Life cycle primary energy use of nearly-zero energy building and low-energy building

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Abstract

Energy legislations are increasingly driving towards buildings with very low operation final energy use as part of efforts to reduce energy use and climate impact of the built environment. In this study we analyse the life cycle primary energy use of a recently constructed Swedish conventional 6-storey apartment building and compare it to variants designed as nearly-zero energy building or as low-energy building with a combination of improved thermal envelope and passive design strategies. We maintain the architectural design of the constructed building and improve the thermal properties of the envelope to achieve a low-energy building and also nearly-zero energy building including solar thermal collectors. We consider scenarios where the building variants are heated with renewable energy using cogenerated district heating, also complemented with solar heating system. We follow the life cycle of the building versions and analyse their total primary energy use, considering the production, operation and end-of-life phases. The results show that the relative significance of the production phase increases as buildings are made to achieve very low operational energy use. The production phase accounts for 17 % of the total primary energy use for production, operation and demolition of the constructed building for a 50-year lifespan. The corresponding values for the nearly-zero energy and low-energy building variants ranges between 30 to 31 %. Overall, the life cycle primary energy use for the nearly-zero energy and low-energy building variants are about 30–35 % lower compared to the constructed building.

Introduction

Buildings of very low operation final energy use are a key part of the strategy to reduce both primary energy use and greenhouse gases emissions in the European Union (EU) [1]. In the EU, the energy performance of buildings directive (EPBD) requires all new buildings to be nearly-zero energy building from 2020 and mandates member states to set up national strategies and specific definitions to facilitate the deployment of such buildings [1]. In the directive, a nearly-zero energy building is broadly described as very high energy performance building with very low operation energy demand, covered largely by on-site or nearby renewable energy sources. However, explicit definition and calculation methodology for nearly-zero energy buildings vary widely in literature and for different countries [2-5]. In Sweden, definition and calculation guidelines for nearly-zero energy buildings are still under development as those proposed by the National Board of Housing, Building and Planning in 2015 [6] were not accepted. The calculation guidelines are suggested to be ambiguous, e.g. regarding accounting approach for photovoltaic generated electricity [7].

Measures typically used to achieve high energy performance buildings as nearly-zero energy buildings include improved thermal envelope insulation, energy-efficient windows and heat exchanger for ventilation heat recovery (VHR). While these measures reduce operational final energy use, they also increase the use of materials as well as the importance of the building production phase. Studies (e.g. [8, 9]) show that focusing only on optimizing the energy performance in the operation phase may result in potential trade-offs in other life cycle phases of buildings. Feist [10] found that a building with lower operation energy may have higher total lifecycle primary energy use because of its high production energy. The life cycle of a building encompasses production, retrofitting, operation and end-of-life phases, which all are interlinked and a system-wide perspective is needed to minimize energy use and climate impacts of buildings. The production phase of a low-energy building may constitute a large share of the total life cycle impacts [11]. Liljenström et al. [12] showed that upstream and downstream environmental impacts of newly constructed concrete-frame apartment buildings are about the same as that for operation for a 50-year period. Tettey et al. [13] showed that careful design strategies can contribute significantly in reducing both primary energy use for building production and operation.

In this study we analyse the life cycle primary energy use of a recently constructed Swedish multi-story building and compare it to variants designed as nearly-zero energy building and low-energy building, with a combination of improved thermal envelope and passive design strategies. We consider scenarios where the building variants are heated with cogenerated district heating, also complemented with solar heating system for the nearly-zero energy building. We follow the life cycle of the buildings and analyse their total primary energy use, considering the production, operation, and end-of-life phases.

Studied building variants

Our study begins with a constructed building to which we modelled changes to achieve a nearly-zero energy and a low-energy building variants. The newly modelled building variants have improved thermal envelope properties but the same architectural characteristics as the constructed building. Table 1 summarizes the thermal envelope properties as well as key design strategies of the building variants. Faucets and electric appliances for the constructed building are based on standard technologies whereas those for the low-energy and nearly-zero energy buildings are based on today's best available technologies.

CONSTRUCTED BUILDING

The constructed building is a 6-storey multi-family concrete-frame building (Figure 1) built in 2014 in the southern Swedish city of Växjö (latitude 56° 87' 37" N; longitude 14° 48' 33" E). It contains 24 apartments, with a total heated floor area of 1686 m^2 and was built to the Swedish building code of 2012 with significantly lower specific energy use than required under the code. The foundation is made up of layers of 200 mm crushed stone, 300 mm cellplast insulation and a 100 mm concrete ground floor slab. The external walls consist of 100 mm and 230 mm concrete on the outside and inside respectively, with a 100 mm layer of cellplast insulation material between them. The roof is made up of 250 mm concrete slab and 500 mm loose fill rock wool insulation with wooden trusses and a roof covering over layers of asphalt-impregnated felt and plywood.

NEARLY-ZERO ENERGY BUILDING

The nearly-zero energy building variant is designed following the Swedish National Board of Housing, Building and Planning's 2015 proposal [6], which suggested specific energy use not exceeding 55 kWh/m^2 for such buildings in climate zone III, where the analysed building is located. The specific energy use is defined to include purchased energy for space heating, tap water heating and electricity for fans and pumps but to exclude electricity for household appliances and lighting. Energy supply for the building is assumed to be complemented with solar heating system, as suggested by the EPBD [1]. Based on Berggren et al. [14], installation of solar thermal collectors of 0.030 m^2 per total heated floor area is assumed for the building. This corresponds to an area of 51 m^2 for the flat plate solar thermal collectors assumed in this study.

Table 1. Thermal properties and architectural characteristics of the analysed building variants.

Description	Constructed	Nearly-zero energy	Low-energy
Passive design strategies:			
Window to floor area ratio	0.19	0.19	0.11
Orientation of largest windows	West	West	North
g-values of windows	0.6	0.4	0.2
U-values:			
Ground floor	0.11	0.11	0.11
Exterior walls	0.32	0.11	0.11
Windows	1.2	0.8	0.8
Doors	1.2	0.8	0.8
Roof	0.08	0.053	0.053
Infiltration (l/s m^2 @50 Pa)	0.6	0.3	0.3
Ventilation:			
Type	Balanced with VHR	Balanced with VHR	Balanced with VHR
Heat recovery efficiency (%)	76 %	76 %	76 %
Air flow rate (l/s m^2)	0.35	0.35/0.1	0.35/0.1
Specific fan power (kW/[m^3/s])	2	2	2
Supply systems:			
Heating	District heating	District heating + Solar heat	District heating
Electricity	Grid	Grid	Grid
Appliances and lighting	Standard	Best available technology	Best available technology
Faucets	Standard	Best available technology	Best available technology

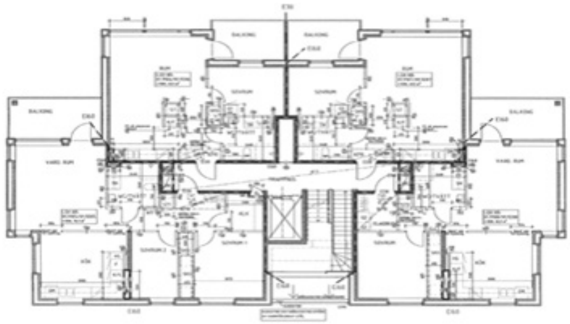

Figure 1. Photograph (left) and ground floor plan (right) of the constructed building in Växjö, southern Sweden.

LOW-ENERGY BUILDING

The low-energy building variant is designed based on the Swedish criteria suggested by LÅGAN [15] that such buildings ought have at least 25 % lower specific energy use compared to the requirements of the prevailing building code. It incorporates passive design strategies which reduce the overall energy for building production and operation, in contrast to the other building alternatives. The strategies are described in detail by Tettey et al. [13] and include optimised building orientation, window areas and solar thermal transmittance (g-values).

Methods

We calculate the primary energy use over the life cycle of the buildings, taking into account the production, operation and end-of-life phases.

PRODUCTION PHASE

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 takes material losses during production and construction into account. The final energy to manufacture the building materials is estimated using data mainly from Björklund and Tillman [16] 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. For the solar thermal collectors we use specific material production energy data from Ecoinvent [17]. Based on [18], the solar thermal collectors is assumed to have lifespan of 30 years. The embodied energy in the infrastructure used for the production, distribution and end-use of electricity and district heat is expected to be very minor and is excluded. Brännström-Norberg et al. [19] found the contribution of the infrastructure of an energy conversion plant to be very minor in relation to the energy contents of the fuels used during the infrastructure's life cycle. The production final energy use is converted to primary energy using fuel cycle loss values of 10 % for coal, 5 % for oil and 5 % for natural gas [20]. Electricity used for material production is assumed to be produced in biomass-fired condensing plant, with conversion efficiency of 40 % and distribution loss of 2 %. The primary energy use to assemble the building material is assumed to be 100 kWh/m^2 for the constructed building, based on [21]. We assumed that the primary energy use to assemble the building material for the high performance buildings is proportionally equal to the primary energy use to assemble the building materials for the constructed building, 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 is based on Lehtonen et al. [22].

OPERATION PHASE

Hour-by-hour multi-zone calculations of the final energy balance of the building variants are modelled using the VIP+ software (version 4.0.2) [23].VIP+ is a validated commercially available whole-building dynamic energy simulation software. The software calculates final energy for space heating, ventilation, tap water heating and household electricity and also quantifies energy generated from solar heating systems. The final energy use are simulated using the 1996–2005 climate data of the city of Växjö, and with input parameter values for the Swedish context documented by Dodoo et al.[24]. We assumed an indoor temperature of 21 °C and 18 °C, respectively, for the living and common areas of the building variants. The solar heating systems for the nearly-zero energy building are modelled using data from Berggren et al. [14].

Based on the simulated final energy use of the building variants, the operation primary energy use is calculated with the ENSYST software [25]. In contrast to simplified set of primary energy factors, ENSYST calculates primary energy use based on detailed analysis of the entire energy chains from natural resources extraction to supply of final energy service. We analyse a case where 68 % of the district heat supplied to the building is from a combined heat and power (CHP) plant using woody biomass and steam turbine (BST) technology while the remaining district heat is produced with heat only boilers (HOB) also using woody biomass. For the nearly-zero energy building, solar heat is assumed to complement the district heating. The cogenerated electricity is credited using the subtraction method, assuming that it replaces electricity that would instead have been produced in a stand-alone plant using the same fuel and technology as the CHP plant, based on Gustavsson and Karlsson [26].

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. [27], and use data from Adalberth [21].

Results and discussions

IMPACTS OF BUILDING-RELATED ACTIVITIES

Table 2 presents the production primary energy of the building variants including material production and assembly, and also shows the heating values of biomass residues recoverable for external use as bioenergy (negative numbers). The heating values of the biomass residues are the same for the building variants as they contain the same amounts of wooden materials. The production primary energy for the nearly-zero energy building is about 24 and 10 % higher than that for the constructed and the low-energy buildings, respectively.

Figure 2 presents the annual final operation energy demands for the building variants and shows the influence of energy-related characteristics linked to the configuration of the buildings on energy use, prior to incorporation of energy supply systems. The specific final energy demand, including space and tap water heating, and ventilation electricity, for the low-energy building is about 57 and 18 % lower compared to that for the constructed and the nearly-zero energy buildings, respectively.

Table 3 summarizes the primary energy balance for the end-of-life of the building versions. The benefits through recovering the materials are shown as negative numbers. Recycling of steel gives large primary energy benefit followed by energy recovery of wood, but less benefit is achieved through recycling the concrete which is the main frame material for the studied building. The primary energy benefits from the materials are similar for all buildings, as the quantities are similar for the buildings.

IMPACTS OF SUPPLY SYSTEMS

Figure 3 shows the hourly profile of solar heat generated on-site for the nearly-zero energy building for the climate of Växjö from 1st January to 31st December. Figure 4 compares the solar energy generated to the total final heat demand of the building including space heating and domestic hot water. Annual total heat demand of the building is about 5 MWh while 13 MWh of heat is generated from the solar thermal collectors. The heat generated from the solar thermal collectors is less than the total heat demand of the building for all months.

Literature shows different approaches for accounting for the effect of solar generated energy in zero energy buildings [7].

Table 2. Primary energy balance (kWh/m²) for the production phase of the building variants.

Description	Constructed	Nearly-zero energy	Low-energy
Material production	1,358.2	1,646.4	1,610.0
Material assembly	100.0	121.2	118.5
Total energy use	**1,458.2**	**1,767.7**	**1,728.5**
Heating value of biomass residues	-120.3	-120.3	-120.3
Overall balance	**1,337.9**	**1,647.3**	**1,608.2**

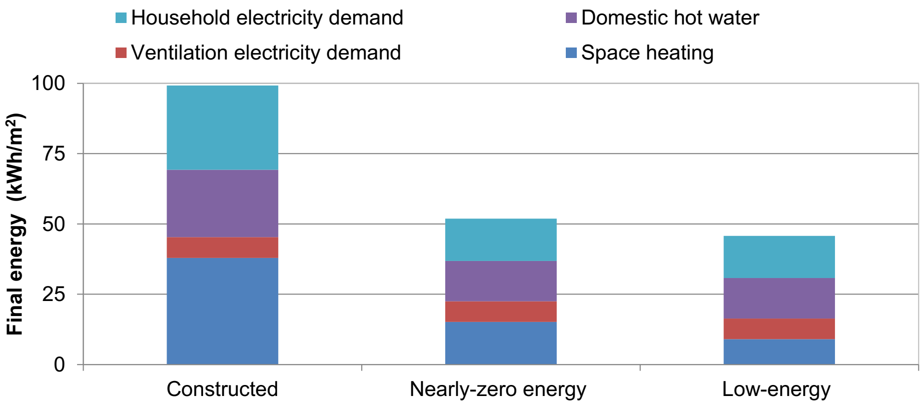

Figure 2. Annual final operation energy demands for the building variants.

Table 3. Primary energy (kWh/m²) balance for the end-of-life phase of building variants.

Description	Constructed	Nearly-zero energy	Low-energy
Disassembly	10.0	12.1	11.9
Concrete recycling	-40.6	-40.6	-40.6
Steel recycling	-365.5	-365.5	-365.5
Heating value of wood residues	-123.8	-123.8	-123.8
Overall balance	**-519.9**	**-517.8**	**-518.1**

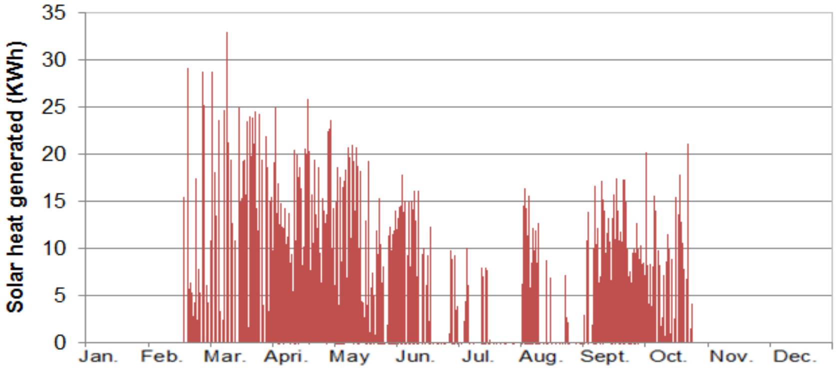

Figure 3. Hourly profile of heat generated from the solar thermal collectors for the nearly-zero energy building.

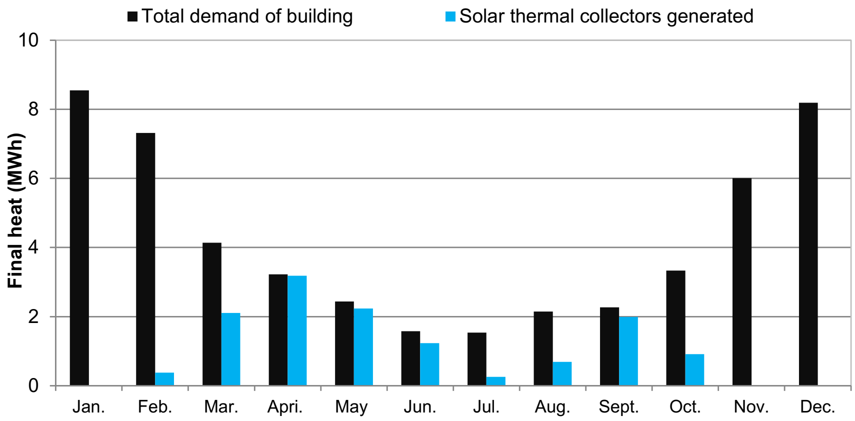

Figure 4. Total heat demand and solar thermal collectors' generated heat for the nearly-zero energy building.

The choice of accounting approach for energy supply is a crucial issue in a life cycle analysis as this steers the outcome. In this study the primary energy for heat generated in solar thermal collectors is calculated using the physical energy content method as documented by the International Energy Agency [28]. Table 4 summarizes the annual operation primary energy use of the building variants and also the solar thermal generated heat. Annual total operation primary energy use for the low-energy building is 46 and 8 % lower compared to that for the constructed and the nearly-zero energy building, respectively.

LIFE CYCLE IMPACTS

Table 5 shows the total life cycle primary energy use, including the production, operation and end-of-life phases for a 50-year lifespan. Biomass-based energy supply is assumed for the electricity and heat for the building operation. For the constructed building, the production phase constitutes 17 % of the total life cycle primary energy for a 50-year lifespan. For the low-energy and nearly-zero buildings, the production phase account for 30–31 % of the total life cycle primary energy use for a 50-year lifespan, respectively. This confirms that primary energy for material production becomes increasingly important as the energy standard of buildings improves [11]. The total life cycle primary energy use are significantly lower for the nearly-zero energy and low-energy building variants compared to the constructed building.

Conclusions

Our study shows that primary energy for building production increases when measures are applied to achieve a low-energy or a nearly-zero energy building. We found that the production phase constituted 30-31 % of the total life cycle primary energy use for the analysed nearly-zero energy and low-energy building variants, compared to 17 % for the constructed building. Thus the relative importance of the production phase of buildings will increase as legislations drive towards buildings with very low operation final energy use. However, current legislations generally do not consider the production phase of buildings. Life cycle perspective is needed to minimise primary energy use and CO_2 emissions of the built environment. Large life cycle primary energy reduction can also be achieved when a building is optimised to high-energy performance standard with a combination of passive design strategies and improved thermal envelope properties. In this study, the total life cycle primary energy use for the analysed nearly-zero energy and low-energy building variants are about 30 and 35 % lower compared to the constructed building, respectively. The analysed building variants have concrete structural framework and life cycle primary energy may be further reduced with wooden framework as noted in a growing body of literature (e.g. [20, 27]). Primary energy use is analysed in this study and the results may differ when considering global warming impact. We

Table 4. Annual primary energy use (kWh/m²) for operation of building variants.

Description	Constructed	Nearly-zero energy	Low-energy
Space heating	22.9	10.7	5.4
Ventilation electricity	20.1	20.1	20.1
Domestic hot water	14.5	10.1	8.7
Household electricity	81.9	40.9	40.9
Total	**139.4**	**81.8**	**75.1**

Table 5. Total life cycle primary energy use (kWh/m²) of the building variants for a 50-year period.

Description	Constructed	Nearly-zero energy	low-energy
Energy use:			
Production phase	1,458.2	1,767.7	1,728.5
Operation phase:	6,965.0	4,090.0	3,755.0
End-of-life phase	10.0	12.1	11.9
Total energy use	**8,433.2**	**5,869.8**	**5,495.4**
Energy benefits:			
Production residues	-120.3	-120.3	-120.3
End-of-life benefits:	-529.9	-529.9	-529.9
Total	-650.2	-650.2	-650.2
Overall balance	**7,783.0**	**5,219.6**	**4,845.2**

have not optimised the cost involved in improving the buildings to nearly-zero energy and low-energy levels and this should be further studied.

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