R&D FUND FOR PUBLIC REAL ESTATE

Climate impacts of wood vs. non-wood buildings

Sveriges Kommuner och Landsting

Preface

The built environment accounts for a large share of the global total energy consumption. Therefore, addressing this issue plays a crucial role in fulfilling our common goal of reaching a sustainable energy consumption and reducing greenhouse gas emissions.

In order to better understand the implications of strategies aiming at reducing energy and climate impacts of the built environment, this report aims to provide a state-of-the-art review of buildings' energy and climate effects through a system-wide life cycle perspective. The main focus of the report is comparing wood and non-wood-based construction systems.

The primary target group for this report is the municipal officials and politicians who make strategic decisions regarding construction of new public buildings.

This project was initiated and financed by the Swedish Association for Local Authorities and Regions' fund for research and development within municipal public real estate. The report is compiled by the researchers Ambrose Dodoo, Leif Gustavsson and Roger Sathre within the Sustainable Built Environment Group (SBER) at Linnaeus University, Växjö, Sweden.

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Abstract

Scientific evidence indicates that the earth's climate is warming due to increasing greenhouse gas (GHG) emissions from anthropogenic activities. Fossil fuels account for a significant share of the primary energy use in our society today and contribute considerably to climate change. A transition to a sustainable society with reduced GHG emission is a major challenge and will require concerted effort from all economic sectors. The building sector is responsible for a large share of the built environment's total primary energy use and GHG emission, and is expected to play a major role in mitigating climate change. In this regard, an issue of growing discussion is the effect of material choice on climate impacts of buildings. This report provides an overview on current scientific research on life cycle energy and climate implications of buildings, with emphasis on the role of structural frame material. Major methodological issues linked to life cycle and system analyses of buildings are also discussed in this report.

In summary, a growing body of literature shows the increasing contribution of the production stage to the life cycle impacts of buildings as dominance of the operating stage is reduced with improved energy efficiency measures. An increasing number of life cycle studies have found that wood-frame building results in lower primary energy and GHG emission compared to non-wood alternatives including concrete and steel. To understand the climate implications of building systems, full life cycle analysis must be conducted, including flows from the production, operation and end-of-life stages of buildings. A comprehensive methodological approach is essential for accurate analysis of life cycle climate impacts of buildings. Such a methodological approach is characterized by: definition of appropriate functional unit; selection of relevant characterization indicators; establishment of effective system boundaries in terms of activities, time, and place; careful consideration of impacts of energy supply systems affected by a decision; and transparent and justified treatment of allocation.

Disposition

The report is structured in six sections. The first section provides a brief background to the climate-related challenge facing our society today, and gives an overview of sustainability challenges associated with the global, European and Swedish energy systems as well as with buildings. The second section synthesizes existing research and case-studies on life cycle analysis (LCA) of buildings, focusing on energy and climate impacts of wood vs non-wood structural frame materials. The third section deals with climate implications of modern innovative wood-based construction systems. Different methodological issues linked to life cycle and system analysis of buildings are discussed in the fourth section. In the fifth section examples of wood-based low-energy and multi-story public buildings are presented. Conclusions as well as recommendations for comprehensive analysis of life cycle impacts of buildings are presented in the last section.

Acronyms

The following acronyms have been used in the report.

CH_4	Methane
CO_2	Carbon dioxide
$CO_{2\text{-eq}}$	Carbon dioxide equivalent
$CaCO_3$	Calcium carbonate
CaO	Calcium oxide
CORRIM	Consortium for Research on Renewable Industrial Materials
EU	European Union
Gt	Gigaton
GHG	Greenhouse gas
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LCA	Life cycle analysis
N_2O	Nitrous oxide
SMHI	Swedish Meteorological and Hydrological Institute

Introduction

Aim of the report

Energy efficient buildings are suggested as key parts of the overall strategy to break Sweden's dependence on fossil fuels to achieve a sustainable society (Swedish Government Bill 2005/06:145). To understand the implications of strategies aiming at reducing energy and climate impacts of the built environment a system-wide life cycle perspective is needed. This report is prepared with the aim of providing a state-of-the-art review of buildings' energy and climate effects from a system-wide life cycle perspective, focusing on wood and non-wood-based construction systems.

This section of the report gives an overview of the climate- and energy related challenges which are currently facing our society. Recent trends in primary energy supply for the world, European Union (EU) and Sweden are described in this section. To identify effective strategies for improved resource efficiency and climate change mitigation, the Swedish energy system needs to be considered in the context of the world and the EU.

Climate change

Growing evidence shows that increasing atmospheric concentration of greenhouse gases (GHGs) is affecting the global climate system. Global mean surface temperatures have increased by 0.65-1.06 ºC in the last century and are further projected to increase for 2081–2100 relative to 1986-2005 levels between 0.3 to 4.8 ºC (IPCC, 2014).

Figure 1 of the Intergovernmental Panel on Climate Change (IPCC) shows observed and projected changes in global annual average surface temperature profile under low and high emission scenarios as well as expected mean temperature between 2080 and 2100 also for two less extreme scenarios (IPCC, 2014). The climate change scenarios are based on the Representative Concentration Pathways (RCPs), used in the IPCC's fifth assessment report (IPCC, 2014). The RCPs are based on how much radiative forcing will change over time, based on greenhouse gas (GHG) concentrations, aerosols and pollutants in the atmosphere (Moss et al., 2010). The RCPs define four sets of future climate pathways resulting in radiative forcing of 2.6, 4.5, 6.0 and 8.5 W/m^2 by 2100. Radiative forcing is a measure of the imbalance between incoming and outgoing radiation in the earth system, influenced by GHG emission rates and concentration in the atmosphere.

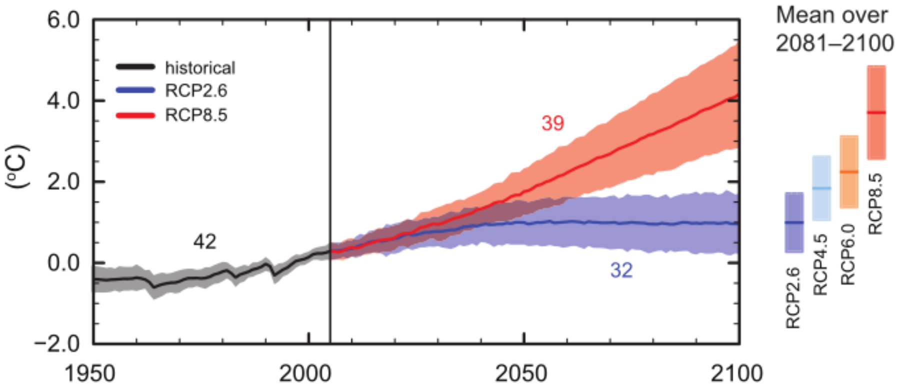


Figure 1. Observed and projected changes in global annual mean surface temperature relative to 1986–2005 (Source: IPCC, 2014).

The different pathways are based on different assumption linked to global population, energy system, land use, air pollution, gross domestic product, and technology developments (van Vuuren et al., 2011). In contrast to the other pathways, RCP8.5 assumes highly energy-intensive storyline with high population growth and lower rate of technology development (van Vuuren et al., 2011). In all the RCPs, fossil fuels dominate the global total primary energy use, although their absolute contributions vary for the different pathways. Total use of fuels in RCP8.5 exceeds the overall energy use (both fossil and non-fuel fossils) in each of the other RCPs. For RCP2.6, fossil fuels use is assumed to be coupled with carbon capture and storage (van Vuuren et al., 2011). Figure 2, from van Vuuren et al. (2011), shows plausible developments of the global total primary energy and oil use for different RCPs.

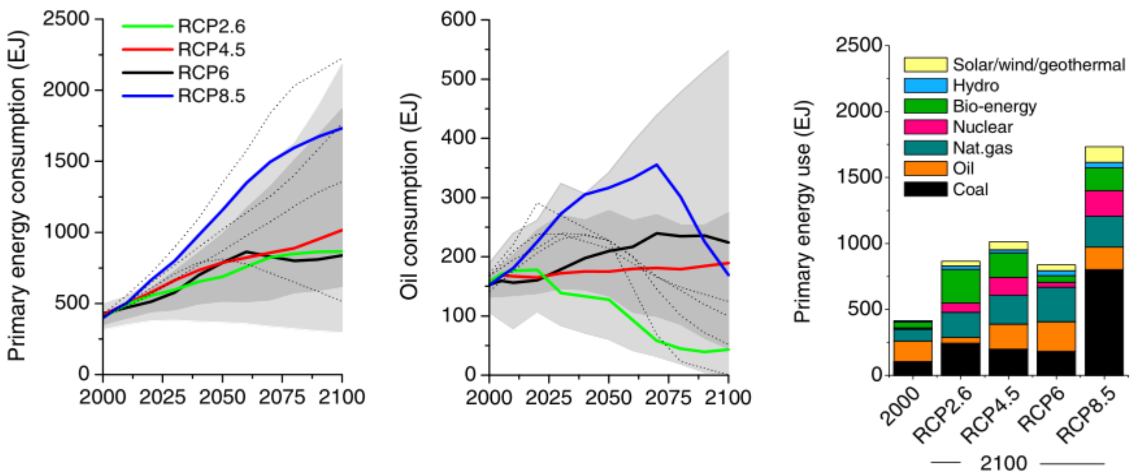


Figure 2. Global primary energy and oil use developments (direct equivalent) for different RCPs (Source: van Vuuren et al., 2011).

In Sweden, the climate projections suggest mean annual temperature increase of 1.81 to 5.93°C by 2100, compared to 1961-1990 levels, with warmer winters and summers (SMHI, 2013). Figure 3 of the Swedish Meteorological and Hydrological Institute (SMHI, 2013) presents projected temperature for Sweden for different climate change scenarios.

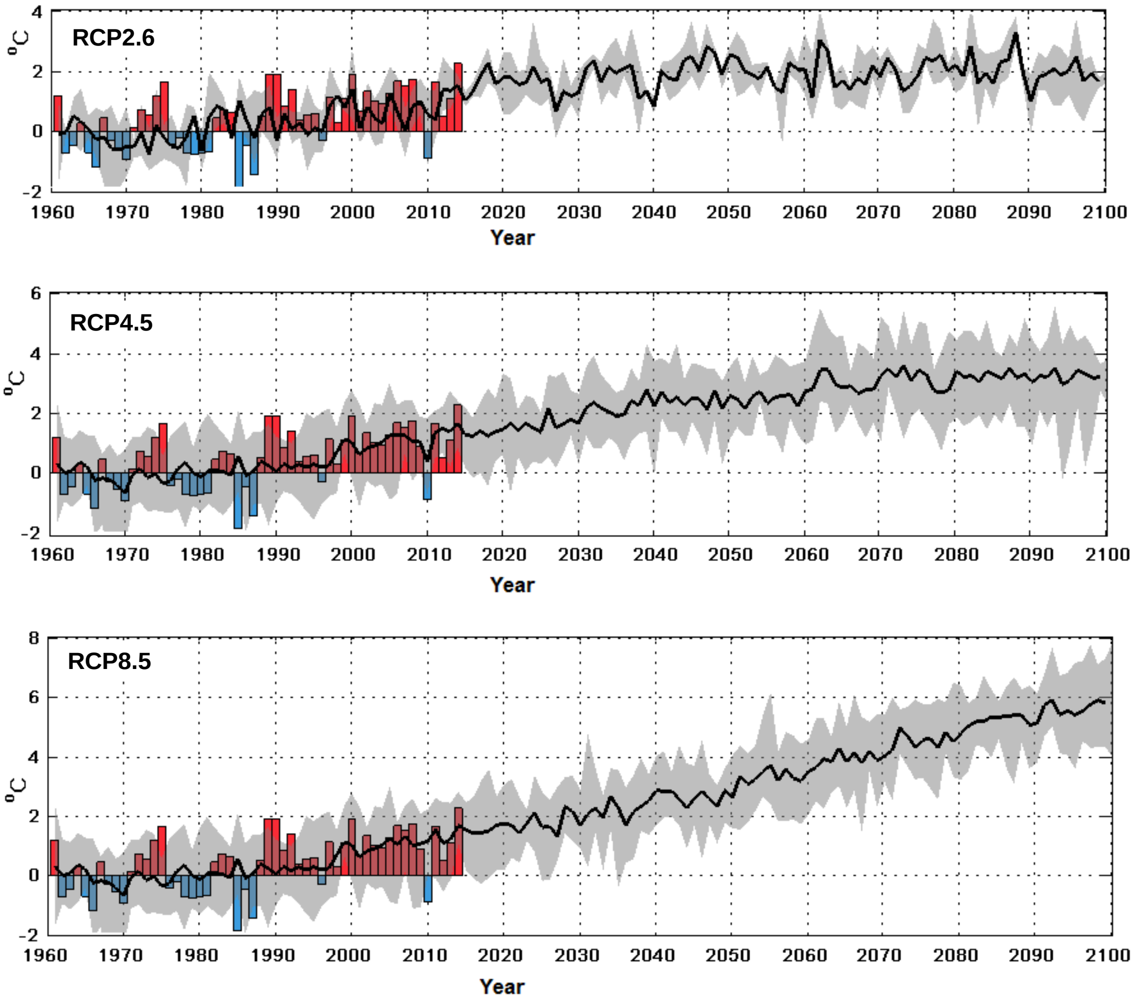


Figure 3. Historical and projected temperatures relative to the average for 1961-1990 for Sweden for low (RCP2.6), medium (RCP4.5) and high (RCP8.5) emission scenarios. (Adapted from SMHI, 2013)

Atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (NO_2) have increased about 40%, 150% and 20% compared to pre-industrial levels, respectively (IPCC, 2014). Fossil fuel combustion is the major anthropogenic source of GHG emissions. A less significant share of anthropogenic GHG emission is connected to non-energy related activities including land-use practices and industrial process reactions. Worldwide, energy supply and use account for 84% of all CO_2 emission and for two-thirds of all GHG emissions in 2010 (IEA, 2010; 2013a). Specifically, 20%, 36% and 43% of the total CO_2 emission from fuel combustion were from fossil gas, oil and coal in 2010, respectively (IEA, 2012).

Fossil fuel combustion and industrial process reactions accounted for 78% of the global total GHG emission increase between 1970 and 2010 (IPCC, 2014). The International Energy Agency (IEA) anticipates that global CO_2 emission may increase by 20% by 2035 with the current trends in energy use and planned measures to mitigate climate change (IEA, 2013a). This might result in global average temperature rise of about 3.6°C (relative to pre-industrial levels), much more than the 2°C limit suggested to avoid dangerous climate change (European Environmental Agency, 2008; European Commission, 2007).

It is estimated that stabilization of atmospheric GHG concentrations at around 450 ppm $CO_{2\text{-eq}}$ may lead to a fifty-percent chance of achieving the 2°C limit (European Commission, 2007). Stern review emphasized the need for timely actions to stabilize atmospheric GHG concentration and suggested that stabilization at 450 ppm $CO_{2\text{-eq}}$ may be difficult, considering current atmospheric CO_2 emission and concentration trends (Stern, 2006). Furthermore, a recent study based on the RCP climate scenarios suggested that global temperatures are likely to rise beyond the 2°C target (Sanford et al., 2014). Global carbon emission is suggested to be reduced by 50% by mid-century relative to 1990 levels (Peters et al., 2013) to keep temperature rise below 2°C. The latest climate agreement in Paris suggested aiming for a temperature rise of 1.5°C (COP21, 2015). This will require radical changes in the global energy and material systems.

Climate change present significant risk to environmental, infrastructural and economic systems (Stern, 2006). Both effective mitigation and adaptation strategies are essential to minimise the potential impacts, risks and costs that may be associated with climate change for buildings (Boverket, 2009).

Fossil fuels dependence

Currently, our society is heavily dependent on fuels which provided 533 EJ (97%) of the global total primary energy use of 549 EJ in 2011 (IEA, 2013b). The contributions of non-fuels sources (including hydro, solar, wind, waste heat and geothermal to the total primary energy use) is small, amounting to about 3%, 4% and 12% for the world, EU-28 and Sweden, respectively (see Figure 4). Fossil fuels supply 82% of the world's total primary energy, to which oil, coal and fossil gas contribute 32%, 29% and 21%, respectively (IEA, 2013b). Despite a significant increase in the renewable energy share in the EU-28 from 6% in 2001 to 10% in 2011, still about 75% of the total primary energy use in the EU-28 came from fossil fuels in 2011 (Eurostat, 2013), while in Sweden fossil fuels accounted for about 36% of the primary energy use in 2011 (Swedish Energy Agency, 2013). While fossil fuel resources are limited, there is no consensus on future recoverable amounts or extraction rates. However, oil and fossil gas resources are more limited compared to coal. The latest assessment by BP (2015) suggested global reserve-to-production ratios of 53, 54 and 110 years for oil, fossil gas and coal, respectively.

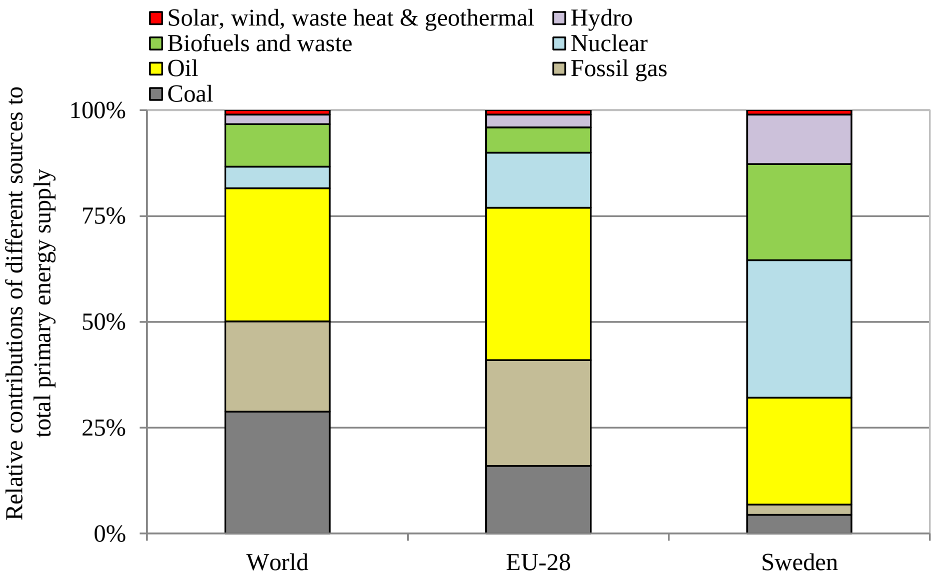


Figure 4. Contributions of different sources to the total primary energy supply of the world, EU and Sweden of 549, 71 and 2.05 EJ, respectively, in 2011. Data for the world and Sweden are from IEA (2013a; 2013c) while that for EU-28 is from BP (2012).

Medium and long-term scenarios of the global energy system suggest that fossil fuels are likely to remain the dominant energy source, even with measures to improve resource efficiency and reduce climate impacts (IEA, 2012; IPCC, 2000). Fossil fuels use are suggested to increase in different scenarios constructed by the IEA for the timeframe 2009–2035, including the existing policies scenario; the new policies scenario with increased measures to reduce fossil fuels use and GHG emissions; and the 450 scenario limiting atmospheric CO_2 concentration to 450 ppm (IEA, 2011a). In the existing and new policies scenarios, global primary energy demand is projected to increase by 51% and by 40% over 2009 levels by 2035, respectively, resulting in an increase use of fossil energy in both scenarios.

Primary energy use and climate impacts of buildings

Energy is used during the life cycle of buildings for material production, transport, construction, operation, maintenance and demolition. The building sector's final energy use amounted to about 32% of the global final energy use and for about 38% of the total final energy use in the EU-28, both in 2011 (IPCC, 2014; Eurostat, 2013). The residential and service sectors' share of the total final energy use in Sweden was about 38% in 2011 (Swedish Energy Agency, 2013). Building energy use accounted for about 19% of the global total GHG emission in 2010 (Figure 5) (IPCC, 2014). Non-energy related source of CO_2 emission linked to the building sector is cement calcination emission. Cement production accounts for about 5% of all anthropogenic global CO_2 emission, of which nearly half is from calcination and the remainder from energy combustion (IEA, 2009).

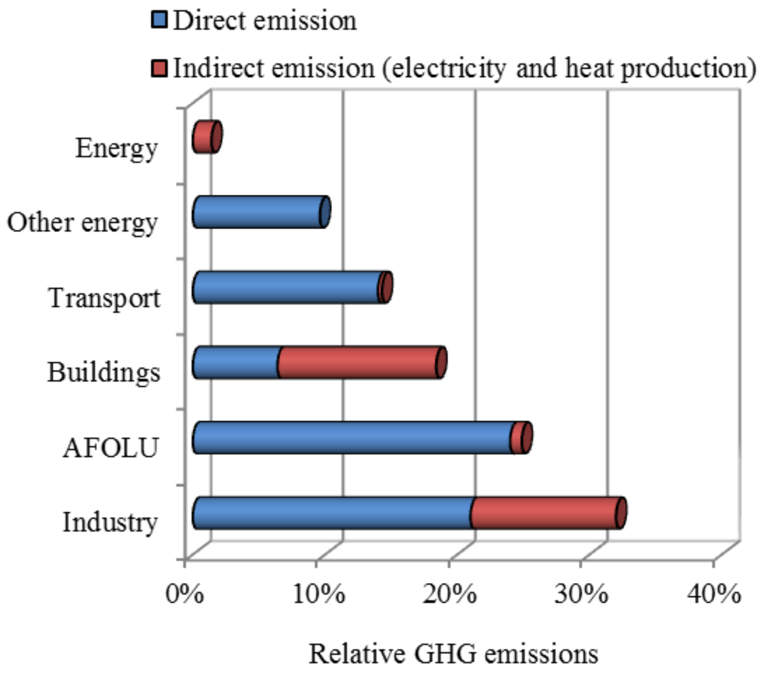


Figure 5. Relative contribution of different economic sectors to the global total anthropogenic GHG emissions of 49 GtCO $_{2\text{-eq}}$ in 2010, based on data from IPCC (2014). AFOLU refers to Agriculture, Forestry and Other Land Use. “Other energy” refers to emission sources in the energy sector other than from electricity and heat production.

Within the EU, various initiatives are being made to reduce primary energy use and climate impact of buildings. Buildings are suggested as key to meeting the EU 20-20-20 targets of reducing GHG emissions by 20% below 1990 levels, increasing the share of renewable energy to 20% of the total energy mix, and reducing primary energy use by 20% compared with projected levels, all by 2020 (European Commission, 2011a). Under the EU Directive on Energy Performance of Buildings member states are required to set minimum energy efficiency standard for buildings. The Swedish government’s bill on energy efficiency and smart construction aims to reduce total energy use per heated building area by 20% by 2020 and 50% by 2050, using 1995 as the reference (Swedish Government Bill 2005/06:145).

There is great potential to improve the primary energy efficiency of buildings and thereby reduce GHG emissions. Reducing energy use of buildings is also suggested to present a low GHG emission mitigation cost (IEA, 2008). A variety of strategies can be used to realize this potential, including reduced heating demand, increased efficiency in energy supply chains, greater use of renewables and less carbon-intensive materials and efficient post-use management of building materials. Comprehensive analysis of life cycle implications including carbon footprint assessment can play an important role in making informed decisions from a climate mitigation perspective.

LCA Of Buildings: Literature review

Buildings contribute substantially to climate change through GHGs emissions, and climate change may have significant effects on buildings. This section presents a summary of studies on LCA of building structural systems and materials.

Life cycle perspective

A growing body of literature has studied life cycle energy and climate implications of buildings, with different scope and methodological approaches. For example, Jönsson et al. (1998) conducted a LCA of concrete and steel building frames, including energy use and CO_2 emissions. Scheuer et al. (2003) conducted a process-based analysis of the primary energy and environmental impacts over the life cycle of a new building, including production, operation and end-of-life stages. Ochoa et al. (2002) used an economic input/output approach to assess the total energy use and environmental impacts of a building. Keoleian et al. (2001) analysed the life cycle primary energy use and greenhouse gas emissions of two alternative energy efficiency levels for a building. Junnila et al. (2006) assessed the life cycle energy use and environmental emissions of one European and one US building, taking into account material production, construction, operation, maintenance and building demolition. Gustavsson et al. (2010) calculated the primary energy use and CO_2 emissions of a new eight-story wood-framed apartment building, considering the production, operation and end-of-life stages, as well as heat supply from different end-use systems and energy supply technologies. Aye et al. (2012) compared the life cycle GHG performance of three multi-storey building systems including a modular prefabricated timber building. The production and operation stages of the buildings are considered in the analysis.

Most LCA studies (e.g. Monahan and Powell, 2011, Ochsendorf et al., 2011, Aye et al., 2012) are based on static calculation, where life cycle balances are calculated including summation of all flows that occur during the study time horizon, regardless of when they occur. Very few LCA studies using time dependent approach are reported in literature (e.g. Levasseur et al., 2010; Fouquet et al., 2015).

LCA studies using attributional- or consequential-based approach are noted in literature. Consequential-based LCA takes into account the consequences of changes in the level of production and characterizes both direct and indirect effects that may be associated with changes in output in a system. In contrast, attributional-based LCA characterizes the impacts of processes to produce, consume and dispose an average single unit of a product and does not include induced effects from changes in outputs. Attributional-based life cycle modelling typically utilizes average data on a product and this may be less suitable when the effect of marginal change is of interest. Dodoo et al. (2014a) used a consequential-based LCA approach to explore the climate implications of wood-based building systems including GHG flows linked to fossil energy, industrial process reactions, changes in carbon stocks in materials, and potential avoided fossil emissions from substitution of fossil energy by woody residues. Kua and Kamath (2014) analysed the environmental implications of replacing concrete with bricks when using both attributional- and consequential-based LCA approaches.

Materials and structural elements comparisons

Various comparative life cycle studies have explored energy and climate implications of different building materials and structural elements. Koch (1992) estimated the carbon balance implications of a proposed reduction in timber harvest from US forests, by using data from Boyd et al. (1976) comparing production energy use of wood products and functionally equivalent non-wood materials like steel, aluminium, concrete and brick. He concluded that if non-wood materials were used instead of structural wood products, net CO_2 emission would increase substantially.

Buchanan and Honey (1994) compared CO_2 emissions from building production for wood- steel- or reinforced concrete-framed versions of several different types of buildings. 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.

Björklund and Tillman (1997) conducted LCA 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 stage dominate over those of the construction stage, 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. They found that the wood-framed buildings emitted less fossil and process emissions during material production in all cases.

Cole and Kernan (1996) analysed the total life cycle energy use of a building constructed with wood, steel, or concrete structural material. They found that the concrete and steel buildings used more energy than the wood building. Cole (1999) investigated the energy use and GHG emissions due to the on-site construction activities of buildings made with wood, steel or concrete structural material. He found that the energy used and GHG emissions were lowest for constructing the steel building, slightly higher for the wood building, and significantly higher for the concrete building.

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.

Adalberth (2000) quantified the primary energy use of functionally equivalent buildings with wood and concrete frames. The wood version of the building was found to have lower primary energy use during the production stage than the concrete version. The operation energy was slightly lower for the concrete-frame building than for the wood-frame building, but the overall life cycle energy balance, including the production, operation and end-of-life stages was slightly lower for the wood-frame building than for the concrete-frame building.

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.

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. However, the authors may underestimate the climate advantage of wood construction because they do not consider calcinations emissions of cement production and the use of bioenergy in the wood products industry.

Eriksson (2004) reviewed 12 life cycle studies comparing the GHG emission and energy use of wood vs. concrete or steel buildings. He found that the wood buildings have lower GHG emission than the non-wood buildings in all the studies. The wood buildings have lower energy use than the non-wood building in all, except one of the studies. In this study the feedstock energy of wood is counted as part of the energy to produce the wood materials, resulting in methodological inconsistency.

The Consortium for Research on Renewable Industrial Materials (CORRIM) compared the net energy use and GHG emission of concrete- and steel-framed houses to functionally equivalent wood-framed houses, in a series of studies and found the wood alternative to have lower energy use and emission in all cases (Lippke, 2004; Johnson, 2005; Perez-Garcia, 2005). Lippke and Edmonds (2006) showed that external walls with wood-based assemblies have lower climate impact than alternatives with steel-based assemblies for different US climates.

Gustavsson et al. (2006) calculated the primary energy and CO_2 balances of buildings constructed with wood or concrete frames, taking into account various life cycle parameters that included energy available from biomass residues from logging, wood processing, construction, and demolition. They found that the wood building used less production energy and emitted significantly less CO_2 than the concrete building. Gustavsson and Sathre (2006) explored the variability in primary energy and CO_2 balances of wood and concrete buildings. They found that recovery of biomass residues has the single greatest effect on the primary energy and carbon balances of the buildings, followed by land use issues and concrete production parameters.

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 stage, 12% during the construction stage, and less than 9% was due to maintenance. Emission of NOx, SOx and suspended particulate matter were also lower for the wooden building than for the concrete building.

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 $CO_{2\text{-eq/yr}}$ and reduces net energy use by 132 PJ/yr. They reported that the comparison of carbon balances of wood and non-wood construction is sensitive to how land-use is modelled.

Sathre and O’Connor, (2008, 2010) reviewed several studies on the GHG impacts of wood product use and conducted a meta-analysis of the displacement factors of wood products substituted in place of non-wood materials using data from 21 different international studies. The studies agree that substituting wood products in place of non-wood products reduces GHG emission.

Nässén et al. (2012) showed that a wood-frame building results in lower carbon emission than a concrete-frame building under the current European production and energy systems. Gong et al. (2012) found that a wood-frame building has much lower production and life cycle CO_2 emission compared to a concrete frame or a light-gauge steel frame alternative.

Dodoo et al. (2012) compared the net life cycle primary energy use of functionally equivalent wood and concrete-frame buildings, including the effect of thermal mass. They found the wood building to have less net life cycle primary energy use, also when the impact of thermal mass is accounted. Oliver et al. (2014) showed that significant CO_2 savings are achieved for wood-based building components compared to alternative steel and concrete building components (Figure 6). However, the magnitude of the CO_2 savings achieved varies significantly, depending on the application and substitution systems.

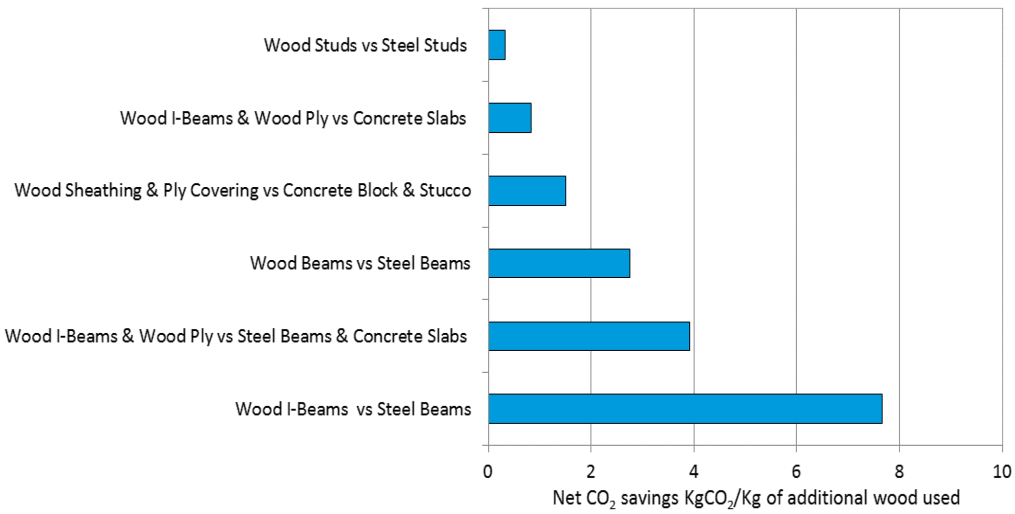


Figure 6. Carbon saving efficiencies of wood-based building components compared to alternative steel and concrete building components. (Based on data from Oliver et al., 2014).

Relative contribution of production stage

The production stage of a modern building may constitute a substantial share of the total life cycle primary energy use, depending on a building's location, climate, energy supply system and lifespan, as well as on methodological choices. Ramesh et al. (2010) reviewed studies on life cycle energy analysis of 73 residential and office buildings in 13 countries in Asia, Australia, North America, and in northern and central Europe. They found that the production energy use generally contributes to 10 to 20% of the buildings' life cycle energy use. Adalberth (2000) studied Swedish buildings built around early 1990s and found that production of the buildings accounted for 11-12% of the total life cycle energy use. Sartori and Hestnes (2007) found that the primary energy for building production becomes relatively more important as measures are applied to reduce the operation energy use. In a hybrid life cycle analysis of a Belgian residential building, Stephan et al. (2013) estimated the production stage of a passive house to represent 77% of the total primary energy for production and operation of the building for 100 years. Thormark (2002) found the production stage of a Swedish low-energy house to account for 45% of the total life cycle energy use for 50 years, based on a bottom-up LCA. Dodoo et al. (2012, 2011) performed process-based LCA of Swedish buildings, and found the contribution of the production stage of a passive house to the total primary energy for production, space heating and ventilation for 50 years to range from 20% to 30%. They found that the relative contribution of the production stage depends on the choice of heat supply and is greater when more efficient heat supply systems are used.

Effects of material choice on operation stage

Building structural materials used may have effect on the operation stage of buildings through the mechanism of thermal mass. Thermal mass describes the heat storage capacity of a material and it indicates the ability of the material to provide inertia against temperature variations. Effective thermal mass material can absorb and store significant amounts of heat, and this can help to level out temperature variations. The thermal mass of a material is mainly a function of the heat capacity, density and thermal conductivity of the material. The effectiveness of thermal mass in buildings depends on the interactions of several parameters including climatic location, orientation, window area, insulation, ventilation, heating load profile and occupancy pattern of buildings (Dodoo et al., 2012). Hence, designing to optimize thermal mass of buildings is a complex issue.

Various comparative studies have been conducted to assess the effect of the thermal mass of building frame material on the final energy for space heating and cooling buildings. Norén et al. (1999) analysed the effect of thermal mass on the final energy for space heating in Swedish buildings and concluded that the benefit of thermal mass is less where buildings located in a Nordic climate have ample insulation with plasterboard cladding.

Zhu et al. (2009) compared identical buildings constructed with wood and concrete frames in a hot US climate where thermal mass is considered favourable. They found that a wood-frame building used more space heating energy but less space cooling energy than the concrete-frame building.

Kalema et al. (2008) used a quasi-steady approach to estimate the heat capacity and time constant associated with the building mass and analysed the effect of thermal mass on the space conditioning energy use for a Nordic building. They concluded that the amount of final energy savings due to the benefit of thermal mass was significant. However, Jokisalo and Kurnitski (2005) used a dynamic analysis approach and concluded that the amount of final energy savings of thermal mass in a Finnish apartment building was not significant. The interaction between building mass configuration and thermal condition is complex, and a detailed dynamic analysis is needed to accurately determine the impact of thermal mass.

A comprehensive analysis of the impacts of thermal mass in buildings needs to include the various building life cycle activities and the full energy chains. Dodoo et al. (2012) analysed the effect of thermal mass on space heating energy use and life cycle primary energy balances of a concrete- and a wood-frame building in Sweden. The analysis includes primary energy use during the production, operation and end-of-life stages. Based on hour-by-hour dynamic modelling of heat flows in building mass configurations the energy saving benefits of thermal mass during the operation stage of the buildings was calculated. The results showed that the energy savings due to thermal mass is small and varies with the climatic location and energy efficiency levels of the buildings. A concrete-frame building gives slightly lower space heating demand compared to a wood-frame alternative (see Figure 7), due to the benefit of thermal mass inherent in concrete-based materials. Still, a wood-frame building gives a lower life cycle primary energy balance than a concrete-frame alternative. This is due primarily to the lower production primary energy use and greater bioenergy recovery benefits of the wood-frame buildings. These advantages outweigh the energy saving benefits of thermal mass. The authors concluded that the influence of thermal mass on space heating energy use for buildings located in Nordic climate is small and that wood-frame building has a lower carbon balance over its lifecycle than a comparable concrete-based building.

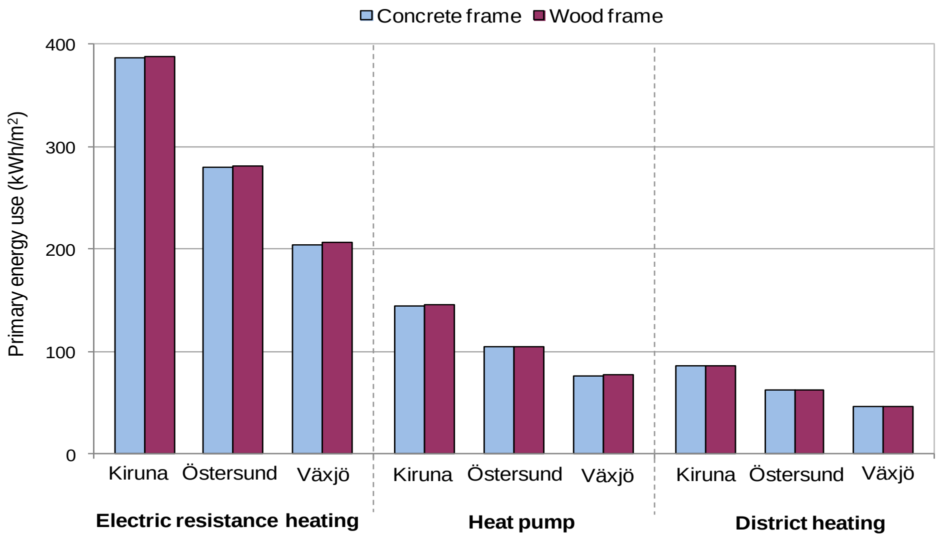


Figure 7. Annual primary energy use for space heating of buildings in three locations with different heating systems (Adapted from Dodoo et al., 2012).

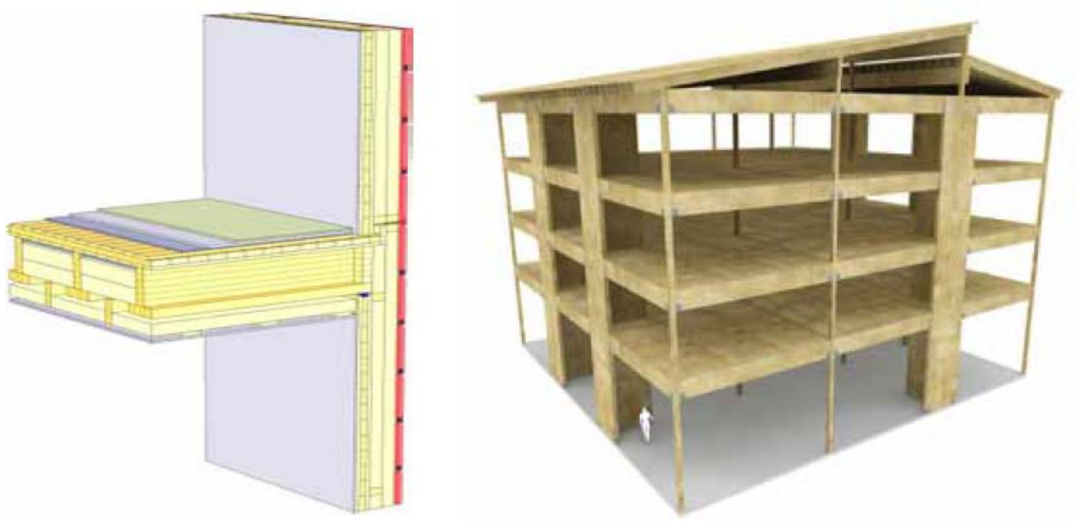
End-of-life implications of material choice

In several life cycle studies comparing the impacts of structural building materials, the implications of the end-of-life stage has not been considered. In few studies which have considered the implications of the end-of-life stage, the post-use materials are assumed to be landfilled. For example, Junnila et al. (2006) considered demolished material to be landfilled in an assessment of the life cycle impacts of a European and a US building. Ochoa et al. (2002) estimated the impacts during the post-use stage of a building, assuming demolished materials are landfilled. Keoleian et al. (2001) analysed the impacts during the post-use stage considering the energy to demolish the building and transport the demolished material to a recycling plant. Dodoo et al. (2009; 2012) explored the effects of post-use material management on the life cycle balances of wood-frame and concrete-frame building, assuming demolished concrete, steel and wooden materials are recovered. They found wood-frame building to give greater end-of-life primary energy benefit than a concrete alternative. Energy recovery from demolition wood resulted in large primary energy benefit, while less benefit was achieved through recycling steel and concrete.

Wood in modern building systems

Modern wood construction techniques

Innovative construction techniques have been developed to design and construct multi-story wood-frame green buildings with improved fire, hygrothermal and structural performances. These include systems with structural elements made of cross laminated timber (CLT), glulam and laminated veneer lumber (LVL) beams-and-columns, and volumetric modules (see Figure 8).



a) CLT system (Photo: Martinsons Group) **b) beam-and-column system (Photo: Moelven Töreboda)**

Figure 8. Structural elements of some modern timber building systems.

While several comparative life cycle studies on timber vs. non-timber building systems have been reported, few comparative analyses have been reported on the climate implications of different timber building systems or modern timber construction techniques. Quale et al. (2012) compared the life cycle global warming potentials of residential timber buildings constructed with conventional construction or off-site fabricated modular systems. Monahan and Powell (2011) explored the cradle to site CO_2 emission for production of two residential buildings including an off-site fabricated modular timber frame building. Salazar and Meil (2009) compared the carbon balances of two residential building alternatives including a typical timber house with conventional materials and a timber-intensive house with full substitution of wood in place of non-wood alternative materials. John et al. (2009) conducted a carbon footprint analysis of new forms of timber multi-storey building systems using LVL structural elements. Kim (2008) conducted a partial life cycle assessment of residential timber-frame buildings using off-site fabricated modular system or conventional site-built system. Barrett and Weidmann (2007) compared the carbon footprint of a conventional on-site built house and an off-site manufactured house which maximised the use of timber. Dodoo et al. (2014a,c) analysed the energy and carbon implications of conventional and low-energy versions of innovative Swedish timber multi-storey building systems made of massive wood using CLT elements; beam-and-column using glulam and LVL elements; and prefabricated modules using light-frame volume elements.

Low-energy buildings

A large number of published studies have reported substantial operational energy savings for buildings designed or built to low-energy standards (Dodoo et al., 2014a,c; IPCC, 2014). For example, Dodoo and Gustavsson (2013) showed that the final energy use for space heating and ventilation of a Swedish residential building could be reduced by 22% when it is designed to the energy efficiency level of passive house standard instead of the building code of 2012. Flodberg et al. (2012a) investigated strategies to achieve low-energy office buildings and found demand-controlled ventilation, optimal façade glazing, efficient lighting and equipment as well as well-insulated and airtight building envelope to be key in achieving such building. The authors used dynamic hourly simulation to demonstrate that an office building's energy use can be reduced by 48% compared to the Swedish building code requirement, with these measures. In a comparison of two buildings, Feist (1997) found that the building with lower operation energy had higher total life cycle primary energy use because of its high production energy. Thus although reducing the operation energy is important, a focus solely on the operation stage may bring less overall benefits due to potential trade-offs in other life cycle stages.

Energy and climate benefits of wooden materials

There is a considerable amount of literature on the potential for reducing energy use and climate impact of the built environment by use of sustainably produced wood-based materials in place of other materials (e.g. IPCC, 2014, Dodoo and Gustavsson, 2013; Upton et al., 2008). Less energy input is needed to manufacture wood products compared with alternative materials (Sathre and O'Connor, 2010). Wood-based building materials mainly use biomass residues for processing energy (e.g. kiln drying) and have lower carbon and primary energy balances than alternative materials. The storage of carbon in wood materials and the increased availability of forest and woody by products for energy purposes are other dynamics by which the use of wood-based material affects climate. Significant quantities of biomass residues are produce from the wood product chain and can be used instead of fossil fuels (Figure 9). Using wood-based material instead of fossil fuel intensive materials provides permanent and cumulative reduction in CO_2 emission, while sequestration of biological carbon is typically temporary (Schlamadinger and Marland, 1996).

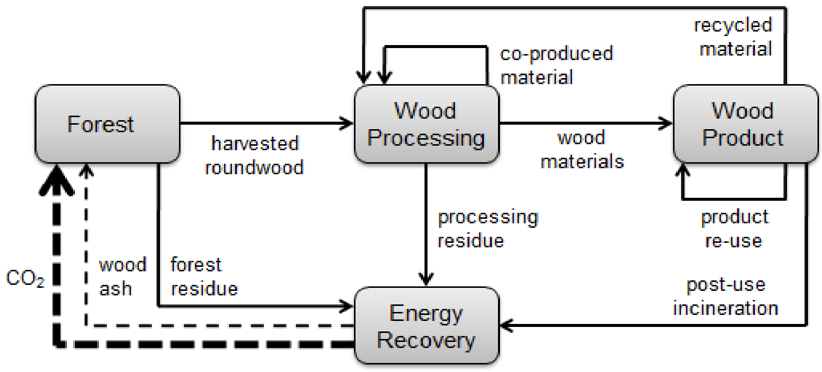


Figure 9. Schematic diagram of system-wide integrated material flows of wood products (Source: Dodoo et al. 2014b).

In the EU, increased use of wood products is suggested as an important potential contributor to efforts to tackle climate change (European Commission, 2011b). Sathre and Gustavsson (2009) noted that sustainably produced wood products can significantly reduce fossil fuel use while giving low climate-related external cost. A similar conclusion was reached by Sathre and Gustavsson (2009) in a comprehensive review of climate implications of wood-based products substitution. The IPCC (2007) highlighted the critical role that wood products substitution can play in the ongoing efforts to create a built environment with low climate impacts, and suggested options to increase the climate benefits of wood products. The options include improved quality and processing efficiency of wood products and effective post-use management of wood materials. Great climate benefits are achieved at the very end-of-life of wood materials if they are used for energy purposes instead of fossil fuels. Gustavsson et al. (2006) reported that the carbon mitigation efficiency of wood is significantly better if it is used to replace a non-wood building material than if it is used directly as bioenergy. Reid et al. (2004) summarized evidence related to the use of wood-based products for climate change mitigation. They noted that besides climate change mitigation, increased use of wood-based products could give additional economic, environmental and social benefits.

LCA methods and issues for buildings

In this section, LCA standards and methods for analysis of buildings are described. Key issues involved in system analysis of the climate effects of building structural systems are also discussed.

Challenges in LCA of buildings

LCA of buildings is 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). Furthermore, buildings are complex systems of multiple components and functions, and are dynamic due to their different life cycle stages, which are interlinked with energy supply activities. A comprehensive analysis of the climate change effects caused by buildings requires a system-wide life cycle perspective. However, most analyses of climate change effects have used a GHG balance approach, where all emissions and uptakes that occur during the study time horizon are summed up, regardless of when they occur. A system with lower net GHG emissions at the end of the time period is considered to be more climate-friendly than a system with higher net emissions.

This approach, however, does not fully take into account the atmospheric dynamics of GHGs. The temporal pattern of carbon emissions and uptakes can affect the resulting radiative forcing, and hence the climate change effects, depending on when the emissions and uptakes occur and the time horizon under consideration. Radiative forcing is a measure of the imbalance between incoming and outgoing radiation in the earth system. GHGs allow shortwave radiation (for example, visible light and ultraviolet radiation) to enter the earth's atmosphere but restrict the exit of longwave heat radiation (for example, infrared radiation), resulting in an accumulation of energy within the earth system. When summed over time, the accumulated energy is termed cumulative radiative forcing (CRF), a measure of total excess energy trapped in the earth system. Positive CRF implies global warming and negative CRF implies cooling. CRF can be considered as a proxy for surface temperature change and hence disruption to physical, ecological and social systems. Using the CRF metric instead of the GHG balance metric to calculate the climate change effects over a given time horizon requires greater temporal resolution (e.g. annual) of GHG emissions over time.

LCA and carbon footprint standards

The standards ISO 14040:2006 and 14044:2006 provide general framework and guidelines for LCA. These standards suggest that a LCA study should include all stages and impacts throughout the life cycle of a product. LCA includes several impact categories e.g. acidification, global warming potential, eutrophication, ozone depletion, human toxicity and abiotic resource depletion. In carbon footprint analysis the focus is exclusively on the global warming potential impact category. General guidelines for carbon footprint analysis are outlined in ISO 14067 (2013). According to the standard, scientific approach should be used to assess carbon footprint with emphasis on relevance, completeness, consistency, accuracy, and transparency for the entire life cycle of a product. Other standards and frameworks increasingly referred in carbon footprint studies are the Publicly Available Specification (PAS) 2050:2011 and the Greenhouse Gas Protocol (2011). In general, existing standards provide broad guidelines regarding analytical approaches, but more specific methods are required for detailed analysis of life cycle impacts including carbon footprint of buildings.

Functional unit

Definition of an appropriate functional unit is important in a LCA study. Functional unit refers to the unit of analysis and provides a reference to which the inputs and outputs of a product system is related. The functional unit should be ‘‘consistent with the goal and scope of the study’’ (ISO/TS 14067:2013). Different functional units have been used in LCA of buildings. These units include, for example, 1 m^2 of a building’s gross or usable floor area, total gross or usable floor area, and a complete building. Functional units based on material mass, volume or isolated structural characteristics of building components are often insufficient for informed decision making. Equal amounts of different materials may not fulfil the same function and thus provide different services. For example, 1 kg of lumber may not fulfil the same function as the same quantity of steel. The functional unit should reflect the complex interactions between multiple components and functions of a system. In life cycle and carbon footprint analyses of building and construction systems this could be achieved by considering the complete building (Gustavsson and Sathre, 2011). When analysing at the level of an entire building and different material choices it should be recognised that a choice of a structural frame of a certain material does not imply that the entire building is constructed of that material. The objective may be to favour the use of one material over another in cases where either material could practically be used, and not to completely replace one of the materials.

Building codes can be used as a measure of function of a building, thus different buildings that 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 performs 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.

Impacts characterization indicators

Indicators in the form of typical LCA categories are described in the standards SS-EN 15978:2011 and SS-EN 15804:2012+A1:2013 and include indicators of environmental impacts, resource inputs, and waste and output flows. According to the standards, the following indicators shall be included in the assessment of building materials and buildings:

Indicators describing environmental impact (characterisation factors according to EN 15804)

- Global warming potential (GWP[1])
- Depletion potential of the stratospheric ozone layer (ODP)
- Acidification potential of soil and water (AP)
- Eutrophication potential (EP)
- Formation potential of tropospheric ozone (POCP)
- Abiotic depletion potential for fossil resources (ADP-fossil fuels)
- Abiotic depletion potential for non-fossil resource (ADP-elements)

Indicators describing resource use

- Use of renewable primary energy excluding renewable primary energy resources used as raw materials
- Use of renewable primary energy resources used as raw materials
- Total use of renewable primary energy resources (primary energy and primary energy resources used as raw materials) (prescribed only in EN 15804)
- Use of non-renewable primary energy excluding non-renewable primary energy resources used as raw materials
- Use of non-renewable primary energy resources used as raw materials
- Total use of non-renewable primary energy resources (primary energy and primary energy resources used as raw materials) (prescribed only in EN 15804)
- Use of secondary material
- Use of renewable secondary fuels
- Use of non-renewable secondary fuels
- Use of net fresh water

Information describing waste categories

- Hazardous waste disposed
- Non-hazardous waste disposed
- Radioactive waste disposed

Information describing output flows

- Components for re-use
- Materials for recycling
- Materials for energy recovery
- Exported energy

Primary energy use, distinct from final energy use, includes all energy inputs along the full chain from natural resources to delivered energy services. Net primary energy use includes energy used for various purposes, minus energy that is made available for external use, for example from by-products generated during the building life cycle. The net primary energy use describes the use of

[1] GWP expresses the relative climate change effects of a GHG compared to an equal mass of carbon dioxide over a defined time period.

all energy resources. Fossil fuel use results in fossil carbon emissions and bioenergy use results in biogenic carbon emissions. Hence, there is a need to distinguish between fossil primary energy use and renewable energy use. Primary energy use should be broken down by source, e.g. coal, oil, fossil gas as well as renewable primary energy e.g. bioenergy and non-bioenergy resources. Yearly primary energy balances should be calculated over the lifetime of the buildings, to give the base for calculating the net annual GHG emissions. CO_2 emissions over time per functional unit is needed when calculating the climate change effects over the life cycle of a building, but other GHG should also be included if their climate change effects are significant. In this regard, the carbon footprint of different GHGs is quantified in CO_2-equivalent, as the multiplication of the mass of the GHGs and their respective global warming potential factor over a given time horizon. All GHG emissions should be measured on a net basis, equalling emissions to the atmosphere minus removals from the atmosphere. The ISO/TS 14067:2013 suggests a 100-year time horizon for an analysis and provides global warming potential factors for different GHGs for this period. As earlier mentioned, this approach does not fully take into account the atmospheric dynamics of GHGs.

System boundaries

In a LCA and carbon footprint analyses, all life cycle stages need to be considered (Verbeeck and Hens, 2007). For buildings, these encompass the production, operation, retrofitting and end-of-life stages (Figure 10). There exists a range of factors that affects primary energy use and annual GHG emissions, and system boundaries should be established to ensure that all significant effects of these factors are included in the analysis. The way that a system boundary is defined is crucial to the accuracy of life cycle and carbon footprint analyses (Matthews et al., 2008; Gustavsson and Sathre, 2011). Boundaries should be established broadly enough to capture the significant impacts of interest, but not so broad as to make the analysis too unwieldy. ISO/TS 14067:2013 indicates that an analysis shall "consider all stages of the life cycle of a product when assessing the [carbon footprint], from raw material acquisition to final disposal" and "include all GHG sources and sinks together with carbon storage that provide a significant contribution to the assessment of GHG emissions and removals arising from the whole or partial system being studied''. Analyses with cradle-to-grave or cradle-to-gate perspective can be found in life cycle literature. Cradle-to-grave system boundaries track the flows and impacts of a system from the stage of raw material extraction through to use and post-use stages. Cradle-to-gate system boundaries consider the flows and impacts up to the factory exit gate, and thus omit the use and post-use stages. Narrow system boundaries are incapable of establishing the full climate impact of wood-products and buildings, as use of wood products involves material and energy flows in different economic sectors (Gustavsson and Sathre, 2011). Establishment of effective system boundaries in terms of activities, time and space is fundamental to the credibility of LCA for wood-based systems and buildings (see Gustavsson and Sathre, 2011; Sathre et al., 2012; Lippke et al., 2011).

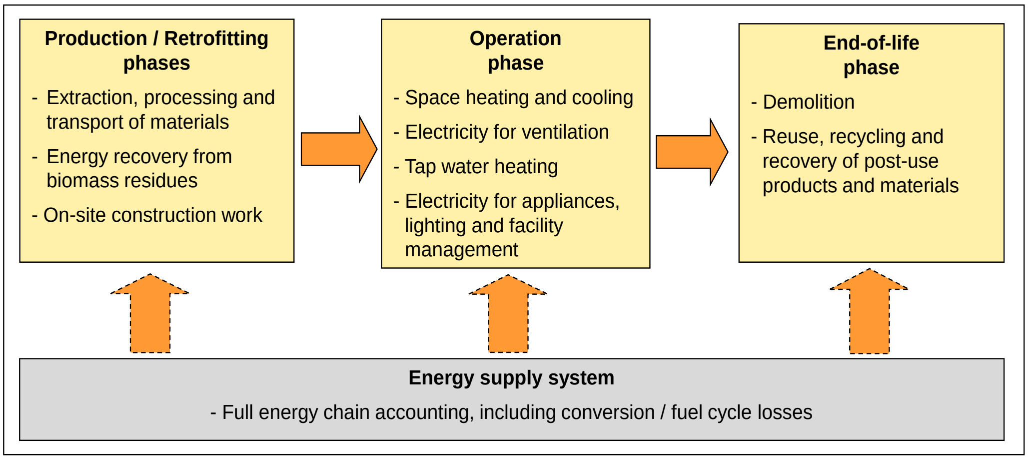


Figure 10. Key activities in LCA and carbon footprint analysis of a building.

Activity-related system boundaries

Key activity-related life cycle system boundary issues are connected to production, operation and end-of-life stages of buildings (Figure 10).

Production stage

Energy is expended during the production stage of buildings for a range of activities including acquisition of raw materials, transport and processing of raw materials into building materials, and fabrication and assembly of materials into a ready building. GHGs may be emitted from fossil fuel combustion, land-use practices and industrial process reactions when undertaking these activities. Biomass residues are produced during the production stage of wood-based product systems, e.g. from forest thinning and harvesting, wood processing industries and construction sites. Accounting of climate impact of wood-based products needs to consider the flow of residues from the wood product chain (Schlamadinger et al., 1997). An appropriate system boundary for carbon footprint analysis for non-biological materials e.g. mineral ores may be from the point of extraction. In the case of cultivated bio-based material such as sustainably produced wood, the system boundary need to be defined to encompass the technological (i.e. human directed) energy used for biomass production. This includes the GHG flows from fuels used for the management of forest land, the harvesting of timber, and the transport and processing of wood materials (Gustavsson and Sathre, 2011).

CO_2 flows which occur during cement reaction need to be considered when modelling carbon footprint of cement-based products. Calcination emissions result from a chemical reaction that converts heated limestone ($CaCO_3$) to calcium oxide (CaO) and CO_2, during cement manufacture. Over the life cycle of cement-based products, parts of the CO_2 are re-absorbed into the concrete matrix by carbonation reaction. The net CO_2 emission from cement reaction includes the effects of the reactions of calcination and carbonation. The net CO_2 emission from cement process reactions can be a significant part of the carbon footprint of cement-based products (Dodoo et al., 2009).

Specific energy data for material production is required to determine the fossil GHG emission resulting from material production. A variety of factors may affect the production energy requirement for building materials. These may include geographical specific factors as well as factors linked to technological processes and primary fuels used to produce materials. Different technological options and fuels may be used to produce the same material in the same or different geographical regions, each resulting in unique carbon footprint or impacts. For example, cement clinker may be produced with wet-kiln or dry-kiln technology, steel may be produced from ore or scrap iron, and wood could be oven dried or air dried. On average, 35% more energy may be used when cement clinker production is based on wet-kiln technology compared to when it is based on dry-kiln technology (von Weizsäcker et al., 2009). Thus there may be significant differences in carbon footprint for the same type of material.

ISO/TS 14067:2013 states that data "shall be representative of the processes for which they are collected". Methods and system boundaries for compilation of data may vary and this may have impact on life cycle and carbon footprint analyses. Material production data may be site specific e.g. from a particular sawmill, or may be average across an entire industrial sector. Data choice should generally reflect the production structures, technologies and fuels used to produce a material in a given geographical region.

Data availability and quality are key challenges in LCA. For example, Tettey et al. (2014) found that the primary energy required for production of alternative insulation materials for elements of a building differ significantly when using different datasets (Figure 11). Björklund and Tillman's dataset is based on the Swedish situation and was compiled in the late 1990s. Ecoinvent's dataset is generally representative of the central European average situation and was compiled in the late 2000s. 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. Nevertheless, both datasets in Figure 11 show consistency in the ranking of the insulation materials.

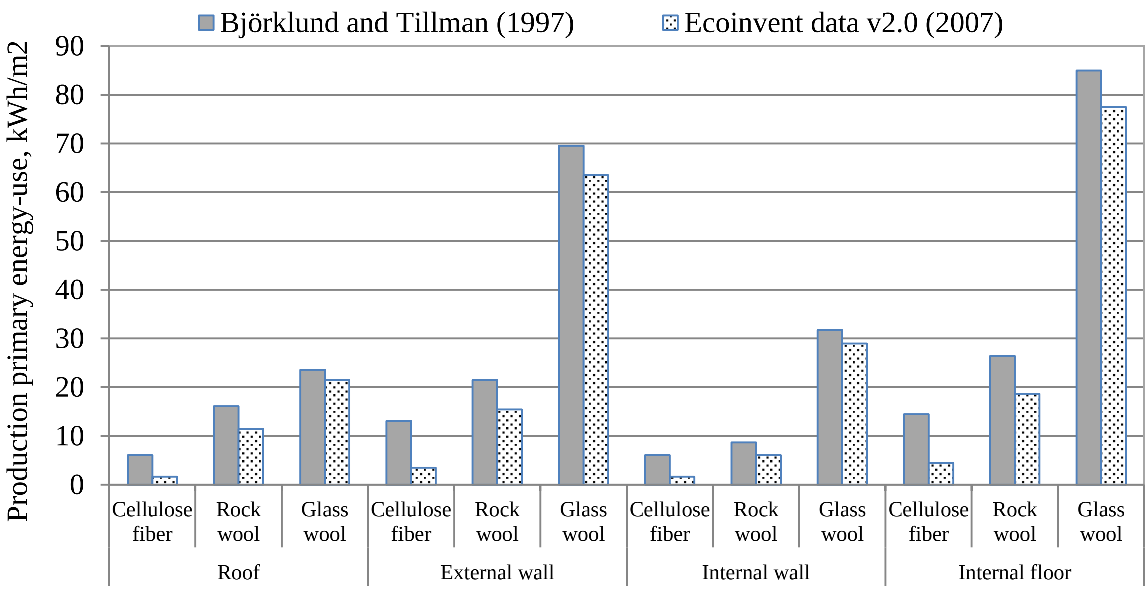


Figure 11. Comparison of primary energy required for production of insulation materials for elements of a building when using different data sets (Adapted from: Tettey et al., 2014).

Figure 12 shows the primary energy used for production of materials for concrete- and wood- 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 concrete vs. wood materials is consistent (Gustavsson and Sathre, 2004).

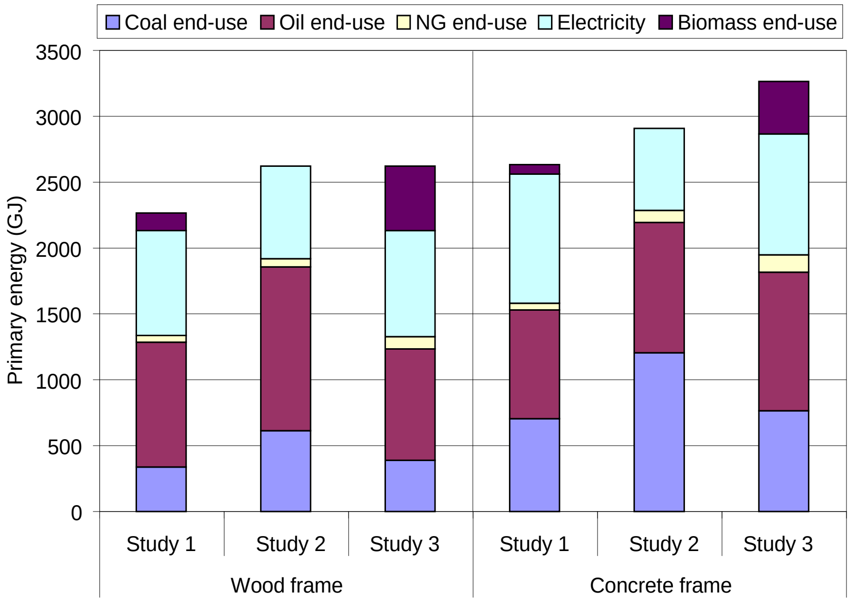


Figure 12. Primary energy used for production of materials for concrete- and wood-framed versions of a building, using specific energy use data from three different process analyses. Study 1 is Fossdal (1995), Study 2 is Worrell et al. (1994) and Study 3 is Björklund and Tillman (1997). (Adapted from Gustavsson and Sathre 2004).

The impacts of off-site and on-site construction activities connected to buildings also must be included in life cycle accounting. The climate impacts from building construction may vary, depending on the method of construction, the type of building materials and the parameters included, e.g. fuel use to transport construction equipment, workers and off-site fabricated components, etc. Adalberth (2000) estimated the energy for erection of a wood-frame building to be about half of that for a comparable concrete-frame alternative. To determine carbon footprint resulting from primary energy use for building construction activities, it is necessary to know the mix of on-site construction-related primary energy use, e.g. its breakdown between end-use electricity and diesel fuel (Gustavsson et al., 2010).

Operation stage and service-life

The operation stage is crucial as this typically dominates the life cycle impacts of buildings (Sartori and Hestnes, 2007). Activities in the operation stage, for example of a building comprise space conditioning (heating and cooling), tap water heating, and electricity for ventilation, facility management, and for appliances and lighting. The space conditioning and ventilation loads of a building are essentially linked to the building's construction system and energy efficiency level, in contrast to the other operation stage activities such as tap water heating and electricity for appliances and different activities. A range of interrelated factors influence the space conditioning loads of buildings including those inherently linked to buildings' design, construction systems, HVAC systems and operational schedules as well as those linked to climatic and geographic variables. To comprehensively account for the impact of operation stage of buildings, the dynamics of these factors need to be accurately characterized. Dynamic energy simulation models that can accurately characterize the complex interaction of factors which influence final energy demand of buildings are essential. Comprehensive simulation models can allow for one, two and three dimensional modelling of thermal transmissions of buildings' components and for detailed thermal bridge and thermal mass modelling. Some of the commonly used dynamic models in Sweden include DEROB-LTH, ESP-r, IDA-ICE, TRNSYS and VIP-Energy.

The reliability of results obtained from building energy simulation depends in part on the quality of input data used in simulation software. Various studies have shown the implications of input data and assumptions for energy balance modelling and simulation of buildings. Poirazis et al. (2008) performed energy simulations for office buildings in Sweden and assessed the impact of 3 different indoor air temperature control set-points on the heating and cooling energy use of the buildings. The results showed variations of 7-24% and 39-64% in the heating and cooling energy use of the buildings, respectively, depending on the share of window area and architectural plan of the buildings. Danielski (2012) explored possible causes of large variations in the energy use of 22 buildings in Sweden. The analysis was based on comparison of simulated and monitored specific final energy use of the apartments. The studied buildings were found to have large variations in their specific energy use, despite similarities in construction and energy systems. The simulated specific final energy use was about 19% lower than the monitored values for most of the buildings. This was attributed to uncertainties in input data for the building energy models, the time difference between completion of the construction of the buildings and actual measurements, shape factor and relative size of common areas in the buildings. Dodoo et al. (2015) noted that input data and assumptions used for energy balance calculation vary significantly in the Swedish context, giving considerably different estimated annual final energy demands for a case-study building (Figure 13). The authors found a 75 kWh/m^2 difference in calculated annual final space heating demand of a building when the extremes of parameter values found in scientific literature are used to perform calculations. Detailed sensitivity analyses may be useful to explore the implications of uncertainties and variabilities in parameter values that have considerable impacts. Among these parameters are internal heat gains, ground solar reflection and window shading.

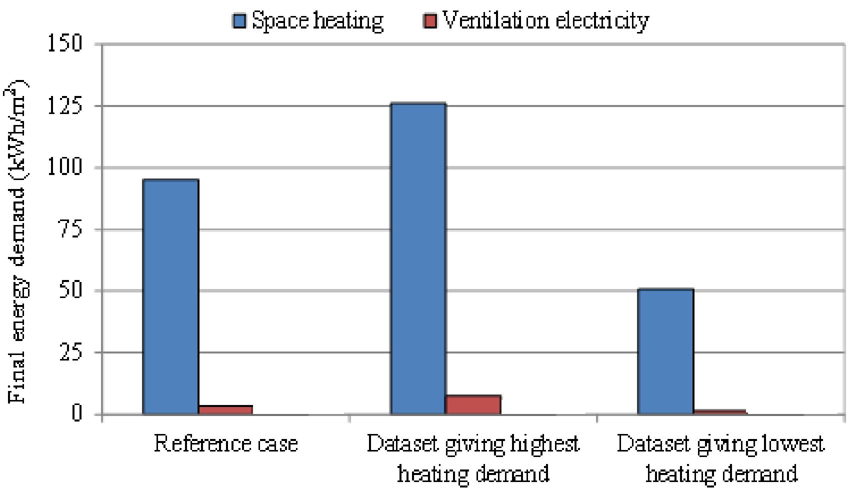


Figure 13. Effects of different parameter values reported in scientific literature for the Swedish context on calculated annual final operation energy use of a building. (Source: Dodoo et al., 2015).

The energy services required in a building can be provided by several kinds of technologies and supply systems which can result in significantly different life cycle impacts and carbon footprints. Activities and processes along the energy supply chain, from the extraction of raw material to refining, transport, conversion to heat and electricity, and distribution to the user can also be performed with different efficiencies and with varying GHG emissions (Gustavsson and Joelsson, 2007). A comprehensive analysis of the impacts of operation stage of a building needs to include the entire energy chain from natural resource extraction to final energy supply, taking into account the fuel inputs at each stage in the energy system chain and the energy efficiency of each process.

Maintenance and renovation

During the service-life of buildings, materials and components may be maintained, replaced and renovated. The impacts of these activities might be significant (Cole and Kernan, 1996) and are increasingly included in life cycle studies. When analysing impacts and carbon footprint over the life cycle of buildings, a key challenge often confronted is formulating credible maintenance and material replacement scenarios (IEA, 2001).

End-of-life stage

Energy and GHG flows arising from the end-of-life stage of buildings can have significant impact from a life cycle perspective (Dodoo et al., 2009; Salazar and Meil, 2009). ISO/TS 14067:2013 indicates that "all the GHG emissions and removals arising from the end of life stage of a product shall be included in a [carbon footprint] study". For wood-based building systems, end-of-life management option is the single most significant variable in a complete carbon accounting (Sathre and O'Connor, 2010; Gustavsson and Sathre, 2006). End-of-life management activities of buildings include demolition or disassembly of materials and post-use management of material e.g. disposal, recycling, reuse, energy recovery, etc. Different end-of-life management regimes for buildings may occur far in the future, when today's new buildings reach their end-of-life, and this uncertainty poses a challenge in life cycle studies of buildings.

Few life cycle studies have comprehensively analysed the carbon implications of end-of-life management options for building materials. However, efficient management of post-use building materials is receiving increasing attention in many countries and regions, including in the EU (European Commission, 2011b). Also, post-use concrete, steel and wood materials have high recovery and recycling rates in many countries. In studies where the end-of-life stage of a building is considered, plausible post-use material management scenarios reflecting the context of the studies are constructed and analysed. Dodoo et al., (2009) assessed end-of-life scenarios where post-use wooden material is used as bioenergy, concrete is recycled as crushed aggregate and steel is recycled as feedstock for production of new steel products. These scenarios reflect the typical end-of-life treatment for the materials in Sweden today.

In the EU, most post-use wooden materials are typically recovered for energy or used as raw material for further processing (Dodoo et al., 2014a). For example, 90% of recovered wood in Sweden is used as bioenergy, while 70% of recovered wood in France is used as raw material for further wood processing (Mantau et al., 2010). Typically, most post-use steel materials are recovered and used as scrap for production of new steel products. Krogh et al. (2001) noted that the production of new concrete reinforcement bars is based on scrap steel in Sweden. Recycled concrete aggregates are typically used in below-ground applications in Sweden (Engelsen et al., 2005). Post-use management of concrete may entail crushing it into aggregate and stockpiling it for a period. This increases the surface area of the concrete exposed to air and thus facilitates the carbonation process. A complete analysis of the carbon footprint should consider such possible carbon dynamics of end-of-life management of concrete materials (Dodoo et al., 2009).

ISO/TS 14067:2013 suggests that assumptions for modelling the carbon footprint of end-of-life stage of products shall be ‘‘based on best available information, based on current technology, and documented in the [carbon footprint] study’’. The quantification of GHG dynamics of end-of-life wood is not straightforward. Major methodological issues in the quantification of GHG implications of recovered wood include reference fuel or material replaced when post-use wood is recovered for energy or recycled, landfill dynamics and uncertainties about how post-use wood products will be handled if not recovered (Gustavsson and Sathre, 2011).

Recovery of energy by burning the wood is a resource-efficient post-use option where material reuse of recovered wood is not suitable. The use of recovered post-use wood for bioenergy instead of fossil fuels reduces fossil carbon emissions and affects the carbon footprint of wood. Still, in several areas deposition in landfills is the most common fate for post-use wood material increasing the climate change impact of wood.

Time-related system boundaries

Temporally-explicit GHG flows within a system should be taken into account in analysis of life cycle impacts of buildings. Lippke et al. (2011) discussed the life cycle impacts of wood utilization and indicated that consideration of time-related aspects is an important part of full accounting of the climate impact of wood-based systems.

When modelling wood-based systems a relatively long timeframe is typically under consideration due to the nature of activities and processes associated with forestry and the wood supply chain, e.g. seed germination, forest growth, harvest as well as regrowth, etc. Forest management regimes can have significant impact on GHG balances of wood products (Gustavsson and Sathre, 2011). Sustainable forestry, meaning that wood that is removed for products use do not exceed net forest growth, is fundamental for carbon benefit of wood-based products. In Sweden, annual forest stemwood growth is about 120 million m^3 while the current total annual harvest ranges between 85 and 90 million m^3 (Nordic Forest Owners’ Associations, 2014). In the EU-27, net annual increment of forest was reported to be 630 million m^3 while annual felling was 469 million m^3, in 2010 (Forest Europe, 2011).

Forests sequester carbon from the atmosphere during photosynthesis and part of this carbon is stored in wood products. Depending on the service-life span of wood products from sustainably managed forests and the forest rotation period, the harvested forest stand may re-grow during the building life cycle, sequestering about the same amount of carbon as before the forest was harvest for wood products. At the end-of-life, carbon contained in the wood product may be released as CO_2 through burning for energy or natural decomposition.

Another temporal aspect connected to buildings is the cement process reaction of carbonation. Carbonation is a chemical process in which the CaO present in hardened cement products binds with CO_2 in the atmosphere to form calcium carbonate. The rate of concrete carbonation depends on a number of factors including the composition of the cement used to make the concrete, the temperature and relative humidity of the environment, and the conditions and duration of concrete exposure to air (Gajda and Miller, 2000). Figure 14 shows the carbon flows from the cement calcination reaction and the carbonation uptake for functionally equivalent concrete- and wood-frame buildings. The magnitude of the carbon flows from calcination and carbonation reactions in the buildings reflect the quantities of cement used in each building. The results suggest that carbonation uptake increases gradually over the service life of a building and increases considerably if post-use concrete material is crushed at the end of the service life and exposed to air. Nevertheless, carbonation uptake is always less than the initial calcination emission (Dodoo et al., 2009).

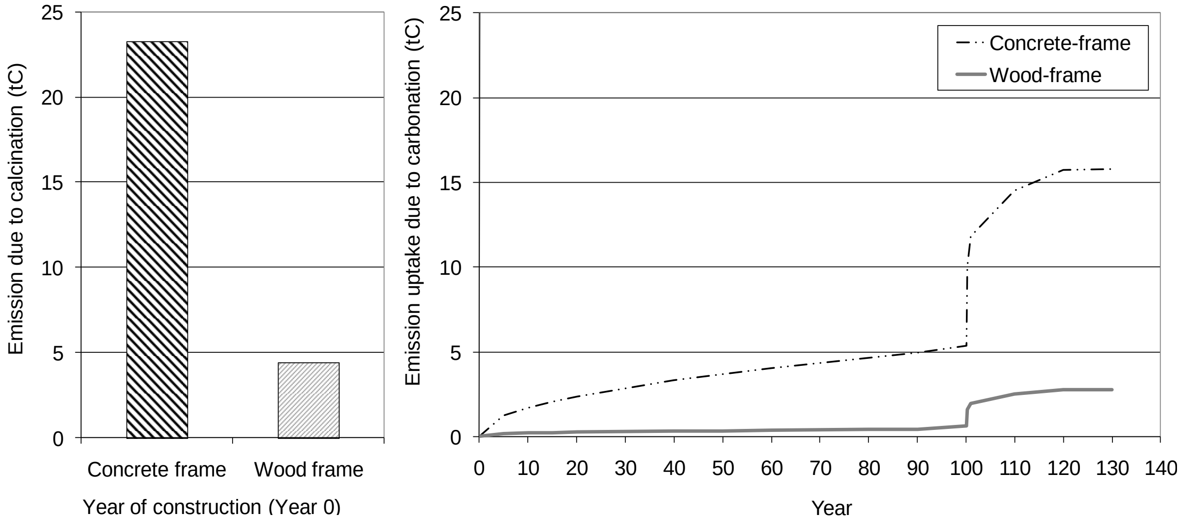


Figure 14. Carbon emission to atmosphere due to cement calcination (left) and carbon emission uptake from atmosphere due to carbonation of concrete and cement mortar during the service life and after demolition (right) for a concrete- and a wood-frame building (Dodoo et al., 2009). Concrete material is crushed at the end of service life, assumed to be 100 years, and exposed to air for 30 years.

It is difficult to know how long a building will be in use, as various factors will have a significant impact on the service life of a building, e.g. quality of materials, construction and maintenance. However, O'Connor (2004) noted that the main reason for building end-of-life is not related to materials. It is more related to economics and building function, and whether the building still plays a useful role in the built environment. The IEA (2011b) reported typical lifespans of energy-related capital stock and noted the typical lifespan of buildings to range from 50 to 150 years, with 80 years as average. Assumed lifespans of 50, 75 and 100 years are commonly found in life cycle studies. To assess the significance of uncertainties associated with a building's lifespan in life cycle analysis, sensitivity analysis can be conducted.

Space-related system boundaries

Spatial system boundaries are relevant when assessing life cycle impacts and carbon footprint of wood-based products. The dynamics of forest carbon flow will differ depending on whether an analysis is done from a stand-level or landscape-level forest perspective. When a tree or stand is harvested, the carbon in living biomass is transferred into other carbon pools such as wood products and forest floor litter. At the landscape level, the dynamic patterns of the individual trees or stands are averaged over time as carbon flows into and out of various carbon pools associated with trees at differing stages of development. Thus, at the landscape level the total carbon stock in living biomass can be fairly stable over time or even increasing, as the harvest of some trees during a given time period is compensated by other trees growing during the same period. At a landscape level, the stand-level carbon flows associated with many different stands at different stages of their rotation cycles will be aggregated and produce overall trends. For example, the standing stock of stem wood in Swedish forests has been increasing during the last 60 years, and is expected to continue increasing during the coming 100 years due to improved forest management and the effects of climate change (Figure 15). This provides opportunities to increase use of renewable forest resources as part of a strategy to transition to a more sustainable, carbon-neutral society.

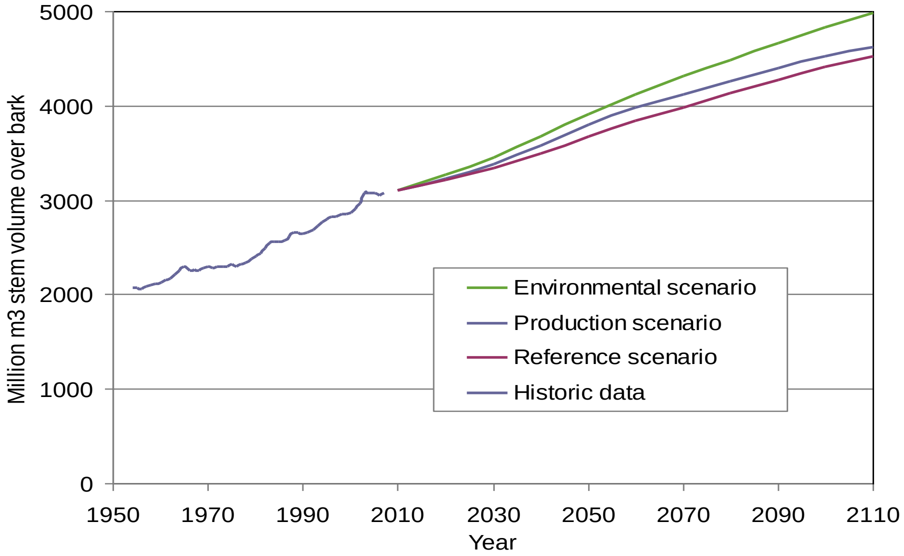


Figure 15. Historic and projected future standing stem volume on productive forest land in Sweden (Swedish Forest Agency, 2008).

Wood-based buildings require greater amounts of biomass, and thus larger forest area, than non-wooden alternative. Accurate and objective characterization of the implication of different land-use requirements when comparing wood vs non-wood product systems is a major challenge in LCA. Different approaches to deal with this challenge are presented by Gustavsson et al. (2006) who explored this issue in detail. One approach is to assume that the incremental wood material is produced through more intensive management of forest land, or from land that was not previously used for wood production. Another approach is to assume that an equal area of forest land is available to both the wood and non-wood systems, and that the forest land not needed in the non-wood system is left unmanaged as carbon storage.

Accounting for electricity production

The choice of electricity production and supply systems are crucial in LCA as this steers the outcome of a study. Fossil fuels accounted for 67% of the share of fuels used for electricity production worldwide, in 2011 (IEA, 2013a). In the EU, the electricity generation mix is comprised of 27% nuclear, 25% coal and lignite, 24% fossil gas, 21% renewables and 3% oil (European Environment Agency, 2013). Electricity production is typically dominated by stand-alone power plants with large losses and excess waste heat (IEA, 2012; Eurostat, 2011). The average conversion efficiency for electricity production worldwide was 37% in 2005 (Harvey, 2010). The Swedish electricity production system is dominated by hydro and nuclear power (Figure 16).

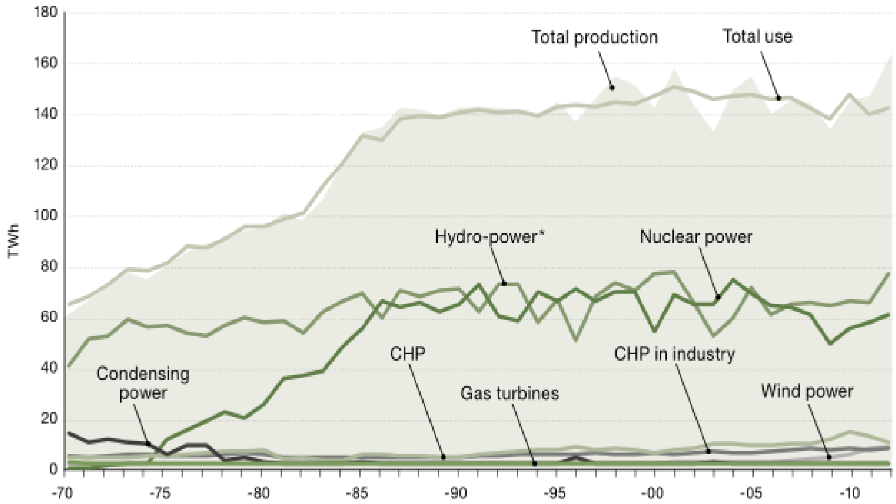


Figure 16. Electricity production, by type of power, and total electricity use in Sweden 1970–2012. (Source: Swedish Energy Agency, 2014)

The average and marginal approaches are two distinct methods for accounting for GHG emission for electricity systems in LCA studies. The different approaches are characterized by significant variation in GHG emissions and estimations. The average accounting approach considers the emissions per unit of delivered electricity, based on the average power mix of a region or country. In contrast, the marginal accounting approach considers the marginal changes in electricity supply system in estimating the emission resulting from a unit change in electricity demand (Hawkes, 2014).

A major discussion in LCA literature is the choice of accounting method to accurately capture the impacts of electricity demand and supply. The accounting method employed in a LCA must reflect the purpose and relevance of the study. Weidema et al. (1999) suggested the consideration of marginal technologies in prospective comparative life cycle studies, as this gives the best reflection of the actual impact of a decision. The marginal accounting method captures the consequences of small changes due to variation in system parameters, and reflects the technologies and inputs affected by a variation in a system. The average accounting method is typically not suitable in a consequential-based analysis, because small changes do not readily reflect at the average level (Hawkes, 2014). The determination of marginal technology for electricity production is influenced by a complex interplay of several factors including investments cost, GHG reduction policies, and strategic and security reasons (Gustavsson et al., 2006; Lund et al., 2010). In the Nordic, coal-fired condensing power plants are usually considered to be the marginal source of electricity at the moment (Amiri and Moshfegh, 2010; Sjödin and Grönkvist, 2004). The Swedish electricity production system is connected to the NordPool, a network where some European countries trade electricity (see Figure 17). Changes in electricity production and use in Sweden affect the NordPool.

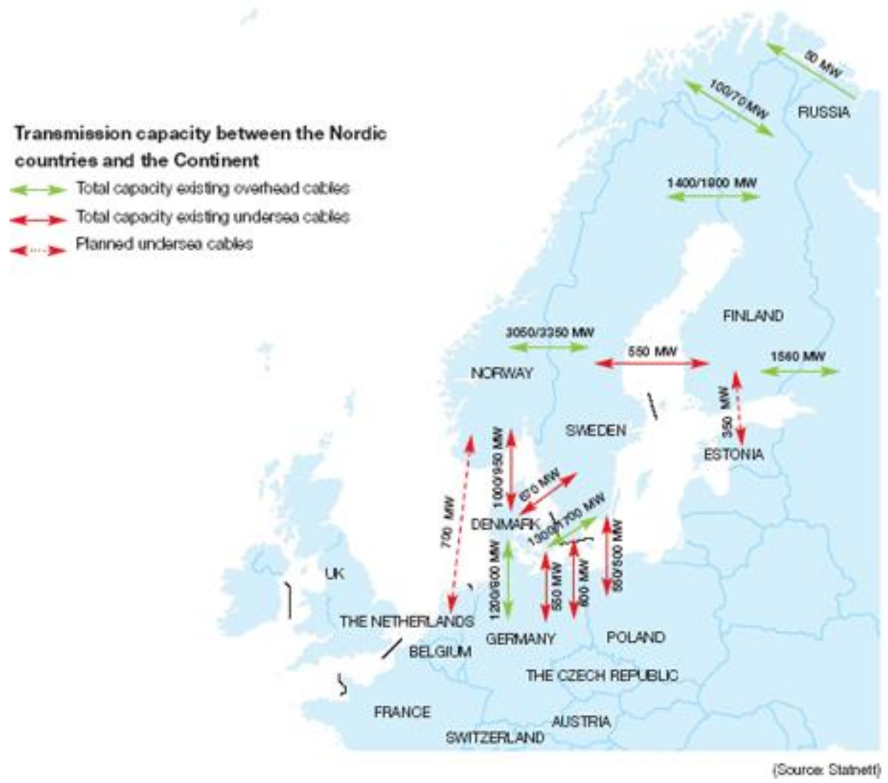


Figure 17. Electricity transmission network in the NordPool (Source: statkraft.gosu.no)

Treatment of allocation

In systems that co-produce more than one product, the issue of allocation between co-products of burdens and benefits arises. The way allocation is treated can have a significant impact on the results of a life cycle and carbon footprint analysis. However, allocation should be avoided as it can be complex and subjective (ISO 14044:2006). The ISO/TS 14067:2013 also states that ‘‘wherever possible, allocation should be avoided’’. Two procedures are suggested by the ISO/TS to avoid allocation; ‘‘dividing the unit process to be allocated into two or more sub-processes and collecting the input and output data related to these sub-processes’’; and ‘‘expanding the product system to include the additional functions related to the co-products’’. When evaluating systems involving combined heat and power (CHP) plant, the issue of allocation is encountered. Figure 18 illustrates how allocation can be avoided in such systems, based on Finnveden and Ekvall (1998) and Gustavsson and Karlsson (2006). One way (I) is expanding the systems by adding an alternative means of producing heat or electricity to systems that produce only one of the energy carriers, thereby making the systems multi-functional. Another way (II) is subtracting either heat or electricity production from the CHP production. In this way only electricity or heat will become the functional unit.

Allocation based on physical relationships (e.g. mass, volume, energy content, etc.) of co-products is suggested where allocation cannot be avoided. Allocation based on economic value of co-products might be used but this is suggested as the last option for dealing with allocation (ISO/TS 14067:2013), as economic values are market driven and may not be stable over time. In this case a sensitivity analysis should be conducted across a range of potential economic values of each co-product.

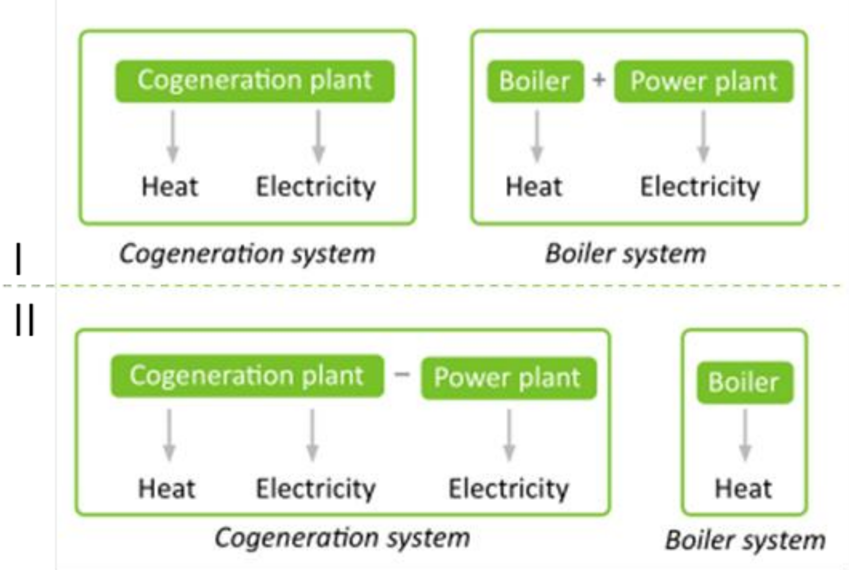


Figure 18. Different approaches to avoid allocation when analysing systems involving a combined heat and power plant. Approach I entails system expansion with multi-functional products in the functional unit. Approach II entails system subtraction with cogenerated electricity subtracted so that the functional unit is heat (Finnveden and Ekvall, 1998; Gustavsson and Karlsson, 2006).

Choice of data

Reliable datasets are needed to accurately determine the life cycle impact of buildings. There are various databases that provide estimates of energy and climate impacts for materials and products. However, caution should be taken when selecting data for LCA as primary energy use and carbon footprint values for the same type of material can vary widely from one database to another. Key issues to be considered in the choice of data include the age of the data, the time over which the data were collected, the geographical scope of the data, the type of technical systems covered by the data, the precision of the data, the consistency of the data, the completeness and representativeness of the data, and the uncertainty of the quality of the data (ISO/TS 14067:2013). In a situation where data is not available in a study's context, data from closely related studies may be used. Sensitivity analyses may be conducted to determine the significance of the data uncertainty.

Examples of wood-frame public buildings

This section presents examples of modern wood-frame multi-story and low-energy public buildings. In contrast to low-energy residential buildings, very few low-energy public multi-storey buildings including office premises have been built with wood-frames in Sweden and other parts of Europe (see Flodberg et al., 2012a; Flodberg, 2012b).

Alpha and Bravo buildings, Videum Science Park, Växjö

Alpha and Bravo buildings are two 4-storey wood-frame multi-storey buildings built in the Videum Science Park in Växjö. The total heated floor areas are 3396 m^2 and 3981 m^2 for Alpha and Bravo, respectively. In both buildings the basements are made of reinforced concrete while the remaining structure is made of wooden materials. The buildings' facades is made of glass and timber. The buildings became operational in 2002 and spaces in the buildings are mainly offices.

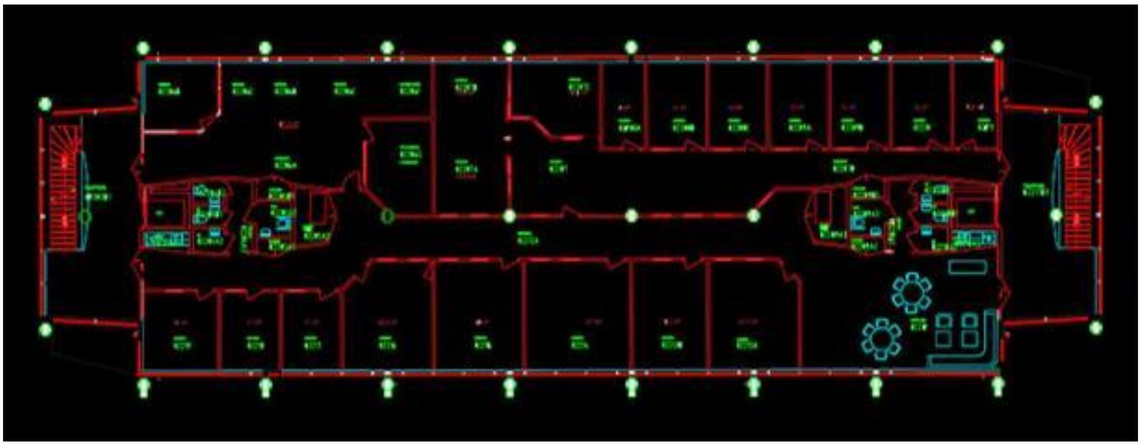


Figure 19. Photograph (top) and ground floor plan (bottom) of the Alpha and Bravo wood-frame buildings, Videum Science Park, Växjö

Building-M, Linnaeus University, Växjö

The building-M is a 3-storey educational facility constructed with a combination of steel and wooden structural elements in Växjö. The building was constructed in 2002 and has a gross total area of 11300 m^2. The ground floor of the building comprises mainly lecture halls while the second and third floors comprise offices and seminar rooms. The building has basement below ground level which serves as laboratories and space for electrical and ventilation installations. The facades of the building consist of glass and wood panels.

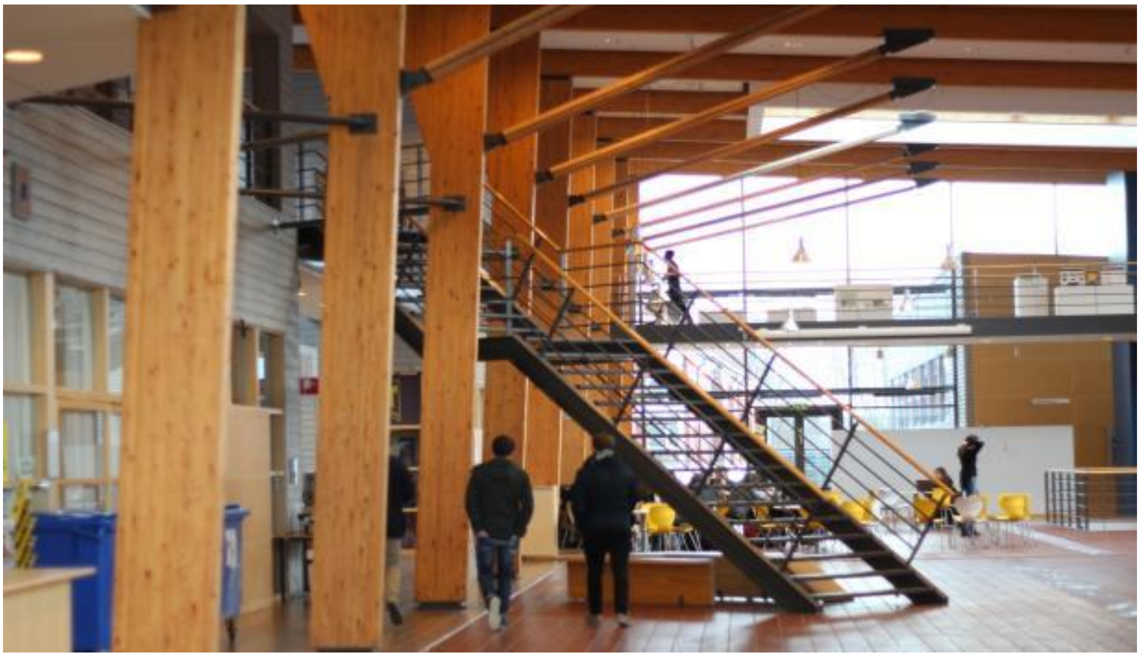


Figure 20. Photographs of outdoor view (top) and inside view (bottom) of Building-M, Linnaeus University, Växjö

Building-N, Linnaeus University, Växjö

This building is an educational facility at Linnaeus University’s campus Växjö, with a total floor area of 6800 m^2. The building was completed in 2010 and comprises lecture halls, seminar rooms and offices. It is constructed with timber beam-column structural system using laminated veneer lumber (LVL) and glulam elements. The facades are made of a combination of large glazing and wood panels.

Figure 21. Photographs of outdoor view (top) and inside view (bottom) of Building-N, Linnaeus University, Växjö

Mälardalen university library, Västerås

The timber-glazed library building situated on Mälardalen University's Västerås campus was built in 2002 with laminated timber structural elements. Key green aspects of the building include the use of organic insulation, low-emission paints and energy-efficient lighting and appliances (see http://en.white.se/projects/malardalen-university/).

Figure 22. Photographs of the Mälardalen University library built with wood-frame and glass in Västerås. (Photograph credit: Åke E:son Lindman).

Tamedia Building, Zurich

The Tamedia building is a 7-storey wood-frame office building, which was opened in 2013, in Stauffacher, Zurich. The building is constructed with prefabricated timber structural elements and has large glazed facades. It has total floor area of 8905 m^2.

Figure 23. Photographs of outside view (top) and inside view (bottom) of the Tamedia wood-frame Building, Zurich. (Photograph credit: http://www.tamedia.ch/)

Conclusions and recommendations

There is growing recognition that anthropogenic GHG emission is destabilising the earth's climate system. Fossil fuels account for a significant share of the primary energy use in our society and contribute considerably to climate change. Effective strategies are essential to reduce GHG emission and thereby minimise potential impacts of climate change. The building sector is responsible for a large share of the built environment's total primary energy use and GHG emission, and is expected to play a major role in mitigating climate change. Various initiatives are being made at various levels of society to reduce energy use and GHG emissions in the building sector. In this regard, an issue of growing discussion is the effect of material choice on climate impacts of buildings. In this report the scientific state of the art of life cycle energy and climate implications of buildings, with emphasis on the role of structural frame material is discussed.

Life cycle studies have reported varying contributions of the production stage to the life cycle impacts of buildings, due to varying system boundaries, methodological choices, building lifespan assumed, and regional as well as technological differences of the studies. Contributions of the production stage to life cycle primary energy use of buildings in the range of 10 to 77% are noted in the literature reviewed in this project. Typically, the operation stage dominates the life cycle impacts of buildings. However, recent studies show the increasing importance of the production stage as measures that results in very low operation energy use are implemented in buildings. A large number of LCA studies show that wood-frame building results in lower primary energy and GHG emission compared to non-wood alternatives including concrete and steel. Less energy, in particular fossil fuels, is needed to manufacture wood-based building materials compared with alternative non-wood materials. Wood-based materials use primarily biomass residues for processing energy. Wooden materials also store carbon during their lifetime, temporary sequestering carbon from the atmosphere. Large amounts of biomass residues are produced during the manufacture and end-of-life of wood products, and these can be used to replace fossil fuels. Hence, wood-based buildings are appropriate for long-term strategies for reducing fossil fuel use and GHG emissions when combined with sustainable forestry.

Modern wood construction systems have been developed to design and construct more energy efficient multi-story wood-frame buildings with improved fire, hygrothermal and structural performances. However, research is needed to explore how these systems could be optimized from system-wide life cycle perspective. Greater understanding of the life cycle implications of buildings may help the promotion and wider dissemination of energy-efficient wood buildings. An efficient energy supply system is of great importance also for a low energy building and should be an integral part of the effort to create a low energy built environment.

A system-wide life cycle perspective is fundamental to analyse the life cycle impacts of buildings. To understand the climate implications of building systems, full life cycle accounting must be conducted, including flows from the production, operation and end-of-life stages of buildings. A robust and comprehensive analysis of the energy and climate impacts of buildings would be characterized by: definition of appropriate functional unit; selection of relevant characterization indicators; establishment of effective system boundaries in terms of activities, time, and place; careful consideration of impacts for energy supply systems affected by a decision; and transparent and justified treatment of allocation.

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Climate impacts of wood vs. non-wood buildings

This report documents the findings of a project commissioned by the Swedish Association of Local Authorities and Regions on energy and climate implications of building structural-frame materials from a life cycle perspective.

The report is compiled by researchers within the Sustainable Built Environment Group (SBER) at Linnaeus University, Växjö, Sweden, and it addresses the terms of reference of the project agreement, including review of existing literature and reports on energy and climate implications of wood-frame and non-wood-frame building systems.

The report's primarily focus is: the effect of material choice on different life cycle stages of a building; the significance of building frame material in relation to the total primary energy use and climate impact of a building; key methodological issues linked to life cycle analysis of buildings; and the importance of system perspective in analysis of a building's climate impacts.

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