annual Swedish GHG emission by up to 0.8%, and total annual energy use by 0.16%. At the level of Europe, we estimate that full scale substitution of multi-family buildings can reduce total annual European GHG emission by up to 1.2% and total annual energy use by 0.56%, while the respective figures for single-family buildings are 0.29% and 0.18%.

The overall conclusion of this report is that wood product substitution has the potential to significantly reduce primary energy use and greenhouse gas emissions. However, there is substantial variation in the energy and climate effects of different wood substitution applications. Both the meta-analysis (Section 4) and scale-up analysis (Section 5) showed large differences in the efficiency with which a unit of biomass reduces energy use and GHG emissions. Thus, additional research is needed to identify the most suitable material applications for the limited supply of forest biomass. It is clear, however, that the integration of biomass and energy flows among the sectors of forestry, manufacturing, construction, energy, and waste management will result in the most efficient use of the available resources. As the effects of sustainable forestry and efficient wood use on energy security and climate stability become better understood, wood product substitution will likely be an increasingly significant contributor towards sustainable development.

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