Life Cycle Primary Energy Use in Buildings of High Energy Standards

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ABSTRACT

In this study, we examine the life cycle primary energy use of buildings. Our analysis starts with a conventional timber-frame building. We maintain the architectural design, but alter the thermal properties of the envelope components and include heat recovery of ventilation air to achieve buildings with similar thermal properties as three existing passive house in Sweden. We also vary the building frame material from timber to concrete, and the heat supply system between district heating and electric resistance heating. We then follow the life cycle of the buildings, analyze and compare their life cycle primary energy use, including the production, operation and end-of-life energy uses. The results show that the life cycle primary energy use of a passive house building is substantially lower when it is constructed with a timber instead of a concrete frame and heated with district heating instead of electricity. A passive house with electric heating does not achieve lower primary energy use than a conventional house with district heating. Material production accounts for a relatively large share of the life cycle primary energy use in passive standard buildings, and is proportionally more significant if the heat supply is from district heating. Material choice is thus relatively more important as buildings become more energy efficient and energy-efficient heat supply systems are used.

Introduction

Buildings account for a large share of the primary energy use globally, and the building sector offers significant potential to reduce primary energy use and thereby reduce CO_2 emission (IPCC 2007). Several strategies including the construction of high energy standard buildings can be used to realize this potential. Passive house construction is one approach to achieve high energy standard buildings. A key goal of the passive house standard is to minimize the final energy demand for space heating. Primary energy use is also considerably reduced in passive houses. For example, results from the CEPHUS project suggest that about 50% reduction in the operating primary energy is achievable in passive houses (Feist et al. 2005). Maximum final energy demand for space heating of 15 kWh/m^2-year, and maximum overall operating primary energy use of 120 kWh/m^2-year is required to comply with the European passive house standard (UNEP 2007). Measures to achieve the passive standard include improved thermal envelope and heat recovery from ventilation air. Envelope and ventilation heat losses dominate heat losses in buildings. Therefore, by improving the thermal envelope and recovering heat in ventilation air the heating load needed to maintain a comfortable indoor environment is reduced, and hence the energy need for space heating (IEA 2003).

It is possible to design a building's thermal envelope (walls, doors, windows, roof, foundation) in different ways to achieve the passive house standard. However, the design options may have potentially different life cycle primary energy implications. The life cycle of a building includes the extraction of raw materials; the processing of raw materials into building materials; the assembly of materials into a ready building; the occupation or use; the maintenance, and the demolition of the building as well as the disposal or re-use of the materials. Transport of materials is involved in several phases. The concept of life cycle primary energy is used to denote the energy needed over a building's life cycle in order to generate the final energy service, including inputs and losses along the energy chains.

All the processes along the energy chain, from the extraction of raw material to refining, transport, conversion to heat and electricity and distribution to the user can be performed with different energy efficiency and with varying emissions. All the energy input and emissions from these processes need to be included for a full description of a particular energy system.

The purpose of this study is to analyze the life cycle primary energy use of buildings with different passive house thermal envelope components. Our analysis includes the primary energy use during the production, operation and end-of-life phases of the buildings. We evaluate the impact of building material and heat supply system choice on the life cycle primary energy use of the buildings.

Method

Our study begins with a reference 4-storey timber-frame building with 1190 m^2 heated floor area and 16 apartments, and final space heat use of 70 kWh/m^2-year. The building was constructed around 1995 in Växjö in southern Sweden. This building is shown in Figure 1.

Figure 1. Reference 4-Storey Timber Frame Building in Växjö, Southern Sweden

Using this building as a control we modeled the changes, including the addition of a ventilation air heat exchanger and the alteration of the thermal envelope characteristics, to achieve buildings with envelope components similar to three different existing passive houses in Sweden. We chose these types of components as they exist in real passive house constructions. The passive houses considered are situated in Lindås, Glumslöv and Lidköping and we denote them after their locations. We selected these passive houses because they have some different thermal envelope characteristics, but similar final space heating demand. Details of the design and thermal envelope characteristics of these passive houses are documented by Janson (2008).

Table 1 shows the thermal envelope characteristics and final space heat use of the buildings modeled using the ENORM software (EQUA, 2004).

Table 1. Characteristics of the Reference and the Three Passive Buildings

Description	Reference	Lindås	Glumslöv	Lidköping
Floor U-value (W/m^2 K)	0.23	0.11	0.10	0.09
Wall U-value (W/m^2 K)	0.20	0.10	0.10	0.09
Window U-value (W/m^2 K)	1.9	0.85	0.90	0.94
Door U-value (W/m^2 K)	1.19	0.80	0.90	0. 60
Roof U-value (W/m^2 K)	0.13	0.08	0.08	0.07
Airtightness (l /m^{2}s) at 50 Pa	0.8	0.3	0.3	0.3
Heat recovery efficiency (%)	-	83	83	83
Final space heat use (kWh/m^2)	70	15	15	14

The Lindås house has the lowest window thermal transmittance while the Lidköping house has the lowest floor, roof, door and wall thermal transmittance. The thermal transmittance values for the envelope components in the Glumslöv house are somewhat similar to the Lindås house except for windows and doors. The walls and doors in Glumslöv house have slightly higher thermal transmittance.

In addition to varying the thermal characteristics of the reference building, we also modeled the use of different construction materials for the building frame. We analyzed a functionally-equivalent building that is made with a reinforced concrete frame instead of a timber frame, based on data (Table 2) from Sathre (2007).

Table 2. Quantities of Materials (Tonnes of Air-Dry Material) Contained in the Reference Timber-Frame and Concrete-Frame Buildings

Material	Timber-framed building	Concrete-framed building
Concrete	223	1,352
Blocks	4	4
Mortar	24	23
Plasterboard	89	25
Lumber	59	33
Particleboard	18	17
Plywood	21	20
Steel	16	25
Copper/Zinc	0.6	0.6
Insulation	21	10
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

We quantified the primary energy use during the production, operation and end-of-life phases of the buildings. The production primary energy use encompasses the energy to acquire, process, transport and assembly the building materials, and potential bioenergy recovered from biomass residues in the wood product chain. Our assessment took into account material losses during production and construction. The final energy to manufacture the building materials was estimated using data from Björklund & Tillman (1997) and Björklund, Jönsson & Tillman (1996) on specific final energy for building material production in Sweden. For steel we assumed that the production is based on 50% ore and 50% scrap steel. The specific final energy for production of selected materials is listed in Table 3.

Table 3. Specific Final Energy ($kWh_{end\ use}/kg$) 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 production final energy use was converted to primary energy using fuel cycle loss values of 10% for coal, 5% for oil and 5% for natural gas (Gustavsson, Pingoud & Sathre 2006). Electricity used for material production was assumed to be produced in coal-fired condensing plant, with conversion efficiency of 40% and distribution loss of 2%. The primary energy use to assemble the building material was 50 kWh/m^2 for the reference timber-frame building and 100 kWh/m^2 for the reference concrete-frame building, based on Adalberth (2000). We assumed that the primary energy use to assemble the building material for the passive buildings is proportionally equal to the primary energy use to assemble the building materials for the reference building of similar frame, weighted by the relative amounts of primary energy for material production. The assessment of the distribution of biomass residues available from the wood product chain was based on Lehtonen et al. (2004) and Sathre (2007).

We considered operation primary energy use for space heating, ventilation, domestic hot water heating and household electricity. The final energy used for space heating and ventilation is modeled using the ENORM software (EQUA 2004). This program calculates the final energy use based on the building's characteristics including the heated floor area, U-value of envelope measures, glass areas, orientation, location and climate, heating and ventilation supply systems and indoor temperature. The software also takes into account the heat gains from lighting, appliances, human bodies and solar radiation. We assumed an indoor temperature of 22^{o}C and used climate data for Växjo in southern Sweden. The calculations of final energy use for heating domestic water and household electricity were based on the following standard equations from Swedish National Board of Housing, Building and Planning (Boverket 2003):

$$E_{\text{water heating}} = 1800 \text{ x number of apartments} + 18 \text{ x heated area } [m^2]$$
$$E_{\text{household electricity}} = 2200 \text{ x number of apartments} + 22 \text{ x heated area } [m^2]$$

where $E_{\text{water heating}}$ = final energy use for domestic hot water (kWh), and $E_{\text{household electricity}}$ = final electricity for household lighting and appliances (kWh). Energy-efficient hot water taps will give about 40% reduction in final energy use for domestic water heating (Swedish Energy Agency 2006).

Based on the operation final energy use, we calculated the operation primary energy use using the ENSYST software (Karlsson 2003). This software estimates primary energy use taking into account the entire energy chain from natural resources extraction to supply of final energy. We used the software's default assumptions regarding the source, production and transport of primary fuels. We considered electric resistance heating and district heating. For the electric resistance heating, 95% of the electricity was assumed to be supplied from stand-alone plant using biomass steam turbine (BST) technology and the remaining from light-oil gas turbine. We assumed that the district heat is supplied from a combined heat and power (CHP) plant using BST technology. We assumed that the CHP plant accounts for 85% of the district heat production and light-oil boilers account for the remainder (Gustavsson et al. 2010). Table 4 provides a summary of key data input used in the ENSYST software for the primary energy analysis. We allocated the cogenerated electricity using the subtraction method, assuming that the cogenerated power replaces electricity that would instead have been produced in a stand-alone plant using the same fuel and technology as the CHP plant (Gustavsson & Karlsson 2006).

Table 4. Capacity and Efficiency of the Power Plants, Cogeneration Plants and End-Use Heating Technologies

Technology	Capacity	Efficiency
Stand-alone power plants:	(MW_{elec})	(η_{elec})
BST	200	0.47
Light-oil gas turbines	120	0.27
Cogeneration plants:	(MW_{elec}/MW_{heat})	(η_{elec}/η_{heat})
CHP-BST	36/72	0.3/0.60
End-use heating:		(η_{heat})
District heating		0.95
Resistance heaters		0.97

We assumed that the buildings are demolished at the end of their assumed 50-year lifespan. The end-of-life primary energy use was calculated as the net primary energy used to disassemble, transport and recover the building materials as well as the energy benefits from recycling and recovering the end-of-life material (Dodoo, Gustavsson & Sathre 2008). The primary energy to demolish the reference building was taken to be 5 and 10 kWh/m^2 for the timber-frame and concrete-frame buildings, respectively (Adalberth 2000; Dodoo, Gustavsson & Sathre 2008, 2009, 2010). We assumed that the demolition primary energy use for the passive buildings is proportionally equal to the demolition primary energy use for the reference building of similar frame, weighted by the relative amounts of material production primary energy use. The end-of-life concrete and reinforcing steel were assumed to be recycled while bioenergy was assumed to be recovered from the wooden material. We assumed that 90% of each material becomes recycled or recovered for energy. The steel and concrete were assumed to be recycled into feedstock, replacing ore-based steel and crushed granite, respectively. The final energy for crushing a tonne of concrete was taken to be 24.4 kWh of oil and 2.5 kWh of electricity (Pommer & Pade, 2005). The diesel fuel used to transport a tonne of demolished concrete was taken to be 7.8 kWh (SIKA, 2002). The energy benefit of recycled steel was calculated using data from Björklund and Tillman (1996). The diesel fuel used to recover and transport the demolished wood was taken to be 1% of the lower heat energy content of the wood (Gustavsson, Pingoud & Sathre 2006).

The lag effect of thermal mass can affect the energy use for space heating, but this depends on the climatic location of buildings and the adequacy of their insulation (Oak Ridge National Laboratory 2001). Norén et al. (1999) analyzed the effect of thermal mass on the final space heating demand in functionally equivalent concrete and timber buildings located in the northern European climate. They found the effect of thermal mass to be minor where the buildings have ample insulation with plasterboard. As the buildings analyzed here have ample insulation, we expect the effect of thermal mass to be minor. In this analysis we did not include the energy to remove the moisture in the buildings after the construction stage, which would increase the primary energy use linked to the production of the buildings, particularly for concrete-frame buildings.

Results

Table 5 summarizes the production primary energy use of the buildings. Negative numbers denote energy that is available from recovered biomass residues. The timber-frame alternatives have lower production primary energy use and higher bioenergy recovery. The production primary energy balance for the timber-frame buildings is about 50 % lower than for the concrete-frame alternatives.

Table 5. Primary Energy Balance (kWh/m²) During the Production Phase of the Buildings

Description	Timber frame				Concrete frame			
	Reference	Lindås	Glumslöv	Lidköping	Reference	Lindås	Glumslöv	Lidköping
Material production	579	650	648	661	757	825	823	833
Material assembly	50	56	56	57	100	109	109	110
Biofuel recovery	-345	-355	-355	-357	-208	-217	-217	-219
Total	284	345	343	354	649	708	706	714

In Figure 2 the production primary energy is compared to the space heating and ventilation primary energy. In the reference building, primary energy for space heating and ventilation is dominant, and is substantially greater with electric resistance heating. For the passive house standard buildings with electric resistance heating, primary energy used for space heating and ventilation is still substantial. The production primary energy required to achieve the passive house standard is lower for the timber alternatives compared to the concrete alternatives.

Figure 2. Primary Energy Use for Production and Space Heating During the Service Life of the Timber-Frame and Concrete-Frame Buildings

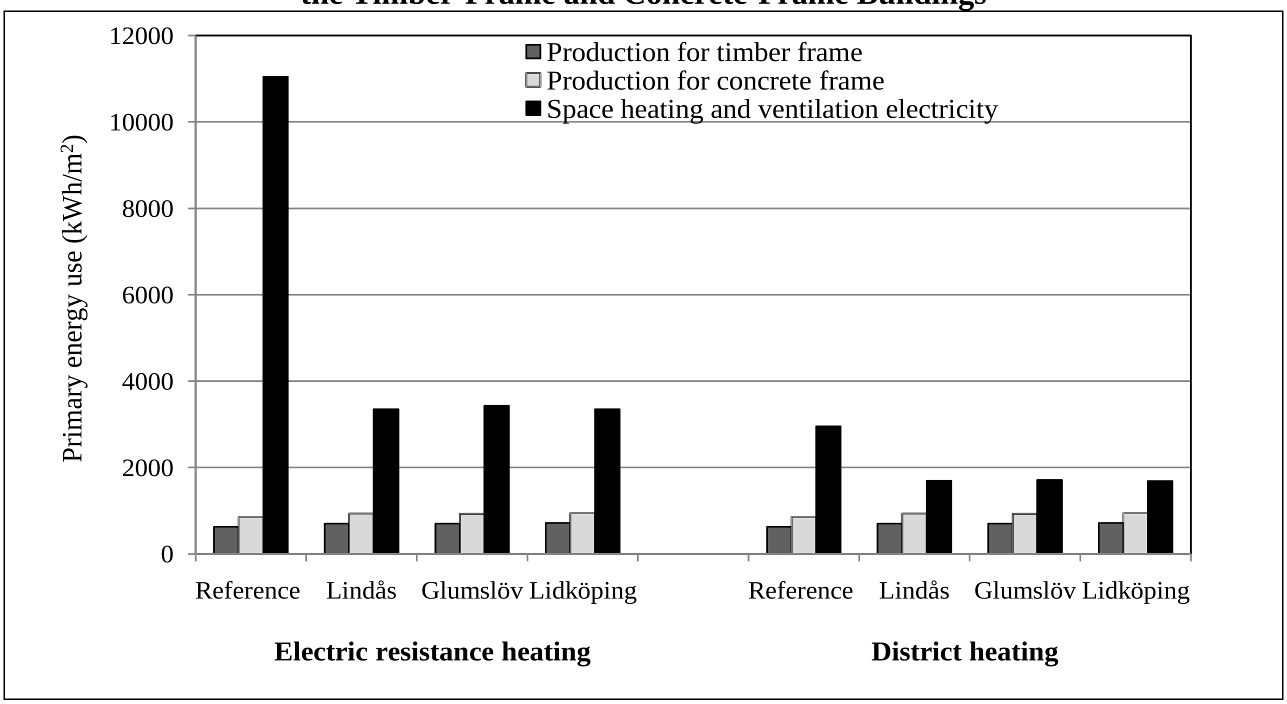

Table 6 shows the operating primary energy used during the 50-year lifespan of the buildings. The space heating primary energy use for the reference building with district heating is lower compared to the passive houses with electric resistance heating. This suggests that the heat supply system is important. The primary energy use for tap water heating and for household and facility electricity constitutes a significant part of the operation energy, but these demands depend to a large extent on the users and not on the construction. Household electricity accounts for the greatest share of the primary energy for operation in the passive houses and is proportionally more significant for the district heated buildings.

Table 6. Operation Primary Energy Use for the Buildings (kWh/m^2) for 50 Years

	Electric resistance heating				District heating			
Description	Reference	Lindås	Glumslöv	Lidköping	Reference	Lindås	Glumslöv	Lidköping
Space heating	10450	2158	2240	2156	2355	500	518	491
Ventilation electricity	597	1194	1194	1194	597	1194	1194	1194
Domestic hot water	5971	3583	3583	3583	1241	744	744	744
Household electricity	7763	7763	7763	7763	7763	7763	7763	7763
Total	24781	14698	14780	14696	11955	10201	10220	10192

The primary energy balance for the end-of-life of the buildings is shown in Table 7. Negative numbers mean that net primary energy benefit is achieved through recovering the end-of-life materials. The timber-frame buildings give greater end-of-life primary energy benefit than the concrete alternatives. Energy recovery from wood gives large primary energy benefit, but less benefit is achieved through recycling the concrete. The primary energy benefit through recycling of concrete or steel are similar for all buildings with the same type of frame material, as the quantities of concrete or steel do not differ between the buildings.

Table 7. Primary Energy (kWh/m^2) Balance for the End-of-Life Phase of Buildings

Description	Timber frame				Concrete frame			
	Reference	Lindås	Glumslöv	Lidköping	Reference	Lindås	Glumslöv	Lidköping
Disassembly	5	6	6	6	10	11	11	11
Concrete recycling	-3	-3	-3	-3	-19	-19	-19	-19
Steel recycling	-60	-60	-60	-60	-96	-96	-96	-96
Wood recovery for energy	-305	-311	-311	-313	-214	-219	-219	-220
Total	-363	-368	-368	-370	-319	-323	-323	-324

Table 8 shows the total life cycle primary energy use, including the production, operation and end-of-life phases. The life cycle primary energy use is lower for the district heated compared to electric resistance heated buildings, and for the timber frame compared to the concrete frame buildings. Electric resistance heating instead of district heating increased the life cycle primary energy use by 30-31% for the passive standard buildings and for the reference building by 51-52%. The passive standard buildings with timber framework have 2-4% lower life cycle primary energy use compared to those with concrete frame.

Table 8. Total Life Cycle Primary Energy Use (kWh/m²) of the Buildings

Description	Electric resistance heating		District heating	
	Timber frame	Concrete frame	Timber frame	Concrete frame
Reference	24703	25112	11876	12286
Lindås	14676	15084	10179	10586
Glumslöv	14754	15162	10195	10603
Lidköping	14680	15086	10176	10582

When heat is supplied by electricity, the Lindås alternatives have the lowest life cycle primary energy use. However, the Lidköping alternatives have the lowest life cycle primary energy use if the reference heat is supplied by district heating. Thus the design combination that achieves the lowest life cycle primary energy use is also influenced by which heat supply is the reference. But the variations in the total life cycle primary energy use resulting from the different passive house thermal envelope designs are very minor.

Discussion

We have analyzed the life cycle primary energy use of buildings with identical designs besides different thermal envelope characteristics and frame materials to reach passive house standard. We found that the primary energy use is lower for timber-frame than for concrete-frame building, supporting the findings of Gustavsson & Sathre (2006) and Sathre (2007). Passive house standard buildings with district heating have substantially lower life cycle primary energy use than those with electric resistance heating. This confirms the finding of Gustavsson & Joelsson (2008). The lowest life cycle primary energy use is achieved through timber-frame buildings with district heat supply.

The Lidköping example gives the lowest thermal envelope losses but not always the lowest life cycle primary energy. The primary energy ranking of the passive houses varies, depending on the heat supply source. But the variations in primary energy use between the different passive house standard buildings are very minor when the same heating system and framework is used.

This analysis confirms that primary energy for material production becomes increasingly important as the energy standard of buildings improves (Sartori & Hestnes 2007). Our results show that the primary energy for production is less than half that for space heating with electric resistance heating. With district heating, however, the primary energy used for production is greater than that for space heating for the 50-year service life. Thus, the relative importance of primary energy for material production increases with more energy-efficient heat supply systems as suggested by Gustavsson & Joelsson (2010).

This analysis shows that significant primary energy savings can be achieved by constructing buildings with high energy standards with timber frames and by using energy-efficient heat supply systems. An important strategy to promote such buildings is the refurbishment of existing buildings to achieve the passive house standard, as addition of new buildings to the dwelling stock in Europe is low. It has been suggested that tighter energy demand requirement be imposed for electric heating so that only passive houses are permitted (SEAC 2004). Although this is beneficial, we have found that passive house standard buildings with electric heating do not perform better than conventional buildings with district heating, from a primary energy perspective. If minimizing primary energy use is a goal for constructing passive houses, district heating should be encouraged in passive houses when possible and electric resistance heating should be avoided. In summary, timber-frame passive house standard buildings with energy-efficient heat supply reduce the life cycle primary energy use. The diffusion of such buildings and heating systems may therefore be encouraged. For example, measures that provide incentives for, and eliminate barriers against, passive house with timber frame may be instituted. Sathre & Gustavsson (2009) showed that carbon damage cost of €92/t C and €260/t C corresponding to the 550 ppm and the Business as Usual emission scenarios by Stern (2006) increase the economic competitiveness of timber construction relative to concrete construction. Carbon cost will also increase the competitiveness of efficient energy and renewable energy supply (Sathre & Gustavsson, 2007; Gustavsson et al. 2010), as well as the competitiveness of energy-efficient buildings. The development of standards for timber construction on the regional scale is also crucial for the diffusion of timber-frame buildings. Mahapatra & Gustavsson (2008) have analyzed the diffusion of multi-storey timber-frame buildings in Sweden and have discussed these issues further.

Conclusions

The variations in the life cycle primary energy use resulting from the different passive house thermal envelope designs are minor. Buildings meeting the passive standard using electric heating do not achieve lower life cycle primary energy use than conventional buildings with district heating. Thus the choice of heat supply system is as important as final heat reduction measures. Primary energy use for material production accounts for a relatively large share of the life cycle primary energy use over a 50-year lifespan, in passive standard buildings. If the heat supply for passive house is from district heating, the primary energy used for material production is greater than for space heating for 50 years. Material choice is thus relatively more critical as buildings become more energy efficient through the application of passive house standard envelope and the use of more efficient heat supply systems.

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