



Thesis for the degree of Doctor of Philosophy

**Life Cycle Primary Energy Use and Carbon Emission
of Residential Buildings**

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2011

Mid Sweden University Doctoral Thesis 115

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Mid Sweden University Doctoral Thesis 115
ISBN 978-91-86694-57-9
ISSN 1652-893X

Cover illustration by Ben Arhin

Printed by Kopiering Mittuniversitetet, Sundsvall, Sweden, 2011

“When we build, let us think that we build forever. Let it not be for present delight nor for present use alone; let it be such work as our descendants will thank us for.”

— *John Ruskin, The Seven Lamps of Architecture, 1849*

Abstract

In this thesis, the primary energy use and carbon emissions of residential buildings are studied using a system analysis methodology with a life cycle perspective. The analysis includes production, operation, retrofitting and end-of-life phases and encompasses the entire natural resource chain. The analysis focuses, in particular, on to the choice of building frame material; the energy savings potential of building thermal mass; the choice of energy supply systems and their interactions with different energy-efficiency measures, including ventilation heat recovery systems; and the effectiveness of current energy-efficiency standards to reduce energy use in buildings. The results show that a wood-frame building has a lower primary energy balance than a concrete-frame alternative. This result is primarily due to the lower production primary energy use and greater bioenergy recovery benefits of wood-frame buildings. Hour-by-hour dynamic modeling of building mass configuration shows that the energy savings due to the benefit of thermal mass are minimal within the Nordic climate but varies with climatic location and the energy efficiency of the building. A concrete-frame building has slightly lower space heating demand than a wood-frame alternative, because of the benefit of thermal mass. However, the production and end-of-life advantages of using wood framing materials outweigh the energy saving benefits of thermal mass with concrete framing materials.

A system-wide analysis of the implications of different building energy-efficiency standards indicates that improved standards greatly reduce final energy use for heating. Nevertheless, a passive house standard building with electric heating may not perform better than a conventional building with district heating, from a primary energy perspective. Wood-frame passive house buildings with energy-efficient heat supply systems reduce life cycle primary energy use.

An important complementary strategy to reduce primary energy use in the building sector is energy efficiency improvement of existing buildings, as the rate

of addition of new buildings to the building stock is low. Different energy efficiency retrofit measures for buildings are studied, focusing on the energy demand and supply sides, as well as their interactions. The results show that significantly greater life cycle primary energy reduction is achieved when an electric resistance heated building is retrofitted than when a district heated building is retrofitted. For district heated buildings, the primary energy savings of energy efficiency measures depend on the characteristics of the heat production system and the type of energy efficiency measures. Ventilation heat recovery (VHR) systems provide low primary energy savings where district heating is based largely on combined heat and power (CHP) production. VHR systems can produce substantial final energy reduction, but the primary energy benefit largely depends on the type of heat supply system, the amount of electricity used for VHR and the airtightness of buildings.

Wood-framed buildings have substantially lower life cycle carbon emission than concrete-framed buildings, even if the carbon benefit of post-use concrete management is included. The carbon sequestered by crushed concrete leads to a significant decrease in CO₂ emission. However, CO₂ emissions from fossil fuels used to crush the concrete significantly reduce the carbon benefits obtained from the increased carbonation due to crushing. Overall, the effect of carbonation of post-use concrete is small. The post-use energy recovery of wood and the recycling of reinforcing steel both provide higher carbon benefits than post-use carbonation.

In summary, wood buildings with CHP-based district heating are an effective means of reducing primary energy use and carbon emission in the built environment.

Sammanfattning

I den här avhandlingen analyseras flerbostadshus primärenergianvändning och koldioxidutsläpp i ett livscykelperspektiv. Analysen inkluderar husens produktion, drift, underhåll och rivning och omfattar hela naturresurskedjan. Särskild studeras husens energieffektivitet, stommaterial och uppvärmningssystem, samt hur dagens byggnorm och passivhusstandard påverkar primärenergianvändningen i byggnader. Resultaten visar att ett flerbostadshus med trästomme har lägre primärenergibehov än ett likvärdigt hus med betongstomme. Det beror i huvudsak på en lägre primärenergianvändning och en större möjlighet att återanvända olika trärester vid produktion av trästommehuset jämfört med betongstommehuset. Timvis dynamisk modellering av hur husens termiska massa påverkar primärenergianvändningen visar att huset med betongstomme har ett något lägre uppvärmningsbehov än huset med trästomme. Hur mycket lägre uppvärmningsbehovet är varierar något med i vilken klimatzon husen är belägna och med husens energieffektivitet. Men fördelen med betongstommehusets värmetrögheten är betydligt mindre än de fördelar som trästommehuset har i produktionsfasen.

Dagens byggnorm och passivhusstandard medför att den slutliga energi som används för uppvärmning minskar kraftigt jämfört med tidigare byggnormer. Men ett eluppvärmt passivhus kan ge högre primärenergianvändning än en byggnad byggd på 1990-talet med kraftvärmebaserad fjärrvärme. Det beror på att energieffektiviteten varierar starkt för olika uppvärmningssystem. I ett livscykelperspektiv ger ett passivhus med trästomme kombinerat med energieffektiva uppvärmningssystem en mycket låg primärenergianvändning. För att minimera den totala primärenergianvändningen över ett hus livscykel är det nödvändigt att beakta husets alla olika faser, produktion, drift, underhåll och rivning liksom energitillförselssystemens effektivitet.

Produktionen av nya byggnader är låg jämfört med den befintliga bebyggelsen. Energieffektivisering av den befintliga bebyggelsen är därför viktigt för att reducera byggsektorns primärenergianvändning. Men olika energieffektiviseringsåtgärder på byggnadsnivå påverkar olika energitillförselsystem på olika sätt. Därför har vi studerat hur energieffektiviserande åtgärder interagerar med energitillförselsystem. Resultaten visar att en signifikant större primärenergibesparing uppnås när åtgärder genomförs i en eluppvärmd byggnad än om samma åtgärder genomförs i en fjärrvärmd byggnad. I fjärrvärmda byggnader varierar den primärenergibesparing som en energiåtgärd innebär kraftigt beroende på fjärrvärmeproduktionens utformning och typ av energieffektiviseringsåtgärd. Ventilationssystem med värmeåtervinning kan ge kraftigt minskade uppvärmningsbehov i själva byggnaden. Men det kan ge låg primärenergibesparing för fjärrvärmda byggnader, särskilt om fjärrvärmeproduktionen i huvudsak baseras på kraftvärmeproduktion. Vilken primärenergibesparing som erhålls beror av uppvärmningssystemet, av hur mycket elektricitet som används i ventilationssystemet och byggnadens lufttäthet förutom av ventilationssystemets värmeåtervinningseffektivitet.

Krossad betong som utsätts för luft binder en signifikant mängd koldioxid över tiden. Men i ett livscykelerspektiv ger ändå trästommehuset markant lägre koldioxidutsläpp än betongstommehuset. Betongkrossning kräver mycket primärenergi vilket kraftigt reducerar fördelarna med att krossa betongen. Utvinning av energi från rivningsvirke och återanvändning av armeringsjärn innebär större primärenergi- och koldioxidfördelar än att återvinna betong.

Sammanfattningsvis ger trähus byggda med passivhusstandard och uppvärmda med fjärrvärme från biobaserade kraftvärmessystem låg primärenergianvändning och mycket låga koldioxidutsläpp i ett livscykelerspektiv med biomassa från ett hållbart skogsbruk används.

Preface

This research was conducted within the Ecotechnology Research Group at the Mid Sweden University, Sweden. The financial support of the European Union, Jämtland County Council, Sveaskog AB, and the Swedish Energy Agency is gratefully acknowledged.

I would like to express my profound gratitude to my main supervisor, Prof. Leif Gustavsson, and to my assistant supervisor, Dr. Roger Sathre, for their guidance in this research. Prof. Gustavsson and Dr. Sathre have provided indispensable support.

I acknowledge the staff of the Department of Engineering and Sustainable Development and colleague researchers for their cooperation and assistance. I am grateful for all the enjoyable times, especially the “unofficial meetings.”

Special thanks are due my mother, siblings and buddies for their support. I am indebted to Rosemond, and also to Naa Ofeibea. I have been very fortunate to have their support and encouragement during this remarkable journey.

I dedicate this work, with much admiration, to the memory of my father, in appreciation of his dedication to my scholarship.

Ambrose Dodoo

Östersund, September 2011

List of Papers

This doctoral thesis is based on the following papers:

- I. Dadoo, A., Gustavsson, L. and Sathre, R. 2011. Building energy-efficiency standards in a life cycle primary energy perspective. *Energy and Buildings*, 43 (7): 1589-1597.
- II. Dadoo, A., Gustavsson, L. and Sathre, R. 2011. Effect of thermal mass on primary energy balances of a wood and a concrete building. Journal article manuscript.
- III. Dadoo, A., Gustavsson, L. and Sathre, R. 2010. Life cycle primary energy implication of retrofitting a Swedish apartment building to passive house standard. *Resources, Conservation and Recycling*, 54 (12):1152-1160.
- IV. Gustavsson, L., Dadoo, A., Truong, N.L., and Danielski, I. 2011. Primary energy implications of end-use energy efficiency measures in district heated buildings. *Energy and Buildings*, 43 (1): 38-48.
- V. Dadoo, A., Gustavsson, L. and Sathre, R. 2011. Primary energy implications of ventilation heat recovery in residential buildings. *Energy and Buildings*, 43 (7): 1566-1572.
- VI. Dadoo, A., Gustavsson, L. and Sathre, R. 2009. Carbon implications of end-of-life management of building materials. *Resources, Conservation and Recycling* 53 (5): 276-286.

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1 Introduction

1.1 Background

Energy systems are fundamental for human activity and play a critical role in economic development. However, energy systems have environmental implications, including the emissions of greenhouse gases (GHGs) into the atmosphere and ecosystem degradation. Sustainable development requires that the current generation meet its needs without limiting the ability of future generations to meet its needs (WCED, 1987). A transition to a sustainable society will require efficient use of energy and minimization of energy-related environmental impacts.

There is growing recognition that the current trends in energy supply and demand are not consistent with the goals of sustainable development. The global total primary energy use increased yearly by 2% between 1981 and 2008 (IEA, 2010a). The current global energy system is heavily dependent on fossil fuels; oil, coal and fossil gas account for 33%, 27% and 21% of the total primary energy use world-wide, respectively (IEA, 2010b). Figure 1 shows a breakdown of the global primary energy supply by fuel type between 1971 and 2008.

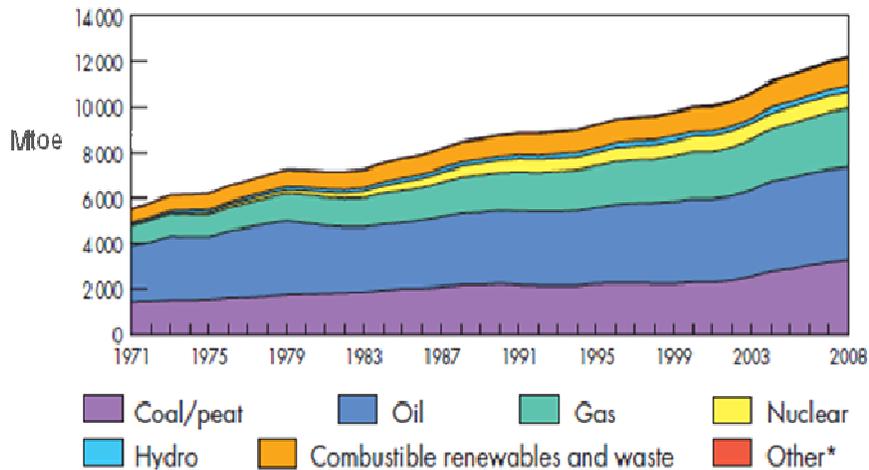


Figure 1. Global primary energy supply by fuel type between 1971 and 2008, in Mtoe. Other* includes geothermal, solar, wind. (Source: IEA, 2010b)

The future development of energy systems is difficult to predict and may be driven by several dynamics, including population, technological development and socio-economic factors. However, scenario studies (e.g., IEA, 2011a; IPCC, 2000) suggest growing energy demand in the coming decades. The International Energy Agency (IEA) has examined different global energy scenarios in detail and has indicated that global primary energy use is likely to increase by 36% between 2008 and 2035 (IEA, 2010a). These findings may heighten current concerns about energy security. Furthermore, fossil fuels are very likely to account for a significant share of future primary energy use, unless effective measures are implemented to promote sustainable energy systems in the global community (IEA, 2011a).

Fossil fuel combustion is a major anthropogenic source of carbon dioxide (CO₂) emissions (IPCC, 2007a). Currently, energy supply and use account for about 84% of all anthropogenic CO₂ emission and can be linked to 65% of all anthropogenic GHG emission (IEA, 2010c). Global CO₂ emission linked to fuel combustion increased by 5%, to 30.6 Gt, between 2008 and 2010 (IEA, 2011b). In terms of fuel share (Figure 2), oil, coal and fossil gas accounted for 37%, 43%, and 20%, respectively, of total CO₂ emissions from fuel combustion in 2008 (IEA, 2010d).

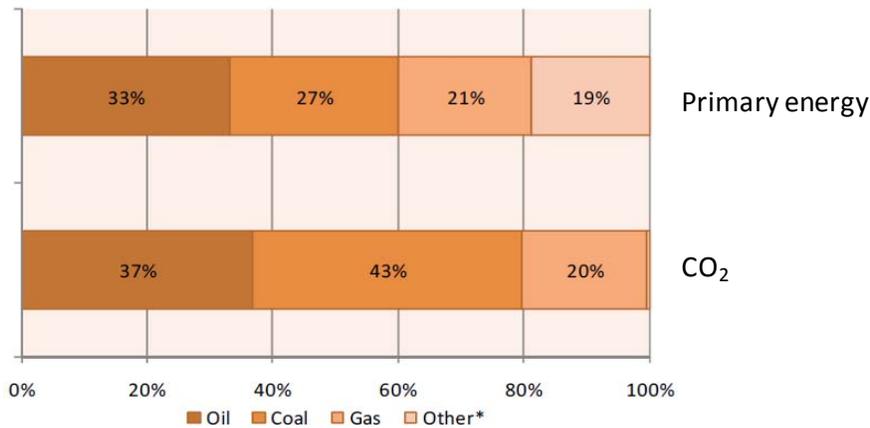


Figure 2. Percent share of world CO₂ emission from fuels. Other* includes combustible renewable/ waste, nuclear, hydro, geothermal, solar, wind, and tide. (Source: IEA, 2010d)

The Intergovernmental Panel on Climate Change (IPCC) documents the science, impacts and mitigation options of climate change. In a series of synthesis reports (e.g. IPCC, 1996; 2001; 2007a) the IPCC reported strong evidence that the increasing concentration of GHG in the atmosphere is altering the global climate system, and would cause significant negative impacts to ecological, socio-economic and technological systems, unless timely and effective mitigation strategies are implemented. The IPCC's conclusion is based on rigorous assessment of climate data and consensus within the scientific literature. It also highlights the complexity involved in studies of the global climate system. There has been much discussion in the scientific literature about the dangerous level of anthropogenic interference with the global climate system; various reports (e.g., European Commission, 2007; IPCC, 2007b; O'Neill and Oppenheimer, 2002) have suggested a global mean temperature increase that is likely to be associated with significant negative impacts, including heat waves, drought, flooding, a rise in sea level, coastal erosion and the failure of food production systems. The European Union (EU) suggests that limiting temperature increases to 2° C, relative to pre-industrial levels, would fulfill the objective of avoiding dangerous climate change (European Commission, 2007; European Environmental Agency, 2008). The emissions pathway required to avoid this climate change is difficult to predict, because of the complexity of the global carbon system. However, the EU Climate Change Expert Group (2008) suggests that stabilization of atmospheric GHG concentration levels below 450 ppm CO₂-eq would be necessary to have a 50% chance of avoiding an increase in temperature above 2° C. The Stern review on the economics of climate change emphasized the need for strong and timely action to reduce GHG emission and stabilize atmospheric GHG concentration (Stern, 2006). However, the review suggested that stabilization at 450 ppm CO₂-eq may be difficult, considering current CO₂ emission and concentration trends in the atmosphere, unless strong and immediate action is pursued. According to Stern, stabilization of atmospheric GHG concentrations at 550 ppm CO₂-eq is

feasible and would cost the global community about 1% of its GDP. Stern's review has been the subject of much criticism for several reasons, including the discount rate used to evaluate the cost of mitigating climate change and its conclusions (Mendelsohn, 2006; Tol and Yohe, 2006; Nordhaus, 2007). The IPCC has presented a range of GHG emission scenarios and their likely climatic implications (IPCC, 2000; 2007c). Significant progress toward climate change mitigation can be achieved by strategies that reduce CO₂ emission, such as reducing fossil fuel use, and by strategies that increase carbon sinks, such as sustainable forestry practices.

Various attempts and initiatives have been made at the global and regional levels to address climate change over the years. These include the United Nations Framework Convention on Climate Change treaty (United Nations, 1992) and the Kyoto protocol (UNFCCC, 1998). The EU (then EU-15) has ratified the Kyoto protocol and is obliged to reduce its collective GHG emissions by 8% below 1990 levels between 2008 and 2012 (UNFCCC, 1998). The EU has further set a target of a GHG emission reduction of 20% by 2020, relative to 1990 levels (European Commission, 2010). The Swedish society must reduce GHG emissions by 4% as part of the EU ratification of the Kyoto protocol. Its long-term goal is to phase out fossil fuels for heating purposes by 2020 and to reduce GHG emission by 50% by 2050 (Swedish Government, 2006). Governments around the world are seeking effective strategies to reduce GHG emission. The reduction of GHG emissions will require concerted effort from all sectors of the economy.

1.2 Buildings and climate change

The role of the building sector in the development of a sustainable built environment is substantial. Globally, building energy use accounts for 30-40% of total primary energy use, and the building sector is expected to play a major role in reducing CO₂ emission to mitigate climate change (UNEP, 2007; IPCC, 2007c). Energy is used during the life cycle of buildings for material production, transport,

construction, operation, maintenance and demolition. CO₂ is emitted by fossil fuel combustion, land-use practices and industrial process reactions. Building energy use accounts for about a third of global total CO₂ emission (UNEP, 2007; Price et al., 2006). About 50% of the total global final energy use in the building sector is used in space conditioning and tap water heating (IEA, 2011a). There is great potential to improve the primary energy efficiency of buildings and thereby reduce CO₂ emissions (IPCC, 2007c; IEA, 2008). Reducing the energy use of buildings also present the lowest cost for GHG emission mitigation (IEA, 2008). Several strategies can be used to realize this potential, including reduced heating demand, increased efficiency in energy supply chains, greater use of renewables and less carbon-intensive materials and efficient post-use of building materials.

Generally, buildings have long life spans and should be designed and constructed to have low primary energy use and carbon emission over their entire life cycle. Energy efficiency measures may be cost effective and may be more feasible during the construction stage of buildings. Effective building standards may specify minimum energy use and CO₂ emission limits for buildings and can be important instruments in the development of an energy-efficient built environment. Currently, building energy standards have an orientation toward the construction of buildings with low operation phase impacts. Building to the passive house standard is increasingly suggested to be a beneficial solution from both energy and economic perspectives (Passive House Institute, 2007). The construction of new low-energy buildings is important in the long term. However, this may have little effect on the building sector's overall energy use in the short term, because the rate of addition of new buildings to the building stock is low (Bell, 2004; Itard et al., 2008). Measures to improve the energy efficiency of existing buildings offer a significant opportunity to reduce primary energy use and CO₂ emissions in the short term (Harvey, 2009). Therefore, to address primary energy use and CO₂ emissions in the building sector, both existing and new buildings should be targeted. The IEA has identified measures

that can contribute to lower CO₂ emissions in new and existing buildings. These measures include building energy standards and certification schemes, low-energy buildings including passive house standard buildings and energy efficiency retrofit measures for existing buildings (IEA, 2008).

Improved energy efficiency in buildings is a priority in Sweden and the rest of the EU (European Commission, 2005). In the EU, 40% of total primary energy is used in the building sector, and a large share of the final energy is used for space and tap water heating in buildings. About 60% of the total final energy in the Swedish residential and service sector is used for space and tap water heating (Swedish Energy Agency, 2010). The EU Directive (2002/91/EC) on Energy Performance of Buildings requires Member States to implement improved energy efficiency legislation for buildings. The directive seeks to improve the carbon performance of building stock through the use of sustainable energy strategies and requires member states to follow a framework methodology to regulate the energy efficiency and carbon performance of buildings. Efforts to achieve climate and energy policy goals in many parts of the EU include instruments such as fees and taxes on landfilling that promote efficient post-use of building materials (European Commission, 2001). The Swedish government, through the Bill on Energy Efficiency and Smart Construction, aims to reduce total energy use per heated building area by 20% by 2020 and 50% by 2050, using 1995 as the reference (Swedish Government Bill 2005/06:145). Swedish building energy regulations have been revised three times between 2006 and 2009 to improve end-use energy efficiency of buildings. The Swedish building construction sector aims to divert about half of its post-use building materials from landfill (Swedish Government, 2003). These policy actions are aimed at promoting effective environmental protection for sustainable built environment and thereby contribute to mitigate climate change.

Decisions on strategies to reduce primary energy use and CO₂ emission in the building sector may be based on a number of factors. However, detailed information

on effective means to improve energetic and climatic impacts of buildings is necessary to inform policymakers and facilitate effective decision making. This thesis endeavors to increase understanding of strategies to improve primary energy efficiency and minimize climatic impacts of new and existing residential buildings.

1.3 Literature review

The oil crises of the late 1970s raised concerns about energy use in buildings and motivated research to reduce energy for space heating, particularly measures to reduce transmission loss and to optimize solar gain (Verbeek and Hens, 2007). Since then, research has further considered strategies to improve operational energy efficiency and life cycle environmental performance of buildings.

In recent decades, various studies have been conducted to analyze energy and carbon implications of building and construction systems. The studies differ in scope, methodology and building life cycle activities analyzed. Most research has concentrated on the operation phase of buildings, mainly on issues related to space conditioning and ventilation. Balaras et al. (2005) conducted a comprehensive survey of buildings across five European countries and assessed the influence of thermal insulation and heating systems on the energy use and environmental impacts of the buildings. They found a high degree of variability in heat use of buildings within the same climate. Jokisalo et al. (2003) simulated the performance of ventilation heat recovery (VHR) systems in a typical Finnish apartment building using centralized or decentralized ventilation units. They found that energy performance of decentralized ventilation units is not significantly improved when VHR is installed. Sherman and Walker (2007) analyzed the energy impact of different ventilation norms in typical US buildings. They found that VHR generally increased net energy use, as the energy used by the blower offset the energy savings from space conditioning. Karlsson and Moshfegh (2007) conducted a study of the energy use and CO₂ emission of low energy buildings in Sweden. They showed that

assumptions about energy supply and electricity mix can have a significant impact on the calculated energy use and CO₂ emission of buildings.

Some studies (e.g., Hamza and Greenwood, 2009; Asdrubali et al., 2008; Beerepoot and Beerepoot, 2007; Tommerup et al, 2007; Bell and Lowe, 2000) have analyzed and discussed the energy impacts of building standards, but most focus on energy use during the operation phase of buildings. Casals (2006) analyzed the primary energy use of a building constructed to the new Spanish building code and showed the importance of including production energy in building energy assessment. Several studies (e.g., Janson, 2008; IEA, 2006; Dascalaki and Santamouris, 2002; Hestnes and Kofoed, 2002; Balaras et al., 2000) have also analyzed the impact of energy efficiency retrofitting measures on final energy use during the operation phase.

Some studies have analyzed the interactions between end-use energy efficiency measures and heat supply systems. Gustavsson (1994a,b) analyzed the potential space and tap water heat savings in district heated buildings and explored the effect of this on district heating system design and cost. He found cost and energy saving potential to largely depend on the specific building and district heating system. Gustavsson and Joelsson (2010) analyzed the primary energy savings in district heated buildings, including fuel inputs at each stage of the energy chain based on annual average final energy demand and annual average district heat production. Gustavsson and Joelsson (2010) also showed that it is essential to consider primary energy use when analyzing building operation energy, instead of focusing on final energy. They found that the primary energy use to heat a district heated conventional building was lower than for an electrically heated passive house, even though the passive house had substantially lower final energy use.

Various comparative studies have been conducted to assess the effect of the thermal mass of building frame material on the final energy for space heating and cooling buildings. Norén et al. (1999) analyzed the effect of thermal mass on the final

energy for space heating in Swedish buildings and concluded that the benefit of thermal mass is less where buildings located in a Nordic climate have ample insulation with plasterboard cladding. Zhu et al. (2009) compared identical buildings constructed with wood and concrete frames in a hot US climate where thermal mass is considered favorable. They found that a wood-frame building used more space heating energy but less space cooling energy than the concrete-frame building. Kalema et al. (2008) used a quasi-steady approach to estimate the heat capacity and time constant associated with the building mass and analyzed the effect of thermal mass on the space conditioning energy use for a Nordic building. They concluded that the amount of final energy savings due to the benefit of thermal mass was significant. However, Josikalo and Kurnitski (2005) used a dynamic analysis approach and concluded that the amount of final energy savings of thermal mass in a Finnish apartment building was not significant. The interaction between building mass configuration and thermal condition is complex, and a detailed dynamic analysis is needed to accurately determine the impact of thermal mass.

Some life cycle studies have analyzed the energetic and climatic implications of buildings, including several aspects of the life cycle activities and flows. For example, Jönsson et al. (1998) conducted a life cycle assessment of concrete and steel building frames, including energy use and CO₂ emissions. Scheuer et al. (2003) conducted a comprehensive life cycle assessment of the primary energy and environmental impacts of a new building, including production, operation and end-of-life stages. Ochoa et al. (2002) assessed the total energy use and environmental impacts of a building using an economic input/output life cycle assessment and considering system-wide direct and indirect impacts. Keoleian et al. (2001) analyzed the life cycle primary energy use and greenhouse gas emissions of two alternative energy efficiency levels for a building. Junnila et al. (2006) assessed the life cycle energy use and environmental emissions of one European and one US building, taking into account material production, construction, operation, maintenance and

building demolition. Gustavsson et al. (2010) calculated the primary energy use and CO₂ emissions of a new eight-story wood-framed apartment building, considering the production, operation and end-of-life stages, as well as heat supply from different end-use systems and energy supply technologies.

Comparative life cycle studies of building systems show that the choice of building frame material affects primary energy use and greenhouse gas emissions of buildings. Cole and Kernan (1996) analyzed the total life cycle energy use of a building constructed with wood, steel, or concrete structural materials. They found that the concrete and steel buildings used more energy than the wood building. Cole (1999) investigated the energy use and greenhouse gas emissions due to on-site construction activities of buildings made with wood, steel or concrete structural materials. He found that energy use and greenhouse gas emissions were lowest for constructing the steel building, slightly higher for the wood building, and significantly higher for the concrete building. Adalberth (2000) quantified the primary energy use of functionally equivalent buildings with wood and concrete frames. She found that the operation energy was slightly lower for the concrete-frame building than for the wood-frame building, but the overall life cycle energy balance, including the production, operation and end-of-life stages, was lower for the wood-frame building than for the concrete-frame building. Gustavsson et al. (2006) calculated the primary energy and CO₂ balances of buildings constructed with wood or concrete frames, taking into account various life cycle parameters that included energy available from biomass residues from logging, wood processing, construction, and demolition. They found that the wood building used less production energy and emitted significantly less CO₂ than the concrete building. Gustavsson and Sathre (2006) explored the variability in primary energy and CO₂ balances of wood and concrete buildings. They found that recovery of biomass residues has the single greatest effect on the primary energy and carbon balances of the buildings, followed by land use issues and concrete production parameters.

Some studies show the increasing importance of the production phase primary energy. Sartori and Hestnes (2007) conducted a review of energy use in the life cycle of buildings. They found that the primary energy for building production becomes relatively more important as measures are applied to reduce the operation energy use. Thormark (2002) found the production energy to represent 45% of total life cycle primary energy use in a low energy building.

1.4 Knowledge gaps

Previous comparative life cycle studies have made significant contributions. Nevertheless, most existing life cycle studies on energy and carbon implications of buildings are based on final energy use or do not include the entire life cycle and energy chains. While thermal mass and carbonation in the post-use stage of concrete have been investigated in a few studies, there were no comprehensive research linking these to comparative life cycle primary energy and carbon analyses of concrete and wood-frame buildings, in 2007, when this research began. Current building energy standards are oriented toward buildings with low space heating energy. However, there is a lack of research on the complete life cycle implication of this approach in general, and on current energy efficiency standards. In general, little work has been done on how different building systems and life cycle activities interact with various energy supply systems.

1.5 Study objectives

This thesis investigates the primary energy use and carbon emissions of residential buildings, including different construction and energy supply systems. A goal of this thesis is to increase understanding of strategies to reduce primary energy use and minimize carbon emissions over the life cycle of buildings. The specific objectives of this research are to

- compare the life cycle primary energy balance of concrete- and wood-frame buildings and explore the effect of thermal mass on their life cycle primary energy balance;
- analyze the life cycle primary energy implications of different building energy-efficiency standards and explore the effectiveness of current standards;
- explore the primary energy implications of different building energy efficiency retrofit measures, focusing on their interaction with different heat supply systems and their system-wide impacts;
- compare the life cycle carbon balance of concrete- and wood-frame buildings and explore the effect of carbonation during the post-use phase of concrete on the life cycle carbon balance of the buildings.

1.6 Organization of thesis

This thesis is based on six original papers and is organized in two main parts. The first part provides a broad background of the thesis, and synthesizes and integrates the papers presented in the second part. The second part contains the six original papers, which provide detailed accounts of the analyses and findings. Papers I and II analyze the life cycle primary energy of buildings including the life cycle activities, energy supply systems and the entire natural resources chain. The analysis includes a comparison of wood and concrete buildings, the effect of thermal mass is accounted for, and the effectiveness of different buildings standards to reduce primary energy use in buildings is explored. Paper III explores the implications of building retrofitting from a life cycle primary energy perspective. Papers IV and V present detailed analyses of the impacts of different building energy efficiency retrofit measures on the operation primary energy use of buildings. The emphasis is on the complex interaction between the measures and district heating systems and the implications of VHR when the heat supply is based on different end-use heating systems. Paper VI compares the life cycle carbon balance of

concrete- and wood-frame buildings and the implications of different post-use management options for demolished building materials. The paper includes detailed analysis of the carbon dynamics of concrete-based materials, including calcination and the effect of carbonation on the service life and post-use phase of concrete material.

2 Methodological issues and approaches

2.1 Life cycle and systems perspectives

A comprehensive analysis of the impacts caused by a building requires a system-wide life cycle perspective. The life cycle of a building includes production, retrofitting, operation and end-of-life phases. Life cycle assessment (LCA) is one of the methods for assessing the environmental implications of a product during its life cycle. LCA identifies and quantifies the environmental impacts associated with the flow of energy and materials in a system. The ISO 14040 series of standards provides a general framework for LCA and suggests that an LCA study should include all phases and impacts throughout the life cycle of a product (ISO, 1997; 1998; 2000a; 2000b). However, the ISO standards do not provide details of specific flows to be quantified in a LCA study. LCA methodology comprises four stages: definition of the goal, inventory assessment, impact assessment, and interpretation of the results. Impacts often considered in LCA include acidification, global warming, eutrophication, ozone depletion, human toxicity and abiotic resource depletion. There is lack of methodological consistency in the assessment of some of these impacts, e.g., human toxicity (Scheuer et al., 2003).

Different tools developed to facilitate LCA have been applied in the building and construction sector, for example, in the analysis of the environmental impact of building materials. There are additional challenges involved in using these tools to analyze buildings. Buildings are complex systems comprising multiple components; their life cycle activities are interlinked and interact with energy supply activities. Furthermore, buildings have a relatively long life span, and their design and construction conditions are typically heterogeneous, making each building unique (IEA, 2001). Thus, the traditional LCA methodology is inadequate for a complete analysis and investigation of activities that must be optimized for the whole building (Verbeeck and Hens, 2007). Lave et al. (1995) asserted that the detailed focus of LCA may lead to neglect of potentially important flows.

While LCA emphasizes consideration of all life cycle activities, it tends to ignore the interactions and synergies between these activities. A systems perspective is essential in order to account for the interaction and complexities between building life cycle and energy supply activities. A system comprises a set of interrelated component parts working as a whole toward a goal. Systems analysis approaches emphasize the importance of considering the interactions and synergies between systems, their component parts and their environment, because their interactions produce unique outcomes (Checkland, 1999). Reductionist analytical approaches, in contrast to the systems approach, separate the component parts of a system and consider them as isolated entities. This approach may facilitate an in-depth analysis of various details but may be inadequate for a thorough understanding of buildings as energy systems.

Systems analysis methodology with a life cycle perspective is employed in Papers I, II, III and VI. This methodology is similar to the life cycle inventory assessment of LCA and accounts for the synergies and interactions between the life-cycle and energy supply activities. Papers IV and V analyze the interactions between energy efficiency measures and heat supply systems and their effect on operation primary energy using a systems analysis approach.

2.2 Energy systems analysis

Energy systems encompass the various activities and processes along energy chains, from energy supply to energy end-use. It begins from extraction of energy carriers to refining and conversion, transport, conversion to heat and electricity, and distribution to the end-user. This is then used to provide various energy services, including heating or lighting in buildings. The concept of primary energy is used to denote the total energy needed in order to generate the final energy service, including inputs and losses along the entire supply chain. Primary energy use, in contrast to final energy use, determines the natural resource use and the

environmental impact of supplying the energy services (Fay et al., 2000). All the processes along the energy chain can be performed with variable energy efficiency and with varying emissions. All the energy inputs for these processes need to be included for a full description of a particular energy system.

Bottom-up and top-down approaches are two complementary methods to model energy systems. A bottom-up approach begins with detailed disaggregated information for a system and then generates aggregate system behavior to characterize the relationship between the individual components of the system (Sathre, 2007). This approach provides specific information about the individual processes and systems studied, allowing for detailed comparison of the alternatives. The top-down approach begins with the aggregate information for a system and then proceeds to disaggregate this to characterize the components (Sathre, 2007). Some top-down studies assert that a significant share of energy use in the production phase of a building is indirect and is not recognized when using a bottom-up approach, resulting in truncation energy outside of the system boundaries (Lenzen and Treloar, 2002; Nässén et al., 2007). In this thesis, several alternative systems are compared and therefore bottom-up models of mass and energy flows are used to allow detailed comparison of the alternatives. The significance of truncation production primary energy arising from using the bottom-up instead of top-down approach is explored in Paper II.

2.2.1 Electricity supply

There are different electricity production systems and these are characterized by significant variation in their primary energy use and CO₂ emission. Two different approaches to accounting for primary energy use and CO₂ emission from electricity supply and use are the average and marginal methods. There is much discussion in literature about which method should be employed in an analysis (e.g., Sjödin and Grönqvist, 2004; Ekvall and Weidema, 2004). In principle, the method employed

should reflect the purpose and relevance of a study. In this thesis, the marginal accounting method is used because it captures the consequences of changes due to variation in system parameters. The average accounting method is not suitable because changes do not readily reflect at the average level (Hawkes, 2010). In addition, this approach does not reflect the technologies and inputs affected by a variation in a system.

The Swedish electricity production system is dominated by hydro and nuclear power and is connected to the NordPool, a network where Nordic countries trade electricity. Changes in electricity production and use in Sweden affect the NordPool. Sweden imported a net of 2.0 and 4.7 TWh of electricity in 2008 and 2009, respectively (Swedish Energy Agency, 2010). Coal-fired condensing plants are the dominant marginal electricity production plants in the Nordic system today (Swedish Energy Agency, 2002; Gustavsson et al., 2006). However, this may change in the future as a result of several factors, including investments, GHG reduction policies, and strategic and security reasons (Gustavsson et al., 2006). In this thesis, end-use electricity for material production is assumed to be produced from a coal-fired marginal plant with 40% conversion efficiency and 2% distribution loss for high-voltage electricity.

2.2.2 Heat supply

The heat demand of a building can be provided by various types of end-use heating systems and energy supply technologies, including electricity-based systems. In Sweden, district heating is mostly used in multi-story apartment buildings; 82% of such buildings were district heated in 2008 (Swedish Energy Agency, 2010). Electric heating and heat pumps are more common in detached houses. In 2008, electric heating and heat pumps were used in 31 and 20% of such houses, respectively (Swedish Energy Agency, 2010; Swedish Energy Agency, 2009). In this thesis, end-use heating with district heating (Papers I-V), bedrock heat pumps

(Papers II, III, V) and electric resistance heating (Paper I-III, V), in combination with different energy supply technologies, are studied. For electric resistance heating and heat pumps, 95% of the electricity was assumed to be supplied from a stand-alone base-load power plant and the remaining from a light-oil gas turbine plant. Scenarios where the stand-alone base-load plant is based on biomass steam turbine (BST) or biomass integrated gasification combined cycle (BIGCC) technologies were analyzed. The district heating system is assumed to be based on combined heat and power (CHP) plants and oil boilers. The dimensioning of a CHP plant in district heating systems may affect primary energy use (Joelsson, 2008). To explore this dimensioning, scenarios where the CHP plant accounted for different shares of the average district heat production are analyzed. In Papers I and II, scenarios where the CHP account for 85% of the district heat production and light-oil boilers account for the remainder were studied. In Paper III, the CHP plant is assumed to account for 90% or 50% of the heat production, with light-oil boilers accounting for the remainder. In Paper IV, the combination of CHP plants and heat-only boilers that provide minimum cost district heat production under different taxation scenarios is explored, using a reference local district heat load. CHP production accounts for 68-83% of the total heat production for the minimum cost district heat production systems and 92% for the reference district heat production system (Paper IV). The interactions of several combinations of CHP and heat-only boiler productions and VHR systems, and their effect on operation primary energy use, are studied in Paper V.

2.2.3 Allocation in CHP production

District heating systems with CHP production may present allocation issues, as electricity is co-produced with heat. Different methods have been suggested to address allocation in co-product systems (Ekvall and Finnveden, 2001). A method that avoids allocation is preferred because allocation can be challenging and

subjective (ISO, 1998). In this thesis, the subtraction method of system expansion was used to avoid allocation. With this method, the cogenerated electricity is assumed to replace electricity that would instead have been produced in a stand-alone plant using the same fuel and technology as the CHP plant (Gustavsson and Karlsson, 2006). The primary energy that would have been used to produce the replaced electricity in the stand-alone plant is subtracted from the CHP plant to obtain the primary energy for the heat.

2.3 Parameters

Buildings produce different environmental impacts during their life cycle and a considerable share of these are closely connected to energy use (Björklund and Tillman, 1997). Cumulative primary energy use largely determines the environmental impacts of material production and energy supply activities (Huijbregts et al., 2010). Buildings carbon emissions may be connected to energy activities and non-energy activities. There is a close link between CO₂ emissions and the current changes in the global climate system (IPCC, 2007a). Here, two parameters, primary energy use (Papers I-V) and carbon emission (Paper VI), are used in a comprehensive evaluation of the climatic impacts of buildings.

2.4 Functional unit

Functional unit provides a reference to which the inputs and outputs of a system may be related. Different functional units may be used in the energy and carbon analyses of buildings (Gustavsson and Sathre, 2011). These units include 1 m² of a building's gross or usable floor area, total gross or usable floor area and the complete building. In this thesis the functional unit is defined at the level of an entire building. The results also include per usable floor area to readily facilitate comparison.

2.5 System boundaries

System boundaries show the activities included in an analysis. In Papers I-III, the system boundaries are defined to include the production, (and also retrofitting in Paper III), operation and end-of-life phases, as well as their interaction with energy supply activities. A schematic diagram of this is shown in Figure 3. In Papers IV and V the system boundaries were defined to cover the building operation phase and the entire energy chain, including their interactions.

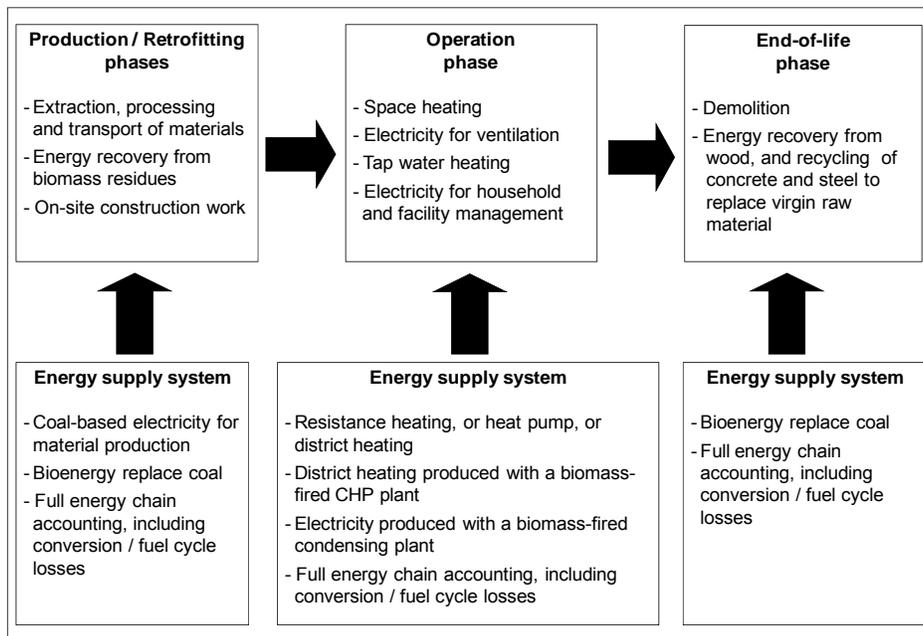


Figure 3. Building life cycle and energy supply activities modeled. (Paper III)

Paper VI analyzes the life cycle carbon balance of a wood-frame and a concrete-frame building. The system boundary was defined to encompass the processes and activities outlined in Table 1. The emission in the operation phase was not included in the analysis because this is expected not to differ significantly between the buildings (Adalberth, 2000). In comparative life cycle studies activities that are equivalent may be omitted if it is sufficiently apparent that the activities do not

influence the results of the comparison (Kotaji et al., 2003). Nevertheless, the results of including emission in the operation phase of the buildings are addressed in Chapter 6. The energy use for operating conventional buildings clearly dominates over the energy used for the production of building materials, so lowering the operating energy is important for reducing life cycle carbon emission.

Table 1. Processes and activities included in the analysis of the life cycle carbon balance.

Description	Process considered	Carbon implication analyzed
Building construction (<i>Production phase</i>)	Material extraction, processing and transportation; Building construction; Forest harvesting.	Fossil fuel use for material production; Calcination of limestone; Wood residue replaces fossil fuel; Carbon stock changes in building and forest.
Service-life (<i>Operation phase</i>)	Reaction of atmospheric CO ₂ with cement products in building frame; Forest re-growth.	Carbonation of concrete and cement mortar; Carbon uptake in re-growing forest.
End-of-life	Demolition of building; Recovery and crushing of concrete; Recycling of steel; Energy recovery of wood material; Reaction of atmospheric CO ₂ with demolished concrete and cement mortar.	Fossil fuel for end-of-life activities - material demolishing, transportation, recovery; Benefit from recycling of steel Wood residue replaces fossil fuel; Carbonation of demolished and crushed concrete

2.5.1 Studied building systems

The case-study building analyzed is the Wälludden building constructed in Växjö, Sweden. This building is a 4-story residential wood-frame building with 16 apartments and a total heated floor area of 1190 m². In Papers II and VI, the wood-frame building is compared with a functionally equivalent and identical building with a concrete frame. Detailed information, including drawings and thermal properties of the versions of the building with a concrete frame and a wood frame was reported by Persson (1998). A summary of the construction characteristics of the

components of the wood-frame version of the building is presented in Table 2. The concrete-frame version of the building has similar construction characteristics. However, for the concrete-frame version, 23 cm reinforced concrete slab replaces the light timber joists, floors, and the load-bearing timber studs, and 15 cm reinforced concrete wall replaces the stucco and plaster-compatible mineral wool panels of the external wall in the wood-frame building. Mineral wool insulation (20.5 cm) is fixed between the reinforced concrete walls and the outer façade of cement render.

Table 2. Construction characteristics of the components of the wood-frame building.

Component	Description
Ground floor/ Foundations:	1.5 cm oak board laid on 16 cm concrete slab foundation, 7 cm expanded polystyrene, and 15 cm crushed stone.
Floor Joist:	Light timber joists consisting of several layers, including mineral insulation, to a total thickness of 42 cm.
External Walls:	Three layers, including 4.5 cm plaster-compatible mineral wool panels, 4.5 x 12 cm lumber studs @ 600 c/c with mineral wool between the studs, and a wiring and plumbing installation layer consisting of 4.5 x 7 cm lumber studs @ 300 c/c with mineral wool between the studs.
Façade:	Two-thirds of the facade is plastered with stucco while the facades of the stairwells and the window surrounds consist of wood paneling.
External doors:	Wood framing with double glazed window panels.
Windows:	Double glazed.
Roof:	Two layers of asphalt-impregnated felt, wood panels, 40 cm mineral wool between wooden roof trusses at 120 cm c/c, polythene foils and gypsum boards.

Calculations were made for the mass of materials required to construct the concrete and wood versions of the buildings (Adalberth, 2000). Descriptions of the buildings are presented in the appended papers. The case-study building was constructed during the regime of the 1994 Swedish building code. The material mass

contained in the different versions of the building is shown in Table 3, and Table 4 shows the thermal properties of the buildings. The building thermal properties are also modeled to energy-efficiency requirements of current building standards in Papers I, II and VI.

Table 3. Quantities of materials (tons of air-dry material) contained in the reference wood-frame and concrete-frame buildings.

Material	Concrete-framed version	Wood-framed version
Concrete	1,352	223
Blocks	4	4
Mortar	23	24
Plasterboard	25	89
Lumber	33	59
Particleboard	17	18
Plywood	20	21
Steel	25	16
Copper/Zinc	0.6	0.6
Insulation	10	21
Crushed stone	315	315
Glass	4	4
Paper	2	2
Plastic	2	2
Putty/Fillers	4	4
Paint	1	1
Ceramic tiles	1	1
Porcelain	0.6	0.6
Appliances	3	3

Table 4. Thermal properties for concrete- and wood-frame buildings.

Building	U-value (W/m²K)					Air leakage at 50 Pa (l/s m²)	Mechanical ventilation
	Ground floor	External walls	Windows	Doors	Roof		
Wood frame	0.23	0.20	1.90	1.19	0.13	0.8	Exhaust air
Concrete frame	0.23	0.20	1.90	1.19	0.13	0.8	Exhaust air

2.6 Primary energy calculations

2.6.1 Production/ retrofitting phase

The production/retrofitting phase primary energy balance is calculated as the primary energy expended for material production and on-site construction minus the net energy of by-products that can be recovered and made available for external use during the material life cycle (Gustavsson et al., 2006).

Material production primary energy

The material production primary energy balance includes the primary energy expended to extract, process and transport the materials; this quantity is calculated as follows:

$$E_{production} = \sum_i \left\{ \sum_k [F_{i,k} \times (1 + \alpha_k)] + \frac{L_i}{\eta} + B_i \right\}$$

where $E_{production}$ = total primary energy use for material production (kWh);

i = individual types of materials in the building;

F = end-use fossil fuel energy used to extract, process and transport the materials (kWh);

k = fossil fuels: coal, oil, and natural gas;

α = fuel cycle energy requirement of the fossil fuel;

L = end-use electricity to extract, process, and transport the materials (kWh_e);

η = conversion efficiency for electricity production;

B = heat content (lower heating value) of the biofuels used in material processing (kWh).

The end-use fossil fuel and electricity used to extract, process and transport the materials, as well as the heat content of the biofuels used in material processing, was calculated for each material using data primarily from a Swedish study by Björklund and Tillman (1997). These data are supplemented by data from closely related

studies: Björklund et al. (1996), Fossdal (1995) and Worrell et al. (1994). The specific final energy for production of selected materials is listed in Table 5.

Table 5. Specific final energy ($\text{kWh}_{\text{end use}}/\text{kg}$) to extract, process, and transport selected materials.

Material	Coal	Oil	Fossil Gas	Biofuel	Electricity
Concrete	0.09	0.10	-	-	0.02
Plasterboard	-	0.79	-	-	0.16
Lumber	-	0.15	-	0.70	0.14
Particleboard	-	0.39	-	1.40	0.42
Steel (ore-based)	3.92	0.86	1.34	-	0.91
Steel (scrap-based)	0.06	0.08	0.44	-	0.57
Insulation	2.00	0.36	0.02	-	0.39

The fuel cycle energy requirements of the fossil fuels are taken to be 10% for coal, 5% for oil and 5% for natural gas (Gustavsson and Sathre, 2006). The electricity to produce the materials was assumed to be produced from a coal-fired plant, as described in Section 2.2.1.

On-site construction

The on-site construction primary energy includes the primary energy use for on-site fabrication and assembly of the materials into building components and the complete building. Adalberth (2000) calculated the primary energy to assembly the case-study wood and concrete buildings to be 50 and 100 kWh/m^2 , respectively. These numbers are used in all the calculations, and are adjusted for other versions of the buildings with greater material mass (Papers I - III).

Bioenergy recovery

Biomass residues can be recovered from the wood product chain from forest tinning and harvesting, wood processing and construction and demolition waste. This is often used as an energy source in sawmills and wood kiln and as fuels in heat and power plants in Finland and Sweden. In this thesis, the primary energy available

from recovered biomass residues from forest harvesting, wood processing and construction activities is calculated as follows:

$$E_{byproducts} = \sum_j \{M_j \times H_j \times [1 - \beta_j \times (1 + \alpha_{diesel})]\}$$

where $E_{byproducts}$ = net energy from recovered biomass residues (kWh);

j = different types of residues: forest, processing and construction;

M = mass of the recovered residue (oven dry tons);

H = lower heating value of the biomass residue (kWh /oven dry ton);

β = diesel fuel energy required to recover and transport the residue, expressed as a proportion of the heat energy contained in the residue;

α = fuel cycle energy requirement of the diesel fuel.

The mass of the residue available from the wood product chain was calculated using biomass expansion factors from Lehtonen et al. (2004). Recovery of 75% of available forest residues and 100% of processing and construction residues was assumed (Gustavsson and Sathre, 2006). The lower heating value for the residues and the diesel fuel used to recover the forest biomass residues are calculated using data from Gustavsson and Sathre (2006).

2.6.2 Operation phase

The operation phase activities analyzed in this thesis (Papers I-V) are space heating, tap water heating, electricity for ventilation fans and pump, and electricity for household and facility management. The energy simulation software ENORM (EQUA Simulation AB, 2004) was used to calculate the space heating and ventilation final energy use in Papers I, III and V. The software calculates the energy and power demand for a 12-month period, on a 24-hour basis. ENORM was also used to calculate the final energy for tap water heating and electricity for household and facility management in Paper V. In Papers I and II, the final energy for these

activities was calculated with the following standard equations from the Swedish National Board of Housing, Building and Planning (Boverket, 2003):

$$E_{\text{water heating}} = 1800 \times \text{number of apartments} + 18 \times \text{heated area [m}^2\text{]}$$

$$E_{\text{household electricity}} = 2200 \times \text{number of apartments} + 22 \times \text{heated area [m}^2\text{]}$$

where $E_{\text{water heating}}$ = final heat energy use for domestic hot water (kWh), and

$E_{\text{household electricity}}$ = final electricity for household lighting and appliances (kWh).

The final energy for all the operation activities in Papers II and IV was calculated with VIP+ software (Strusoft, 2010). The VIP+ is a dynamic energy balance program that models hourly final energy. The software considers the hourly variation of heat flux and heat storage capacity of buildings, allowing for analysis of thermal mass in reducing energy use. The ENSYST program (Karlsson 2003) was used to calculate the primary energy needed to provide the final energy for space heating, tap water heating, electricity for ventilation fans and pumps, and electricity for household and facility management. The program calculates primary energy use considering the system-wide energy chain, from natural resources extracted, transported and refined to produce the delivered energy.

The space heating demand is modeled for different locations in Sweden: Växjö (Papers I, II, III and V), Östersund (Papers II and IV) and Kiruna (Paper II). Table 6 shows the climate data for the different locations.

Table 6. Climate locations for analysis of the buildings space heating demand.

Location	Relative location	Latitude	Longitude	Annual outdoor temperature (°C)		
				Maximum	Minimum	Average
Växjö	South	56°9' N	14°5' E	28.0	-18.0	6.5
Östersund	Middle	63°2' N	14°4' E	24.0	-28.0	2.5
Kiruna	North	67°8' N	20°0' E	24.0	-33.0	-1.2

An indoor temperature of 22° C was assumed for all the base calculations in the thesis. In Paper I, the effect of varying the indoor temperature to 20 or 24° C was explored in a sensitivity analysis. The operation primary energy use was calculated for a 50-year building lifespan in the base calculations and also for a 100-year service life in the sensitivity analyses in Papers I and II. In Paper III, analyses are made for operation primary energy use before and after building retrofitting at 15 and 50 years, respectively. In Papers IV and V, calculations are made for building operation primary energy use for a year.

2.6.3 End-of-life phase

Post-use concrete, steel and wood materials have high recovery and recycling rates in many European countries (European Commission, 2001). The analysis considers the energy use to demolish the buildings and recover and recycle 90% of the demolished concrete, steel and wood materials. The demolished wood is assumed to be used for energy (Krook et al., 2008). The demolished concrete is assumed to be recycled into crushed concrete aggregate, replacing crushed stone for below-ground filling applications (Engelsen et al., 2005). The primary energy implication if the recycled concrete were to replace natural aggregate is discussed in Paper I. The recovered steel is assumed to be used in place of 100% ore-based steel (International Iron and Steel Institute, 2008). Scenarios where the recycled steel substitutes 50% ore-based and 50% scrap-based steel are analyzed in a sensitivity analysis in Papers I and II.

The primary energy benefit of end-of-life concrete or steel is calculated as the primary energy use avoided due to the recovered concrete or steel minus the primary energy used to recover the concrete or steel. The primary energy benefit from end-of-life wood is calculated as the bioenergy available for recovery minus the fossil energy used to recover and transport the wood. The primary energy to demolish the case-study wood and concrete buildings was assumed to be 5 and 10

kWh/m², respectively (Adalberth, 2000). These numbers are used as the basis of the calculations in this thesis. Further details about the assumptions for the end-of-life phase calculations are provided in Papers I-III.

2.7 Carbon balance calculations

The life cycle carbon balance is calculated as the resultant of material production carbon emission, the carbon emission avoided by substituting biomass residues in place of fossil fuels, the net carbon emission from cement reactions, and changes in carbon stock due to the use of wood building materials.

2.7.1 Material production carbon emission

The material production carbon balance is the emission due to fossil fuel used to extract, process and transport the material comprising the buildings and is calculated as:

$$C_{\text{production}} = \sum_k [C_k \times F_k] + C_L \times \frac{L}{\eta}$$

where $C_{\text{production}}$ = total CO₂ emissions from material production (kg C);

k = the fossil fuels: coal, oil, and fossil gas;

C = the fuel-cycle carbon intensity of the fossil fuel (kg C/kWh end-use fuel);

F = the end-use fossil fuel energy used to extract, process, and transport the materials (kWh);

C_L = the fuel-cycle carbon intensity of the reference fossil fuel to produce electricity (kg C/ kWh fuel);

L = the end-use electricity to extract, process, and transport the materials (kWh_e);

η = the conversion efficiency for electricity production.

The fuel-cycle carbon intensity of the fossil fuels is assumed to be 0.11, 0.08 and 0.06 kg C/kWh end-use fuel for coal, oil, and fossil gas, respectively (Gustavsson and

Sathre, 2006). Further details about data used to calculate the parameters are appended in Paper VI.

2.7.2 Substitution of fossil fuel by recovered biofuel

The carbon emission avoided due to replacing fossil fuel with recovered biomass residues is calculated with the equation:

$$C_{avoided} = \sum_j [M_j \times H_j] \times C_f \times \psi_f - [C_{diesel} \times D_{residues}]$$

where $C_{avoided}$ = net CO₂ emissions avoided due to replacing fossil fuel with recovered biomass residues (kg C);

j = the different types of recovered biomass residues

M = the mass of the recovered biomass residues (oven dry tons)

H = lower heating value of the biomass residues (kWh /oven dry ton)

C_f = the fuel-cycle carbon intensity of the reference fossil fuel replaced by the recovered biomass residues (kg C/ kWh end-use fuel)

ψ_f = the relative conversion efficiency of recovered biomass residues versus reference fossil fuel (%)

C_{diesel} = the fuel-cycle carbon intensity of diesel fuel (kg C/ kWh diesel)

$D_{residues}$ = the quantity of diesel fuel used to recover and transport the biomass residues (kWh).

2.7.3 Net cement reactions

In addition to fossil fuel emission from cement manufacture, the carbon dynamics of concrete materials include the chemical reactions of calcination and carbonation that occur over the cement life cycle. The calcination process emissions result from the chemical reaction that converts limestone to calcium oxide (CaO) and CO₂ during cement manufacture. Carbonation is a chemical process in which the

CaO present in hardened cement products binds with CO₂ in the atmosphere to form calcium carbonate.

The amount of carbon emitted during the calcination of limestone in the manufacture of cement is calculated as follows, based on Pommer and Pade (2005):

$$C_{\text{calcination}} = [\beta \times W_{\text{cement}} \times p_{\text{clinker}}]$$

where $C_{\text{calcination}}$ = CO₂ emissions due to calcination of limestone (kg C);

β = CO₂ emitted per kg of clinker produced;

W_{cement} = the amount of cement used to construct the building (kg);

p_{clinker} = the proportion of clinker contained in the cement (%).

The carbonation process occurs throughout the life cycle of concrete products and its rate depends on the surface area of the concrete exposed to air. It is also influenced by several other factors, including the exposed uncoated surface area of the concrete, the composition of the cement used to make the concrete, the relative humidity and temperature of the environment and the exposure conditions (Gajda and Miller, 2000). The atmospheric CO₂ absorbed during the service-life and post-use life of concrete and cement mortar is estimated using a model from Pade and Guimaraes (2007). Inputs to the model include the volume of carbonated concrete, CaO available for carbonation, mass of clinker per unit volume of concrete, share of CaO in cement clinker and the molar ratio of CO₂ to CaO. The volume of carbonated concrete is calculated as the product of the surface area of the concrete and the depth of carbonation. In Paper VI, the uptake is calculated during the service life of the buildings and for periods ranging from 4 months to 30 years following the demolition of the buildings, when the concrete is crushed. The assumptions, values and steps used for the calculations are described in detail in Paper VI.

2.7.4 Carbon stock changes and land-use modeling

Trees sequester carbon from the atmosphere during photosynthesis and store part of this carbon in wood products. The mechanism by which this process affects the carbon balance of buildings is included in the analysis. The carbon stock change at the time of building construction is calculated as the amount of carbon contained in the wood building materials minus the carbon in the total tree biomass harvested to make the wooden material. All the tree biomass that is not contained in the building is assumed to be used for energy or decayed to produce CO₂. A sustainably managed forest with an average rotation period of 100 years is assumed, which is consistent with Swedish forestry practice (Gustavsson et al., 2006). During the 100-year service life of the buildings, the forest that was harvested will have re-grown, sequestering about the same amount of carbon that was released during harvesting. The carbon contained in the wood building material is assumed to be released as CO₂ through burning for energy or decomposition at the end of the life of the building.

Wooden buildings require greater amounts of biomass, and thus larger forest area, than non-wooden buildings. Addressing this issue in comparative analysis of wood and non-wooden buildings is a major challenge. In this thesis, three different land-use modeling approaches are used. The first assumes that the incremental wood material is produced through more intensive use of forest land, or from land that was not previously used for wood production. The second assumes that an equal area of land is available to both the wood-frame and concrete-frame buildings, and analyzes the carbon balance impacts of biological carbon sequestration on the “surplus forest,” or the part of the land not used for building material production. The last approach assumes that the difference in wood quantity between the wood and concrete buildings is used for energy instead of for construction. These forest modeling approaches are described in greater detail in Paper VI.

2.7.5 End-of-life carbon implications of materials

The buildings are assumed to be dismantled and the concrete, steel and wooden materials recovered. The end-of-life options considered include recycling of steel and energy recovery from the wooden material to replace fossil fuels. The demolished concrete is assumed to either be landfilled or crushed into aggregate followed by exposure to air to increase carbonation uptake of CO₂. The end-of-life carbon analysis includes the energy used to carry out the end-of-life option and the fossil emissions avoided with this option.

3 Life cycle primary energy analysis

3.1 Production primary energy balance

Analysis of the primary energy use during the life cycle of the case-study building is described in Papers I, II and III. Figure 4 shows the production primary energy balance of the concrete- and wood-frame buildings. The wood-frame building has lower primary energy use for material production and on-site construction and greater biomass residues for external use. The production primary energy balance of the concrete-frame building is about twice that of the wood-frame building.



Figure 4. Production primary energy balance of the concrete- and wood-frame buildings. (Adapted from Paper II)

3.2 Operation primary energy use and thermal mass effect

Paper II analyzes the influence of thermal mass on space heating energy use and life cycle primary energy balance for concrete- and wood-frame buildings. The analyses are conducted for different energy efficiency levels and climatic locations.

Sweden is divided into three climate zones, and the buildings are analyzed for each of the zones. The results show that the concrete-frame building has a slightly lower space heating demand than the wood-frame building, because of the benefit of thermal mass. The profiles of the annual final space heating demand of the concrete- and the wood-frame buildings in different locations arranged in descending order are shown in Figure 5. The dashed lines show the concrete-frame building and the corresponding solid lines show the wood-frame building. The difference between the dashed line and the corresponding solid line is the energy savings of thermal mass and is generally minor. Final energy reductions about 0.3–0.7 kWh/m² are achieved as a result of a thermal mass benefit. This reduction is about 0.5–2.45% of the overall annual space heating demand.

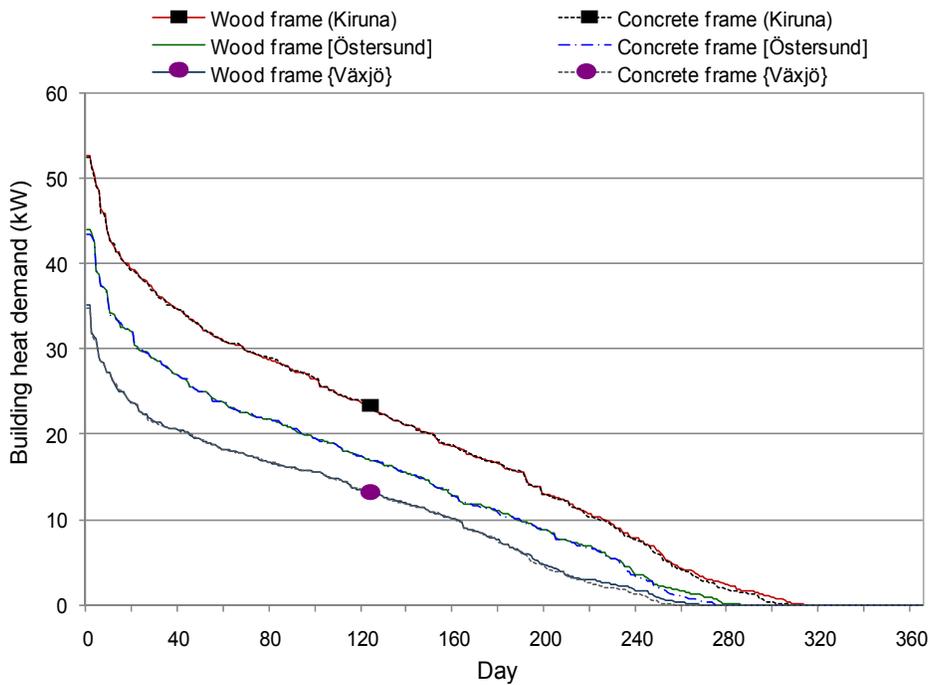


Figure 5. Annual profiles of final space heating demand arranged in descending order for the concrete and wood-frame buildings in three different locations. (Paper II)

The operation primary energy use of the concrete- and wood frame buildings is evaluated in Paper II. Papers I, III, IV and V also contain a detailed analysis of the primary energy use related to the operation phase of the wood-frame building. Figure 6 shows the annual primary energy use for space heating the buildings in various locations with different end-use heating systems and energy supply from BST technology. The district heating is based on 85% CHP production and 15% light oil boiler production. The results show that the choice of heat supply system significantly affects the space heating primary energy use of the buildings. The electric-based supply systems provide higher operation primary energy use, because of the lower system efficiency of the electricity chains. The difference between the operation primary energy of the concrete- and wood-frame buildings is due to thermal mass and is not significant, in particular when using energy-efficient supply systems.

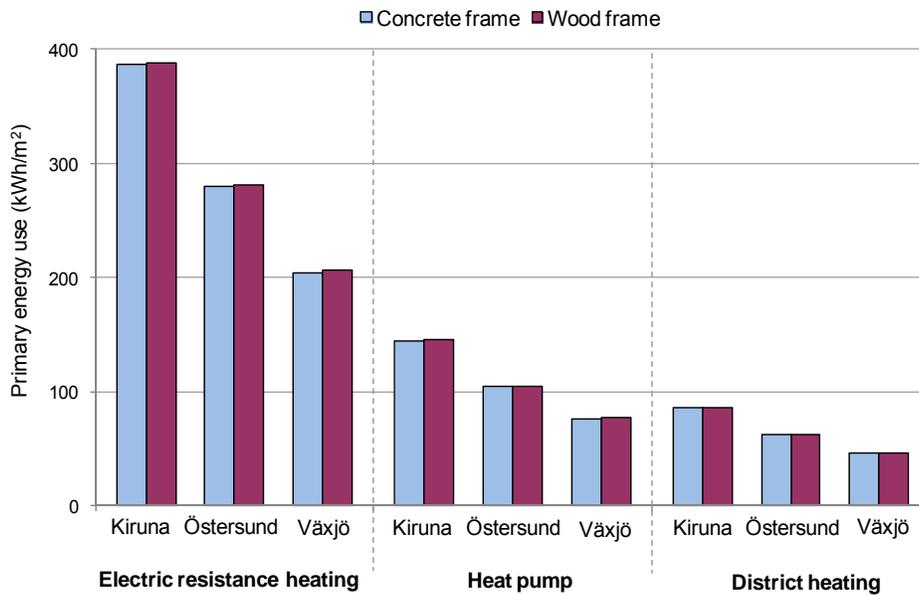


Figure 6. Annual primary energy use for space heating of buildings in three locations with different heating systems. District heating is based on 85% CHP. (Adapted from Paper II)

Figure 7 shows the annual operation primary energy use for the buildings, including space heating, tap water heating and the electricity for ventilation and household purposes. The difference in operating primary energy between concrete- and wood-frame buildings is negligible. Space heating dominates the operation phase primary energy use when the buildings are resistance heated, accounting for nearly half of the total operation primary energy use. Household electricity accounts for the greatest share of the primary energy for operation in the heat pump and district heated buildings and is also significant for the resistance heated building. Although the primary energy use for tap water heating and household electricity constitutes a significant part of the operation energy, these demands depend to a large extent on building users and not on the construction.

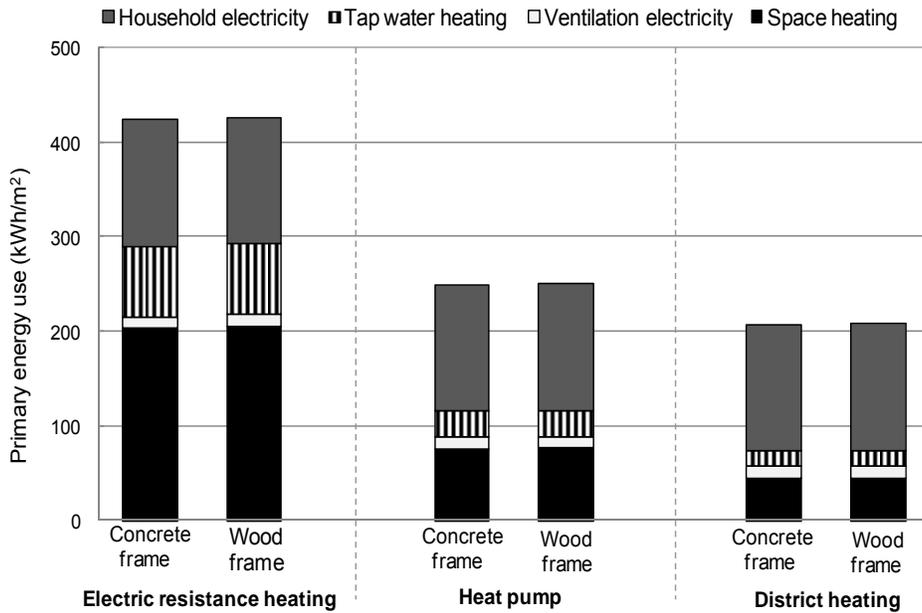


Figure 7. Annual operation primary energy use for the concrete- and the wood-frame buildings with different heating systems located in Växjö. District heating is based on 85% CHP. (Adapted from Paper II)

3.3 End-of-life primary energy balance

Figure 8 shows the primary energy balance for the end-of-life phase of the buildings. The negative balances mean that a net primary energy benefit is achieved through recovering end-of-life materials. The primary energy used for demolition is minor compared with the primary energy benefits of the post-use management options. The wood-frame buildings provide a greater end-of-life primary energy benefit than concrete alternatives. Energy recovery from demolition wood provides large primary energy benefits, and less benefit is achieved by recycling the concrete.

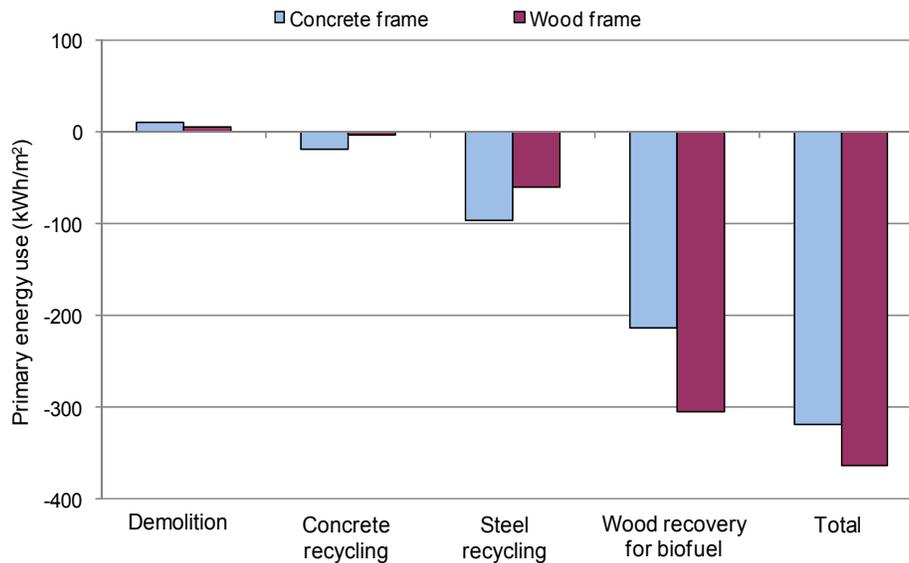


Figure 8. End-of-life primary energy balance for the concrete- and the wood-frame buildings. (Adapted from Paper I and II)

3.4 Complete life cycle primary energy balance

Table 7 shows the total life cycle primary energy use of the concrete- and wood-frame buildings in Växjö, with an assumed building lifespan of 50 years. The end-use heating is based on district heating and the energy supply is based on BST technology. The net primary energy difference between the concrete-frame and

wood-frame buildings is only negative for the operation phase, because of the space heating energy benefit of thermal mass. The lower production primary energy use and greater end-of-life benefits of the wood-frame building more than offset its additional operation primary energy use, and thus, the wood-frame building has about 4% lower net life cycle primary energy balance than the concrete-frame building.

Table 7. Life cycle primary energy balance for district heated buildings in Växjö for a 50-year life span. District heating is based on 85% CHP and the energy supply is based on BST technology. (Adapted from Paper II)

Description	Primary energy use (kWh/m ²)		
	Concrete frame	Wood frame	Net difference
<i>Production energy use:</i>			
Material production	757	579	178
On-site construction	100	50	50
Total	857	629	228
<i>Operation energy use:</i>			
Space heating	2268	2290	-22
Ventilation electricity	605	605	0
Tap water heating	829	829	0
Household electricity	6684	6684	0
Total	10386	10408	-22
<i>End-of-life energy use:</i>			
Demolition	10	5	5
Total energy use over life cycle	11253	11042	211
<i>Production biomass residues</i>	-208	-345	137
<i>End-of-life recycling and recovery:</i>			
Concrete recycling	-19	-3	-16
Steel recycling	-96	-60	-36
Wood recovery for bioenergy	-214	-305	91
Total	-537	-713	176
Total energy balance over life cycle	10716	10329	387

4 Building energy-efficiency standards analysis

The case-study building (Section 2.5.1) was constructed during the regime of the 1994 Swedish building code (*BBR 1994*). The Swedish building code has been significantly improved since then, partly because of the implementation of the EU directive on energy performance of buildings. A stringent building code (*BBR 2009*) and criteria for passive houses (*passivhus*) (Janson, 2008) has been developed for different energy efficiency targets in Swedish buildings. The BBR 2009 became mandatory in January 2010 and specifies limits for the specific energy use of buildings, encompassing the final energy use for space heating, domestic hot water and electricity for fans and pumps, but excluding electricity for household appliances and lighting. The specific energy use standard for buildings depends on whether electric resistance or nonelectric resistance heating is used and varies for three climatic zones. The Passivhus defines a maximum amount of purchased energy for buildings, excluding household electricity. The maximum purchased energy varies for two climate zones: the south and north (Paper I). Paper I explores the life cycle primary energy implications of building to the energy efficiency levels of the BBR 2009 and Passivhus.

4.1 Annual final and primary energy use for operation

Figure 9 shows the impact of the standards on annual final energy use; Figure 10 shows the primary energy use for building operation when using energy supply based on BST technology. The final energy use for heating is greatly reduced if the building is constructed to the improved standards. The specific final energy use for the BBR 1994 district heated building is about twice as high as for the electric heated buildings to the BBR 2009 or the Passivhus. Nevertheless, the operation primary energy use of the BBR 1994 district heated building is considerably lower than that of the electric heated buildings to the BBR 2009 and the Passivhus. This result is because of the high overall efficiency of district heating systems with CHP plants.

The cogenerated electricity from the CHP plants replaces electricity that otherwise would have been produced in a stand-alone plant with lower overall efficiency.

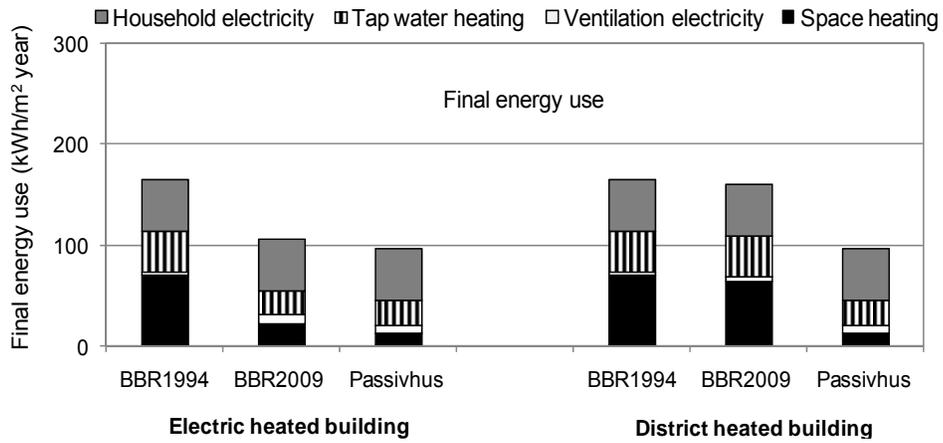


Figure 9. Annual final energy use for building operation. (Paper I)

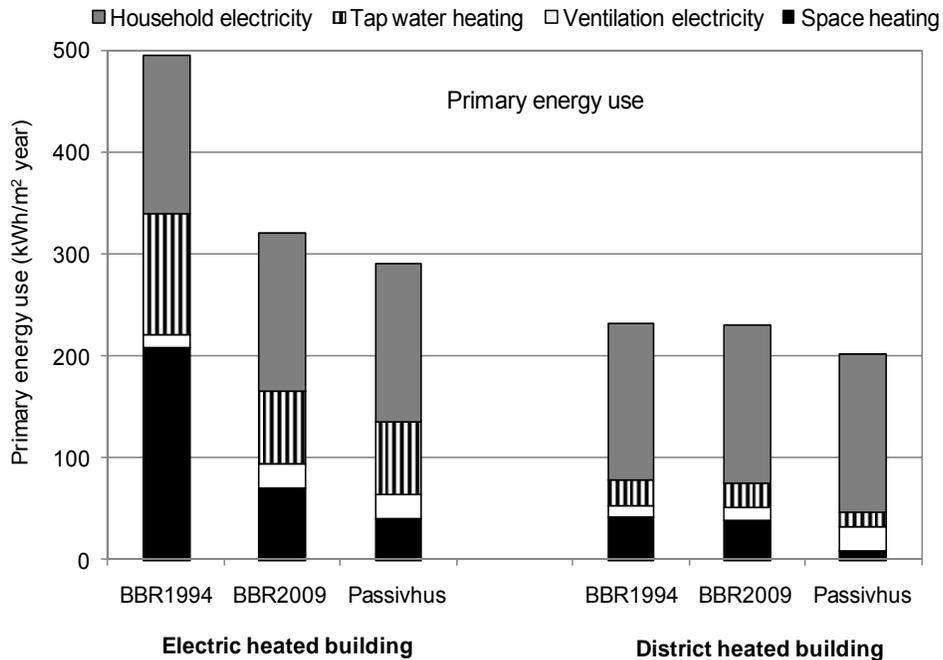


Figure 10. Annual primary energy use for building operation. District heating is based on 85% CHP. (Paper I)

4.2 Distribution of production and space heating primary energy

The relationship between the primary energy for production, excluding the energy gained from biomass residues, and for space heating and ventilation during a 50-year lifespan for the building constructed to different standards is shown in Figure 11. Material production primary energy becomes proportionally more significant as buildings are built with higher energy-efficiency and more efficient heat supply systems are used (Paper I).

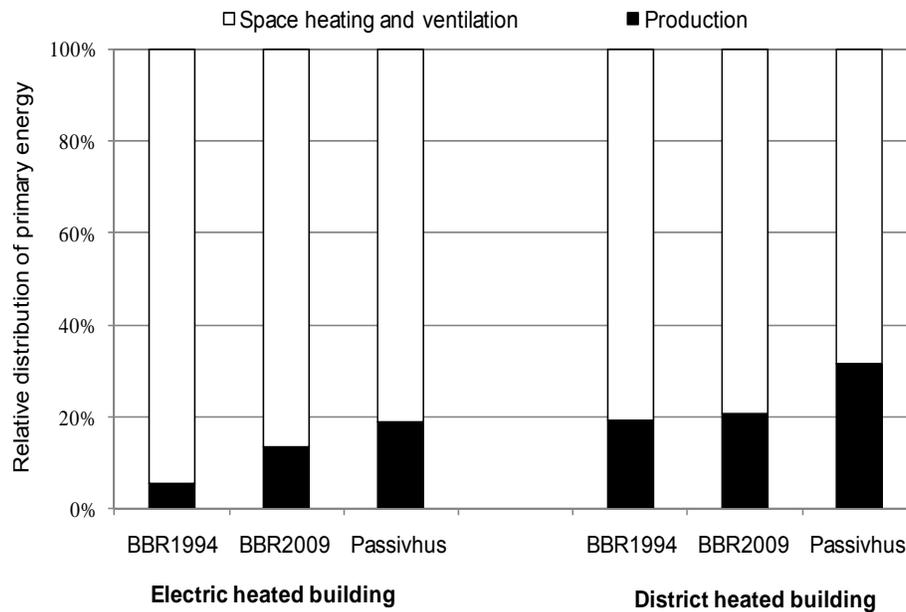


Figure 11. Relative distribution of primary energy for production, and for space heating and ventilation. (Paper I)

4.3 Life cycle primary energy implications

Considering all life cycle phases, including the production, operation and end-of-life primary energy and the entire energy chains, a district heated building built to the BBR 1994 has 17-25% lower primary energy use than an electric heated building built to the BBR 2009 or the Passivhus (Figure 12). The results underscore the

importance of system-wide primary energy perspectives and the impact of heat supply systems in reducing building primary energy use (Paper I).

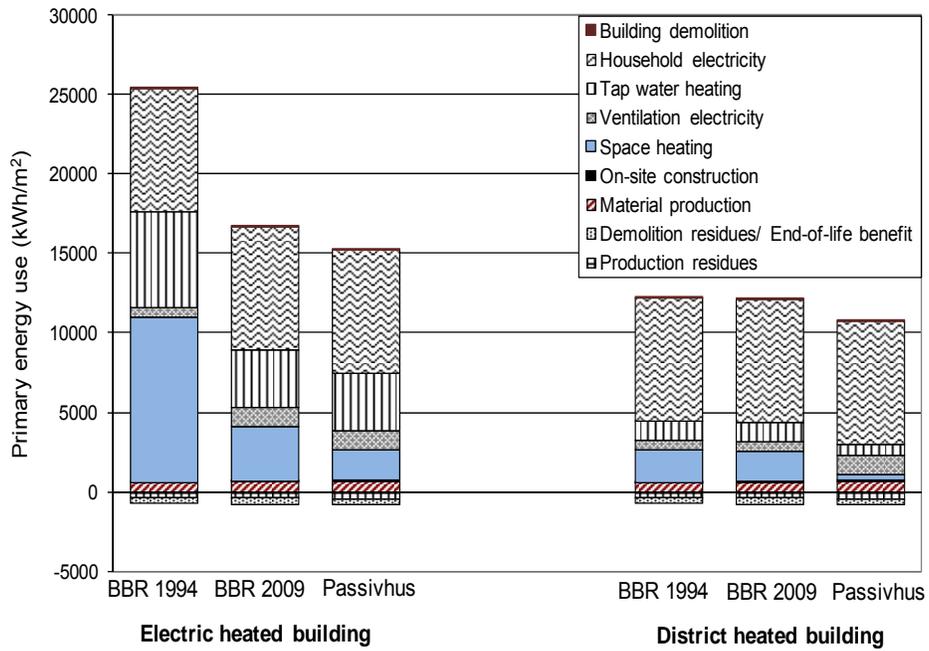


Figure 12. Primary energy use of the life cycle phases of the building built to different standards, assuming a 50-year operation lifespan of the buildings.

5 Primary energy impact of energy efficiency retrofits

Different energy efficiency retrofit measures implemented in buildings to reduce the operation energy use were compared in Papers III, IV and V. The measures analyzed are improved windows and doors, increased insulation in attic and exterior walls, installation of improved water taps, and installation of a heat recovery unit in the ventilation system. The measures are modeled to the case-study building to achieve a Passivhus in Paper III.

5.1 Annual final and primary energy savings

Table 8 shows the final energy use reduction of the measures for the case-study building, modeled with the ENORM software.

Table 8. Annual final operation energy before and after energy retrofit measures are applied.

Description	Energy retrofit measures	Final energy use (kWh/m ² year)				
		Space heating	Tap water heating	Ventilation electricity	Household electricity	Total
Initial	–	70	40	4	52	166
Tap water heating	Efficient hot water taps	70	24	4	52	150
Roof	U-value from 0.13 to 0.08	69	24	4	52	149
Windows	U-value from 1.90 to 0.90	51	24	4	52	131
Doors	U-value from 1.19 to 0.90	51	24	4	52	131
Ground floor	U-value of 0.23 maintained	51	24	4	52	131
External walls	U-value from 0.20 to 0.10	43	24	4	52	123
Ventilation	Heat recovery, $\eta = 85\%$	13	24	8	52	97

^a U-values in W/m²K

In Paper IV, the measures are also modeled using VIP+ software to determine the effect of the reduced heat demand on different district heat production systems.

VIP+ and ENORM software differ in principle and complexity (Section 2.6.2). VIP+ is a dynamic energy balance model that calculates energy balance on an hourly basis while ENORM simulates energy use on a 24-hour basis. Nevertheless, the patterns of the calculated final energy savings of the measures by the two programs were consistent. Figure 13 shows the effectiveness of each retrofitting measure in reducing the primary energy use for space and tap water heating and ventilating the building when using different types of heating systems with energy supply from BST technology (Paper III). Heat recovery of ventilation air provides the largest single decrease in primary energy use for heating except for district heating with 90% CHP. For district heating with 90% CHP, more efficient windows result in the highest primary energy use reduction. The use of a VHR system decreases heat demand, but the increased electricity use to operate the system erodes a substantial share of the primary energy reductions when using district heating with 90% CHP.

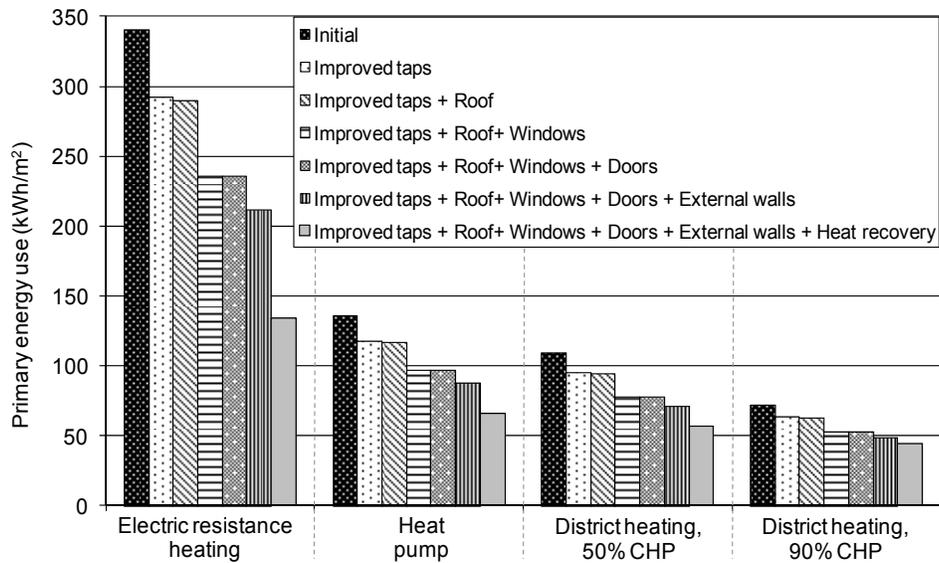


Figure 13. Annual primary energy use for heating (space and tap water) and ventilation with various energy retrofit measures and heating systems, with energy supply from BST technology. (Adapted from Paper III)

5.2 Cumulative primary energy savings

Figure 14 shows the cumulative primary energy use over time, with and without energy efficient retrofitting measures, including the primary energy use during the production, retrofitting, operation and end-of-life phases (Paper III). The case-study building was built in about 1995, assumed to be retrofitted in 2010, and used until the year 2060. The primary energy for building operation from 2010 to 2060 is significantly lower for the retrofitted building (dashed lines) than if the buildings had not been retrofitted (solid lines). The net life cycle energy benefit of the retrofitting is the difference between the dashed and the corresponding solid lines at the year 2060. The benefit is positive in all cases and is greatest when the building uses electric resistance heating.

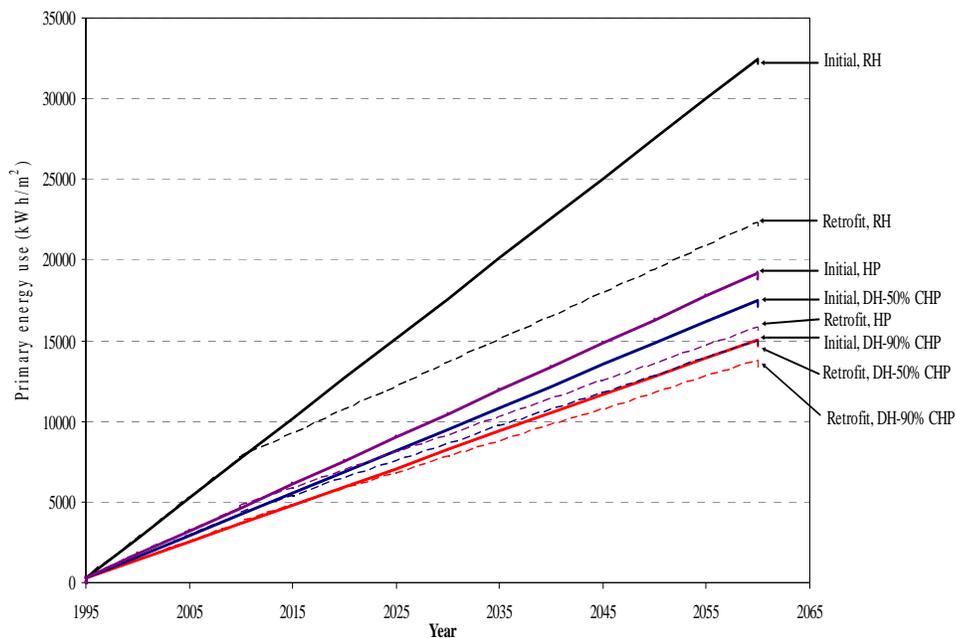


Figure 14. Cumulative primary energy use over time for the building with (dashed lines) and without (solid lines) the retrofit measures, with resistance heating (RH), heat pump (HP) or district heating (DH) end-use heating systems and energy supply from BST technology. (Paper III)

5.3 Life cycle primary energy implications

Figure 15 shows the implication of implementing the energy retrofit measures from a life cycle primary energy perspective (Paper III). The primary energy use during the operation phase dominates the life cycle primary energy. Retrofitting a building to Passivhaus reduces primary energy use, but the overall significance largely depends on the type of heat supply system. The more efficient the heating and energy supply systems are, the less the primary energy savings resulting from retrofitting are.

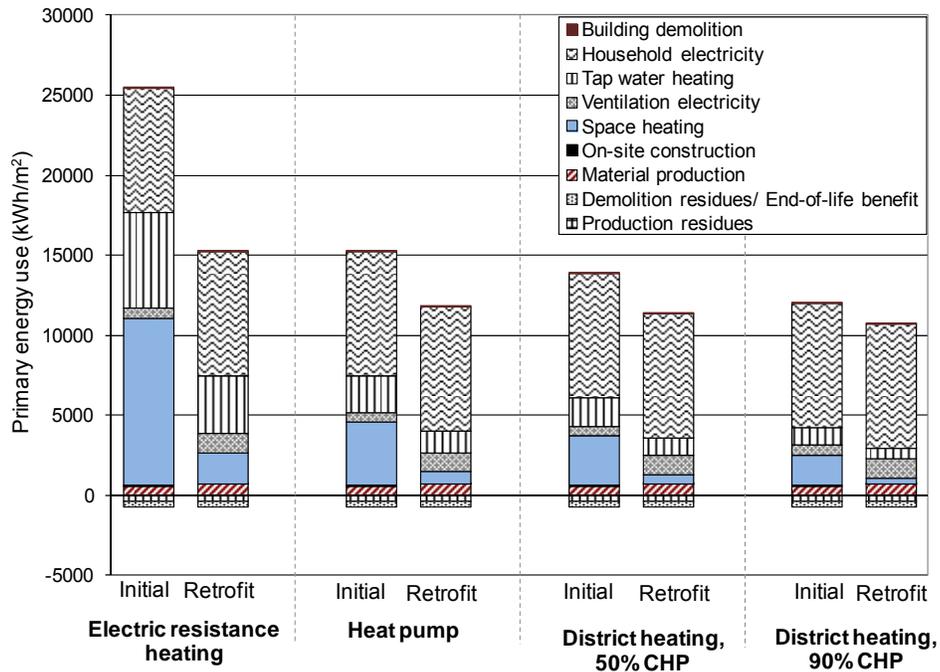


Figure 15. Primary energy use of the complete life cycle of the buildings, with an assumed lifespan of 50 years. (Adapted from Paper III)

5.4 Impact of ventilation heat recovery systems

The results of Papers III and IV suggest that heat recovery ventilation should be considered with caution. Paper V specifically analyzes the impact of VHR systems on space heating demand and operation primary energy use when using different supply systems in detail. Analyses are conducted for the case-study building built to conventional and passive house standards. Table 9 shows the thermal characteristics of the conventional building and the passive building. In addition to lower U-values, the passive building is much more airtight than the conventional building.

Table 9. Thermal properties of the building components.

Building	U-value (W/m ² K)					Air leakage (l /s m ²) at 50 Pa
	Ground floor	External walls	Windows	Doors	Roof	
Conventional	0.23	0.20	1.90	1.19	0.13	0.8
Passive	0.23	0.10	0.85	0.80	0.08	0.3

The electricity for VHR is based on the default value (4 kWh/m²) given by the ENORM software or the typical value (7 kWh/m²) reported by Tommerup and Svendsen (2006). VHR decreases the final heat use for ventilation loss heating, but increases the electricity used to operate the ventilation system and the air infiltration. Overall, VHR considerably reduces the final energy for operation. Figure 16 shows the net savings in annual primary energy use for space heating and ventilation electricity when using VHR with different end-use heating systems with energy supply from BST or BIGCC technology. Less primary energy savings or no primary energy savings are achieved when using district heating with 90% CHP. The savings due to VHR are high for the more airtight building. The BIGCC technology provides similar results to the BST technology, but the net primary energy savings are lower compared with the BST technology.

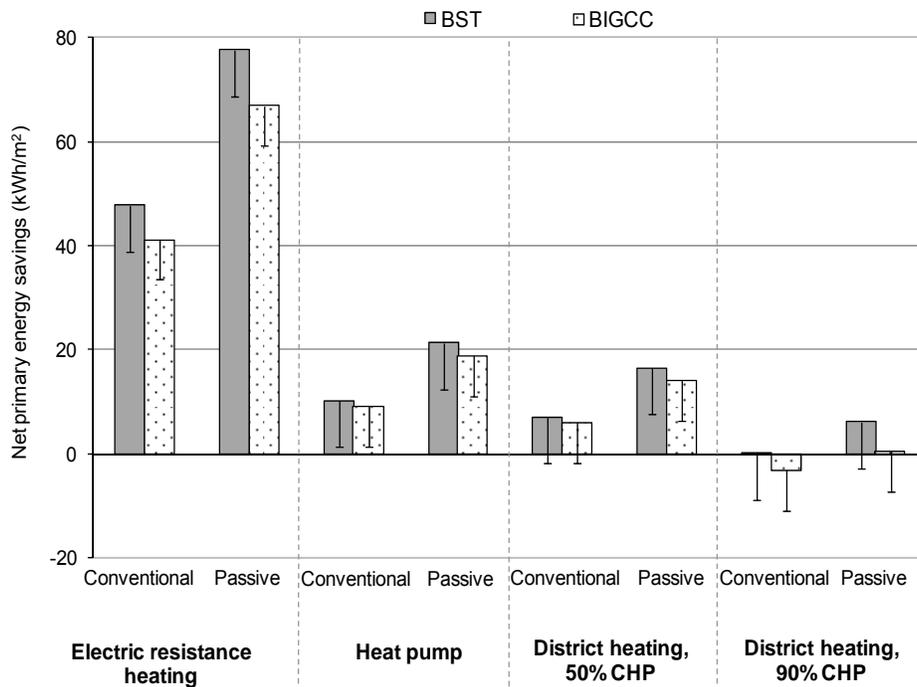


Figure 16. Net annual primary energy savings for VHR when using BST or BIGCC energy supply technology. The main bars show when electricity use for the VHR is 4 kWh/m² and the error bars show the savings when electricity use for the VHR is 7 kWh/m². (Paper V)

Paper IV explores the optimal district heat production cost and primary energy use when different environmental constraints are applied. The results show that the optimal CHP production in district heat production systems was 80-83% for BST technology and 76-78% for BIGCC technology. Figure 17 shows the net primary energy savings for VHR when CHP production is based on the lower and upper optimal limits according to Paper IV. VHR always increases net primary energy use when the electricity use for VHR is 7 kWh/m². The net savings are also very low for conventional buildings with electric efficient VHR systems with electricity use of 4 kWh/m². These results show that the primary energy benefit of VHR systems largely depends on the type of heat supply system, as well as the amount of electricity used for VHR and the airtightness of buildings.

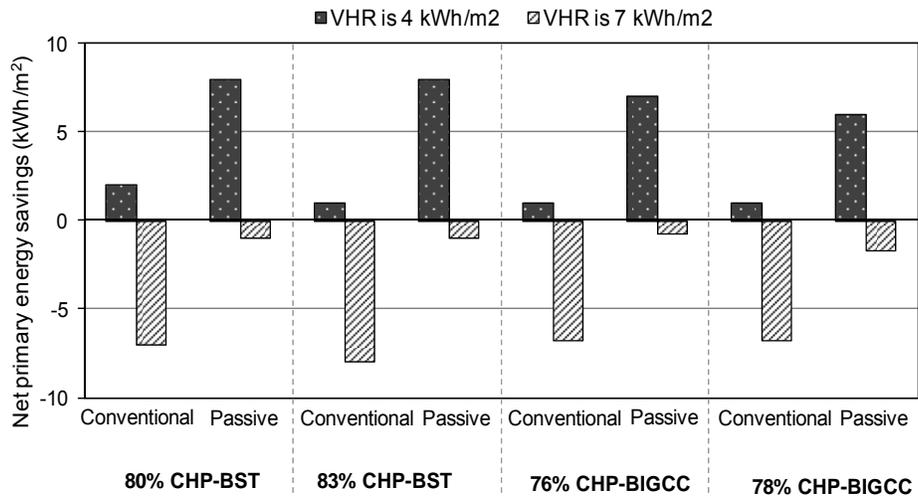


Figure 17. Net annual primary energy savings for VHR when more optimally designed CHP production systems are used. (Paper V)

6 Life cycle carbon balance analysis

6.1 Cement reactions emissions

Figure 18 shows the carbon flows from the cement calcination reaction and the carbonation uptake for the concrete- and wood-frame buildings. The magnitude of the carbon flows from calcination and carbonation reactions in the concrete-frame and wood-frame buildings reflect the quantities of cement used in each building. At the end of the service life (after year 100), carbon uptake of the concrete-frame building is 23% of the calcination emission. The corresponding figure for the wood-frame building is 14%, which is lower than that for the concrete building because the concrete used in the foundation in the wood building has lower exposure to the air. The carbon uptake in the buildings increases substantially after crushing of the demolished concrete (year 100). This result is due to the increase in the exposed surface area of the concrete. The proportion of total calcination emission absorbed is 43 and 36% for the concrete- and wood-frame buildings, respectively, after the crushed concrete is exposed for 4 months.

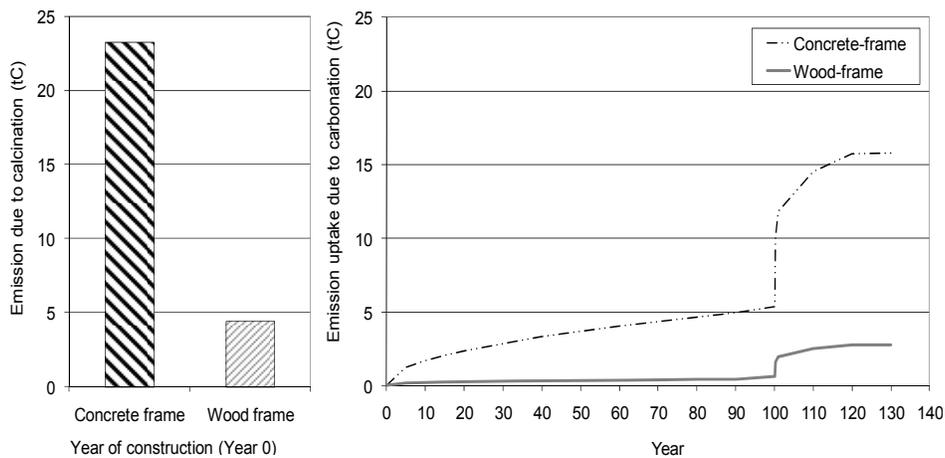


Figure 18. Carbon flows through cement calcination (left) and carbonation of concrete and cement mortar during the service life and after demolition (right) for the concrete- and wood-frame buildings, when using CEM II cement. (Paper VI)

6.2 Carbon emissions at the year of construction

The life cycle carbon emission of the concrete- and wood-frame buildings at the year of construction is shown in Figure 19. At year 0, the year of construction, the carbonation uptake is zero and only calcination contributes to the net cement reactions. The carbon balance for the wood-frame building is 14% lower than for the concrete-frame building. Forest harvesting results in the most carbon emissions, releasing 93.1 tC for the concrete-frame building and 144.3 tC for the wood-frame building. Of this forest carbon, the concrete-frame and wood-frame buildings temporarily sequester 28.2 tC and 40.3 tC, respectively, in the wooden building materials.

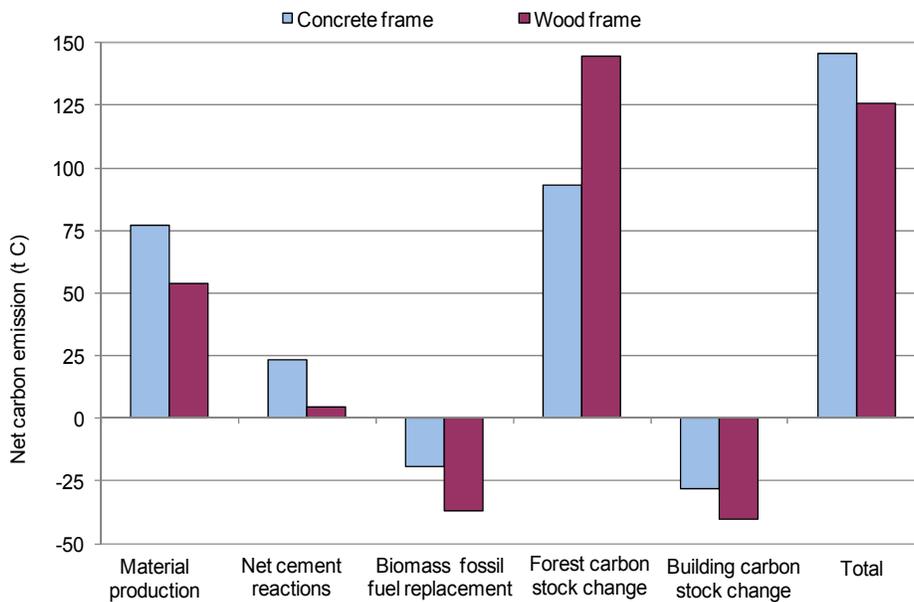


Figure 19. Net carbon emissions (tC) of the concrete and wood-frame buildings at the year of construction. Positive values are emissions to the atmosphere; negative values are flows out of the atmosphere or avoided fossil fuel emissions. (Adapted from Paper VI)

6.3 Carbon emissions over complete building life cycle

Over the complete life cycle (Figure 20), the wood-frame building has a carbon benefit of about 24 tC while the concrete-frame building emits about 37 tC, giving a difference of 61 tC. This difference is largely due to differences in emissions from fossil fuel use and calcination reaction as well as the different amount of biomass residue available to replace fossil fuel. There is no net change in carbon stock in wood material and living tree biomass over the full life cycle of the buildings (Paper VI). Recycling of concrete and reinforcing steel together provides a small carbon benefit because the fossil fuel used to crush concrete is significant and erodes the gains. The replacement of fossil fuel by recovered demolition biomass provides a large carbon benefit (Paper VI).

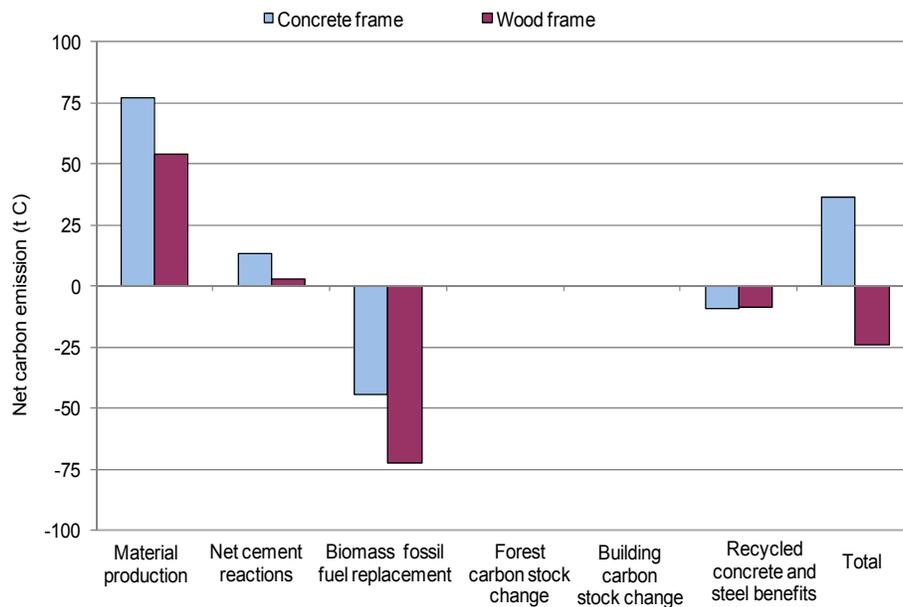


Figure 20. Net carbon emissions (tC) of the concrete- and wood-frame buildings over the life cycle of the buildings. Positive values are emissions to the atmosphere; negative values are flows out of the atmosphere or avoided fossil fuel emissions. (Adapted from Paper VI)

The carbon emission from the operation phase of the building is not included in the analysis in Paper VI (see Section 2.5). The carbon emissions from building operations largely depend on the primary fuels used in the supply systems (Joelsson, 2008). The calculations in Table 7 show that the difference in building operation primary energy between the concrete- and wood-frame buildings is 0.4% if a building lifespan of 100 years and energy supply based on district heating with BST technology are assumed. According to the analysis in Table 7 and assuming a 100-year building lifespan, the total operation carbon emissions (including space heating with thermal mass benefit, tap water heating, electricity for ventilation and for household purpose) are 135.6 and 135.8 tC for the concrete- and wood-frame buildings, respectively. Thus, the total carbon balance of the concrete-frame buildings would be about 172.6 tC while that of the wood-frame would be 111.8 tC, giving a difference of 60.8 tC. The net life cycle carbon balance of the wood-frame building is thus 35% lower than for the concrete-frame building.

6.4 Impact of parameter variations

Table 10 shows the effect on the carbon balance of the buildings of the following variations: the duration of exposure of crushed concrete, from the base case of 4 months to 1 or 30 years; the cement type, from the base case of CEM II to CEM I; the end-of-life option for concrete, from the base case of crushing and reuse as aggregate to landfilling; the allocation of the emissions from concrete crushing, from the original building to the subsequent use; the production of original steel, from the base case of ore-based steel to scrap-based steel; the substitution of recovered steel, from the base case of ore-based steel to scrap-based steel; the fossil fuel displaced by the recovered biofuel, from coal to fossil gas; the fuel displaced by the demolition biomass, from coal to a non-carbon emitting energy system; the forest land-use for concrete construction, from traditional forest management to intensified forest management where surplus forestland is used for bioenergy or left standing. Most of

the parameter variations reduce the emission difference between the wood and concrete buildings, as most of the values of the parameters have been chosen to maximize the carbon benefits for concrete. Nevertheless, in all cases, the wood-frame building has significantly lower carbon emission than the concrete-frame building. The emission difference between the buildings decreases by 50% if the surplus forestland in the concrete case is used for bioenergy. However, this is very unlikely to occur due to the low economic added value (Paper VI).

Table 10. Differences in life cycle carbon emission (tC) between the concrete- and wood-frame buildings in different cases due to variation of parameters. (Adapted from Paper VI)

Parameters evaluated	Base value	Variation	Net difference (tC) (Concrete - Wood)
Base case	-	-	60.7
Concrete-related			
Crushed concrete exposure	4 months	1 year	59.3
Crushed concrete exposure	4 months	30 years	56.1
Allocation of concrete crushing emission	Original building	Next use	58.5
Cement type	CEM II	CEM I	62.2
Concrete end-of-life option	Crush into aggregate	Landfilling	68.1
<i>Best case concrete building</i>			
CEM II, 30 years exposure of crushed concrete, crush emission to next use	-	-	53.9
<i>Worst case concrete building</i>			
CEM I, landfilling of concrete	-	-	70.0
Steel-related			
Original steel production	Ore-based	Scrap-based	54.3
Recovered steel substitution	Replaces iron-ore	Replaces scrap steel	66.6
Fossil fuel-related			
Fuel displaced by recovered biofuel	Coal	Natural gas	50.0
Fuel displaced by demolition biomass	Coal	Carbon neutral fuel	49.8
Land use-related			
Forest management: concrete building	Traditional forest management	Intensive forest management and surplus land used for bioenergy	30.2

7 Conclusions

7.1 Life cycle primary energy use and thermal mass effect

In these analyses, a concrete-frame building has slightly lower space heating demand than a wood-frame alternative, because of the benefit of thermal mass in the concrete-based system. The energy savings benefit due to thermal mass generally varies with the climatic location and energy efficiency levels of the buildings. Overall, the final energy savings benefit due to thermal mass is small, both in absolute terms and in relation to the final space heating demand. The absolute primary energy benefit of thermal mass is higher when using less energy efficient heating systems, but such systems considerably increase the space heating primary energy use. The life cycle primary energy balance of the studied wood-frame building was lower than that of the concrete-frame alternative, primarily because of the lower production primary energy use and greater bioenergy recovery when using wood framing material. These advantages more than outweigh the energy saving benefits of thermal mass. The production phase primary energy balance approximately doubles when the buildings are constructed with concrete frames rather than wood. The recovery of biomass residues during the production and end-of-life phases completely offsets the primary energy used for production of the buildings. Significant quantities of biomass residues are produced, because of the use of wood framing material. The operation phase dominates the life cycle primary energy use, but to a lesser extent when buildings and supply systems are energy-efficient; such efficiency increases the relative importance of the other life cycle phases and the choice of framing material.

7.2 Building energy-efficiency standards

The building energy-efficiency standards analysis shows the importance of a life cycle primary energy perspective and the choice of heating system in reducing primary energy use in the built environment. The specific final energy use for a district heated building built during the regime of the BBR 1994 is at least twice as

high as that permitted for a new electric heated building built to the BBR 2009 or the Passivhus. The Passivhus building with district heating achieves 30% lower life cycle primary energy use than one with electric heating, emphasizing the importance of heat supply system. The primary energy use of buildings is significantly lower if the energy supply is based on BIGCC rather than BST technology. This result suggests that efficient energy supply systems are of great importance for a low energy building and should be an integral part of the effort to create a low energy built environment. As building energy-efficiency standards continue to improve, strategies to reduce the production primary energy use will become more important. The primary energy use related to household electricity dominates the operation primary energy use for the buildings, but the BBR 2009 and Passivhus currently do not consider household electricity use. In the district heated buildings about two-thirds of the primary energy use for operation is due to household electricity. Incorporation of a household electricity standard in future building energy-efficiency standards would further reduce overall primary energy use in the built environment.

7.3 Energy efficiency retrofit measures

Retrofitting a building to passive house standards reduces final energy use, but the primary energy significance of this change largely depends on the type of energy supply system. A significant reduction in life cycle primary energy use is achieved when an electric resistance heated house is retrofitted to the passive house standard while retrofitting a district heated house achieves a much lower reduction because of the high energy efficiency of the district heating supply.

Retrofitting the initial building to passive house standards increases primary energy use for building production, but the operation primary energy savings have an energy pay-back period of less than 4 years. The primary energy used for building production is largely offset by the recovery of biomass residues during the production phase and the end-of-life recovery of demolition wood and steel.

The primary energy savings for the different energy efficiency measures depend on the energy supply system. Therefore, the interaction between individual measures and the energy supply system needs to be considered—in particular, the electricity use for ventilation heat recovery together with district heating with a large share of CHP production. Both demand and supply sides, as well as their interaction, need to be analyzed in order to minimize the primary energy use of district heated buildings.

The primary energy savings of VHR can be very significant, depending on the type of heat supply system, the airtightness of buildings, and the increased use of electricity to operate the VHR system. The greatest savings are achieved when VHR is installed in a resistance heated building. However, less primary energy savings are achieved when the VHR is installed in CHP-based district heated buildings. VHR provides much less primary energy savings for district heated building with large share of CHP. For district heating systems mainly based on CHP, the reduced heat demand reduces the potential to cogenerate electricity and is more significant for efficient energy supply technology.

7.4 Life cycle carbon balance and carbonation

Carbonation uptake during the service life and post-use phase is less than that of other carbon flows such as fossil fuel emission from material production and the replacement of fossil fuel by biomass residues. The carbonation of concrete is underestimated if the post-use phase of concrete is not considered. However, carbon emission from fossil fuels used to recover the post-use concrete is higher than the uptake from carbonation during the four months' exposure of the crushed concrete to air. The carbon emission during construction is much higher for the concrete-frame building than for the wood-frame building. The post-use phase of the buildings gives a carbon benefit, mainly because of replacement of fossil fuel by recovered demolition wood while the concrete carbonation benefit during the service

life is small. In the post-use phase the wood-frame building has a slightly higher carbon benefit compared with the concrete-frame building.

The carbon benefit in the post-use phase is substantially greater than the carbon emissions in the construction stage for the wood-frame building, giving a life cycle net carbon benefit to the wood-frame building, but not the concrete-frame building. This is mainly because the wood-frame building has lower emissions from fossil fuel and cement calcination and because it provides a greater amount of biofuel to replace fossil fuel.

The emission difference between the wood and concrete buildings is sensitive to how forest land-use is considered in the analysis. The results of this study show that a wood-framed building has substantially lower life cycle carbon emissions than a concrete-framed building, even if the carbon benefit of end-of-life concrete management is included.

7.5 Uncertainties

Uncertainties in parameters inherent in different life cycle activities may affect the primary energy and carbon balances of a building. These uncertainties may be due to lack of precise knowledge about parameter values or to choices at the methodological, technological or geographical level. For example, the specific primary energy use for building material production may vary, as different geographical regions and plant may use different production technologies and primary fuels. Steel building materials may also be produced from ore or scrap iron, and recovered steel material may substitute ore or scrap iron. Sensitivity analyses were performed in Papers I, II, IV and VI to determine the effects of uncertainty and variability on the results. The parameters explored relate to production of steel, recycled steel substitution, building life span, indoor air temperature, choice of energy supply systems, type of fossil fuel to be substituted by recovered biofuel, land-use modeling approach, handling options for end-of-life materials, exposure

conditions of crushed concrete and their influence on carbonation, and potential truncation errors resulting from a bottom-up modeling approach. Assumptions relating to energy supply systems were also varied in Papers III and V to show the usefulness of the findings. The uncertainty analyses show that the conclusions of the studies are robust.

8. Future works

Increasingly, measures to reduce building envelope heat losses are being implemented and buildings are becoming more airtight. These measures may be associated with a potential risk of overheating and increased cooling demand, particularly in summer periods. Studies using hour-by-hour dynamic modeling may be useful to investigate the implications of this change on operation energy use and the life cycle environmental impacts of buildings. Emphasis may be placed on the role of thermal mass in overheating and cooling load reductions. The analysis on the effect of thermal mass in Paper II could be further expanded to explore how the heat storage capacity of building systems interacts with heating systems and how quickly a heating system can respond to temperature variation. More studies could be conducted to increase understanding of how climate change may affect life cycle primary energy and environmental performance of buildings.

District heating and cogeneration systems have been recognized as important parts of an overall strategy to reduce the environmental impact of buildings in Europe. The economic viability of these systems often depends on heat density, and therefore, reduced final heat demand in buildings may be a concern for such systems if there are no capacity constraints. Increasingly, policies are being implemented to drive buildings with lowest possible energy use and at the same time encourage increased use of district heating and cogeneration systems. The recast EU Directive on Energy Performance of Buildings requires all new buildings to be nearly zero-energy from 2020 and suggests that the feasibility of alternative energy-efficient supply systems including district heating should be considered for buildings. The EU directive on promotion of cogeneration based on a useful heat demand in the internal energy market is expected to promote cogeneration systems and may have significant impacts on the expansion of district heating systems. The results of Paper IV show that it is important to design district heat and cogeneration production systems based on long-term heat demands, in order to avoid unnecessarily high

costs and primary energy use. Extensive studies are necessary to explore how district heat and cogeneration systems may be optimized and made economically competitive for buildings in the near future. The implementation of energy efficiency measures in a significant share of the district heated building stock may affect the heat density and the profile of the heat load duration curve. The methodological approach used in Paper IV could be further developed to investigate the implications of this issue.

Research efforts and policy instruments to reduce environmental impact of buildings have largely focused on final heat reduction measures, and have encouraged buildings with low space heating energy. Electricity for household management is becoming increasingly important, and strategies to reduce this may be a focus of future studies.

The energy used for moisture drying of concrete elements and the resulting CO₂ emissions were not analyzed in the comparative analysis of the concrete- and the wood-frame buildings. This may have resulted in underestimation of the primary energy use and carbon emission of the concrete building. Nevertheless, the wood building has lower primary energy use and carbon emissions than the concrete building. The energy for moisture removal from concrete elements is increasingly understood to be significant and should be considered in future studies.

Modern wood construction techniques have been developed to design and construct more energy efficient multi-story wood-frame buildings with improved fire, hygrothermal and structural performances. Recent experience also shows that wood multi-story buildings can be economically competitive with alternative building systems. There are different wood construction systems and it may be of further interest to explore how these systems may be optimized from life cycle primary energy, carbon emission and cost perspectives at the same time.

There is a need to update and improve the data on specific energy use for building material production in Europe. Most comprehensive data on specific energy

use for building material production were compiled in the mid- and late 1990s. Some recent data have been reported from individual industrial sectors, but comprehensive data covering the entire building material industry have not been reported.

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