Towards a Sustainable Building Sector: Life Cycle Primary Energy Use and Carbon Emission of a Wood-Framed Apartment Building with Biomass-Based Energy Supply

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Abstract

Woody biomass can serve as both material and fuel in a transition to a more sustainable society. In this study we analyze the life cycle primary energy use and carbon dioxide (CO_2) emission of an eight-storey wood-framed apartment building. All life cycle phases are included, including acquisition and processing of materials, on-site construction, building operation, and demolition and materials disposal. The primary energy use includes the entire energy system chains from the extraction of fuels to the delivered end-use energy. Carbon flows are tracked including fossil fuel emissions, process emissions, carbon stocks in building materials, and avoided fossil emissions due to biofuel substitution. The results show that building operation uses the largest share of life cycle energy use, becoming increasingly dominant as the life span of the building increases. We compare various types of energy supply systems, and find that the type of heating system strongly influences the primary energy use and CO_2 emission. A biomass-based system with cogeneration of district heat and electricity achieves low primary energy use and very low CO_2 emissions. The use of biomass residues from the wood products chain to substitute for fossil fuels significantly reduces net CO_2 emission. Excluding household tap water and electricity, a negative life cycle CO_2 emission can be achieved due to the wood-based construction materials and biomass-based energy supply system. This study highlights the potential primary energy and climatic benefits of wood use, and shows the importance of using a life cycle perspective when evaluating the environmental performance of buildings.

Keywords: primary energy; CO_2 emission; life cycle; wood construction; biofuel

Introduction

The global climate system is being affected by the emission of greenhouse gases, of which the most significant is carbon dioxide (CO_2). Sweden and many other countries have set long-term goals for CO_2 emission reduction to mitigate climate change. The building sector accounts for a large part of the total energy use, and has great potential for reducing primary energy use and CO_2 emission by reduced heating demands, increased efficiency in energy supply chains, increased use of renewable energy, and substituting wood materials in place of concrete, steel, and other materials.

The aim of this study is to determine the primary energy use and CO_2 emission over the lifecycle of the Limnologen building in Växjö, Sweden. This eight-storey apartment building is made with a wood structural frame and has 3374 m^2 of floor area and 33 apartments. All the life cycle phases of the building, including the production of materials, construction, operation, disassembly and waste management are considered in this study. We account for the full flows of energy and materials from natural resources to useful services. We determine primary energy use by including the entire energy system chains from the extraction of fuels to the delivered end-use energy. Carbon flows are tracked including fossil fuel emissions, process emissions, carbon stocks in building materials, and avoided fossil emissions due to biofuel substitution. This study is reported in more detail by Gustavsson et al. (2010).

Methods

We estimate the total quantities of materials in the building, broken down by type of material and building component (foundations/ground floor; outer walls; inner walls; floor structure; roof; windows; balconies; and interior fixtures) based on analysis of construction drawings and personal communication with staff of the construction industries involved in the Limnologen project. We account for waste material generated during construction by increasing the material quantities by a specific percentage, depending on the material type (Björklund and Tillman 1997).

Calculation of energy and carbon balances of the materials follows the methodology developed by Gustavsson et al. (2006), Gustavsson and Sathre (2006) and Sathre (2007). We use data on specific energy use for extraction, processing and transport of materials from Fossdal (1995) from Norway, and Björklund and Tillman (1997) from Sweden. Data on forest production energy (seed production, nursery operations, site preparations, and pre-commercial thinning) are based on Berg and Lindholm (2005). Based on total material mass inputs for the buildings (including construction waste), and specific energy demand data for the manufacture and transportation of each material, we calculate the total final-use energy needed to provide the building materials. We then calculate total primary energy use for the building materials by taking into account efficiencies of fuel cycle, conversion and distribution systems.

We assume that 100% of biomass residues from wood processing, construction, and demolition are recovered for use as biofuel. Of harvest residues, we assume the recovery of 75% of branches and 25% of needles. We assume appropriate moisture content and heat values of the various types of biofuels. Energy inputs for the recovery and transport of biomass fuels, which we assume is diesel fuel, is quantified as 5% of the heat energy content of the recovered harvest residues, and 1% of other residues. Biofuel is assumed to replace fossil fuel that otherwise would have been used, resulting in avoided fossil emissions. The two reference fossil fuels we consider for replacement by recovered biofuels are coal and fossil gas. Appropriate combustion efficiency conversion factors are used to relate the heat value of the biofuel to the avoided fossil emission.

Specific full-fuel-cycle CO_2 emission from fossil fuel use is taken to be 0.24, 0.29 and 0.40 kg CO_2/kWh end-use energy, for natural gas, oil and coal, respectively (Gustavsson et al. 1995). We include calcination emissions from the manufacture of cement, and assume a gradual carbonation uptake of 8% of the initial calcination release over a 100-year span. We assume that on-site construction activities for the Limnologen building use 80 kWh/m^2, and assume that half of the construction energy use is electricity and half is diesel fuel.

Calculation of the primary energy use and CO_2 emissions of the building operation follows the methods described by Gustavsson and Joelsson (2007) and Joelsson and Gustavsson (2009). The operation phase includes energy for space heating (energy for heating system and electricity for operating the ventilation system), domestic hot water, and electricity for household use and facility management purposes. Energy use for maintenance during the building life is not included. We consider 2 different life spans: 50 years and 100 years.

The energy use for space heating and ventilation during the operation phase of the building is estimated by computer modelling using ENORM software (EQUA 2001). ENORM computes the energy and average power demand over a twelve-month period based on outdoor temperature and average solar radiation on a 24-hour basis. The program accounts for factors including the thermal transmittances and the areas of the building envelope. The indoor air temperature is assumed to be 22° C inside the apartments and 18° C in other parts of the building.

The primary energy used for operation is calculated by using the computer software ENSYST (Karlsson 2003). It estimates the fuel input at each stage in the energy system chains, and take into account the energy efficiency for each process. The operation phase is also compared with respect to net CO_2 emission, which is calculated in the same way by ENSYST. The assumptions used in ENSYST regarding the production and transportation of fuels for electricity and heat are the same as those made by Gustavsson and Karlsson (2002, 2003). We evaluate the operation phase of the building for several types of energy supply systems. The heating systems compared were electric resistance heating (RH), bedrock heat pump (HP) and district heating (DH). For the bedrock heat pump we assume a heat factor of 3, and an effect of 35 kW which covered 98% of the heat demand. Electric heaters integrated with the heat pump system cover the remaining demand.

All of the heating systems require some electricity to run, and the base-load electricity is supplied from power plants with coal-based steam-turbine (CST) or biomass-based steam turbine (BST) technology. These systems are assumed to cover 95% of the heat demand in the electrical heating systems, while peak production with light-oil-fired gas turbines covers the remaining 5%. For the district heating systems, cogeneration plants cover the base-load heat demand while light-oil-fired boilers cover the peak demand. We assume that the electricity cogenerated in the district heating system replaces electricity that would otherwise have to be produced elsewhere, using condensing power plants based on similar technology and with the same kind of fuel as the corresponding cogeneration plant (Gustavsson and Karlsson, 2006). This cogenerated electricity is hence subtracted from the cogeneration system to give heat as the output function of the system. The domestic hot water and household electricity is generated with technology and fuel corresponding to the heating system (Gustavsson and Karlsson, 2006).

We assume that demolition of the Limnologen building will require 10 kWh/m^2. We calculate demolition-related carbon emissions based on the assumption that the demolition energy is from diesel fuel. We assume that 100% of the wood-based demolition materials are recovered and used as biofuel.

Results

The energy used to produce the materials and assemble the building is shown in Table 1. A total of about 2500 MWh of end-use energy is used, or about 740 kWh/m^2. Taking into account conversion losses and fuel cycle inputs for the different energy types, the total primary energy use is about 3300 MWh, or about 975 kWh/m^2.

Table 1. *End-use and primary energy used for the production of materials and for on-site construction of the case study building. Electricity is produced in a coal-fired power plant.*

	End-use energy		Conversion/Fuel cycle		Primary energy	
	MWh	kWh/m^2	MWh	kWh/m^2	MWh	kWh/m^2
Fossil gas	106	31	5	2	111	33
Coal	470	139	47	14	517	153
Oil	961	285	48	14	1009	299
Biomass	521	154	0	0	521	154
Electricity	442	131	685	203	1127	334
Total	2499	741	785	233	3285	974

Table 2 shows the energy balance of the recovery of residues from forest harvest, wood processing, and construction activities. The net energy available is about 4000 MWh, or 1180 kWh/m^2. The energy value of the processing residue used as raw material for particleboard production for the building is 57 MWh.

Table 2. *Heat value of recoverable biofuel residues for external use, fossil energy (diesel) used for recovery and transport, and the available net energy.*

	Heat value of residues		Recovery/ transport energy		Net energy available	
	MWh	kWh/m^2	MWh	kWh/m^2	MWh	kWh/m^2
Forest harvest residues	1048	311	-52	-16	995	295
Wood processing residues	2782	825	-28	-8	2754	816
Construction site residues	240	71	-2	-1	238	70
Total biomass residues	4070	1206	-83	-24	3988	1182

The carbon balance from the production of materials and the construction of the case study building is shown in Table 3. Positive numbers indicate emissions into the atmosphere, and negative numbers indicate avoided emissions. Net cement reactions are shown, including calcination emission during manufacture minus carbonation uptake during a 100-year lifespan. The stock of carbon in the wood-based materials is temporary and will be lost when the building is demolished and the wood-based materials are burned.

The primary energy use for operation of the building is shown in Table 4, using different energy supply systems. The actual heating system in the Limnologen building most closely corresponds to biomass-based steam-turbine district heating (DH BST). The choice of heating system for space heating and tap water has a great influence on the primary energy use. For coal-based systems, district heating results in 70% less primary energy use for space heating than if using resistance heaters, and 35% less for the total operation. The choice of electricity supply system also makes a difference.

Table 5 shows the CO_2 emission from building operation, which depends heavily on the carbon content of the fuel used in the energy supply systems. The natural gas-based systems have lower emission than the coal-based systems, and the biomass-based systems are the lowest.

Table 3. *Carbon balance of material production and construction of the case study building, with reference fossil fuel of either fossil coal or fossil gas.*

	Fossil coal reference		Fossil gas reference	
	t CO_2	kg CO_2/m^2	t CO_2	kg CO_2/m^2
Material production (fossil fuel end-use)	485	144	485	144
Material production (electric end-use)	393	116	189	56
Cement reactions	91	27	91	27
Carbon stock in wood building materials	-768	-228	-768	-228
On site construction emissions	93	27	71	21
Fossil fuel substitution (forest residue)	-415	-123	-239	-71
Fossil fuel substitution (processing residue)	-1102	-327	-635	-188
Fossil fuel substitution (construction residue)	-95	-28	-55	-16
Fossil fuel used for biofuel recovery/transport	32	10	32	10
Total	-1287	-381	-829	-246

Table 4. *Primary energy use (kWh/m^2) for a 50 year operation phase of the case study building, using different energy supply systems. For a 100 year life span of the building, all values are doubled.*

	Space heating	Ventilation	Tap water heating	Electricity for household use and facility management	Total operation
Coal-based steam turbine (CST)					
Resistance heaters (RH)	1601	1064	4416	5381	12462
Bedrock heat pump (HP)	656	1064	1609	5381	8710
District heating (DH)	447	1064	1077	5381	7969
Biomass-based steam turbine (BST)					
Resistance heaters (RH)	1866	1240	5146	6271	14524
Bedrock heat pump (HP)	756	1240	1854	6271	10121
District heating (DH)	391	1240	942	6271	8843

Table 5. *CO_2 emission (kg CO_2/m^2) for a 50 year operation phase of the case study building, using different energy supply systems. For a 100 year life span of the building, all values are doubled.*

	Space heating	Ventilation	Tap water heating	Electricity for household use and facility management	Total operation
Coal-based steam turbine (CST)					
Resistance heaters (RH)	596	396	1643	2002	4638
Bedrock heat pump (HP)	239	396	586	2002	3224
District heating (DH)	166	396	401	2002	2966
Biomass-based steam turbine (BST)					
Resistance heaters (RH)	61	40	168	204	473
Bedrock heat pump (HP)	37	40	91	204	373
District heating (DH)	20	40	49	204	314

Table 6 shows an overview of the primary energy use and CO_2 emissions for the different life cycle phases: production, construction, fossil fuel replaced by biomass residues, operation with DH BST, and demolition. The biomass recovery from production and construction phases and the recovery of demolition wood show negative primary energy use, since they result in usable energy. The biofuel recovered from production and construction processes corresponds to more primary energy than is used in those processes. Household electricity is by far the largest single user of primary energy.

Table 6. *Primary energy balance (kWh/m²) and carbon balance (kg CO_2/m²) of the life cycle of the case study building, for life spans of 50 and 100 years. The heating system is biomass-based district heating (DH-BST). Positive numbers indicate energy used and CO_2 emitted, and negative numbers indicate energy that is available and CO_2 emissions avoided.*

	Primary energy use		CO_2 emission	
	50 years	100 years	50 years	100 years
Material production	894	894	287	287
Construction	80	80	27	27
Biomass recovery from production	-1182	-1182	-468	-468
Operation	8843	17687	314	627
-Space heating	391	781	20	40
-Ventilation	1240	2480	40	80
-Tap water heating	942	1883	49	97
-Household and facility electricity	6271	12542	204	409
Demolition	10	10	3	3
Biomass recovery from demolition	-571	-571	-225	-225
Total	8074	16918	-62	251

The primary energy use for hot water and for household and facility electricity constitutes a significant part of the energy in the operational phase, but these demands depend to a large extent on the users. Figure 1 shows the primary energy use for Limnologen during 50 years, excluding hot water and household and facility electricity, for four different energy supply systems. The primary energy use is divided in six parts. The space heating constitutes the largest single part, while the primary energy use for on-site construction and demolition together constituted 3% of the primary energy used. The amount of fossil fuels replaced by recovered biomass was the same independent of energy supply system, while the primary energy use for operation varied.

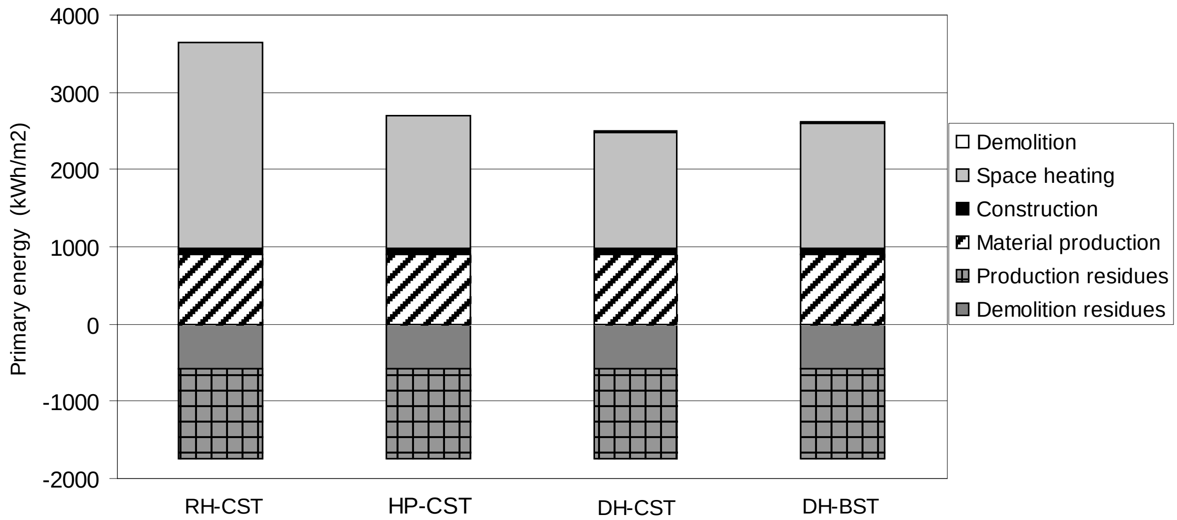

***Figure 1**. Primary energy use (excluding tap water heating and household and facility electricity) for a 50 year life cycle of the case study building using four alternative energy supply systems for space heating: resistance heaters (RH), heat pump (HP) and district heating (DH), combined with coal-based steam turbines (CST) and biomass-based steam turbines (BST)). Space heating includes electricity for ventilation.*

Figure 2 shows CO_2 emissions of a 50 year life span of the Limnologen building, using different energy supply systems. With biomass-based district heat, the CO_2 emission from space heating is small. If the building used resistance heating with fossil electricity, the CO_2 emission from space heating would dominate over the CO_2 emission from the other life cycle phases. The Limnologen building shows negative emission in the production and construction phase due to the replacement of fossil fuel with biomass by-products from the production and construction. A biomass-based energy supply system, including cogeneration of district heat and electricity, gives negative total life-cycle CO_2 emission.

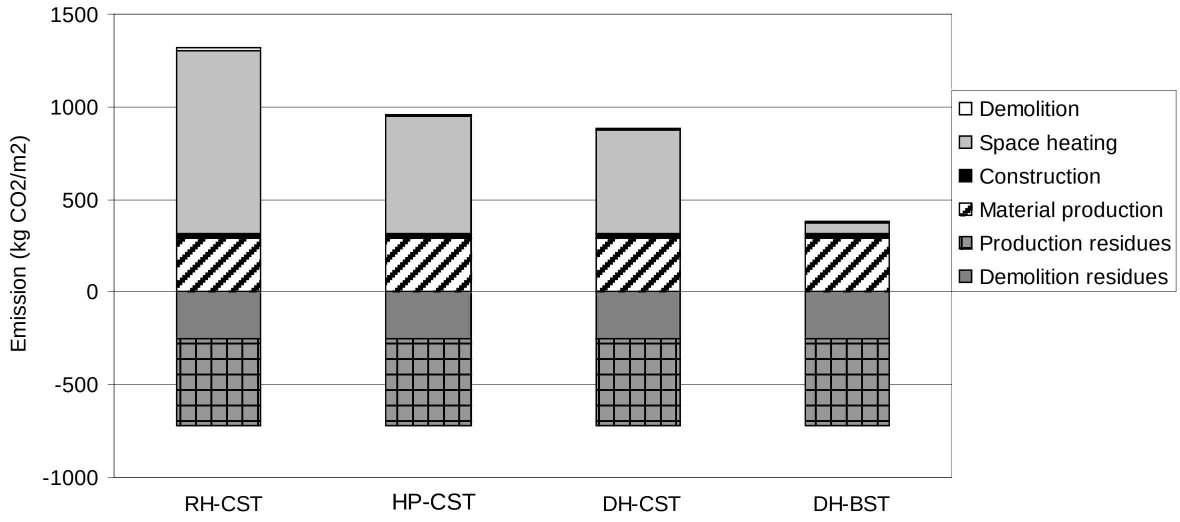

Figure 2*. CO_2 emission (excluding tap water heating and household and facility electricity) for a 50 year life cycle of the case study building using four alternative energy supply systems for space heating. For supply system abbreviations, see Figure 1. Space heating includes electricity for ventilation.*

Discussion and Conclusions

The results of this study show that it is important to adopt a life cycle perspective involving both construction and energy supply when evaluating the primary energy and climatic impacts of buildings. During the construction phase of the Limnologen building, because of its wood frame, more bioenergy can be obtained from residues from the wood products chain (forest residues, wood processing residues, and construction site residues) than is used to produce the building. Additional bioenergy can be obtained at the end of the building life cycle if wood-based demolition residues are recovered and used as biofuel. The use of recovered biofuels to substitute for fossil fuels can significantly reduce the net emission of CO_2.

The choice of heating systems plays a major role for primary energy use and CO_2 emission. District heating and bedrock heat pump are heating systems that can achieve a low primary energy use. Biomass-fired supply systems based on combined heat and power plants provide service with very low net CO_2 emission. Considering only the construction-specific lifecycle inputs, excluding hot water and electricity for household use and facility management, a negative lifecycle emission of CO_2 can be achieved due to the wood-based construction materials and a biomass-based energy supply system.

Quantities of materials in the building were estimated based on construction drawings and information provided by the staff of the construction industries, however there remains some uncertainty regarding material quantities. Some types of materials which exist in small quantities in the building were aggregated to simplify the production energy calculations. Production energy data are not available for all materials, so in these cases we use data for similar materials. Data on material production energy are from studies about ten years old. It is expected that industrial efficiency improvements have been made since then, thus it is likely that energy use for material production has been slightly overestimated in this analysis. We have assumed the use of sustainably managed forests, and the effect of forest management on carbon stocks in forest ecosystems is not considered in this study. The analysis of the energy supply chains is based on detailed assumptions of many different processes and technologies that are representative of Swedish conditions. No alternative exactly matches the conditions in Växjö, although the Limnologen building is heated with district heating based on biomass-based steam turbines (DH-BST).

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