Primary energy and carbon dioxide implications of low-energy renovation of a Swedish apartment building

Ambrose Dodoo
Email: ambrose.dodoo@lnu.se
Sustainable Built Environment Group, Linnaeus University, Växjö 35195

Leif Gustavsson
Email: leif.gustavsson @lnu.se
Sustainable Built Environment Group, Linnaeus University, Växjö 35195

Uniben Y.A. Tettey
Email: uniben.tettey@lnu.se
Sustainable Built Environment Group, Linnaeus University, Växjö 35195

Abstract

Measures to improve energy efficiency in existing buildings offer a significant opportunity to reduce primary energy use and carbon dioxide (CO_2) emissions. The construction of new low energy buildings is important in the long term, but has small effect on the building sector's overall energy use in the short term, as the rate of addition of new buildings to the building stock is low. In this study we analyse the potential for reducing primary energy use and CO_2 emissions in an existing Swedish apartment building with energy efficiency renovation measures. We model changes to a case-study building with an annual final heat energy demand of 94 kWh/m^2 to achieve a low-energy building. The modelled changes include improved water taps, windows and doors, increased insulation in attic and exterior walls, electric efficient appliances and installation of a plate heat exchanger in the ventilation system. We analyse the life cycle primary energy and CO_2 implications of improving the buildings to a low-energy building. We consider different energy supply systems, including scenarios where the end-use heating technology is resistance heating, electric heat pump or district heating. We find that greater lifecycle primary energy and CO_2 reduction are achieved when an electric resistance heated building is renovated than when a district heated building is renovated. Material production primary energy use and CO_2 emission become relatively more significant when the operation energy is reduced. However, the increases in material production impacts are strongly offset by greater primary energy and CO_2 reductions from the operation phase of the building, resulting in significant lifecycle benefits. Additional roof insulation gives the biggest primary energy efficiency when the building is heated with resistance heating. For electric heat pump or district heating, more electric efficient appliances give the biggest primary energy efficiency. Still the heat supply choice has greater impact on primary energy use and CO_2 emissions.

Keywords: Renovation; existing building; lifecycle; primary energy; CO_2 emission; heat supply systems.

Introduction

The building sector contributes largely to the total primary energy use and carbon dioxide (CO_2) emission in many countries, and a large part of this energy is used for operating existing buildings. In the European Union, buildings account for about 40% of the total primary energy use [Tommerup et al. 2007]. In Sweden, the residential and service sectors account for 40% of the total final energy use [Swedish Energy Agency 2013]

There is a large potential to reduce the primary energy use and CO_2 emissions in the built environment [Dodoo et al. 2010]. The European Union Directive on Energy Performance of Buildings [Directive (2002/91/EC)] requires member states to implement legislations for improved energy efficiency in buildings, including existing buildings undergoing major renovation. In Sweden, a large share of the existing apartment buildings was constructed during the million homes programme in the 1960s and 1970s, and they need major renovations [Itard et al. 2008]. Such renovations can be combined with energy efficiency measures and thereby significantly reduce the primary energy use in the Swedish building sector. The construction of new low energy building is important in the long term, but has small effect on the building sector's overall energy use in the short term, as the addition of new buildings to the building stock is generally low [Bell 2004].

Various types of low-energy building criteria have been developed including passive house, self-sufficient house, zero energy house and the Minergie building criteria. The main focus of these low-energy building criteria is to minimize the final energy use for operation of buildings. The LÅGAN programme [LÅGAN 2013] and [Wahlström 2011] documented experiences on low-energy buildings in Sweden, and focused on buildings with specific operation energy use less than 25% of the Swedish building code's requirements. Measures applied to achieve low-energy buildings include efficient water taps, improved windows and doors, thermal insulation, airtightness of building envelope, efficient electric appliances and heat recovery of exhaust ventilation air [Janson 2008]. Low-energy renovation of existing buildings is becoming increasingly common in Europe. [Reinberg 2009], [Janson 2008] and [Peper 2009] reported of examples of existing buildings that have been renovated to achieve low-energy criteria in Austria, Sweden and Germany, respectively.

The life cycle of a building encompasses production, renovation, operation and end-of-life phases, which all are interlinked. The final operation energy use in existing buildings can be reduced considerably by implementing energy efficiency measures, e.g. improved insulation, efficient windows, heat recovery from exhaust ventilation air and efficient appliances. These building renovation measures increase the material use and hence the production and end-of-life energy use while the operation energy use decreases [Dodoo et al. 2010].

The primary energy use depends on the energy supply systems. The energy supply of a building can be provided by different types of supply systems resulting in a large variation in primary energy use for a given final energy use [Gustavsson and Joelsson 2010]. Hence, the primary energy savings of energy efficiency measures depend on the energy supply systems. The difference in final operation energy use before and after implementing energy efficiency measures, therefore, needs to be complemented so the analysis includes all life cycle phases of a building and the entire energy and material chains, from natural resources to final services.

In this study we analyze the potential final energy savings in an existing Swedish apartment building by implementing energy efficiency renovation measures, and explore the life cycle primary energy and carbon dioxide implications of implementing the renovation measures. We consider end-use heating systems using resistance heating, electric heat pumps or district heating.

Method

We calculate the primary energy use and CO_2 emission for all life cycle phases of a case-study building before and after implementing energy efficiency measures, taking into account the production, renovation, operation and end-of-life phases.

2.1 Studied building

Our analysis is based on a case-study multi-storey wood-frame apartment building constructed around 1995 in Växjö, Sweden. It has 4 floors and 16 apartments, and a total heated floor area of 1190 m^2. Two-thirds of the facade is plastered with stucco, while the facades of the stairwells and the window surrounds consist of wood paneling. A mechanical ventilation system for exhaust air is installed in the building. A photograph and floor plan of the building are shown in Figure 1 and the thermal envelope characteristics of the building are shown Table 1.

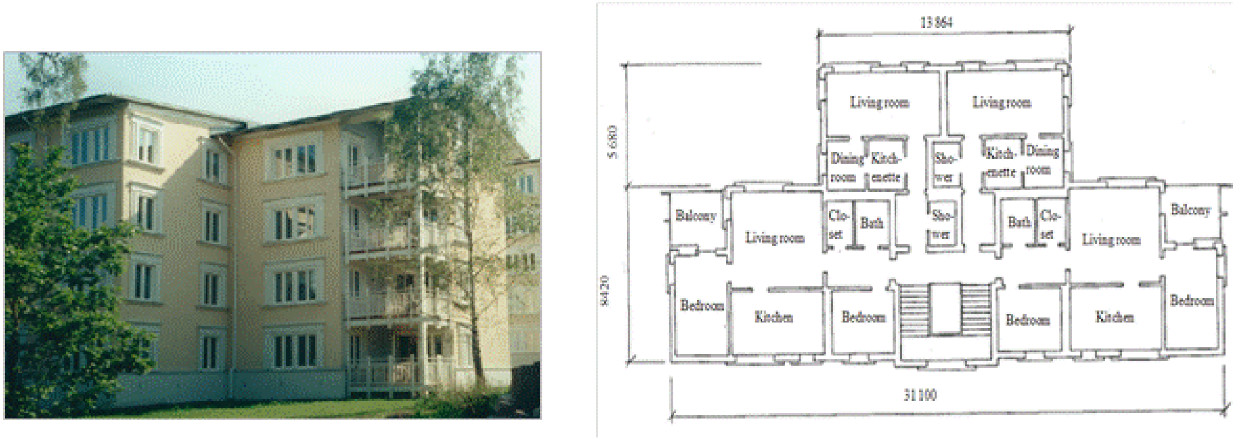

Figure 1. Photograph (left) and ground floor plan of the studied building.

Table 1. Thermal properties of the building.

U-value (W/m^{2}K)					**Air leakage at 50 Pa (l /s m^2)**	**Water taps**	**Mechanical ventilation**
Ground floor	External walls	Windows	Doors	Roof			
0.23	0.20	1.90	1.19	0.13	0.8	Conventional	Exhaust air

2.2 Energy efficiency measures analysed

Table 2 shows the energy efficiency measures considered for the studied building. We calculate the U-values resulting from implementing these measures using the VIP+ software [Strusoft 2008].

Table 2. End-use energy saving measures applied

Description	Effect of improvement
Improved taps	Reduced hot water used by 40%[a]
15 cm additional mineral wool insulation added to the roof	U-value from 0.13 to 0.08 W/m^{2}K
Windows replaced by triple-glazed units with krypton infill	U-value from 1.9 to 0.90 W/m^{2}K
Doors replaced by triple-glazed units with krypton infill	U-value from 1.19 to 0.90 W/m^{2}K
25 cm additional mineral wool insulation added to external walls	U-value from 0.20 to 0.10 W/m^{2}K
Incorporation of ventilation heat recovery unit with 80% efficiency	Reduced ventilation heat loss by 57%[b]
Electric efficient household appliances	Reduced household electricity by 44%[c]

[a] Estimated based on [Swedish Energy Agency 2006].

[b] Modeled with [VIP+ Strusoft 2008].

[c] Estimated based on [Tommerup et al. 2007]

We use simplified assumptions when modeling the measures for the building. For the exterior walls, we assume that additional 25 cm mineral wool insulation is added to the exterior façade of the building, and covered by new stucco and plasterboard cladding supported by wooden studs spaced at 0.6 m apart. We assume that the original roof overhang is sufficient to cover the wider walls. For the roof, we assume that additional 15 cm mineral wool insulation can be installed in the existing attic space. We assume that the ventilation heat recovery unit with 80% efficiency can be installed and that the ventilation ducts for incoming air can be fitted in the buildings [Wahlström et al. 2009]. Based on data from the [Swedish Energy Agency 2006], we assume that final energy for tap water heating is reduced by 40% by changing from conventional to efficient water taps.

2.3 Production and renovation phases

During the production and renovation phases we account for all the materials used in the building, including the initial construction and the energy efficient renovation. We calculate the primary energy used to extract, process, transport and assemble the materials, and also the available bioenergy recovered from biomass residues in the wood product chain [Sathre 2007]. The specific end-use energy for building material production is based on a Swedish study by [Björklund and Tillman 1997]. The on-site construction energy used to assemble the building material is estimated using data from [Adalberth 2000]. We assume that the on-site energy used for the renovation work is proportionally equal to the on-site energy used for the initial building construction, weighted by the relative amounts of energy used to produce the building materials used in the reference building and in the improved building. For calculations of biofuel recoverable from biomass residues we use data from [Lehtonen et al. 2004] and [Sathre 2007]. To convert end-use energy for material production to primary energy, we use fuel cycle loss values of 10% for coal, 5% for oil and 5% for natural gas. We assumed that 95% of the electricity to produce the materials is produced from a stand-alone biomass-fired steam turbine (BST) plant, with light-oil gas turbines producing the remaining. The conversion efficiencies of the BST plant and the light-oil gas turbines plants are assumed to be 40% and 34%, respectively.

2.4 Operation phase

During the operation phase, we calculate operation final energy use for space heating, ventilation, tap water heating and household electricity with the VIP+ simulation program [Strusoft 2010]. We assume an indoor temperature of 22^{o} C in the living areas and 18^{o} C in the common areas of the buildings. We model the space heating demand of the buildings for the climate in Växjö, southern Sweden. Based on the operation final energy use, we calculate the operation primary energy use and CO2 emission using the ENSYST software [Karlsson 2003]. This software estimates primary energy use and CO2 emission taking into account the entire energy chain from natural resources extraction to supply of final energy. We use the program's default assumptions regarding the source, production and transport of primary fuels. We consider three different end-use heating systems: resistance heating, electric heat pumps or district heating. For the resistance heating and electric heat pump, 95% of the electricity is assumed to be supplied from stand-alone biomass-based steam turbine (BST) plant and the remaining from light-oil gas turbine. The district heating is assumed to be supplied from combined heat and power (CHP) plant and heat-only boilers (HOB). We assume that 80% of the district heat is supplied from the CHP plant using BST technology, and 16% and 4% are supplied by biomass and light-oil HOB, respectively [Gustavsson et al. 2011]. We allocate the cogenerated electricity using the subtraction method, assuming that the cogenerated power replaces electricity from a similar technology using a stand-alone plant [Gustavsson and Karlsson 2006].

2.5 End-of-life phase

We assume that the building is demolished after its service life, with the concrete, steel and wood materials recovered. We calculate the net end-of-life primary energy use as the primary energy used to disassemble and transport the building materials, minus the primary energy benefits from the recovered concrete, steel and wood. We follow the methodology developed by [Dodoo et al. 2009], and use data from [Adalberth 2000] and [Björklund and Tillman 1997]. We consider carbonation of crushed concrete in the carbon analysis, assuming that the demolished concrete is crushed and exposed to the atmosphere for a period of four months [Dodoo et al. 2009].

Results

Table 3 shows the final energy use for operation of the studied building and after applying each of the energy efficiency measures to the building. The measures cumulatively decrease the operation final energy use by 42%. Heat recovery of ventilation air gives the biggest single decrease in final energy use, followed by improved windows and doors. The use of heat recovery ventilation system also increased the electricity use.

Table 3. ***Annual final energy use (kWh/m^2) for building operation before and after implementation of the energy efficiency measures. Each successive implemented measure includes the effects of all previous implemented ones.***

Description	Space heating	Tap water heating	Ventilation electricity	Household/ facility electricity	Total
Initial	68.7	25	4	45	142.7
+ Improved taps	68.7	15	4	45	132.7
+ Improved windows & doors	50.7	15	4	45	114.7
+ Additional roof insulation	49.7	15	4	45	113.7
+ Additional external walls insulation	43.4	15	4	45	107.4
+ Ventilation heat recovery	18.6	15	8	45	86.6
+ Efficient electric appliances	24.7	15	8	25	72.7

Figure 2 shows the effectiveness of each renovation measure in reducing the primary energy use for operation of the building. The full range of implemented renovation measures decreased the building's operation primary energy use by 49, 43 and 41% for the resistance heating, heat pump and district heated scenarios, respectively. Heat recovery of ventilation air gives the biggest single decrease in primary energy use when the building is heated with resistance heating. Efficient electric appliances give the highest primary energy reduction when the building is heated with heat pumps or district heating.

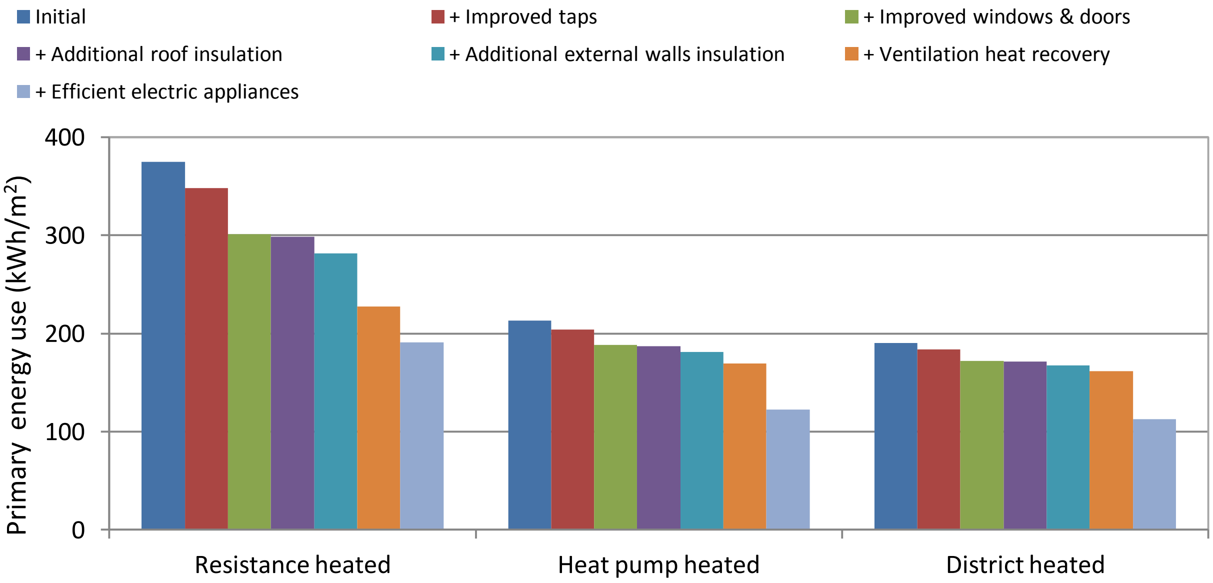

Figure 2. Annual primary energy use for operation with various energy renovation measures and heating systems.

Figure 3 shows the ratio of primary and final energy savings for the different energy efficiency renovation measures. Additional roof insulation gives the biggest primary energy efficiency when the building is heated with resistance heating.

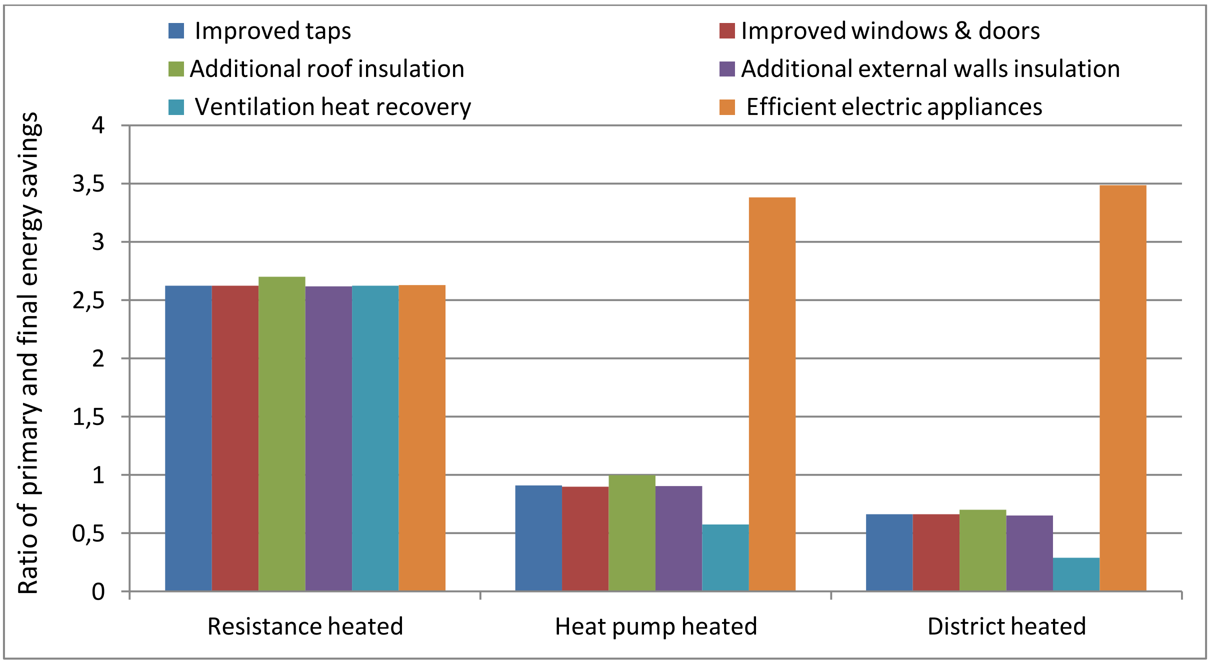

Figure 3. Ratio of primary and final energy savings of the implemented renovation measures.

Table 4 shows the primary energy used for the production of the building in the initial and the improved cases, and the resulting CO_2 emissions. The primary energy balance for the improved building comprises the initial construction primary energy plus the additional primary energy due to the energy efficient renovation. Material production primary energy use and CO_2 emission increase by about 20% and 24% when the measures are cumulatively applied, respectively.

Table 4. Primary energy use and CO_2 emission for the production and renovation of the building systems.

Description	Primary energy use (kWh /m^2)		CO2 emission (kg CO_2/m^2)	
	Initial	Improved	Initial	Improved
Energy or CO_2 emission				
Material production				
Fossil fuels	287	357	93	117
Electricity	179	215	6	8
Bioenergy	90	93		
Net cement reaction			9	9
Total	556	665	108	134
Building construction				
Fossil fuel	25	30	10	12
Electricity	25	29	2	3
Total	50	59	12	15
Total	**606**	**724**	**120**	**149**
Energy or C stock / CO2 avoided				
Carbon in wood material			-124	-131
Biomass residues	-345	-389	-142	-154
Total	**-345**	**-389**	**-266**	**-285**
Overall balance	**261**	**335**	**-146**	**-136**

Table 5 shows the annual operation primary energy use and CO_2 emissions of the initial building and the improved building with all the measures implemented. The cumulatively applied measures results in greater decrease in operation primary energy and CO_2 emissions in the cases where the building is heated with resistance heaters. However, the initial district heated building has about the same operating primary energy and CO_2 emissions as the improved resistance heated building.

Table 5. Annual operation primary energy use and CO_2 emissions of the initial building and of the improved building with different end-use heating systems.

	Primary energy use (kWh /m2)		CO2 emission (kg CO2/m2)	
Description	Initial	Improved	Initial	Improved
Resistance heated				
Space heating	180.3	64.8	6.3	2.3
Tap water heating	65.6	39.4	2.3	1.4
Ventilation electricity	10.5	21.0	0.4	0.7
Household/ facility electricity	118.1	65.6	4.2	2.3
Total	**374.5**	**190.8**	**13.2**	**6.7**
Heat pump heated				
Space heating	62.2	22.3	2.4	0.9
Tap water heating	22.6	13.6	0.9	0.5
Ventilation electricity	10.5	21.0	0.4	0.7
Household/ facility electricity	118.1	65.6	4.2	2.3
Total	**213.4**	**122.5**	**7.8**	**4.4**
District heated				
Space heating	45.5	16.3	1.6	0.6
Tap water heating	16.5	9.9	0.6	0.3
Ventilation electricity	10.5	21.0	0.4	0.7
Household/ facility electricity	118.1	65.6	4.2	2.3
Total	**190.6**	**112.9**	**6.7**	**4.0**

Table 6 shows the primary energy and carbon balances of the end-of-life phase of the initial and the improved buildings. Recovery of wood for use as biofuel gives the greatest end-of-life primary energy benefit, followed by recycling steels to replace ore-based steel. Recycling of concrete as crushed aggregate gives a minor end-of-life primary energy benefit.

Table6. End-of-life primary energy and carbon balances for the initial building ***and improved building***.

	Primary energy use (kWh/m^2)		CO_2 emission (kg CO_2/m^2)	
Description	Initial	Improved	Initial	Improved
Disassembly	5	5	2	2
Concrete recycling	-3	-3	-1	-1
Carbonation of crushed concrete			-2	-2
Steel recycling	-60	-60	-21	-21
Net energy content or carbon stock of recovered wood	-305	-340	-110	-122
Total	**-363**	**-398**	**-132**	**-144**

The total life cycle primary energy use and CO_2 emission for the initial and improved building, including the production, operation and end-of-life phases are shown in Figure 4 and Figure 5, respectively. The primary energy use during the operation phase dominates, but the relative importance of other life cycle phases increases when the energy efficiency renovation measures are implemented. Renovating the building to low-energy standard may result in significant life cycle primary energy and CO_2 savings depending on the end-use heating system.

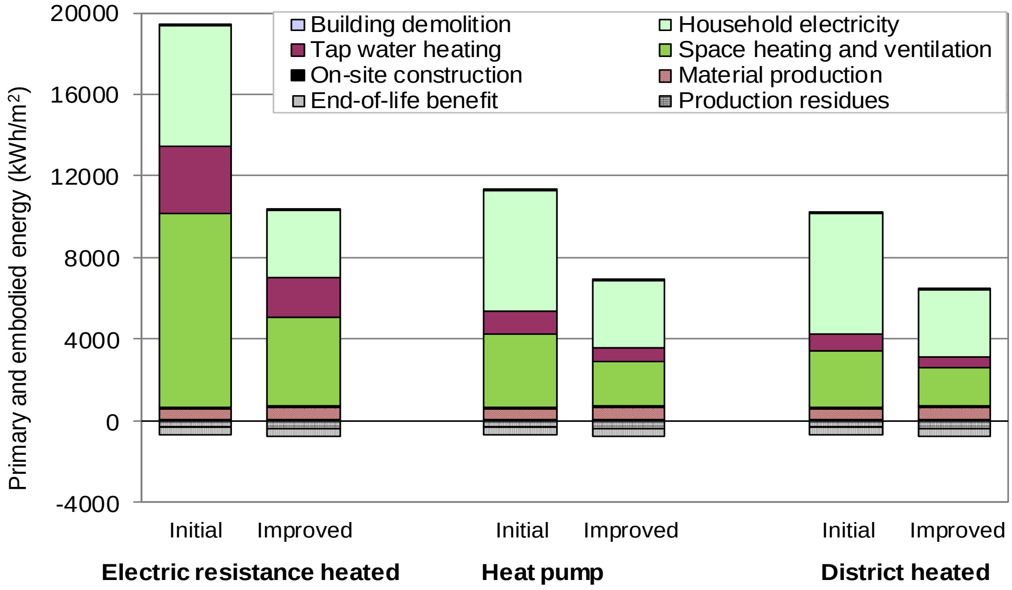

Figure 4. Primary energy for production, operation (50 years) and end-of-life.

The production biomass residues denote the net energy content of the residues from forest thinning and harvesting, wood processing and on-site construction waste. The end-of-life benefit denotes the primary energy benefit from recycling the demolished concrete and steel, and energy recovery of the demolished wood. The negative values denote energy that is available from recovered biomass residues or the energy benefits from recycling demolished concrete and steel.

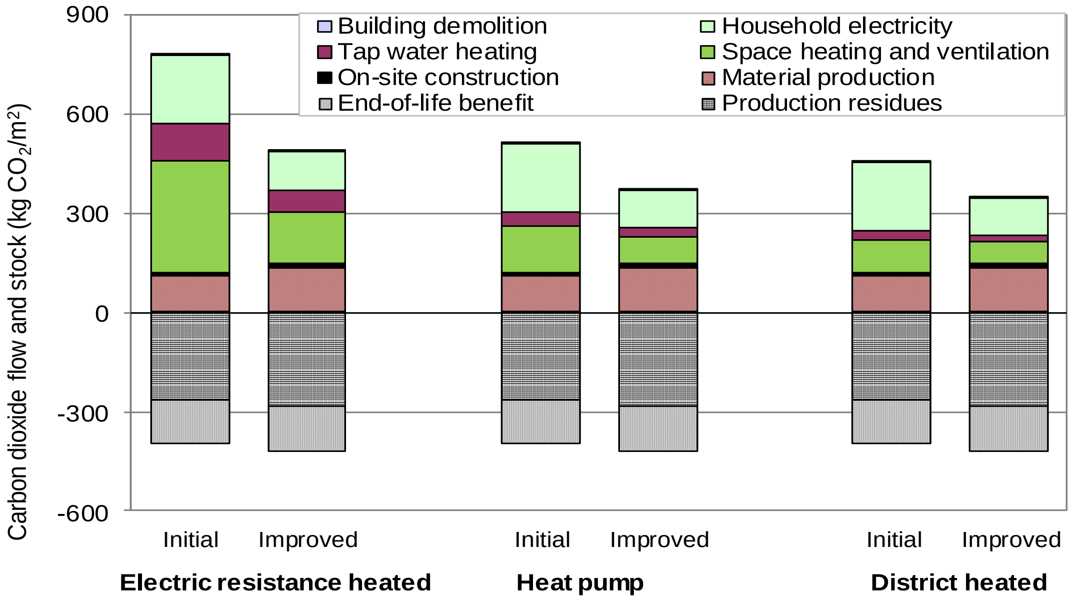

Figure 5. CO_2 emission for production, operation (for 50 years), and end-of-life.

The production biomass residues denote the net carbon stock of the residues from forest harvesting, thinning and on-site construction waste and given as negative values, showing avoided carbon emission to the atmosphere. The end-of-life benefit denotes the avoided carbon emission by recycling the demolished concrete and steel and energy recovery of the demolished wood.

Discussion and conclusions

We have analysed the life cycle primary energy and CO_2 implication of renovating an existing apartment building for low-energy use. The renovation measures are related to domestic hot water reduction, building thermal envelope improvement, ventilation heat recovery, and household electricity savings. We found that the primary energy and CO_2 reduction of different energy efficiency measures depend in part on used heat supply systems. Heat recovery from ventilation air is most effective where heat supply is from resistance heating. Efficient electric appliances are the most effective where heat supply is from electric heat pump or cogeneration-based district heating.

The production primary energy and CO_2 emission become relatively more significant when the operating energy is reduced. However, the increases in material production impacts are largely offset by greater primary energy and CO_2 reduction during the operation phase of the building, resulting in significant life cycle benefits.

We find that the choice of heat supply system has greater impact on primary energy use, confirming the results of [Gustavsson and Joelsson 2010]. Hence, to further minimize primary energy use when buildings are renovated, priority should be given to energy efficient supply systems such as district heating where possible. When selecting energy efficiency renovation measures, attention should be given to the interaction between individual measures and the type of heat supply system.

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