Life-cycle primary energy implication of the new Swedish Building Code

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Abstract

In this study we analyze the life-cycle primary energy use of apartment buildings made with wood- and concrete-frames, and built to meet either the Swedish building code of the mid-1990s or the maximum energy use standard of the new Swedish code (BBR 09). The analysis includes the primary energy use during the production, operation and end-of-life phases. Scenarios are analyzed in which the buildings are heated by district heating or electric resistance heating. We find that an electric resistance heated building built to the new code has greater life-cycle primary energy use relative to a district heated building, although the standard for the electric heating is more stringent. Making an electric resistance heated building to the new code's standard instead of the mid-1990s standard results in a large reduction in primary energy use. However, relatively little primary energy use reduction is achieved if a district heated building is made to the new standard instead of the old standard. Still, the primary energy use is on average 20-34% higher for the electric heated buildings than the district heated buildings. The wood-frame buildings have significantly lower production primary energy and also give greater end-of-life benefit than concrete-frame buildings. The primary energy for production is small relative to that for operation, but it is more significant for the district heated buildings.

Introduction

The building sector offers large energy savings potential (IPCC 2007). Several strategies, including energy efficiency standards in building codes, can be used to realize this potential. Building codes can specify minimum energy performance requirements for design and construction, and in some cases refurbishment, of buildings. Energy efficiency standards in building codes can be important instruments for the development of an energy-efficient built environment. Energy efficiency measures may be implemented at any time in a building's service life, but some energy efficiency measures are more cost-effective when implemented at the construction and refurbishment stages (IEA 2008).

In Sweden, a new building code (BBR 09) was introduced in February 2009. A key goal of this code is to further improve the energy efficiency of new buildings, particularly those heated with electricity. The code specifies standards for the specific energy use and overall envelope thermal performance for buildings. The specific energy use encompasses the delivered energy use for space heating, domestic hot water and electricity for fans and pumps but excludes electricity for household appliances and lighting. The specific energy use standard for buildings varies with climatic zones (I, II, III), and if electric resistance or non-electric resistance heating is used. The maximum specific end-use energy for electrically heated dwellings are 95, 75 and 55 kWh/m^2 year for the climate zones I, II and III, respectively. For non-electric resistance heated houses, the corresponding values are 150, 130 and 110 kWh/m^2 year, respectively. Also, the average U-value for the whole building envelope must not exceed 0.40 and 0.50 W/m^{2}K for electric resistance and non-electric heated buildings, respectively. Different U-values and energy performance requirements are given for dwellings

Table 1. Envelope thermal properties, ventilation and water heating systems in the buildings analyzed

Description	Original buildings (mid 1990s buildings)	BBR 09 district heated buildings	BBR 09 electric heated buildings
Ground floor	U= 0.23 W/m^{2}K	U= 0.23 W/m^{2}K	U= 0.20 W/m^{2}K
External walls	U= 0.20 W/m^{2}K	U= 0.20 W/m^{2}K	U= 0.10 W/m^{2}K
Windows	U= 1.9 W/m^{2}K	U= 1.2 W/m^{2}K	U= 1.0 W/m^{2}K
Doors	U= 1.19 W/m^{2}K	U= 1.19 W/m^{2}K	U= 1.0 W/m^{2}K
Roof	U= 0.13 W/m^{2}K	U= 0.13 W/m^{2}K	U= 0.10 W/m^{2}K
Ventilation system	Mechanical ventilation for exhaust air	Mechanical ventilation for exhaust air	Mechanical ventilation with heat recovery
Hot water tap	Conventional	Conventional	Energy-efficient

with floor areas less than 100 m^2, window and door area less than 20% of floor area and no cooling needs.

While the improved energy efficiency in buildings will further reduce the operation energy use, the energy use in other life-cycle phases has not been explicitly considered in the building code. The operation energy is dominant in conventional buildings, so constructing buildings with low operating energy use is important (Scheuer et al. 2003; Keoleian et al. 2001). However, focusing only on optimizing the delivered energy performance in the operation phase may result in potential trade-offs in other life-cycle phases. For example, Feist (1997) found that strategies to reduce operation energy use do not necessarily reduce total life-cycle primary energy use. The energy for building production becomes increasingly important as measures are applied to reduce the operation energy use (Sartori and Hestnes 2007; Thormark 2002). Also, studies suggest that it is essential to take a primary energy perspective when analyzing the energy use to operate buildings rather than focusing solely on end-use energy. For example, Gustavsson and Joelsson (2008) found that an electrically heated passive house and a district heated conventional house had comparable primary energy use for operation, due to greater energy supply chain losses for the electric heating. Thus, a system-wide life-cycle perspective is needed to reduce the overall primary energy use in buildings.

In this study we analyze the life-cycle primary energy use of wood-frame and concrete-frame buildings, heated with district heat or electricity, and built to meet the energy use standard of either the mid-1990s building code or the new Swedish building code (BBR 09). We employ a life-cycle perspective and calculate the overall primary energy use to produce, operate and demolish the buildings, and we analyze the primary energy savings resulting from following the new building code.

Case study buildings

This study is based on a 4-storey apartment building, constructed with wood-framework, with a total heated floor area of 1190 m^2 and containing 16 apartments. It was built during the mid-1990s in Växjo, Sweden, in the climate zone III. We also consider a functionally identical version of the building with a concrete framework. We modified the properties of the thermal envelope of the original buildings but the original and the modified buildings have similar architectural characteristics. The thermal envelope properties, and types of ventilation systems and hot water taps used in the buildings are shown in Table 1.

Methodology

We calculate the life-cycle primary energy use including the production, operation and demolition of the buildings. The energy use for maintaining the buildings is not included and is expected to be minor compared to the other life-cycle energy uses. The activities included in this analysis are shown in Table 2.

PRODUCTION PHASE

The material mass inputs of the buildings, taking into account material losses during the construction process, are shown in Table 3.

Argon infill gas and low-e coating are used to make the windows in the case of the BBR 09 district and electrically heated buildings. The mass of the argon and low-e coating are relatively small but the primary energy used in their production is significant, is accounted in the calculations.

We calculate the primary energy use to extract, process and transport the materials using the equation:

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

(Sathre 2007)

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

The specific fossil fuel and electricity used to extract, process and transport the materials is based primarily on a Swedish study by Björklund and Tillman (1997). We also use specific energy use data from closely related studies (Björklund et al. 1996; Fossdal 1995; Worrell et al. 1994) where data is not available from Björklund and Tillman (1997). The fuel cycle energy use to extract and transport the energy carriers are taken to be 10% for coal, 5% for oil and 5% for natural gas (Gustavsson and

Table 2. Modeled activities and primary energy flows

Description	Process considered	Primary energy implication analyzed
Production *(year 0)*	Building material extraction, processing and transportation. Construction of building.	Fossil fuel and electricity use for material production. Energy use for on-site erection.
Operation *(year 1-50)*	Operation of buildings.	Energy use for space heating, domestic hot water, electricity for ventilation fan and pumps, and household electricity.
Demolition *(after year 50)*	Demolition of buildings. Recovery and crushing of concrete. Recycling of steel. Energy recovery of wooden material.	Fossil fuel for end-of-life activities - material demolishing, transportation, recovery. Substitution benefit of recycled steel and concrete. Wood residue used as fuel.

Table 3. Quantities of principal materials (tonnes of air-dry material) used in the buildings

Material	Original buildings		BBR 09 district heated buildings		BBR 09 electric heated buildings	
	Wood-frame	Concrete-frame	Wood-frame	Concrete-frame	Wood-frame	Concrete-frame
Concrete	284.4	1724.3	284.4	1724.3	284.4	1724.3
Blocks	4.0	4.0	4.0	4.0	4.0	4.0
Mortar	24.7	23.7	24.7	23.7	25.3	24.3
Plasterboard	98.8	27.8	98.8	27.8	99.4	28.4
Lumber	63.3	35.4	63.3	35.4	65.3	37.4
Particleboard	18.4	17.4	18.4	17.4	18.4	17.4
Plywood	21.6	20.5	21.6	20.5	21.6	20.5
Steel	16.3	25.5	16.3	25.5	16.3	25.5
Copper/Zinc	0.6	0.6	0.6	0.6	0.6	0.6
Insulation	21.5	10.3	21.5	10.3	29.0	17.8
Crushed stone	437.6	437.6	437.6	437.6	437.6	437.6
Glass	4.0	4.0	6.0	6.0	6.0	6.0
Paper	2.0	2.0	2.0	2.0	2.0	2.0
Plastic	2.0	2.0	2.0	2.0	2.0	2.0
Putty/Fillers	4.0	4.0	4.0	4.0	4.0	4.0
Paint	1.0	1.0	1.0	1.0	1.0	1.0
Ceramic tiles	1.0	1.0	1.0	1.0	1.0	1.0
Porcelain	0.6	0.6	0.6	0.6	0.6	0.6
Appliances	3.0	3.0	3.0	3.0	3.0	3.0

Sathre 2006). The end-use electricity to produce the materials is assumed to be produced from a coal-fired plant with a 40% conversion efficiency and 2% distribution loss (Gustavsson and Sathre 2006).

We calculate the primary energy available from recovered biomass residues from forest harvesting, wood processing and construction activities using the equation:

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

(Sathre 2007)

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

We quantify the mass of the residue available from the wood product chain using biomass expansion factors from Lehtonen et al. (2004). We assume the recovery of 75% of available forest residues, and 100% of processing and construction residues. The lower heating value for the biomass residues are from Gustavsson and Sathre (2006): 4253 kWh/oven dry tonne for bark and harvest residues, 4615 kWh /oven dry tonne for processing and 5171 kWh/oven dry tonne for construction residues. The diesel fuel used to recover the forest biomass residues is assumed to be 5% of the lower heat content of the recovered wood (Gustavsson et al. 2006).

The end-use energy to assembly the original version of the buildings is taken as 50 and 100 kWh/m^2 for the wood-frame and concrete-frame building respectively, based on Adalberth's (2000) analysis of the buildings. We assume that energy use for on-site assembly is the same for the mid-1990s buildings and the BBR 09 buildings, since the buildings have largely similar features.

OPERATION PHASE

The delivered energy used for space heating and ventilation was modelled using the ENORM program (EQUA Simulation AB 2004). This program calculates the delivered energy to a building 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 program also takes into account the heat gains from lighting, appliances, human bodies and solar radiation. We assume an indoor temperature of 20°C and use climate data for Växjo, in southern Sweden. We assume a 50-year building operating life in our calculations. The calculations of final energy use for heating domestic water and household electricity are based on the following standard equations from Swedish National Board of Housing, Building and Planning (Boverket 2003):

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

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

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 calculated final energy use for domestic water heating using the Swedish National Board of Housing, Building and Planning's equation is about 76% of new permitted maximum specific energy use of 55 kWh/m² for electric heated building in climate zone III. We assume that energy-efficient hot water taps are used in the BBR 09 electric heated buildings. The final energy used for domestic water heating in this case is calculated using an empirical equation from Janson (2008), who documented experiences in design and construction of several energy-efficient buildings in Sweden:

$$E_{\text{water heating with energy-efficient taps}} \text{ (kWh year)} = 55 \times [12 \text{ x number of apartment} + 80\% \times \{18 \text{ x number of persons}\}]$$

The energy-efficient hot water taps will give about 20% reduction in the *persons-based* part of the equation (Janson 2008). The reference building contains a total of 16 apartments. With 8 of the apartments each having one room and a kitchen, 2 apartments each having two rooms and a kitchen and 6 apartments each having three rooms and a kitchen, we estimate the number of persons living in the building to be 23 using information from Janson (2008).

We consider electric resistance heating with electricity supply from biomass steam turbines (BST), and district heating with district heat from a BST plant cogenerating heat and electricity. We also analyse scenarios where the generating technologies are coal steam turbines (CST), natural-gas combined cycle (NGCC), and biomass-integrated gasification combined-cycle (BIG/CC). We follow Gustavsson and Karlsson's (2006) method and credit the cogenerated electricity to the district heat plant assuming that it replaces electricity produced from a stand alone plant with similar technology and fuel as the cogeneration system. We use the ENSYST program (Karlsson 2003) to calculate the primary energy needed to provide the delivered energy for space heating and ventilation, domestic water heating and household electricity. 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 assumptions regarding the energy used to produce and transport the resources to generate the delivered heat and electricity are based on Gustavsson and Joelsson (2008) and Gustavsson and Karlsson (2002).

END-OF-LIFE PHASE

The buildings are assumed to be demolished by a selective dismantling after their service life. Our analysis considers the energy use to demolish the buildings, and to recover and transport the concrete, wood and steel materials contained in the buildings. We follow Dodoo et al. (2009) method and assume that 90% of each material is recovered. The primary energy to demolish the buildings is assumed to be 10 kWh/m², based on Adalberth (2000). The primary energy implication of the end-of-life concrete is calculated as the primary energy use avoided due to the recovered concrete minus the primary energy used to recover the concrete (Dodoo et al. 2008). The crushed concrete aggregate is considered to be used as filling material, displacing natural aggregate, as recycled concrete aggregate is increasingly used in below-ground applications in Sweden (Engelsen et al. 2005). The end-use energy for crushing a tonne of concrete is taken to be 24.5 kWh oil and 2.5 kWh electricity (Pommer and Pade 2005). The primary energy calculation approach for the end-of-life steel is similar to the end-of-life concrete. In Sweden, the production of steel reinforcement bars is based on scrap steel (Krogh et al. 2001). The delivered energy use for recycling a tonne of steel is taken as 61.2 kWh coal, 80.6 kWh oil, 439.2 kWh fossil gas and 572.7 kWh electricity (Björklund and Tillman 1996). We consider that the demolished wood material is burned as biofuel as this is currently the case in Sweden. We calculate the primary energy benefit from end-of-life wood as the biofuel available for recovery, minus the fossil energy used to recover and transport the wood. We assume that the fuel used is diesel, equivalent to 1% of the lower heating value of the recovered wood (Gustavsson et al. 2006).

Results

PRODUCTION PHASE

The primary energy for the production of the buildings are shown in Figure 1. The wood-frame buildings have lower production energy relative to the concrete-frame buildings. For example, the BBR 09 wood buildings have 23-27% lower production energy relative to the original concrete buildings, suggesting that a wood house built to the new code has substantially lower production energy than a mid-1990s concrete house.

The primary energy available from biomass by-products recovered during the building production stage are 305 and 214 kWh/m², respectively for the original wood and concrete buildings (not shown in figure). For the district heated BBR 09 wood and concrete buildings the values are 315 and 222 kWh/m², respectively. For the electric resistance heated BBR 09 wood and concrete buildings the values are 317 and 225 kWh/m², respectively.

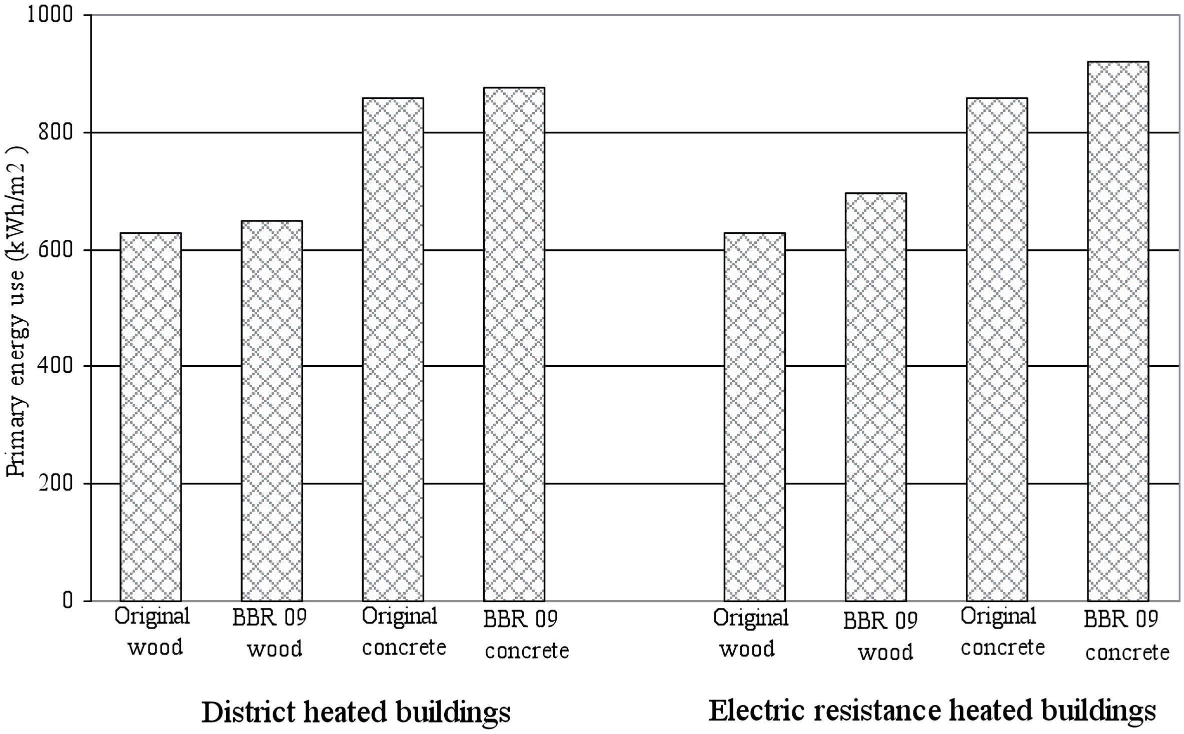

Figure 1. Primary energy use for production of the buildings, including the energy to extract, process, transport and assemble the building materials.

OPERATION PHASE

A significant reduction in primary energy use for operation is achieved when electrically heated buildings are built to the BBR 09 code compared to the mid-1990s standard (Figure 2). The significant primary energy reductions are due to the improved thermal envelope, ventilation heat recovery and efficient water heating measures applied, owing to BBR 09's more stringent standard for electric resistance heated buildings. In contrast, the district heated buildings achieve small reduction in operation primary energy when built to the new code instead of the old standard. The minor operation primary energy reductions achieved by the district heated buildings are due to the relatively small change required to meet the standard, and the relatively low losses in the energy supply system.

Household electricity contributes significantly to the primary energy use for operation. It accounts for about 50 and 70% of the primary energy used for operation in the BBR 09 electric resistance and district heated buildings, respectively. Thus, the primary energy use for household electricity becomes more significant as measures are applied to reduce primary energy use related to heating. The primary energy used for space heating in the electric heated BBR 09 buildings is less than half of that used by the electric heated mid-1990s buildings.

Table 4 shows the total primary energy for building operation, when using the reference biomass-based steam turbines (BST) and alternative energy supply technologies. With district heating using BIG/CC instead of BST technology, overall operation primary energy is reduced by about 20%.

END-OF-LIFE PHASE

Figure 3 shows the primary energy use related to the end-of-life phase of the buildings. Overall, the end-of-life phase gives primary energy benefit. The benefit from energy recovery of demolished wood is most significant, followed by steel recovery. Recovery of demolished concrete gives relatively little energy benefit.

COMPLETE LIFE-CYCLE

The primary energy used over the life-cycle of the buildings for different supply systems is shown in Table 5. A significant reduction of life-cycle primary energy is achieved when an electric resistance heated building is built to the BBR 09 energy use standard instead of the mid-1990 building code. For example, the life-cycle primary energy used in the BBR 09 wood and concrete buildings are 35-36% lower than in the mid-1990s concrete and wood buildings in the electric resistance heated scenario. For the district heated buildings, a life-cycle primary energy reduction of about 2-3% is achieved compared to the mid-1990s buildings. Still, the primary energy use is on average 20-34% higher for the electric heated BBR 09 buildings than the district heated buildings.

For the district and electrically heated buildings, the BBR 09 wood buildings resulted in slightly lower life-cycle primary energy use compared to the BBR 09 concrete buildings. An average life-cycle primary energy savings of about 2% is achieved when the buildings have a wood instead of concrete framework.

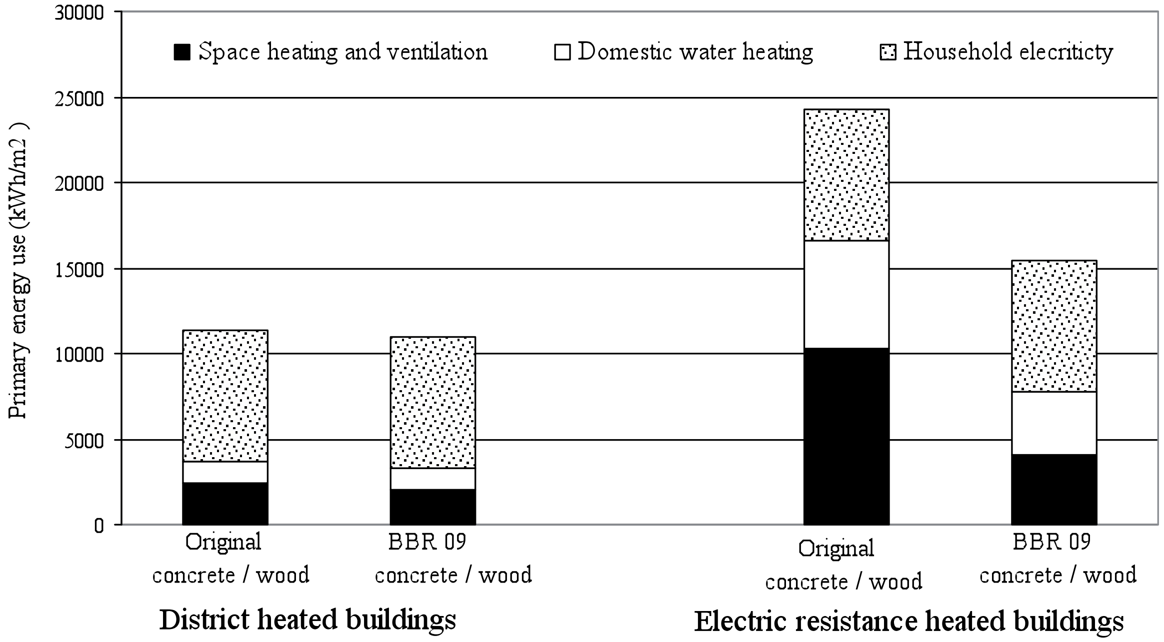

Figure 2. Primary energy use for operation during a service life of 50 years with biomass-based steam turbines supply system (BST).

Table 4. Primary energy use for building operation during a service life of 50 years when using the reference BST and alternative energy supply systems.

Supply system	Building	Total operation primary energy (kWh/m^2)	
		District heated buildings	Electric resistance heated buildings
Biomass steam turbines (reference technology)	Original concrete / wood	11348	24269
	BBR 09 concrete / wood	11016	15424
Coal steam turbines (CST)	Original concrete / wood	10781	20824
	BBR 09 concrete / wood	10400	13234
Natural gas-steam combined-cycle (NGCC)	Original concrete / wood	9169	19139
	BBR 09 concrete / wood	8886	12164
Biomass integrated gasification combined-cycle (BIG/CC)	Original concrete / wood	8947	20919
	BBR 09 concrete / wood	8736	13295

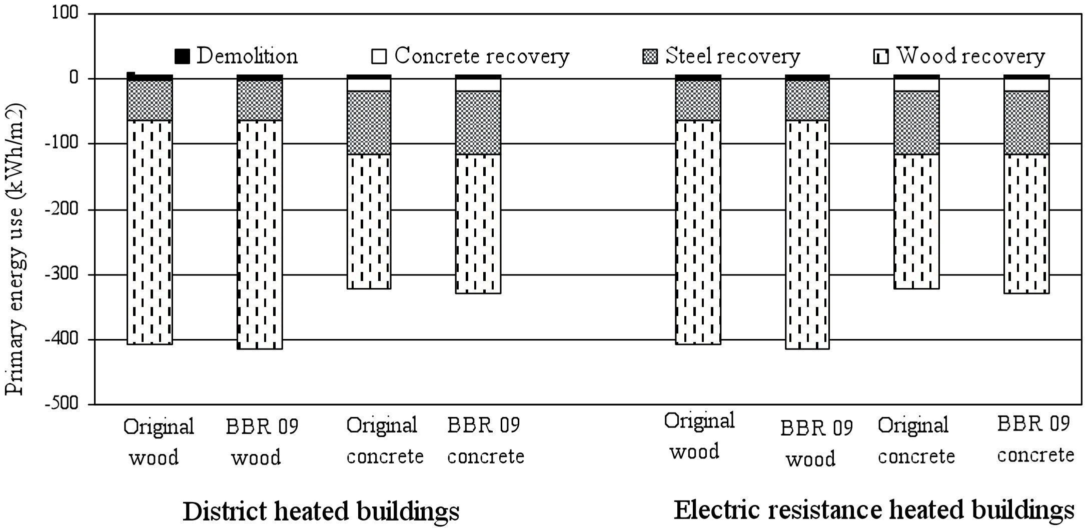

Figure 3. End-of-life primary energy use. Negative values shows primary energy benefits from the energy recovery of demolished wood, and recycling of demolished concrete and reinforcing steel.

Table 5. Life-cycle primary energy use of the buildings, including the primary energy related to the production, operation (for 50 years) and end-of-life of the buildings.

Discription	Total life-cycle primary energy (kWh/m^2)	
	District heated buildings	Electric resistance heated buildings
BST supply system:		
Original wood	11579	24500
BBR 09 wood	11260	15714
Original concrete	11892	24813
BBR 09 concrete	11574	16024
CST supply system:		
Original wood	11011	21055
BBR 09 wood	10644	13525
Original concrete	11325	21368
BBR 09 concrete	10958	13834
NGCC supply system:		
Original wood	9399	19370
BBR 09 wood	9131	12454
Original concrete	9713	19684
BBR 09 concrete	9445	12764
BIG/CC supply system:		
Original wood	9177	21150
BBR 09 wood	8980	13585
Original concrete	9491	21463
BBR 09 concrete	9294	13895

Discussion and Conclusions

A major drive for the updating of the Swedish building code is to impose tighter energy use standards for new electrically heated buildings (SEAC 2004). The new permitted maximum specific energy use is 55 kWh/m^2 in climate zone III if a building is electric resistance heated, or 50% of what is allowed if heated by other means. Our analysis suggests that electrically heated buildings that meet the new code still have substantially higher life-cycle primary energy use compared to district heated buildings. For example, the electrically heated BBR 09 wood and concrete buildings each used 20-34% more primary energy during their life-cycles compared to when the same buildings are instead heated by district heating. Hence, from a life-cycle primary energy perspective the new code's standard for electric resistance heating still falls short. Thus further tightening of standards for electrical heating is required if the life-cycle primary energy gap between electric and district heated buildings is to be reduced.

For the district heated scenario, modification of the mid-1990s buildings to meet the new code requirement is less demanding. With more energy-efficient windows the new standard is achieved. However, in the case of the electric resistance heated buildings, energy-efficient hot water taps and heat recovery of ventilation air, in addition to low envelope U-value is needed to achieve the new standard. Therefore the additional production primary energy involved for such buildings is greater. Still the buildings use considerably more primary energy for operation than the district heated buildings constructed in the mid-1990s. For instance, the electric resistance heated BBR 09 wood building uses an average of 27% more operation primary energy relative to the mid-1990s district heated wood buildings. This supports the finding that heat supply system makes a greater impact than energy efficient envelope measures (Gustavsson and Joelsson 2008).

The primary energy for the building production is lower, and the net primary energy benefit from the end-of-life management is higher, for the wood-frame building compared to the concrete-frame building. Overall, the wood-frame buildings have slightly lower life-cycle primary energy use compared to the concrete-frame buildings. The primary energy for production and end-of-life of the buildings are relatively small compared to that for 50-year operation, which is similar for both the wood- and the concrete-frame buildings. Although the production energy is relatively small when compared to operation energy, it is more significant in the scenario where the buildings are district heated. This supports the findings of Thormark (2002), Citherlet and Defaux (2007), Verbeeck and Hens (2007) Gustavsson and Joelsson (2008), that building material choice is increasingly important for buildings with lower primary energy use for operation.

The BBR 09 standard for electric heated building was here met by improved thermal envelope, ventilation heat recovery measures and efficient water heating system and such measures could also be used to further reduce primary energy use in district heated buildings. The primary energy use related to household electricity supply is substantial. However the new code does not regulate household electricity use. Household electricity could receive greater attention, as in the district heated buildings, about two-thirds of the primary energy use for operation is due to household electricity. Incorporation of household electricity standard in future building code would further improve the overall primary energy use in the built environment.

This analysis shows the significance of primary energy perspective and choice of heating systems in reducing energy use in the built environment. The European Union Directive 2002/91/EC on energy performance of buildings (EPBD) requires that the feasibility of alternative energy-efficient supply systems including district heating is considered when a building of 1000 m^2 floor area is to be built. However, the current EPBD does not include a maximum energy use requirement for buildings. We suggest that further improvement of the EPBD may include maximum energy use requirements for buildings, taking into account heat supply systems, primary energy use, and climatic conditions.

It is more difficult to meet the new Swedish code when buildings are electric resistance heated than when district heated. Still, the primary energy use for electric heated buildings is substantially higher than district heated ones. A lifecycle primary energy perspective is needed to minimize the overall primary energy use, and future codes may reflect the full energy use during a building's life-cycle. This would include primary energy for production, operation, and end-of-life.

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