Boverket

Myndigheten för samhällsplanering, byggande och boende

Linnéuniversitetets underlagsrapport till Boverkets undersökning om ”Byggnaders klimatpåverkan utifrån ett Livscykelperspektiv”

The Swedish Government has instructed Boverket – the National Board of Housing, Building and Planning – to investigate the state of research and knowledge regarding the carbon footprint of buildings in a lifecycle perspective. The assignment states that Boverket shall”analyse the research and knowledge base in Sweden and other relevant countries in the context, and propose areas which may need to be further clarified or strengthened regarding the climate change effects of buildings in a lifecycle perspective, and investigate the need for information, activities and guidelines required for the construction sector and municipal planning.”

The Board asked the undersigned to write comprehensively on the climate change effects of buildings from a lifecycle perspective. This is a complex area with numerous methodological challenges, and encompasses all significant net emissions of greenhouse gases and their time profiles during the building’s lifecycle. It requires accounting for all the energy and materialchains needed during production, operation and decommissioning / disposal of a building.

Climate change effects over the lifecycle of a building

Report on methodological issues in determining the climate change effects over the lifecycle of a building

Final report for Boverket

by

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Abstract

It is increasingly recognized that climate change due to anthropogenic greenhouse gas (GHG) emissions is one of the greatest challenges facing our society, with major implications for both human and natural systems. The built environment is responsible for a significant share of these emissions, for both the production and operation of buildings. In response, diverse initiatives are being developed and implemented at the local, national and international levels to limit the release of GHGs into the atmosphere. These initiatives rely on the assessment, monitoring, reporting and verification of GHG emissions and removals. To ensure that actions are effective at mitigating climate change, the annual accounting of GHG flows associated with buildings should be done in a lifecycle perspective. In other words, the analysis should consider all inputs (e.g. energy, materials) and outputs (e.g. emissions, waste, co-products) for each lifecycle stage including production, operation and end-of-life. Comprehensive analysis of the lifecycle climate change effects of buildings is a complex issue. In this report we discuss the definition of an appropriate functional unit, the determination of suitable indicator metrics, and the establishment of effective system boundaries in terms of activity, time and space. The functional unit can be defined at the level of building component, complete building, or services provided by the built environment. Cumulative GHG emission is a commonly used indicator of climate change effects, thought cumulative radiative forcing more accurately describes actual climate change effects over time. Activity-based system boundaries include lifecycle processes such as material production, building operation, energy supply, and post-use material management. Post-use management options include material reuse, recycling and energy recovery; these can significantly affect energy and carbon balances. Temporal system boundaries include such aspects as the building service life, dynamics of forest growth for wood-based building material production, the availability of numerous co-products associated with the lifecycle of building materials at different times, the carbonization reaction of concrete products, and the duration of carbon storage in products. The establishment of spatial boundaries can be problematic for comparative studies, because using wood-based materials requires more forest land area than is needed for non-wood materials. We discuss several possible methodological approaches to meet this challenge, including the intensification of land use to increase the time rate of biomass production. We discuss issues related to scaling up an analysis from the micro-level to the macro-level of national, regional or global. We discuss the current debate within the LCA community regarding the appropriate use of consequential and attributional LCA methods, and suggest that a more important task is to develop and implement methodologies that accurately describe the overall climate change effects of various building systems, including the effects of current and future options. Reducing climate change effects from the built environment involves optimizing material and energy flows in different economic sectors including manufacturing, construction, forestry, energy and waste management. Integration of resource flows within and between these sectors can significantly reduce the climate change effects of the built environment. Comprehensive LCA can provide a better understanding of the relative impacts caused by different building systems over their full lifecycles, which will be needed to design effective climate change mitigation solutions.

Preface

The Swedish Government has instructed Boverket – the National Board of Housing, Building and Planning – to investigate the state of research and knowledge regarding the carbon footprint of buildings in a lifecycle perspective. The assignment states that Boverket shall "analyse the research and knowledge base in Sweden and other relevant countries in the context, and propose areas which may need to be further clarified or strengthened regarding the climate change effects of buildings in a lifecycle perspective, and investigate the need for information, activities and guidelines required for the construction sector and municipal planning."

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1. Introduction

1.1 Fossil fuel dependence

Globally, our society is heavily dependent on fossil fuels, which supply more than 81% of the world's primary energy. Specifically, oil, coal and fossil gas provide 33%, 27% and 21% of global primary energy supply, respectively (IEA 2010). 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). Both globally (IEA, 2012) and within the European Union (Eurostat, 2011), electricity generation is dominated by stand-alone condensing power plants fired by fossil fuels resulting in large excess of waste heat and CO_2 emission. The International Energy Agency's (IEA) global energy system scenarios for 2009–2035 anticipate that fossil fuels may increase in use and remain the dominant energy source (IEA, 2011). More-over, long-term energy mix scenarios based on the Special Report on Emissions Scenarios (SRES) developed by the Intergovernmental Panel on Climate Change (IPCC) suggest that fossil fuels are likely to contribute at significant levels in the year 2100 (IPCC, 2000). The SRES explored different global energy use and greenhouse gas (GHG) emissions trends up to 2100, considering dynamics related to demographics and technology as well as socio-economic development. The IPCC's latest assessment report (IPCC, 2014) is based on the Representative Concentration Pathways (RCP) and considers how radiative forcing will change over time, based on GHG concentrations, aerosols and pollutants in the atmosphere (Moss et al., 2010). A recent report by the IEA (2015) exploring how the global energy system might evolve up to 2050 suggested that the share of fossil fuels in the global primary energy use might be reduced to 46% in 2050 if ambitious GHG emissions reduction strategies are deployed to achieve short- and long-term climate change mitigation targets. Still, the share of total fuel use is projected to be 80% of the global primary energy use in 2050. Considerable changes are required in the global energy mix to achieve this ambitious suggestion. For example, the current contributions of biomass and nuclear are suggested to be increased by a factor of 3 each, while the contribution of geothermal is suggested to be increased by a factor of 16, between 2012 and 2050. In such a scenario with a high use of biomass, an increased use of wood-based products and building materials will be important to gain residues for use as bioenergy from the wood chain including at end-of-life.

1.2 A lifecycle perspective

The production and use of buildings account for about half of both extracted materials and energy use within the EU (European Commission, 2014) while residential and service buildings account for about 40% of the final energy use in Europe (Eurostat 2013) and in Sweden (Swedish Energy Agency. 2013). Improved energy and material efficiency in the building sector is increasingly suggested to offer significant reduction of GHG emissions at low mitigation costs (IPCC, 2014; IEA, 2013).

Energy standards and regulations are increasingly driving towards buildings with low operational final energy use, as part of efforts to reduce energy use and environmental impacts of the built environment. The European Parliament and Council Directive 2010/31/EU on the energy performance of buildings requires all new buildings to be nearly zero-energy buildings from 2020, and EU Member States are to enact intermediate legislations needed to drive this change. Measures that result in low operational final energy use in buildings, including nearly zero-energy building, will increase the use of building materials and the importance of the building production phase (Dodoo et al., 2011, 2012; Gustavsson and Joelsson, 2010; Sartori, and Hestnes, 2007). Furthermore, other lifecycle phase impacts will become relatively more significant as the dominance of the operating phase is reduced. The choices made in the production phase, including choice of material and building systems, need to be emphasized and integrated into the overall plans to reduce lifecycle energy use and climate change effects of buildings. A lifecycle perspective is needed to understand and analyse the energetic and climate change effects of buildings due to material production, transport, construction, operation, maintenance and demolition, where connections and interactions between different lifecycle phases (Figure 1) are considered (Dodoo et al., 2014a, b).

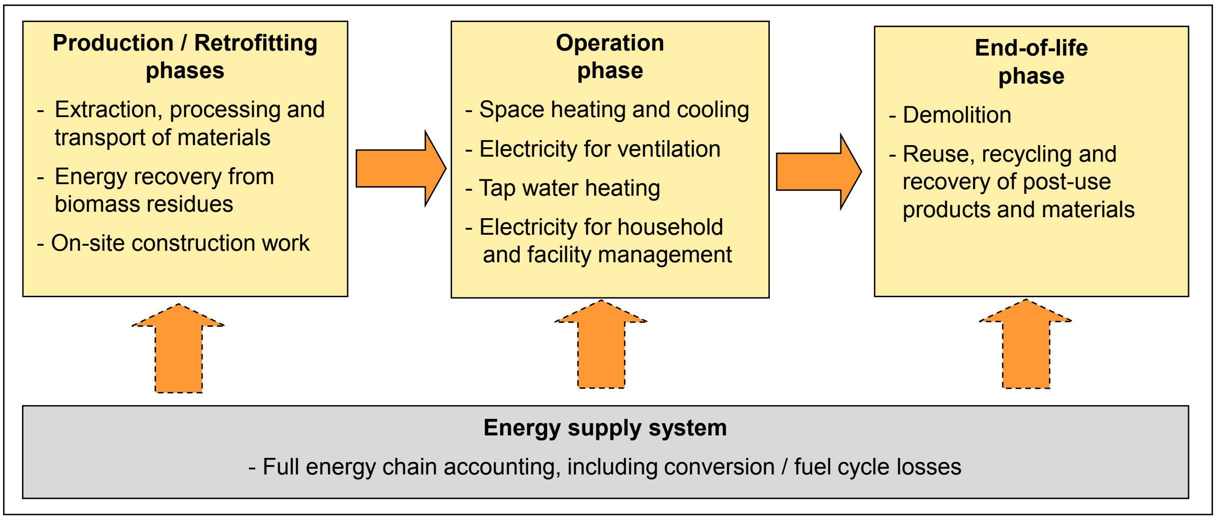

Figure 1. The lifecycle of a building

The understanding of the importance of a lifecycle perspective of buildings has recently increased in Sweden, partly due to the report "Climate impact of the construction process" (IVA, 2014). The calculations in the report indicate that annual GHG emissions from construction processes are about the same as the annual GHG emissions from passenger cars in Sweden. The report emphasized the need for more research on the climate change effects of the building construction process.

Studies show that the production phase of a low-energy building constitutes a large share of the total lifecycle impacts, depending on climate, energy supply and lifespan. Stephan et al. (2013) using a hybrid lifecycle modelling approach estimated the production phase of a Belgian passive house to be 77% of the total primary energy for production and operation of the building for 100 years. Thormark (2002) found the production phase of a Swedish low-energy house to be 45% of the total lifecycle energy use for 50 years. Dodoo et al. (2011; 2012) performed a process-based lifecycle analysis of Swedish buildings, and found the production phase of a passive house to contribute 20-30% of the total primary energy for production, space heating and ventilation for 50 years depending on the efficiency of energy supply. Feist (1997) found that a building with lower operation energy use may have higher total lifecycle primary energy use because of its high production energy. Appropriate selection of building materials and structural systems may give significant reductions in lifecycle primary energy use and climate change effects of buildings (Buchanan, and Honey, 1994; Cole, 1999).

The development of modern concrete- and wood-frame building systems allows the design and construction of energy efficient multi-story buildings with improved performance (Dodoo et al., 2014a,b). These include innovative forms of concrete-based building systems using insulated concrete forms and prefabricated elements, and timber multi-storey building using prefabricated elements, massive timber and engineered composite timber structural systems. While several comparative lifecycle studies have been reported (Adalberth, 2000; Gustavsson and Sathre 2006; Gustavsson et al., 2006; Dodoo et al., 2012) on conventional methods for concrete and timber construction, few detailed comparative analyses have been reported in scientific journals on the implications of different modern construction systems. Moreover, the few existing studies on lifecycle primary energy use of buildings are essentially descriptions of the primary energy and material flows, without an optimisation of the different material selection and building systems. Hence, very little information is available on complete lifecycle optimisation of modern Swedish building systems and building components, from both primary energy and GHG emission perspectives. Such optimisation between building phases appears to be potentially significant; for example, Tettey et al. (2014) showed that the primary energy required for production of insulation materials for elements of a building can be reduced by about 50% when fulfilling the same energy performance in the operating phase.

Although sophisticated tools for the analysis of environmental impacts of many goods and services have been developed over the last several decades, there are additional challenges in analysing products (e.g. Perez-Garcia et al. 2005a). Furthermore, the lifecycle analysis 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 lifecycle; 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 lifecycle impacts of the building; and that the design and construction of each building is typically unique (Kotaji et al. 2003).

Furthermore, to understand the energetic and climate change effects of buildings, the entire energy chains from the natural resource to the delivered energy services need to be considered. Most existing studies on energy implications of buildings are based on final energy use, while primary energy use will more accurately reflect the use of energy resources and is the basis for GHG emission calculation. Different types of energy supply systems can be used to provide the energy needs of a building, with significantly different primary energy use (Gustavsson and Joelsson, 2010; Gustavsson et al., 2010).

1.3 Climate change mitigation strategies

A variety of strategies can be adopted to facilitate a transition from a society driven mainly by fossil fuels and non-renewable resources to one driven mostly by low-carbon fuels and renewable resources exploited at a sustainable rate to mitigate climate change. These include energy-efficient buildings, substitution of material and fuel with less carbon-intensive alternatives, improved efficiencies in energy supply chains, and efficient management of post-use materials. About 33% of the total global CO_2 emission is linked to energy use in buildings (Price et al., 2006). A non-energy related CO_2 emission linked to the building sector is from the calcination reaction that occurs during the manufacture of cement. Globally, cement production accounts for about 5% of all anthropogenic CO_2 emission, of which nearly half is from the calcination process and the remainder from fuel combustion (IEA, 2009).

1.4 Lifecycle assessment

The lifecycle of a building includes production, retrofitting, operation and end-of-life phases (Figure 1). Various assessment standards and tools have been developed to explore the climate implications of the built environment. Lifecycle assessment is a commonly used tool for evaluation of environmental implications of products during their lifecycle stages. ISO 14040:2006 and 14044:2006 provide a general framework and guidelines for such an assessment. These standards suggest that a lifecycle assessment study should include all stages and impacts throughout the lifecycle of a product. An assessment identifies and quantifies the environmental impacts associated with the flows of energy and materials in a system. The assessment includes several impact categories e.g. acidification, global warming potential, eutrophication, ozone depletion, human toxicity and abiotic resource depletion. GHG emission analysis focuses exclusively on Global Warming Potential (GWP), an impact category measured by the climate change potential of GHG emissions in CO_2 equivalent units. The International Organization for Standardization's technical specification (ISO/TS) 14067:2013 provides general principles and guidelines for quantification of GHG emissions of a product. ISO/TS 14067:2013 is based on the ISO 14040 series of standards and suggests a scientific approach should be used in quantifying the GHG emissions of products, focusing on relevance, completeness, consistency, accuracy, and transparency. Other standards and frameworks increasingly referred in GHG emission studies are the Publicly Available Specification (PAS) 2050:2011 and the Greenhouse Gas Protocol (2011).

1.5 Scope and objective

All annual net GHG emissions to the atmosphere associated with the lifecycle of a building influence the climate change effects over the lifecycle of a building. Defining the functional unit, evaluation indicators, and system boundaries are necessary parts of analysing the climate change effects of buildings. A functional unit is the basis on which different objects or services can be compared. An evaluation indicator is a parameter used to describe the impact. System boundaries delineate what is included in the analysis and what is disregarded. System boundaries can be identified in terms of procedural, temporal, or spatial characteristics. These boundaries are not truly independent: an activity always has spatial and temporal boundaries; and without an activity, spatial and temporal boundaries have no significance, but for clarity they may be discussed separately.

Various methodological approaches have been developed by different authors to explore the climate change effects over the lifecycle of a building. In this report we discuss appropriate methods for determining the climate change effects over the lifecycle of a building. The focus is on forward-looking analyses using a scientific based method to support decision makers comparing different alternatives

2. Functional units

An analysis of the climate change effects over the lifecycle of a building requires the definition of a reference entity or "functional unit". A functional unit is a measure of the required properties of the studied system, providing a reference to which input and output flows can be related. These inputs and outputs, which vary between systems, are the flows which determine the climate change effects. These flows are the specific outcomes of fulfilling the functional unit in different ways (Weidema et al. 2004).

The climate change effects can be analysed using a variety of functional units: material mass or volume, building component, complete building, or services provided by the built environment. The functional unit applies to the buildings and materials, not to the energy use or the GHG emissions which are the result of the functional unit being fulfilled.

A commonly used unit by which impacts are calculated is a unit mass of individual materials. For example, industrial process analyses commonly determine the primary energy required to manufacture a kg or tonne of material. This information can be useful input for a more elaborate analysis, but by itself is incomplete because the function of different materials cannot be directly compared. One tonne of lumber, for example, does not fulfil the same functions as one tonne of steel. Similar analysis on the basis of unit volume of material suffers the same shortcoming.

Nevertheless, a particular material may fulfil more than one function (e.g. structural support and thermal insulation), and a given building function may be fulfilled by a combination of materials. Changing one material may impact on other functions in various ways, for example sound transmission, fire protection, and the overall weight of the building which affects the required foundation design. Thus, a more comprehensive analysis is at the building level (Kotaji et al. 2003). This can be based on a generic hypothetical building (e.g. Björklund and Tillman 1997), or a case study of completed buildings (e.g. Gustavsson et al. 2006b; Lippke et al. 2004). An approach between the material and building levels is the analysis of building elements (e.g. Waltjen et al, 2009). In this approach, the functional unit could be defined as e.g. "1 m^2 of element with a defined U-value, fulfilling the required engineering, sound and fire protection values". Hence, building components that provide the same function (e.g. structural support, or wall sheathing) should be compared (see e.g. Jönsson et al. 1997, Knight et al. 2005, Lippke and Edmonds 2006). The functional unit can be defined so that all the options have the same impacts during one lifecycle phase (e.g. operation), potentially simplifying the analysis.

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

Building codes can be used as a measure of function of a building, thus different buildings that each fulfil building codes for e.g., thermal efficiency or fire resistance, might be considered to be functionally equivalent in this regard. However, building codes are minimum standards that must be reached, and a building that 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.

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.

The functional unit is typically described as a demand side variable, i.e. the building or product used. For wood products, however, land use issues and sustainability concepts may also be revealed from a supply side perspective such as the unit of forest that produces such functional units.

The ISO/TS 14067:2013 technical specification on quantifying the carbon footprint of products states that a "study shall clearly specify the functions of the system being studied. The functional unit shall be consistent with the goal and scope of the study. The primary purpose of a functional unit is to provide a reference to which the inputs and outputs are related. Therefore the functional unit shall be clearly defined and measurable" (ISO/TS 2013).

3. Evaluation indicators

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 lifecycle. The net primary energy use describes the use of all energy resources, while 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 time profile of net annual GHG emissions.

Carbon dioxide emissions over time per functional unit is needed when calculating the climate change effects over the lifecycle of a building, but other greenhouse gases (e.g. CH_4, N_2O) should also be included if their climate change effects are significant. All GHG emissions should be measured on a net basis, equalling emissions to the atmosphere minus removals from the atmosphere.

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. Several authors have used CRF or a similar approach to analyse and compare the climate change effects of different systems (Zetterberg, 1993; Korhonen et al. 1993; Zetterberg et al. 2004; Nilsson and Nilsson 2004; Kikinen et al. 2007, 2008, 2009; Holmgren et al. 2007; Bird 2009; Sathre and Gustavsson 2012). 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.

Different GHGs, for example CO_2, N_2O and CH_4, have different climate effects due to their differing residence times (how long they remain in the atmosphere) and radiative efficiencies (how much radiative forcing is caused by a unit of gas). Factors other than atmospheric concentrations of GHGs can alter the earth's energy balance as well, including aerosols from volcanoes and air pollution and the amount of solar radiation delivered by the sun to the earth. Another potentially important factor in the energy balance is albedo, which is a measure of surface reflectivity. Changes in land surface albedo, e.g. between forested and harvested land, can significantly change the balance of solar radiation and hence radiative forcing, particularly in boreal forest regions (Marland et al. 2003).

Biomass is renewable if the harvest is less than the incremental growth, based on sustainable management of land. Thus, land use efficiency can also be an important indicator to evaluate resource efficient construction solutions. This can be measured in units of e.g. hectares of forest land needed per functional unit. This indicator accounts for differing forest productivity due to different geographic regions or forest management intensity. Measuring the consumption of woody biomass per functional unit could show, for example, that although one construction solution could have lower GHG emissions per functional unit, another solution might be favourable because it uses less biomass per functional unit, and therefore a unit of biomass can provide more overall function and reduce more total GHG emissions. However, results from scenario analyses show that it is possible to significantly increase timber production from Swedish forest land without increasing the area of productive forest land or decreasing the carbon stock in forest ecosystems (Skogsstyrelsen 2008; Gustavsson et al. 2015a).

Indicators in the form of typical lifecycle assessment categories are described in the 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

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

    - 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

4. System boundaries: Activities

In a lifecycle analysis, all the lifecycle phases need to be considered (Citherlet and Defaux 2007; Verbeeck and Hens 2007). 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. Boundaries should be established broadly enough to capture the significant impacts of interest, but not so broad as to make the analysis too unwieldy. Procedural system boundaries define which physical activities or processes are considered in the analysis. The European Standard 15978 (2011) state that the system boundary "includes all the upstream and downstream processes needed to establish and maintain the function(s) of the building, from the acquisition of raw materials to their disposal or to the point where materials exit the system boundary either during or at the end of the building lifecycle". The ISO/TS 14067:2013 technical specification on carbon footprint analysis says to "consider all stages of the lifecycle of a product when assessing the [carbon footprint], from raw material acquisition to final disposal" and to "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". For wood products in particular, a complete life-cycle approach is crucial for determining the net carbon annual balance, including forest management and end-of-life material management.

4.1 Building production

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

4.1.1 Raw material supply

For those materials extracted directly from natural deposits, for example mineral ores, an appropriate system boundary for the calculation of energy and GHG balances begins at the point of extraction. For biological materials that are cultivated, for example wood from sustainably managed forests, the analysis includes the technological (i.e. human directed) energy used for biomass production. This includes the primary energy used for the management of forest land, the harvesting of timber, and the transport and processing of wood materials. Intensive management of forests may require e.g. production and application of fertilizer, which must be included in the system boundaries (Sathre et al. 2010). Gross solar energy intercepted by the plants for photosynthesis and growth is generally not included in the energy balance (IFIAS 1974), unless the specific objectives of the analysis require it. Carbon balances of biological materials include the carbon fluxes that occur during the lifecycle of the plants.

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

4.1.2 Material processing energy

Energy is required to process and manufacture building materials, resulting in GHG emissions. A "cradle to gate" analysis of material production includes the acquisition of raw materials, transport, and processing into usable products. The type of end use energy varies, and could include electricity, bioenergy, and various types of fossil fuels. Primary energy required for providing the different types of end use energy, and the resulting GHG emissions, can be determined through consideration of fuel cycle, conversion, and distribution losses in the energy supply systems.

Different physical processes can be used to produce the same material, each process with unique requirements and effects on the environment. The efficiency of industrial technologies has generally improved over time resulting in differences in energy requirements and emissions between materials processed by state-of-the-art technologies and those made in older factories. Variation is also seen geographically, as technological innovations diffuse across countries and regions. Data on industrial energy use can also vary depending on the methodology used to obtain the data. System boundaries of an energy analysis can range from a restrictive analysis of direct energy and material flows of a particular process, to an expansive analysis including energy and material flows of entire industrial chains and society as a whole. Data may be direct measurements of a particular machine or factory, or may be aggregated for an entire industrial sector. Typically, data should be representative of the processes for which they are collected, and site-specific data is preferred over site average data.

Figure 2 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).

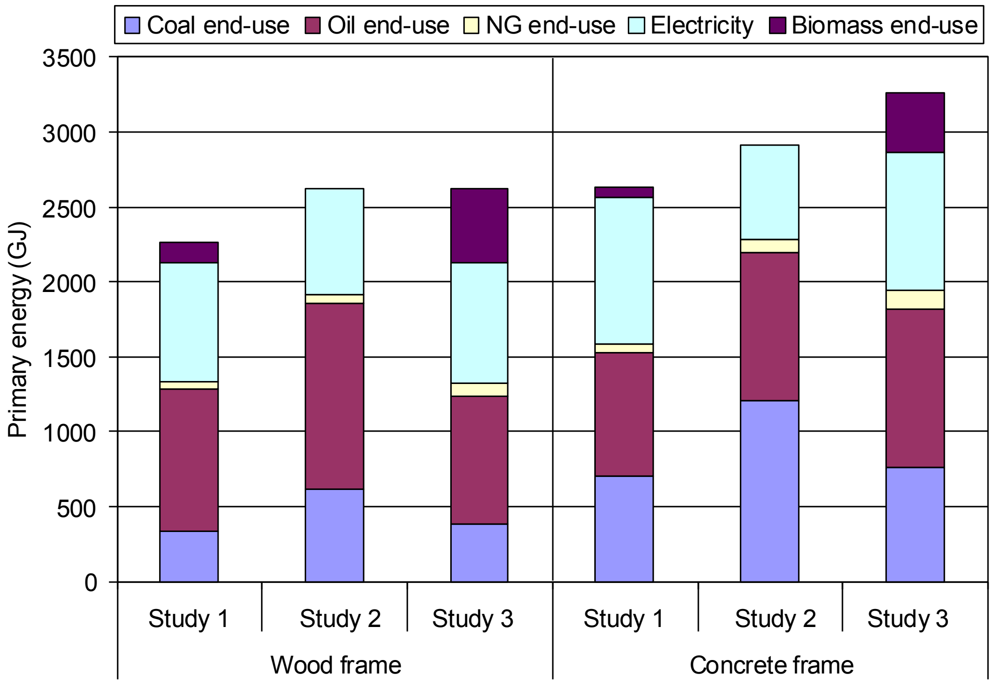

Figure 2. Primary energy used for production of materials for concrete- and wood- framed versions of a building, using specific energy use data from three different process analyses. Study 1 is Fossdal (1995), Study 2 is Worrell et al. (1994) and Study 3 is Björklund and Tillman (1997). (Adapted from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

Data availability and quality are key challenges in lifecycle analysis. For example, Tettey et al. (2014) found that the primary energy required for production of insulation materials for elements of a building improve over time but may differ significantly for some materials when using different datasets (Fig. 3). Björklund and Tillman's dataset is based on the Swedish building material industry 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. Nevertheless, both datasets in Fig. 3 show consistency in the ranking of the insulation materials.

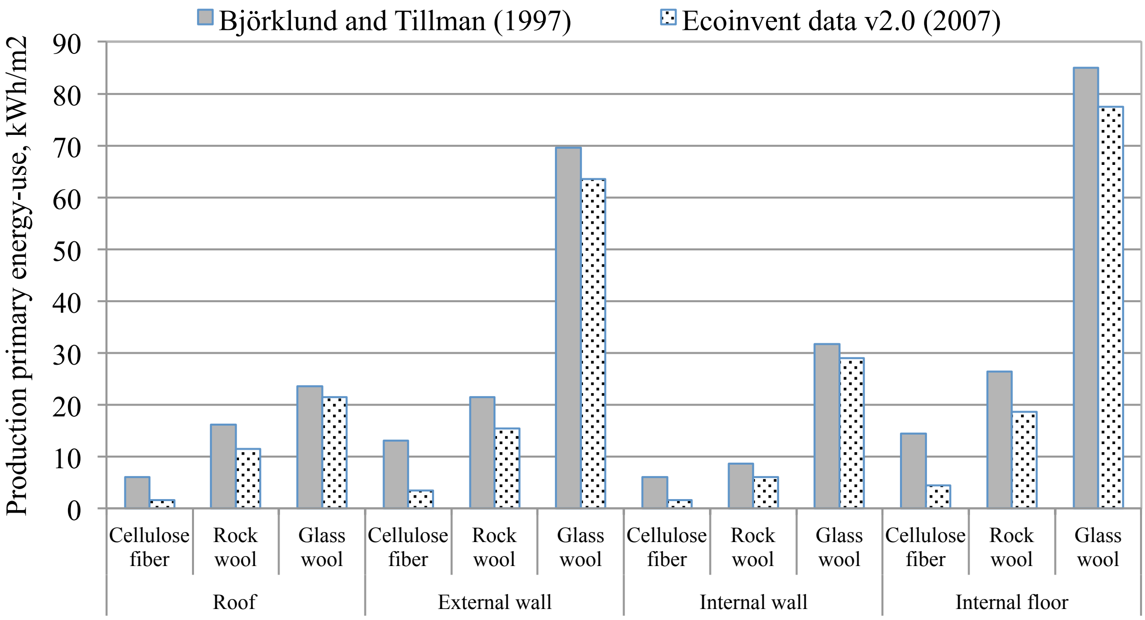

Figure 3. Comparison of primary energy required for production of insulation materials for elements of a building when using different data sets (Adapted from: Tettey et al., 2014).

Examples of sources of variation include specific transportation energy use and transportation distances for raw materials, semi-processed materials, finished materials, and post-use materials. Another source of variation is related to the estimated primary energy use and the associated GHG emissions. For instance, emissions from purchased electricity are usually calculated from average national electricity mix, whereas it is more realistic to consider the marginal electricity production when changes are made to the existing building practice changing the demand for electricity. One major source of variation is the energy used for material processing, caused by spatial, temporal, and technological differences. The potential impact of process improvements (e.g. cement process, wood logistics improvements) may be addressed, as well as the variability of energy supply systems that may give a large variation in primary energy use and resulting GHG emissions.

Efforts to collect, process, and make available improved data needed for accurate analysis of building construction are important. Greater attention should be focused on distinguishing between average and marginal values and the range of variability of key input data needed to analyse energy and GHG flows of building construction.

A linking of lifecycle assessment data and methodology can potentially improve the results. According to some top-down studies (e.g. Nässén et al. 2007) a significant share of energy use in the production phase of buildings appears to be indirect and is not recognized when applying the conventional bottom-up lifecycle assessment methodology. This is due to truncation error in bottom-up analysis, in which direct processes that are central to the object of analysis are studied in great detail, but indirect, secondary processes are analysed in less detail or are ignored. The potential underestimation of GHG emissions due to hidden, indirect energy use may be significant (Nässén et al. 2007).

4.1.3 GHG emissions from process reactions

Manufacture of some products result in industrial process carbon emissions. For example, CO_2 is released during the production of cement due to calcination reaction, when calcium carbonate is heated and broken down into calcium oxide and CO_2. Globally, cement production is the largest source of non-energy-related industrial emission of CO_2. Approximately 0.5 tonne of CO_2 is released for each tonne of cement produced. While calcination reaction emissions are well quantified, there is much uncertainty regarding the net effect of cement process emissions, due to subsequent CO_2 removal by carbonation reactions (Gajda and Miller 2000; Dodoo et al., 2009). Nevertheless, as carbonation removal is less than calcination emission, net process reaction emissions can be a significant part of the GHG emissions of cement products, and should be included in an analysis of climate effect over the lifecycle of a building. This is discussed in more detail in Section 5.4.

4.1.4 Building components

Buildings are composed of different components, for example, foundations, outer walls, inner walls, floor structure, roof, windows, doors, and interior fixtures. For each component, various technical solutions are possible, which may use different combinations of materials and result in different energy use and GHG emissions. For example, Lippke and Edmonds (2006) analysed and compared the environmental performance of various construction subassemblies, including four types of cold-climate wall construction, two types of warm-climate wall construction, and four types of floor construction. The function, including thermal efficiency, of each subassembly was identical. For the cold-climate wall construction, a conventional wood-framed wall system used 76% of the fossil fuel, and produced 69% of the GHGs, compared to a steel-framed wall system. A different wall system using increased amounts of wood products (e.g. wood plywood instead of vinyl siding, wood-fibre insulation instead of fibreglass insulation, plywood panelling instead of gypsum wallboards, and biomass residues instead of fossil fuels for wood processing energy) used 29% of the fossil fuel, and produced 32% of the GHGs of a steel-framed wall system.

Petersen and Solberg (2002) compared the energy use and GHG emissions for roof structures using steel beams and glue-laminated spruce wood beams. They found the total energy use in producing the steel beams to be 2–3 times more and the fossil fuel use to be 6–12 times more than the production of the glulam beams. The most likely scenario for production of the steel beams causes 5 times more GHG emission than the wooden beams. Knight et al. (2005) compared the manufacture of two functionally equivalent doors, one made of fibreglass-reinforced wood, and the other an insulated steel door. They found that from raw material acquisition to the door factory gate, the insulated steel door resulted in 27 times as much GHG emissions as the fibreglass-reinforced wood door. The steel door also had higher energy use. Salazar and Sowlati (2008) compared residential window frames made of aluminium-clad wood, polyvinyl chloride (PVC) and fibreglass frames. They found the window frames made of aluminium-clad wood result in fewer GHG emissions than frames made of polyvinyl chloride (PVC) or fibreglass. Petersen and Solberg (2004) compared the GHG emission and costs per m^2 of floor area for flooring made of solid oak wood, linoleum, vinyl, polyamide and wool carpet. They found the solid wood flooring to give the lowest GHG emission, followed by the wool carpet, polyamide, vinyl and linoleum.

4.1.5 Building assembly

In the assembly phase, the diverse materials and components are put together into a complete building. Studies of conventional construction have concluded that on-site construction activities use only a minor part of the total lifecycle energy use of a building. Lüsner (1996), for instance, showed that the construction process (including the transport of construction materials and products to the construction site) does not exceed 2% (in some rare cases 9%) of the lifecycle impacts for bridges or roads. Bruck and Fellner (2004) came to similar results in regard to residential buildings.

Björklund and Tillman (1997) reviewed the construction of several buildings in Sweden, and reported construction energy use from 17 to 168 kWh/m^2 of building area. Cole (1999) found the contribution of the on-site construction phase of a wood-frame Canadian multi-storey building to average about 5% and 12% of the energy used to produce the building materials, if workers' transport energy is excluded or included, respectively. Forintek (1993) found construction energy to equal about 7% of material production energy. Adalberth (2000) studied seven Swedish buildings and found that building assembly activities used on average 74 kWh/$m^2$of building area. Several studies of construction energy have not made clear whether they report end-use energy or primary energy. However, to determine GHG emissions resulting from primary energy use for building assembly activities, it is necessary to know the primary energy supply.

Some building material is wasted on the construction site, and should be accounted for. The amount of building waste typically varies between materials, and also varies between construction sites. In the absence of specific data, waste material generated during construction of the buildings may be estimated by increasing the material quantities in the finished buildings by specific percentages that are representative for each material. For example, Björklund and Tillman (1997) estimated material waste percentages for Swedish construction sites. Examples of these values are 1.5% for concrete, 7% for insulation, 10% for plasterboard and wood, 15% for steel reinforcement, and 5% for most other materials. These values may vary depending on whether the assembly is on-site or prefabricated.

4.2 Building operation, maintenance and renovation

Activities in the operation phase of a building include maintenance tasks such as cleaning, painting and periodic component replacements, plus energy use for heating, cooling, ventilation, etc. The operation phase generally contributes the greatest share of lifecycle primary energy use and GHG emissions of a typical building in a cold climate region such as Sweden.

The energy performance of buildings is often evaluated based on the operational final energy use. Final energy expresses the energy demand of the house, but does not account for primary energy use and hence the overall impacts due to the supply systems. The various 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 be performed with different energy efficiencies. Karlsson (2003) compared energy supply systems for heating purposes and demonstrated the relationship between different parts of the supply chain, such as fuel, end-use conversion and large-scale heat and power production technology. The size of the heat demand in turn influences the suitable type and capacity of heating system and consequently also the supply system. Hence, the optimisation of the energy and climate performance of a building over its lifecycle requires the consideration of interactions between construction inputs and operational inputs for heating, cooling, and ventilation as well as the connections, trade-offs and synergies between different phases of the lifecycle.

Operating energy use is often not included in comparative studies where the emphasis is on the energy and GHG balances of building production, because operating energy is deemed equivalent between the buildings and can therefore be ignored. In such cases, adding the operational energy use to the lifecycle GHG assessment would increase the total primary energy use for the compared alternatives, but the difference between them would remain the same. ISO standards state that "The deletion of lifecycle stages, processes, inputs or outputs is only permitted if it does not significantly change the overall conclusions of the study. Any decisions to omit lifecycle stages, processes, inputs or outputs shall be clearly stated, and the reasons and implications for their omission shall be explained” (ISO 2006). In cases where a comparative study involves different energy performance between the buildings, then operating energy should be included in the lifecycle analysis (John et al. 2009).

Maintenance and material replacement activities can have a significant climate effect over the lifecycle of a building and can vary substantially as a function of material. The building structure may have the same life span as the building and often needs no maintenance regardless of the structural system used. However, different exterior surface materials and some other building materials may have significantly different service lives or maintenance requirements. For example, Salazar and Meil (2009) compared two functionally-identical houses in North America, one made predominantly of non-wood materials and the other containing more wood-based materials. The first building had brick façade which was assumed to have a 100 year life span, and the second had cedar wood siding with an assumed 20 year life span. The first building had asphalt and felt roof material with an assumed 25 year life span, while the second building had cedar wood shingle roof with an assumed 35 year life span. This shows that the lifetime for the same building component could vary significantly when using different materials.

Depending on the energy efficiency standard that buildings are originally built to, there may be significant lifecycle energy and climate benefits from retrofitting existing buildings to a higher energy efficiency standard (Harvey 2009; IPCC 2007). For example, in Sweden about one million existing apartments are projected to undergo major renovation within the next 20 years, and about 60% of the total final energy use in the Swedish residential and service sector is for space and tap water heating (Itard et al. 2008). Thus significant opportunity exists in the coming decades to reduce primary energy use in a large share of the apartment building stock with energy efficiency measures.

Evaluation of the overall climate change effects of energy efficiency retrofitting requires consideration of GHG emissions associated with the production energy for the retrofitting, operation primary energy reduction over the remaining lifetime of the building due to the retrofitting and end-of-life management of retrofitting materials. Dodoo et al. (2010) analysed the primary energy reduction achieved by retrofitting a multi-storey apartment building to the energy use of a passive house, considering the energy for initial construction, retrofitting, operation and end-of-life of the building and different energy supply systems. They found that production primary energy use for retrofitting was small compared to the reduced operating primary energy use due to the retrofitting, resulting in significant net primary energy savings.

4.3 Co-products

Issues of allocation of lifecycle impacts or benefits may arise due to co-products from processing activities. Co-products are materials or products of some value that are produced simultaneously with the main product. For example, co-products of some industrial processes, including fossil fuel fly ash and blast furnace slag, can be used as cement binders. Construction cement made of a blend of clinker and other additives is becoming more commonly used (Gardner 2004). When cement is made with a blend of clinker and co-products of other industrial processes, total energy use is reduced because less clinker must be produced. CO_2 emissions are reduced in two ways: less fossil energy is needed for the production of the lower quantity of clinker, and lower clinker production means less CO_2 emissions from the chemical reaction of limestone calcination. Another potentially useful co-product is gypsum, which can be obtained from coal flue gas desulfurization.

An example of biomass flows over the lifecycle of a wood-based building material is shown schematically in Figure 4. In addition to the principal flows of round wood and finished wood materials, there are numerous co-product flows. The harvesting of trees, and their processing into wood products, generates considerable biomass residues that can be used for other purposes. Residues are generated during silviculture, harvesting, primary processing when logs are sawn into lumber, and in secondary processing for products such as doors, windows and glue-laminated beams. Such residues may be used as bioenergy, pulp and paper production or as a raw material for particleboard and other composite wood products.

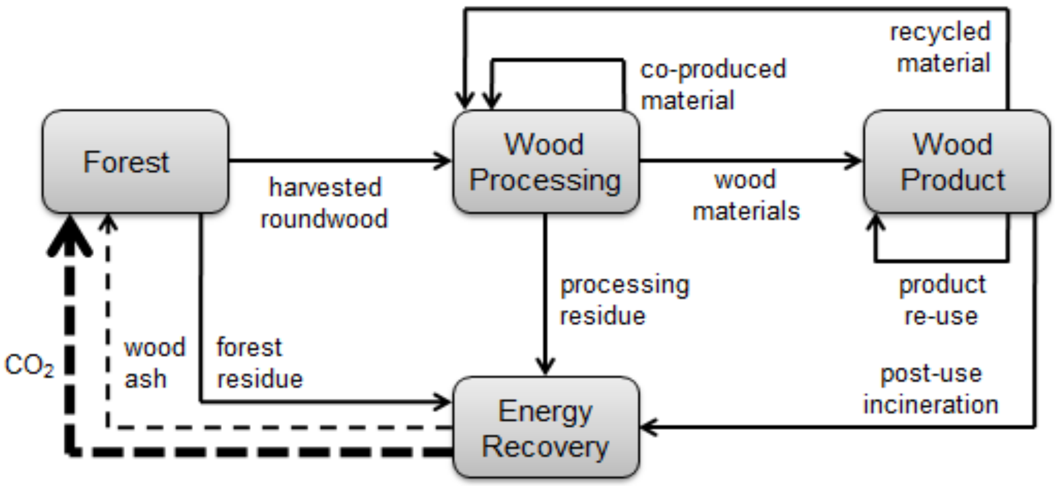

Figure 4. Schematic diagram of system-wide integrated material flows of wood products (Source: Dodoo et al. 2014a).

The choice of co-product allocation procedure can have a significant effect on the results of an analysis (Jungmeier et al. 2002). Allocation is the process of attributing impacts or benefits to a particular part of a process that results in multiple outputs. Allocation is a subjective procedure, and depends in part on the perspectives and values of the analyst (Werner et al. 2007). The ISO 14044 LCA guidelines (ISO 2006) state that allocation procedures must be clearly described, and the sums of inputs and outputs must be the same for the systems regardless of allocation method. If possible, the functional unit should be selected to avoid allocation. Allocation can often be avoided, e.g. by system expansion by adding additional functions to the functional unit so the systems compared have identical functions (Finnveden and Ekvall 1998, Gustavsson and Karlsson 2006). For example, the secondary function of wood residues as an energy source can be compared to an alternative of providing the same energy with fossil fuels. The results of this comparison are highly sensitive to the type of energy source which is substituted. System expansions have to be carried out very carefully and be based on an accurate investigation of the actually affected technology (Weidema 2003).

SS-EN 15804:2012+A1:2013 states the following concerning treatment of co-products: “Allocation shall be avoided as far as possible by dividing the unit process to be allocated into different sub-processes that can be allocated to the co-products and by collecting the input and output data related to these sub-processes. If a process can be sub-divided but respective data are not available, the inputs and outputs of the system under study should be partitioned between its different products or functions in a way which reflects the underlying physical relationships between them; i.e. they shall reflect the way in which the inputs and outputs are changed by quantitative changes in the products or functions delivered by the system. In the case of joint co-production, where the processes cannot be sub-divided, allocation shall respect the main purpose of the processes studied, allocating all relevant products and functions appropriately. The purpose of a plant and therefore of the related processes is generally declared in its permit and should be taken into account. Processes generating a very low contribution to the overall revenue may be neglected. Joint co-product allocation shall be allocated as follows: Allocation shall be based on physical properties (e.g. mass, volume) when the difference in revenue from the co-products is low; In all other cases allocation shall be based on economic values; Material flows carrying specific inherent properties, e.g. energy content, elementary composition (e.g. biogenic carbon content), shall always be allocated reflecting the physical flows, irrespective of the allocation chosen for the process."

4.4 Building end-of-life and post-use material management

The final stage in the lifecycle of a building is the demolition or disassembly of the building followed by the reuse, recycling and recovery or disposal of the materials. The energy used directly for demolition of buildings is generally small (1-3%) in relation to the energy used for material production and building assembly (Cole and Kernan 1996).

Re-use or reprocessing of materials at the end of the building lifecycle can have significant effects on the energy and GHG balances of the material (Sathre and Gustavsson 2006). End-of-life material and product reuse, recycling and recovery may become increasingly important in the future, to reduce the use of natural resources and gain economic value. In such a future scenario, the "design for disassembly" of buildings would become more prevalent to facilitate the removal of materials and products with minimal damage, to maintain their potential for further re-use as a material (Kibert 2003).

Production of steel products from recycled steel scrap requires less primary energy, and emits less GHG emissions, than production of steel from ore. Post-use management of concrete can lead to reduced net CO_2 emissions, by promoting increased carbonation by e.g., crushing the concrete and leaving it exposed to air. Recovered wood material, such as reusing as lumber, reprocessing as particleboard, or pulping to form paper products, may improve the climate performance of the material. Sathre and Gustavsson (2006) compared energy and carbon balances of products made of recovered wood to the balances of products obtained from virgin wood fibre or from non-wood material. They found that several mechanisms affect the energy and carbon balances of recovered wood, including direct effects due to different properties and logistics of virgin and recovered materials, substitution effects due to the reduced demand for non-wood materials when wood is reused, and land use effects due to alternative possible land uses when less timber harvest is needed because of wood recovery. In cases where material reuse of recovered wood is not practical, recovery of energy by burning the wood is a resource-efficient post-use option. The use of recovered demolition wood as a bioenergy directly affects the lifecycle energy balance of the material.

Landfilling of post-use building materials is still in practise in many regions. Carbon dynamics in landfills are quite variable, and can have a significant impact on the GHG balance of organic materials. A fraction of the carbon in landfilled organic materials may remain in semi-permanent storage, providing climate benefits. Another fraction may decompose into methane, which has higher specific climate change effects than CO_2. However, methane gas from landfills can be partially recovered and used as a fuel to replace other fuels. Thus, the landfilling option for post-use wood products carries great uncertainties, and could result in some climate benefit due to partial sequestration in landfills and partial production of methane that could be collected and used to replace fossil energy, or significant climate change impacts due to emission of methane to the atmosphere. There is a lack of consistency in the methods and assumptions used to track carbon during the lifecycle of wood products (Franklin Associates 2004). Particularly in regards to carbon sequestration and methane generation in landfills, a wide variety of methods and assumptions have been used in previous studies, leading to different and potentially contradictory conclusions.

A lifecycle assessment of a material must consider the fate of the material at the end of its service life. ISO technical specification states 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" (ISO/TS 2013).

4.5 Energy supply

4.5.1 Fossil fuels

The use of fossil fuels produces CO_2 emissions in quantities that depend on the carbon intensity and fuel-cycle characteristics of the fuel. Specific GHG emission values must include emissions occurring over the entire fuel cycle, including the end-use combustion of the fuels as well as from fuel extraction, conversion and distribution (Gustavsson et al. 2006b). Uncertainties arise in accounting for fossil fuel GHG emissions, due to methodological differences, heterogeneity of fuels, and imprecision in measuring (Marland 2008). The marginal effects of changes in fossil fuel use, rather than average effects, should be considered.

In cases where the type of fossil fuel is known the GHG intensity of that fuel is used in calculations. In cases where there is some uncertainty as to the appropriate choice of fuel a reference fuel may be employed to determine the significance of the GHG intensity of the fuel that may be used (Sathre 2007). Coal and fossil gas are two potential reference fossil fuels, representing high and low ends, respectively, of a range of GHG intensity of commonly used fossil fuels, thus indicating the range of uncertainty introduced by the fossil fuel used.

4.5.2 Electricity supply

The primary energy use and GHG emissions during the lifecycle of a building are affected by the supply system used to provide electricity for the various activities. Various types of electrical production systems exist, with significant variations in associated primary energy use and GHG emissions. Values for average or marginal primary energy efficiency and GHG emissions from electricity production have been used in lifecycle assessment studies. However, average data would inadequately capture the effect of changes to the system brought about by e.g. changes in the electricity use. This is because changes in electricity supply do not occur at an average level, but at the marginal level (Hawkes 2010). An electricity grid is generally powered by a variety of sources of differing capacities, and some of these sources are brought on-line and off-line depending on changes in demand over time scales of hours, weeks and years; these are defined as marginal sources. A decrease in electricity use, for example through reduced energy use in material processing industries, will cause a decrease in production of electricity from marginal sources. Hence, when analysing changes in electricity use, it is appropriate to use data on marginal electricity production that will be influenced by the changes, rather than data on average electricity production.

The electricity in the EU is produced mainly from conventional, thermal and nuclear plants with low conversion efficiencies (Figure 5). Only some 11% of the EU's electricity is produced in combined heat and power (CHP) plants (Eurostat 2009). Fossil gas plants have dominated investments during the past decade, but a number of coal and lignite plants are also under construction (Kjärstad and Johnsson 2007; The Guardian, 2014). The supply of fossil gas is considered less secure than the supply of coal. The Swedish electricity production system is dominated by hydro and nuclear power. Of Sweden's total installed electricity production capacity of 36 420 MW in 2011, hydro power, nuclear power, wind power and thermal power accounted for 44 %, 26 %, 8 % and 22 %, respectively (Swedish Energy Agency, 2013). There exists power cooperation in Nordpool between the Nordic countries for about the last 20 years, and the integration of electricity system is increasing within the EU. During 2014 the North-Western European power markets were coupled. In the Nordic system, coal-fired condensing power plants are usually considered to be the marginal source of electricity (Amiri and Moshfegh, 2010).

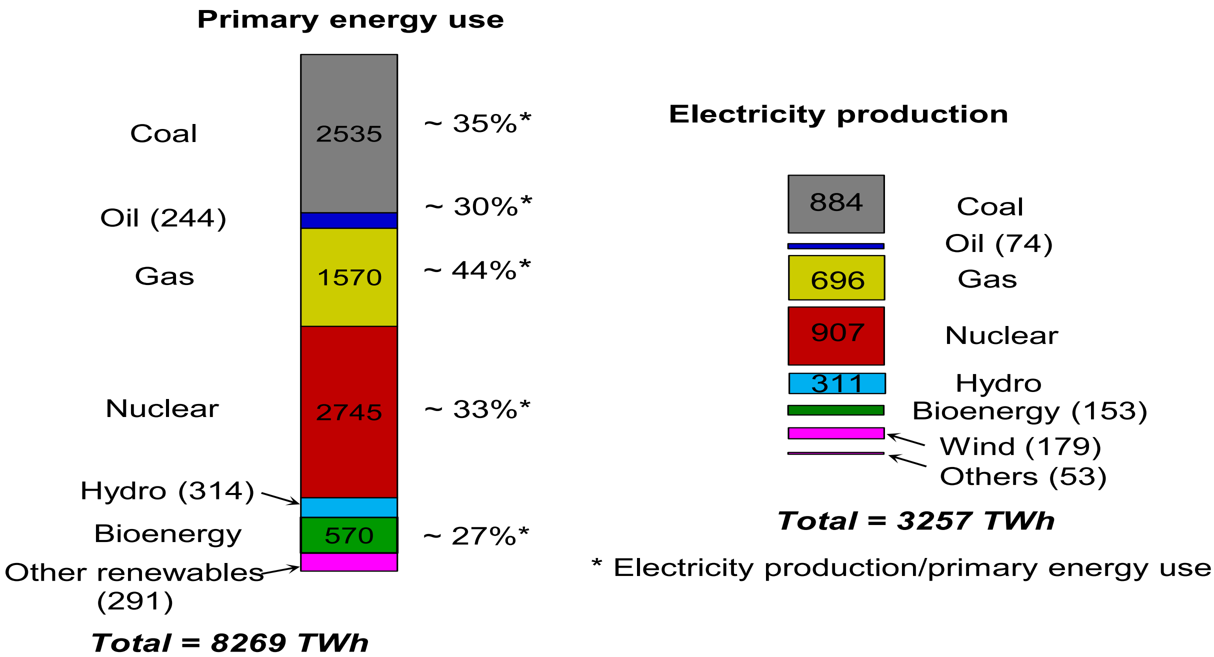

Figure 5. Primary energy use (TWh) and produced electricity (TWh) for different types of electricity production in EU in year 2011. The ratio between produced electricity and primary energy use is given for fuel-based electricity production. (IEA, 2013).

In the years and decades to come, the marginal electricity production will be affected by the evolution and development of the energy system as a whole. New investments in electricity production will be largely determined by relative costs and policy incentives. Existing coal-fired condensing plants will eventually be replaced. The electricity plants that are currently being constructed may be used until 2050 or longer. The production capacity of biomass, wind power and other renewable sources is likely to increase in the future. The identification of marginal electricity production depends on numerous factors including the time frame of analysis, the future development of technology, and the need for and incentives to reduce GHG emissions. Trends in the development of electricity production in EU until 2035 based on current policies are shown in Table 1. Because the electricity production system may not be known with certainty, more than one electricity production system may be considered to estimate the uncertainty range.

Table 1. Trends in the development of the electricity production in EU until 2020, 2030 and 2035 based on current policies. (IEA, 2013)

*CSP: concentrating solar power

	Electricity generation (TWh)		
Year	**2020**	**2030**	**2035**
Total generation	3425	3746	3918
Coal	818	711	658
Oil	38	23	20
Gas	637	904	1023
Nuclear	839	761	745
Hydro	378	395	401
Bioenergy	201	236	259
Wind	376	534	604
Geothermal	9	12	15
Solar PV	119	144	155
CSP*	10	18	25
Marine	1	5	14

4.5.3 Cogeneration of heat and power

A building needs heat for space heating and hot water, and electricity for ventilation (for buildings not using natural ventilation), cooling, facility and activities. The energy required to cover these demands can be supplied through separate or combined systems. For example, a district heating system can cover both space heat and hot water demand, and an electric supply system can cover the total energy demand of a building, including heating with resistance heaters or heat pumps. CHP systems produce both heat and electricity. CHP systems accounted for 45% of the delivered district heat and 17 TWh of the produced electricity in Sweden in 2011 (Swedish Energy Agency, 2013). Sawmills can use wood processing residues to cogenerate both process heat for e.g., kiln drying, and electricity for use within the mill and for export.

Different methods can be used to compare cogeneration and separate heat and electricity production. It is preferable to use a method that avoids allocation (see Section 4.3). To compare cogeneration systems producing both heat and electricity with systems producing only heat or electricity, both the energy carriers should be considered in the functional unit (Finnveden and Ekvall 1998; Gustavsson and Karlsson 2006) (Figure 6). This can be done by 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. In a multi-functional method, the functional unit is expanded to include all products produced. When heat and electricity are co-produced they are both part of the functional unit and either one of them can be considered the main product, but typically heat is the main product.

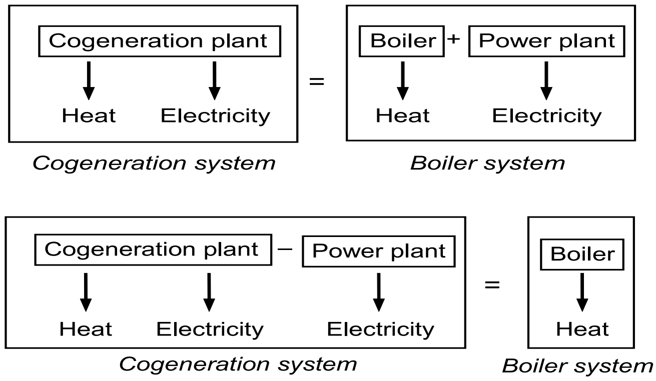

Figure 6. System expansion (top) with multi-functional products in the functional unit, and system subtraction (bottom) where cogenerated electricity is subtracted so the functional unit is heat (Finnveden and Ekvall 1998; Gustavsson and Karlsson 2006).

Subtracting either heat or electricity production from cogeneration is another way of comparing such systems. In this case the functional unit will be only electricity or heat. The subtraction is typically based on the avoidance of an assumed electricity or heat production in stand-alone plants using comparable fuels and technologies. The transparency is poorer when using the subtraction method than when using the multi-functional method (Finnveden and Ekvall 1998). In some cases, however, it may be preferable to use this method, for example when analysing the heating cost for the end user, to whom the cogenerated electricity is of no interest (Karlsson and Gustavsson 2003).

4.5.4 Biomass residues

Biomass residues from forestry and the wood products chain can be used for energy. Using a GHG mitigation strategy to minimise net emissions of GHG, biomass residues should be used instead of fossil fuel with the highest amount of GHG emissions (fossil coal). A strategic transition to a more sustainable society would entail gradually adding more renewable materials and fuel to the society, and substituting the most environmentally impactful materials and fuels, thus producing high marginal benefits.

Important methodological issues when comparing fossil- and bioenergy-based systems are the type of fossil system to be replaced, and the type of bioenergy system used to replace it (Schlamadinger et al. 1997). Because the fossil fuel that will be replaced by bioenergy use may not be known with certainty, several fossil fuel systems may be considered to determine the significance of this uncertainty.

When fossil fuels are substituted, the net fossil GHG emissions reduction should be based on the full fuel-cycle emissions of the avoided fossil fuel, the difference in energy conversion efficiency between the fossil fuel and the bioenergy, and the emission from fossil fuels used for recovery and transport of the bioenergy.

Recovery and utilisation of forest residue is becoming more common. In particular, residue from clear-cut areas is increasingly recovered, and efficient logistical systems are being developed to collect and transport the residue (Eriksson and Gustavsson 2010). Recovery of forest thinning residue is less common, due to its dispersed nature making efficient and economic collection more problematic. Recovery of stumps is a potentially significant source of bioenergy, but is currently not done at a large scale. The use of wood processing residues as bioenergy is common, and often used within the processing facility itself. The recovery of wood-based construction and demolition waste for use as bioenergy is becoming more common, with source separation of different types of wastes occurring on many work sites. Recovered wood that is contaminated with paint or preservative treatment can be incinerated in special incineration plants under suitable combustion conditions with flue gas cleaning and ash disposal. Various regulatory and economic factors affect the amount of wood that is recovered from building construction and demolition sites.

Bioenergy is often assumed to replace fossil fuel that otherwise would have been used. However, in economies where energy and/or material use is supply-limited, the availability of an additional unit of bioenergy may not lead to a unit reduction in fossil fuel use, due to equilibrating effects in the wider economy. In this case, an additional unit of biomass fuel or material may not displace the use of fossil fuel or non-wood material, but instead be used in addition to it. This result in the actual climate benefit of using wood products being somewhat lower than the potential benefits, but will increase the services delivered to society. However, bioenergy is typically more costly than fossil systems, if external costs are not internalized by the use of policy instruments. If such policy instruments are used to increase the cost of fossil energy to reflect their external costs, that will give economic benefits for energy efficiency measures reducing the overall energy demand, besides increasing the competitiveness of bioenergy.

5. System boundaries: Temporal

5.1 Building life span and product duration

The construction and demolition phases are one-time events during the lifecycle of a building. The energy use during the building operation phase, on the other hand, is continuous and depends directly on the service life span of the building. O'Connor (2004) observed that the useful service life of buildings is not related to the type of building materials and structural systems used in buildings. In a survey of 227 buildings demolished between 2000 and 2003 in the city of Minneapolis, USA, the main reasons for the demolition were changing land values, lack of suitability of the building for current needs, and lack of maintenance of various non-structural components. To determine the significance of the service life on a building's lifecycle energy use and GHG emissions, a range of service lives can be analysed.

Another aspect of building life span is the storage of carbon in wood building materials during the service life. The longer a piece of wood is used or reused as a material, the longer that carbon will remain out of the atmosphere. Eventually, however, and in the absence of long-term sequestration in e.g. landfills, all the carbon will be emitted through combustion or decomposition. As part of a dynamic biogeochemical cycle, carbon storage in wood products is an inherently transient phenomenon, though some long-lived wood products may store carbon for centuries. Over the lifecycle of a building, typically there is no change in carbon stock in the building itself. Before the building is built it contains no carbon stock, and after the building is demolished it contains no carbon stock. Combustion of wood-based demolition material means that 100% of the carbon stock is oxidised and re-enters the atmosphere mostly as CO_2. If the demolition material is used as bioenergy to replace coal, the avoided fossil carbon emissions are roughly equivalent to the carbon stored in the wood material during the building lifespan (Gustavsson et al. 2006b).

The total carbon stock of wood-based building materials could increase as a result of general economic growth, whereby more buildings of all kinds are produced, or through a societal transition from non-wood to wood-based products. In the latter case, the carbon stock in wood products increases as non-wood products are replaced by wood-based ones. For example, this would occur if non-wood-framed buildings are replaced by wood-framed ones, which after demolition are always replaced by new wood-framed buildings with a similar carbon stock. This would result in a step increase in carbon stock at the point in time when the non-wood material is replaced by wood. The permanence of the carbon stock in buildings depends on the difference between the amount of wood added to new construction and the amount of wood removed from demolished buildings (Lippke et al. 2010). The stock of wood products will stabilise if the rate of wood entering the wood products reservoir is equal to the rate at which used wood is oxidised and releases its stored carbon to the atmosphere. At this point, the storage of carbon in wood products has no net effect on the atmospheric CO_2 concentration.

5.2 Forest growth

Consideration of forest dynamics is an essential part of an analysis of GHG balances of wood building materials (Lippke et al. 2011). The lifecycle of a wood product begins with the germination of the tree seed, and continues through the growth and harvest of the tree and the manufacture and use of the resulting product. The carbon flux is time-dependent, as the plants grow and accumulate carbon in their tissues, and affects soil carbon content due to the root development and detritus-fall of the plants. This requires an analytical approach that captures the time dynamics of the plant growth, with explicit consideration of temporal scope of the analysis (Schlamadinger et al. 1997). Material inputs to the system include CO_2, water and nutrients (Yaro 1997). The accumulated carbon stock is tracked through the life of the tree and the energy flows begin with the accumulation of solar energy in tree biomass.

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. The carbon in these pools can then be tracked over time, while the carbon stock in living biomass re-accumulates as the forest regrows. Depending on biogeographical factors, the rotation period of forest stands ranges from decades to over a century. Following harvest of the forest stand, assuming no change in land use, the regeneration of the trees initiates another cycle of carbon accumulation in living biomass.

The carbon stocks of forest biomass and soil are affected by forest management regimes, including rotation length, thinning, fertilisation, and harvest (Eriksson et al. 2007). Intensification of forest management would increase the growth increment and the potential for wood product use (Sathre et al. 2010, Poudel et al. 2012). Transition to a management regime involving a longer or shorter rotation length would result in a temporary decrease or increase, respectively, in the harvest levels, as individual stands are harvested later or earlier than they otherwise would have been harvested.

5.3 Biomass residue availability

Over the lifecycle of a wood-based building material, biomass residues will become available at different times. Thinning residues may be generated at different times during the growth phase of the forest. Later, forest residues are created when the forest stand is harvested, processing residues are available when the roundwood is transformed into wood products, and construction site residues are left when the building is assembled. Later still, demolition residues are produced at the end of the building lifecycle. The use of these residues to replace other fuel can result in reduced fossil carbon emissions at different times in the lifecycle of the material. Forest residues left to decompose naturally in the forest slowly release CO_2 into the atmosphere over a time scale of decades, while residues removed from the forest and used as bioenergy release CO_2 when burned. This can result in varied radiative forcing, the significance of which depends on the time horizon under consideration (Holmgren et al. 2007). This effect is more pronounced for slower-decaying biomass such as stumps (Sathre and Gustavsson 2011, Gustavsson et al. 2015b).

5.4 Cement process reactions

As discussed in 4.1.3, chemical reactions affecting the net carbon balance occur at differing rates throughout the lifecycle of cement-based materials. CO_2 emissions occur due to calcination at the time the cement clinker is manufactured, and CO_2 removal occurs due to carbonation throughout the lifecycle of the cement product. Carbonation is a slow reaction that occurs over the lifecycle of cement products, when calcium hydroxide in the hydrated cement reacts with atmospheric CO_2 to form calcium carbonate and water. The extent of carbonation depends on many factors including surface area, surface coatings, cement composition, temperature, and humidity (Dodoo et al. 2009).

Gajda (2001) estimated that 8% of the initial calcination emission is re-absorbed by carbonation over a 100-year life span, but did not consider the post-use phase of concrete products. Demolition and crushing of concrete increases its specific surface area and hence increases the carbonation uptake. Pade and Guimaraes (2007) estimated that between 33 and

57% of the CO_2 released by calcination is re-absorbed by carbonation, assuming a service life of 70 years after which the concrete is crushed and then exposed to air for 30 years. Dodoo et al. (2009) estimated that about one-third of the calcination emission is reabsorbed by carbonation uptake after a 100 year life span followed by crushing and exposure for 4 months (Figure 7), and more than one-third is reabsorbed if the crushed concrete is exposed for 30 years. Thus there is substantial uncertainty about the net lifecycle carbon emissions of a concrete product, depending in part on the post-use management of the material.

Figure 7 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.

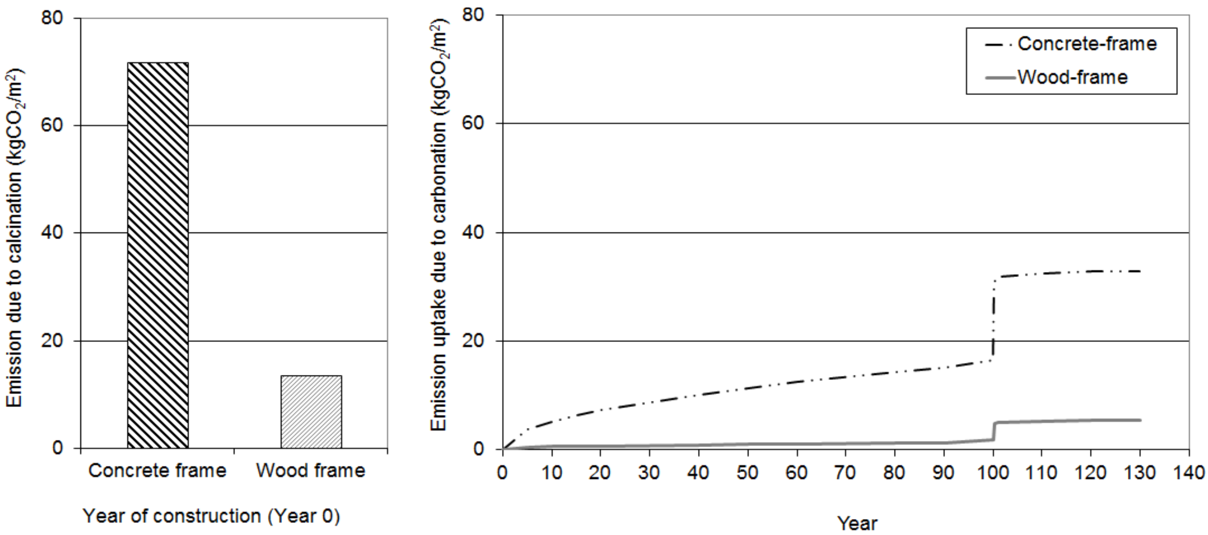

Figure 7. Carbon emissions from cement calcination (left) and carbon uptake from carbonation of cement products during the service life and after demolition (right), for concrete- and wood-frame buildings per m^2 of apartment floor area (adapted from Dodoo et al. 2009). Concrete material is crushed at the end of service life of 100 years and exposed to air for 4 months and thereafter used for below-ground filling.

6. System boundaries: Spatial

A fundamental difference between biomaterials and mineral materials is the regenerative ability of land, subject to appropriate management, to continue to produce the biomaterials during successive rotation periods in perpetuity, via biological processes. Although some materials like metals can be recycled successively, and all materials are naturally recycled over geological time spans, only biomaterials can be indefinitely regenerated on a time scale of use to society. This regeneration is driven by the energy of the sun through the process of photosynthesis, which accumulates the flow resource of solar energy into the renewable fund resource of plant biomass (Swan 1998). Land area for the capture of solar radiation is essential to this process, thus a consideration of the use of land and its productive capacity is an essential element of an analysis of wood building material use.

Careful definition of spatial boundaries, and the general consideration of how land is used, are important issues when determining the carbon balance of building materials. The use of wood-based materials instead of non-wood materials requires greater quantities of biomass, requiring the use of more land area or intensified forest management (Börjesson and Gustavsson 2000). A fundamental basis of climate analyses of wood building material use is that the forest land must be managed sustainably, in such a way that the land use can be continued indefinitely. Essential elements of sustainable land use include the maintenance of levels of soil nutrients and organic matter, the efficient use of available water supplies, and the protection of natural biotic diversity (Reijnders 2006).

A major challenge when comparing the climate effects of buildings is to compare the differences in land use needs between wood materials and non-wood materials. There are several analytical approaches that may be used for such a comparison, though the LCA community has not yet determined that any one approach is preferred over the others. One approach is to assume that an equal area of land is available to the alternatives being compared, and analyse the carbon balance impacts of various usage options for any land not used for material production. Assumptions on alternative land use may be based on a plausible market response, considering supply and demand for forest biomass and forest-related environmental services over different time scales. For example, a reduction in demand for timber may result in a decreased harvest, leading to an increase in forest carbon stock. This approach was used by Haus et al. (2014), who compared a wood-framed and a concrete-framed building with the same amount of land available for both cases, and assumed that forest land not used for building materials is not harvested and left standing as a biological carbon storage. At least three effects on carbon balance can be distinguished if a forest is not managed. First, the forest biomass would continue growing until the stand is mature. At this point a dynamic balance may be reached, where natural mortality equals growth and the long-term average carbon stock remains near-constant. Second, the soil carbon stock would behave in a similar way, i.e. continue to grow at a successively lower rate until a near steady-state situation is reached (Lal 2005). Third, no forest products could be produced and other materials and fuels would be used instead, resulting in a change in net GHG emissions.

A second approach to compare land use needs is to assume that the incremental wood material is produced though more intensive use of forest land, or from land that had not been previously used for wood production. This is a realistic assumption because the current annual harvest of forest land is typically lower than the potential annual harvest. For example, wood harvested in Europe in the mid-1990s was about 60% of the net growth increment of European forests, leaving an unused increment of about 300 Mm^3/yr (UNECE/FAO 2000). Continuation of these harvesting levels would change the landscape-level age class structure towards older age classes and the growth increment would decline in the long run (Nabuurs et al. 2013). If harvesting levels are increased, age class structure would change towards younger age classes and growth increment would increase, further increasing the potential for wood product use. Forest management produces a multiplicative effect whereby energy inputs used for forest management are leveraged into a greater energetic output in terms of biomass harvest. A continuum of forest management intensities is possible, from an intense regime to the non-management and non-use of forests. Intensive forest management can significantly increase biomass production rates (Sathre et al. 2010, Poudel et al. 2012).

A third approach to compare the differences in land use needs between building materials is to consider the biomass production from a unit area of land under different management options, and analyse the carbon balance impacts of using the produced biomass for various purposes. This approach considers the land area as the only functional unit to be compared, as the material output varies between cases and is thus not directly comparable. A fourth approach is to increase the intensity of use of the biomass resources through material cascading, or multiple reuse of wood fibre in applications that require successively lower quality of material, in effect gaining more functional service from the output of a given land area, or alternatively getting the same function from a smaller land area (Sathre & Gustavsson 2006).

Forest carbon flows have different dynamics when analysed at the tree or stand level, or at the landscape level. 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 tends to remain fairly stable over time, as the harvest of some trees during a given time period is compensated by other trees growing during the same period. The maximum carbon stock at the landscape level is lower than the maximum at the stand level, because not all the individual stands will hold the maximum stock at the same time (Kurz et al. 1998). If forests are managed appropriately, the average carbon stock in forest biomass can increase over time (Pingoud et al. 2010). Biomass production in European forests is also expected to increase over time due to the effects of climate change. Simultaneously, the flow of harvested biomass out of the forest gives continually increasing carbon benefits due to fuel and material substitution. If instead the trees are not harvested, the forest biomass would eventually reach a dynamic equilibrium, with the amount of carbon taken up by new growth balanced by the carbon released by respiration in living trees and decay of dead trees, but without the biomass flows available for the society.

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

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

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

Larger-scale analysis may seek to understand the spatial distribution of the GHG benefits of wood product use. The forest growth, wood processing, material use, and waste disposal may occur at different sites, and possibly different countries (Werner et al. 2010). The complexity of wood product substitution across national borders is illustrated by Werner et al. (2005, 2010). In analyses of increased wood use in Switzerland, they found that much of the wood substitutes in place of heavy, nationally-produced materials such as concrete and brick, resulting in decreased emissions in Switzerland. However, wood also substitutes in place of e.g. steel products manufactured outside of Switzerland, leading to decreased emissions in other countries. Some product substitutions resulted in increased emissions within Switzerland, but decreased net global emissions.

7. An example of climate change effect over the lifecycle of a building

To illustrate the concepts discussed in this report, here we conduct a quantitative analysis of the lifecycle CO_2 emissions from a case-study building. We analyse two functionally equivalent multi-story apartment buildings, one constructed with wood-based structural framing and another constructed with a reinforced concrete frame. The building has four storeys containing 16 apartments, with a total usable floor area of 1192 m^2 of which 1045 m^2 is apartment area and 147 m^2 is common area. Figure 8 shows a photograph, ground floor plan and section of the building. The concrete-frame and wood-frame versions studied are functionally equivalent and are designed to comply with the energy regulations of the 2014 Swedish building code (BBR 2014). The wood-frame building uses a cross laminated timber (CLT) building system consists of walls, intermediate floors, load-bearing interior elements and structural systems constructed with massive timber panels using CLT. The buildings are described in detail by Dodoo et al. (2014a, 2014b).

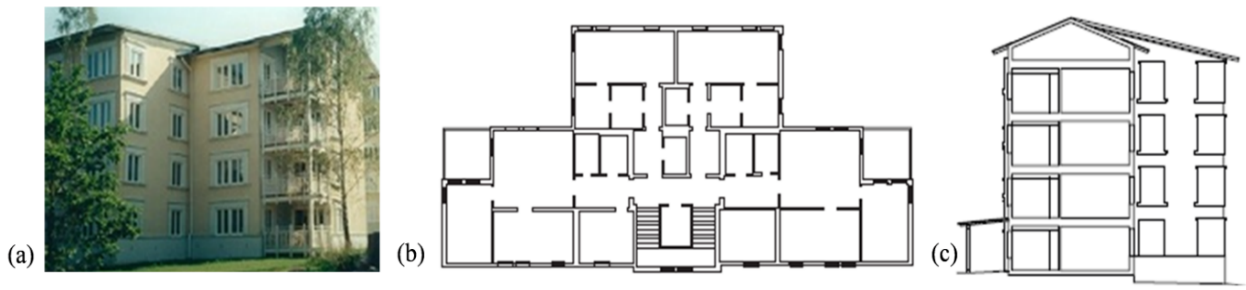

Figure 8. Photograph (a) and sketch of ground floor plan (b) and vertical section (c) of the case-study building.

Figure 9 shows the cumulative fossil CO_2 emissions from the building production of both versions. Fossil fuel use for production of the wood-frame building releases about 161 $kgCO_2$ per m^2 of apartment floor area, while that from the concrete-frame version releases about 242 $kgCO_2/m^2$. Manufacture of cement used in the wood frame building (for example for the building foundations) emits about 8 $kgCO_2/m^2$ due to cement calcination reactions, of which a part is later absorbed by carbonation reactions during the building lifecycle (these processes are illustrated also in Figure 7). The concrete frame building uses much more cement, resulting in calcination emissions of about 79 $kgCO_2/m^2$. About 16 $kgCO_2/m^2$ is re-absorbed by carbonation during the 80-year life span of the building, and an additional 18 $kgCO_2/m^2$ is re-absorbed when the demolition concrete is crushed at the end of the service life.

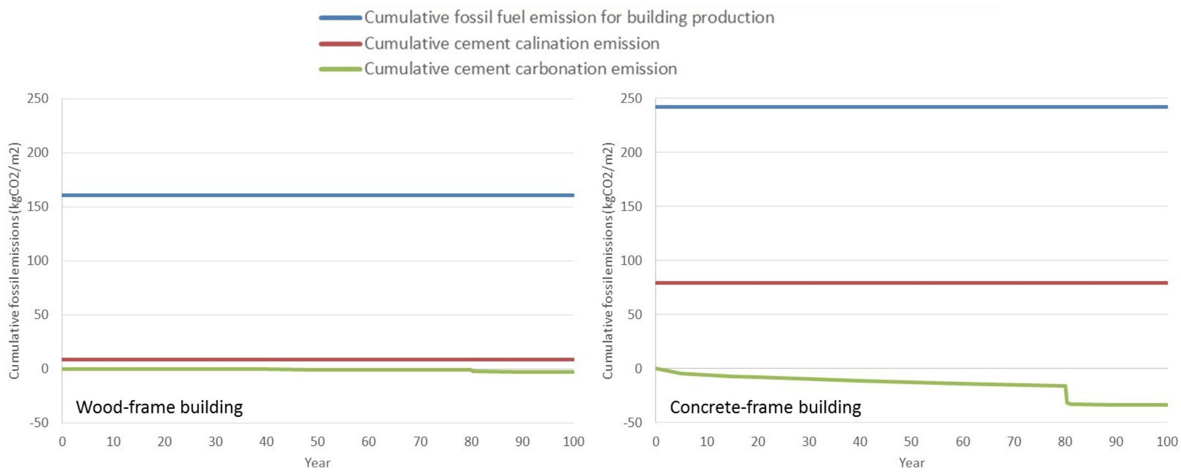

Figure 9. Cumulative fossil fuel and cement process CO_2 emissions during the building production and service life.

Figure 10 shows cumulative net fossil CO_2 emissions when biomass residues from the building production are used to substitute fossil coal. Net emissions are shown, which equal the fossil fuel emissions from recovery and international transport of the residues, minus avoided coal emissions due to fuel substitution (Gustavsson et al. 2011). We assume that both fossil fuels and bioenergy are used in modern large-scale high-efficiency conversion plants (Gustavsson et al. 2015b). Wood processing residues are most significant, leading to a 232 $kgCO_2/m^2$ avoided emissions for the wood-frame building and 83 $kgCO_2/m^2$ avoided emissions for the concrete-frame building. Next most significant is forest harvest slash recovery, followed by stump recovery.

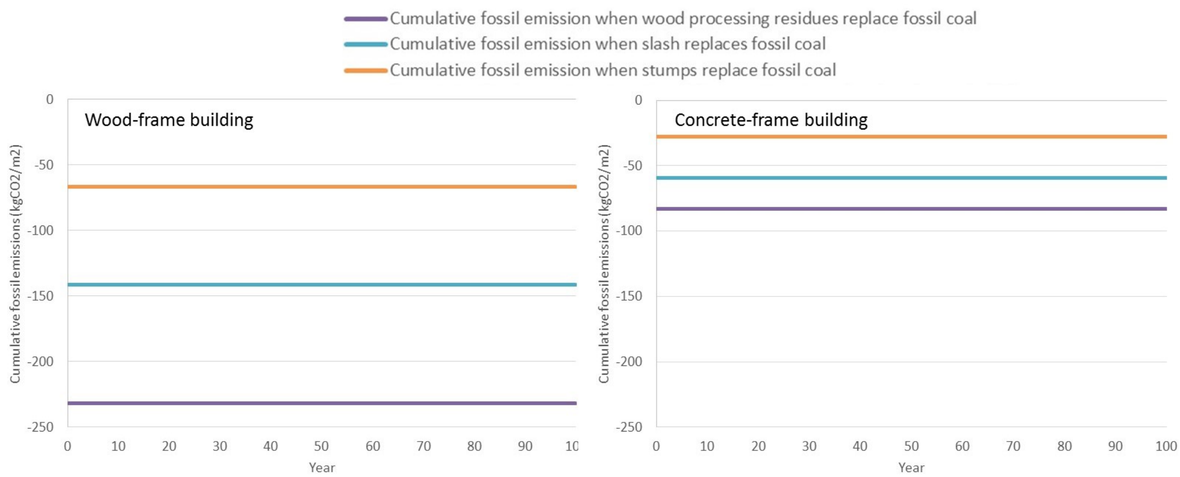

Figure 10. Cumulative net fossil CO_2 emissions when biomass residues from the building production are used to substitute fossil coal.

Figure 11 shows cumulative net fossil CO_2 emissions when biomass residues from building demolition are used to substitute fossil coal at the end of the building's 80-year service life. The shown net CO_2 emissions are fossil fuel emissions from recovery and transport of the residues, minus avoided emissions due to the substitution of fossil coal (Gustavsson et al. 2015b). Using demolition residues from the wood-frame building results in 200 $kgCO_2/m^2$

avoided emissions, while residues from the concrete-frame building leads to 117 $kgCO_2/m^2$ avoided emissions.

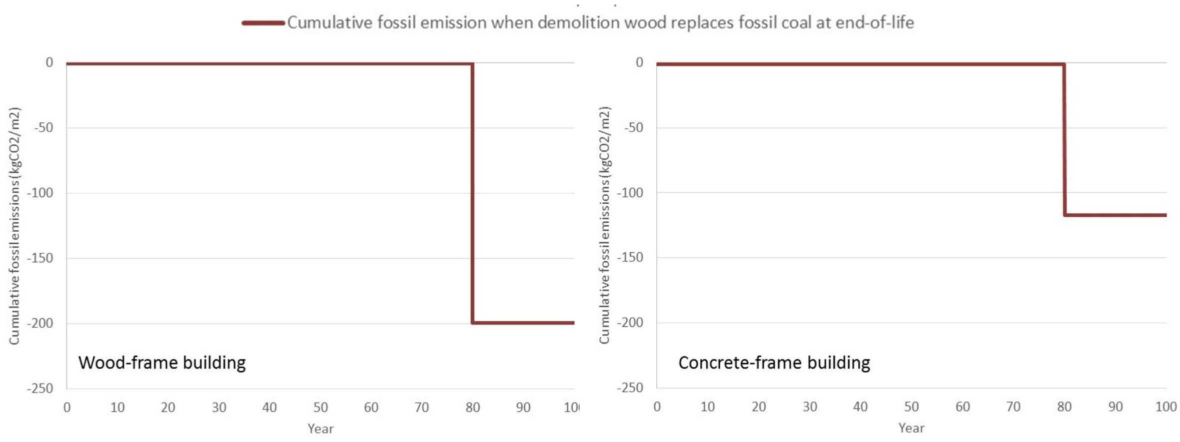

Figure 11. Cumulative net fossil CO_2 emissions when biomass residues from building demolition are used to substitute fossil coal at the end of the building service life.

Figure 12 shows cumulative building production- and demolition-related fossil and process CO_2 emissions over the lifecycle of the two building versions, calculated as the sum of the results shown in Figures 9-11. The calculation includes fossil fuel emissions from building production, cement process emissions, and net fossil emissions from coal substitution with biomass residues from forest harvest, wood processing, and building demolition. The wood-frame and concrete-frame building result in total net fossil and process CO_2 emissions of about –470 $kgCO_2/m^2$ and 0 $kgCO_2/m^2$, respectively, over their lifecycle excluding the operating phase.

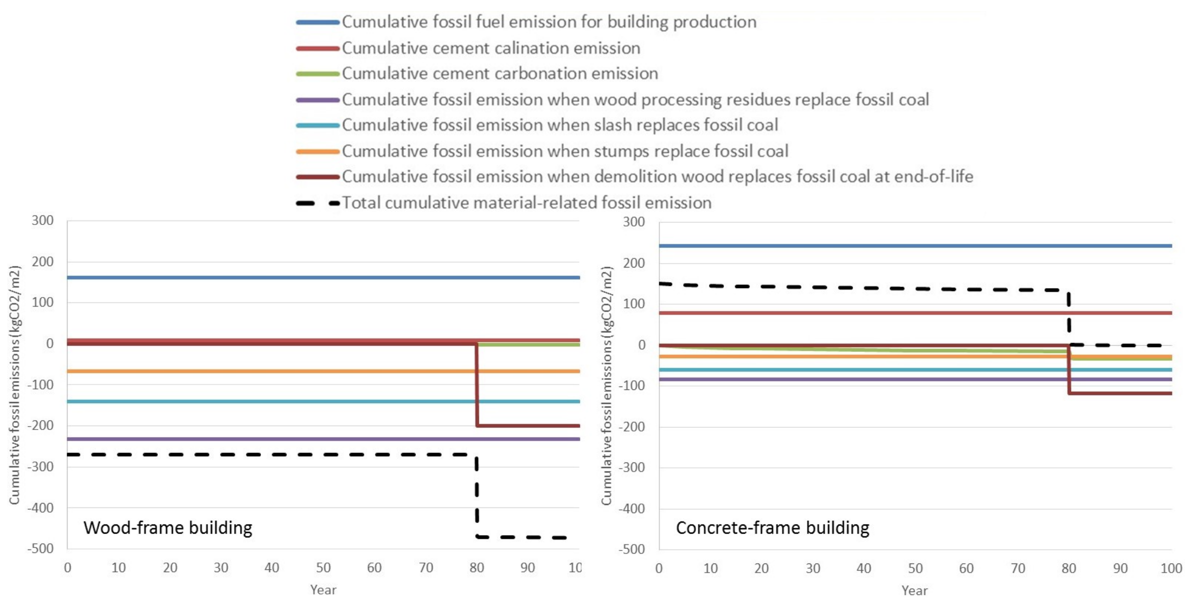

Figure 12. Total cumulative building production- and demolition-related fossil and process CO_2 emissions over the lifecycle of the two building versions, excluding the operating phase.

Figure 13 shows cumulative net fossil CO_2 emissions from space heating and ventilation of the buildings using three different energy supply systems. Because the wood-frame and concrete-frame versions are functionally equivalent and are both designed to the BBR14 building code, they each use the same amount of energy and have the same emissions when they use the same energy supply system. There is a large variation in emissions between the three energy systems. A heat pump is used in all systems, which is powered by electricity produced with either coal steam turbine, fossil gas combined cycle, or biomass steam turbine technology. Using coal steam turbines for electricity results in the greatest emissions, totalling about 1470 $kgCO_2/m^2$ over the 80-year live span of the buildings. Using fossil gas combined cycle technology emits about half that much, while using biomass steam turbine technology results in very minor fossil CO_2 emissions.

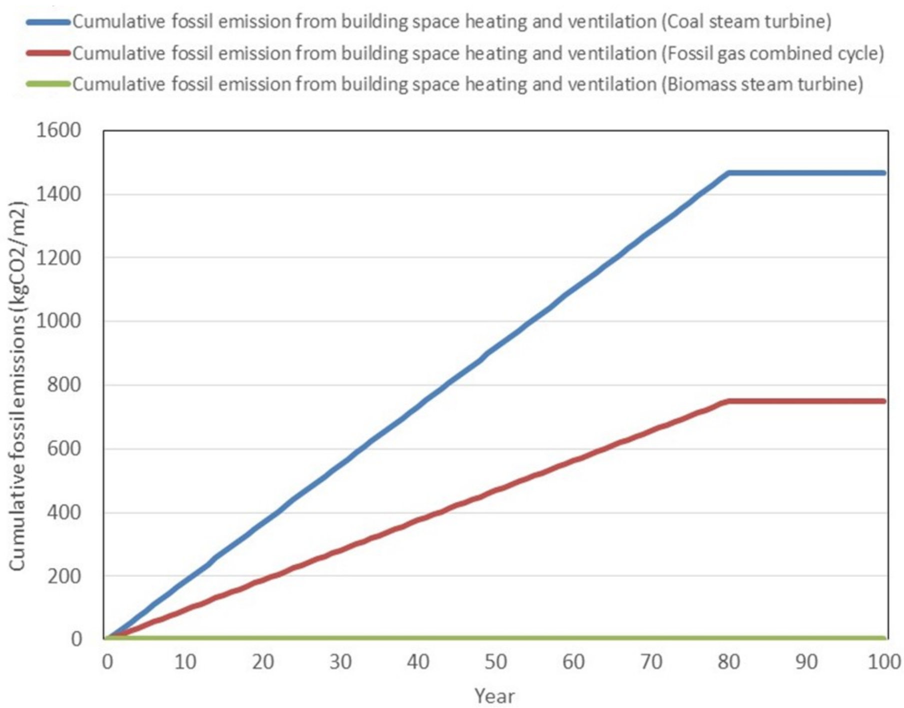

Figure 13. Cumulative net fossil CO_2 emissions from space heating and ventilation of the buildings, using three different energy supply systems.

Figure 14 shows the cumulative lifecycle fossil- and process-related CO_2 emissions for the wood-frame and concrete-frame buildings, using three different energy supply systems for space heating and ventilation of the buildings. Both the building frame material and the building operation energy supply system have significant effects on total fossil emissions. When wood material is used for the building frame, and biomass fuel is used for electricity production for space heating and ventilation, the cumulative net fossil emission is about –470 $kgCO_2/m^2$. On the other hand, when reinforced concrete is used for the building frame and coal fuel is used for electricity production for space heating and ventilation, the cumulative net fossil emission is about +1470 $kgCO_2/m^2$.

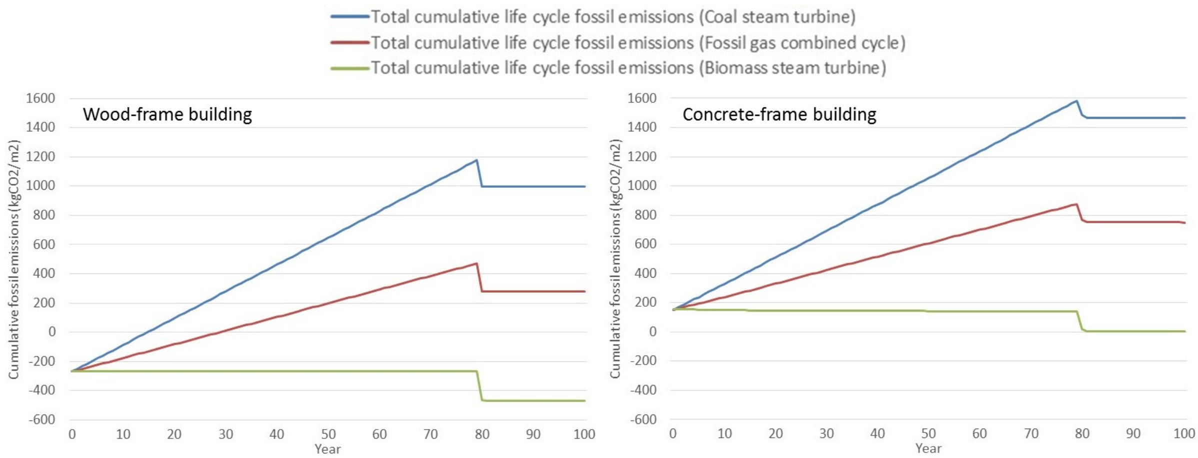

Figure 14. Cumulative lifecycle fossil- and process-related CO_2 emissions for the building versions, using three different energy supply systems for space heating and ventilation.

The above figures show only fossil carbon flows, and do not include biogenic carbon flows. Biogenic carbon flows can be a significant part of total carbon flows associated with buildings that use wood, because carbon comprises about 50% of the dry weight of wood. The wood-frame building in this case-study uses over twice as much wood material as does the concrete-frame building (which uses wood for the roof structure, doors, trim, etc.). While biogenic carbon can be comprehensively tracked as it flows between forest ecosystems, the built environment and the atmosphere (e.g. see Eriksson et al. 2007, Sathre et al. 2010, Poudel et al. 2012, Haus et al. 2015), here we use a simplified approach. 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. Considering Swedish forests as a whole, both the carbon stock in living forests as well as the harvest of timber for wood product manufacture are projected to increase over the next 100 years (Skogstyrelsen 2008, Gustavsson et al. 2015a). We therefore assume that, on a national level, the harvest of additional timber for construction of wood-frame buildings in Sweden will not result in additional biogenic carbon emissions, relative to reduced harvest levels for construction of concrete-frame buildings. Figure 15 shows projected living tree biomass in Swedish forests under three management scenarios from 2010 to 2109, based on the latest forest impact assessment (skogliga konsekvensanalyser) conducted by the Swedish Forest Agency (Gustavsson et al. 2015a). Three scenarios are considered: Business-As-Usual (BAU), Set-aside, and Production. The BAU scenario considers a continuation of current forestry practices, and harvest levels that correspond to forest growth rates. Historical harvest levels during the latest 10 years have varied between 70-85% of the total growth (Skogsdata 2014).The Set-aside scenario considers a doubling of the protected forest area that is not harvested, while all other assumptions are the same as BAU. The Production scenario involves more intensive forest management compared to BAU, including regeneration planting, use of fast growing species (e.g. *Pinus contorta*) and fertilization. In all three scenarios, the total living tree biomass (and hence the biogenic carbon stock) is expected to increase significantly during the next 100 years.

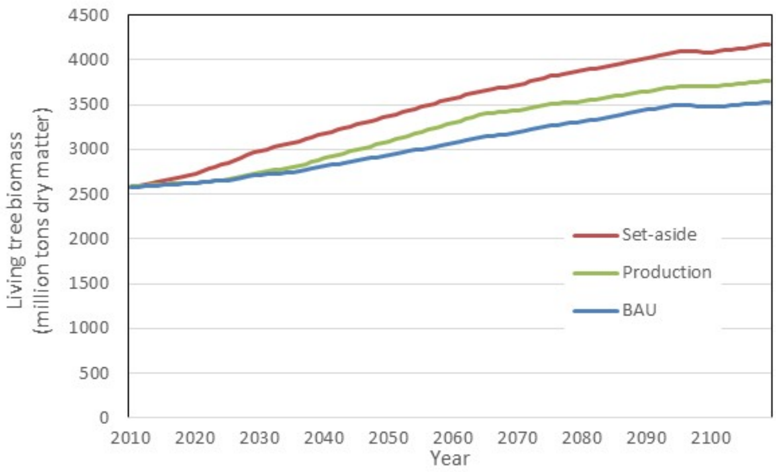

Figure 15. Living tree biomass (million tons of dry matter) in Swedish forests under three management scenarios from 2010 to 2109 (Gustavsson et al. 2015a).

Figure 16 shows projected stemwood harvest in the three scenarios, which is expected to increase from current levels in both the BAU and Production scenarios. During the next 100 years, stemwood harvest in the BAU scenario is projected to increase by about 12 million tons of dry matter per year. The wood-frame building in our case-study contains about 130 dry tons of wood products, requiring a stemwood harvest of about 300 dry tons. The projected BAU increase in annual harvest can thus produce about 40 000 buildings per year, or 640 000 apartments per year. Hence, a substantial numbers of wood-framed housing can be produced with the projected increase in stemwood harvest (Figure 16), without causing a decrease in biogenic carbon stock in Swedish forests from their 2010 level. However a comprehensive study should include detailed analysis of biogenic carbon flows. For comparison, the total housing production (including apartments and houses) in Sweden has remained below about 30 000 units per year for the last 20 years, and peaked at about 110 000 units per year in the late 1960s (Statistics Sweden 2014).

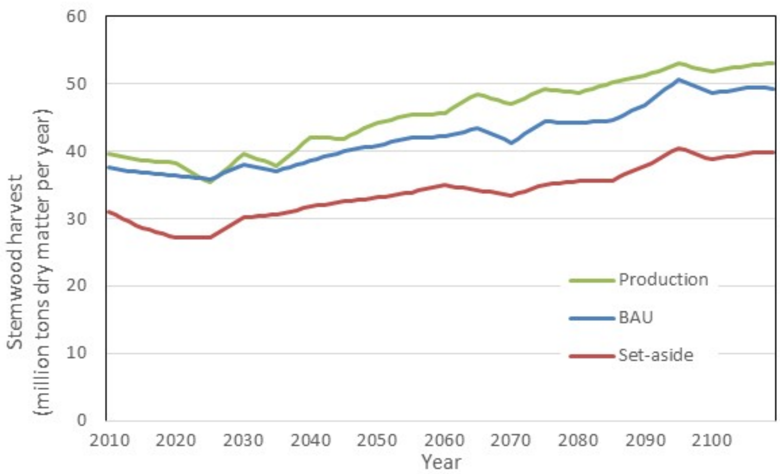

Figure 16. Stemwood harvest (million tons of dry matter per year) from Swedish forests under three management scenarios from 2010 to 2109 (Gustavsson et al. 2015a).

8. Attributional and consequential LCA

The LCA community recognizes at least two forms of LCA: attributional and consequential. Attributional LCA seeks to quantify all relevant energy and material flows associated with the life-cycle of a specific product or service. Consequential LCA describes how relevant energy and material flows will change as a result of a specific decision. Attributional LCA generally uses a descriptive approach that describes the overall characteristics of a static system, while consequential LCA uses a prospective approach that describe the effects of a change (Tillman 2000). Both forms of LCA can be applied for retrospective and prospective purposes, though attributional LCA is more commonly applied to existing or historical situations and consequential LCA is typically used to assess future impacts of a decision contemplated today. The consequential approach has gained considerable interest in the LCA community because it is more focused on evaluating the systems-level effects of decisions and future options (Finnveden et al. 2009). The more traditional attributional LCA, while valuable for understanding critical processes in the life-cycle of a system, is generally focused on evaluating the impacts of a technology or process independent from its role in a larger context.

Distinguishing approaches as either consequential LCA or attributional LCA has created considerable controversy in the LCA community. For example, Plevin et al. (2013) argued that only consequential LCA should be used to inform decision-making, and that attributional LCA can give misleading results if used for informing policy decisions because it ignores indirect effects. In the context of accurate GHG accounting of building construction and the built environment, it is more important to clearly define the purpose of the study and to choose the most suitable and appropriate analytical approach for the purpose than to categorize the LCA modeling technique. Attributional LCA can provide valuable insight on technology-specific questions and the optimization of technological performance. Consequential LCA will provide important information on the effectiveness of future options, and can better capture issues of system dynamics and technological development over time. A comprehensively understanding of the climate change effects over the lifecycle of a building should be structured around a holistic analysis of net annual GHG emissions from all sources associated with the building. As appropriate, this may include elements of both attributional and consequential LCA. In any case, a comprehensive description is required of the system under study, to understand its characteristics and its effects on overall net annual GHG emissions to the atmosphere during (and possibly after) the full lifecycle including production, operation and end-of-life of a building.

LCA studies may involve multiple scenario projections that consider various possible activities or various plausible future occurrences. This range of outcomes may lead to substantial overall uncertainty of the results (compared to analysis of a simpler modelled system with fewer possible outcomes) but greater insight into the true nature of the system under study. For example, management of forest harvest and wood processing residues at the beginning of a building's lifecycle, and of wood-based demolition residues at the end of a building's life-cycle, has been shown to have a large impact on the GHG balance over the lifecycle of the building. In some regions demolition residues are typically landfilled, which may result in permanent sequestration of carbon, but may also result in decomposition of the wood into methane with strong climate change effects. If the residues are instead used for bioenergy, they can substitute for various types of fossil fuels resulting in a range of climate benefit.

Multiple scenario projections allow the LCA practitioner to understand the range of potential outcomes of the system and identify key opportunities for intervention. Policies that are formulated based on a single normative future scenario may produce unintended consequences if future behavior is different than what was assumed, so it is necessary to consider the varied effects of potential future actions. Comprehensive scenario analysis can help identify decision pathways that are robust over a range of uncertainties. Technologies that perform adequately under a range of plausible scenario conditions may be preferred over other technologies that perform superlatively under some conditions but fail under other conditions.

Because consequential LCA considers the effects of discrete changes to an existing system, it is appropriate to employ data reflecting expected changes to the production system rather than average production. Two areas where this is important are material processing technologies and electricity supply. As discussed in Section 4.1.2, different physical processes can be used to produce the same material, each with unique requirements and GHG emissions intensities. The efficiency of industrial technologies has generally improved over time resulting in differences in energy requirements and emissions between materials processed by state-of-the-art technologies and those made in older factories. Variation is also seen geographically, as technological innovations diffuse across countries and regions. For example, Richter (1998) has shown a large variability in cumulative energy demand for wood-based products in different studies, and Josa et al. (2004) have shown a large range of energy use and CO_2 emission in cement production in the European Union. Accurate analysis of the lifecycle GHG emissions of buildings requires an understanding of these differences, and the use of appropriate data on relevant technological processes. Using data on marginal electricity supply is also important. An electricity grid is generally powered by a variety of sources of differing capacities which are brought on-line and off-line depending on changes in demand over time scales of hours, weeks and years. A change in electricity use (e.g. resulting from a change in building material use and its associated change in energy use for material processing) will cause a change in electricity generation from marginal sources. The identification of expected changes in electricity production systems depends on numerous factors including the time frame of analysis, the future development of technology, and the need for and incentives to reduce GHG emissions. Because the affected electricity production may not be known with certainty, more than one electricity production system may be considered to estimate the uncertainty range.

A major focus of some consequential LCA studies is the effects of indirect land use change. With respect to building life-cycle emissions, indirect land use change can be associated with forestry activities for production of wood-based building materials. In Sweden, Skogsstyrelsen regularly conducts forestry impact analyses to determine the long-term impacts that various forestry management alternatives may have on several parameters including timber production. Results from these analyses (Skogsstyrelsen 2008; Gustavsson et al. 2015a) show that it is possible to significantly increase timber production from Swedish forest land without increasing the area of productive forest land or decreasing the carbon stock in forest ecosystems (see also Section 7). This suggests that indirect land use change need not be a major factor in LCA studies of the climate effects of building life-cycles using Swedish timber, because forest management can be adapted to increase timber production without resulting land use-related emissions.

For existing buildings, the historical emissions from building production can be accurately described based on knowledge of the actual supply chains used for the buildings. Current emissions from building operation can also be accurately described based on the characteristics of the building and the type of energy supply systems in use. Potential future changes in operating emissions can be explored through scenario analyses of building retrofitting and energy supply system changes (e.g. connection of a building to a district heating network). Future emissions from the end-of-life phase of existing buildings can be modeled, again using scenario analyses of various options such as landfilling or recovery of concrete and wood-based materials.

New buildings involve more potential technological options, which can be explored through scenario analysis and sensitivity analysis. For example, different building materials can be used, which affects GHG emissions from the supply chain including raw material supply, processing and assembly. The choice of building materials and the technologies used for their production will affect the GHG emissions during the year of construction, which can be quantified using LCA techniques (Gustavsson & Sathre 2006). This choice will also affect GHG emissions later during the building lifecycle, for example due to CO_2 uptake from cement carbonation or avoided emissions due to fossil fuel substitution with wood-based demolition residues, which should also be considered. GHG emissions from building operations during its lifecycle will be strongly affected by choices made during design and construction, for example the thermal performance of the building envelope and the characteristics of the energy supply system. Various scenarios may be examined to determine the lifecycle emissions implications of different building operations options. Finally, emissions from the end-of-life phase of the buildings can be estimated using scenario analyses of various options such as landfilling or recovery of concrete and wood-based materials. Comprehensive analyses of multiple alternatives, including options for building construction, operation and end-of-life, can provide valuable information on the range of lifecycle GHG emissions of buildings, and can help identify opportunities for significantly reducing overall emissions from the building environment.

The LCA community continues to refine the methods of analysis, and the relative merits of various approaches such as attributional and consequential LCA are still debated. We suggest that an important task is to develop and implement methodologies that accurately describe the overall climate change effects of various building systems, including the effects of current and future options. These options include, for example, the choice of building frame material, the energy performance of buildings, the type of heating system including its energy supply, and the management of biomass residues at the beginning and end of the building's lifecycle. Understanding the effects of these options on annual net GHG emissions, and implementing the options that have low climate change effects, is critical to the successful development of a built environment with minor climate change effects.

9. Conclusions

It is increasingly recognized that climate change due to anthropogenic GHG emissions is one of the greatest challenges facing our society, with major implications for both human and natural systems. The built environment is responsible for a significant share of these emissions for both the production and operation of buildings. In response, diverse initiatives are being developed and implemented at the local, national, and international levels to limit the release of GHGs into the atmosphere. These initiatives rely on the assessment, monitoring, reporting and verification of GHG emissions and removals. To ensure that actions are effective at mitigating climate change, the annual accounting of GHG flows associated with buildings should be done in a lifecycle perspective. In other words, the analysis should consider all inputs (e.g. energy, materials) and outputs (e.g. emissions, waste, co-products) for each lifecycle stage including production, operation and end-of-life. Analysis of the climate change effects over the lifecycle of a building is a complex issue. In this report we have discussed some important methodological issues of such analyses, including the definition of a functional unit of comparison, the determination of appropriate indicators, and the establishment of effective and workable system boundaries in terms of activity, time and space.

The functional unit can be defined at the level of building component, complete building, or services provided by the built environment. Energy use or GHG emissions per unit of mass or volume of material can be an important input for a more comprehensive analysis, but by itself is inadequate because equal masses or volumes of different materials do not fulfil the same function. Analysis at the level of a complete building or building service is needed. Cumulative GHG emissions, typically measured in units of CO_2 equivalent, is a commonly used indicator of climate change effects. Cumulative radiative forcing provides a more accurate indication of actual climate change effects, but requires more detailed information on the timing of GHG emissions.

System boundaries determine what is included in the analysis and what is disregarded. Activity-based boundaries include lifecycle processes such as material production, building operation, and post-use material management. Differing production efficiencies and fuel types can result in different primary energy use and GHG emissions for identical materials. Chemical process reactions can be a significant CO_2 emission source for cement-based products. When comparing buildings that are functionally equivalent in the operation phase, such that the emissions occurring during the operation phase are equal, this phase may be dropped from a comparative analysis without affecting the relative results. However, operating emissions (e.g. from energy supply for space heating and ventilation) are typically a significant source of climate change effect of conventional buildings in cold climate regions, so will affect the absolute results. Post-use management options including reuse, recycling and recovery can significantly affect energy and carbon balances. Numerous co-products are associated with the lifecycle of wood-based building materials, and their analytical treatment can significantly affect the results. The use of co-products can be analytically treated through system expansion, and compared to an alternative of providing the same service. The production of electricity used for material processing and building operation is important, and data describing how such production will change due to choices made during building design and construction should be used, rather than data on average electricity production.

Temporal system boundaries include such aspects of the wood product lifecycle as the dynamics of forest growth including regeneration and saturation, the availability of residues at different times, and the duration of carbon storage in products. If a forest stand is not harvested it will eventually reach a dynamic equilibrium, with the amount of carbon taken up by new growth balanced by the carbon released by respiration in living trees and decay of dead trees. Carbon storage in wood products may be temporarily significant during the life span of a building, but will likely be released again to the atmosphere at the end of the building's lifecycle. Carbon sequestration increases only if the total stock of wood products is increasing. Other temporal boundary issues include fossil fuels used at different times during the lifecycle, and cement process reactions (calcination and carbonation) that occur throughout the lifecycle of concrete products.

The establishment of spatial boundaries can be problematic, because wood-based building materials require the use of more forest land area than does non-wood materials. There are several possible approaches to meet this challenge, including the intensification of land use to increase the time rate of biomass production, and the assumption that an equal area of land is available to both the wood-based and non-wood-based product followed by analysis of carbon balance impacts of various usage options for any land not used for material production. Furthermore, scaling up the analysis from the micro-level to the macro-level of national, regional or global scale is important to understand the wider implications of building production.

The LCA community continues to refine the methods of analysis and the relative merits of various approaches such as attributional and consequential LCA are still debated. We suggest that an important task is to develop and implement methodologies that accurately describe the overall climate change effects of various building systems, including the effects of current and future options. These options include, for example, the choice of building frame material, the energy performance of buildings, the type of heating system including its energy supply, and the management of biomass residues at the beginning and end of the building's lifecycle. Understanding the effects of these options on annual net GHG emissions, and implementing the options that have low climate change effects, is critical to the successful development of a built environment with minor climate change effects.

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