CLIMA 2016 - proceedings of the 12th REHVA World Congress

Heiselberg, Per Kvols

Publication date:
2016

Document Version
Publisher's PDF, also known as Version of record

Life cycle embodied and operational energy use in a typical, new Danish single-family house

Freja Nygaard Rasmussen[#1], Harpa Birgisdóttir[*2]

[#*]*Danish Building Research Institute, Aalborg University,*

A.C. Meyers Vænge 15, 2450 Copenhagen SV

[1]fnr@sbi.aau.dk

[2]hbi@sbi.aau.dk

Abstract

For decades, increasing regulatory requirements on the energy performance of buildings have taken the building design to ever more technologically complex levels. A life cycle energy approach can be used to evaluate the savings in operational energy against the use of energy for producing, maintaining and discarding materials integrated in this complex building design. This life cycle energy study analyses how typical structural and technical solutions, used to comply with the Danish 2010, 2015 and 2020 operational energy requirements, differ in the life cycle energy use. In practice, three different building models were evaluated in terms of life cycle embodied and operational energy in a 100-year perspective. The results confirm the importance of the embodied impacts of contemporary low-energy buildings. The building's embodied primary energy uses increase with stricter operational energy performance requirements because more insulation and technical equipment is needed in the building. However, the expenditure in embodied energy use is amply counterbalanced by the savings in primary energy from the reduced operational energy. This holds true as long as the energy scenario for the operational energy is calculated from a static 2015-mix of technologies.

Keywords – Embodied energy, life cycle primary energy use, operational energy, building life cycle assessment, low-energy buildings

1. Introduction

The oil crises in the 1970'ies sparked a lasting concern within building design and operation to limit the need for operational energy in the building's use stage. Since then, increasing regulatory requirements on the energy performance of buildings has taken the building design to ever more complex levels. Thus, a range of additional materials and technologies are implemented in the design with the purpose of limiting the electrical and thermal energy needed for operating the building and servicing the needs of the users. A fundamental issue of the introduction of new materials and technologies in the building is the question of whether operational energy savings from applying these measures actually exceed the embodied energy, i.e. the energy required for producing them, for maintaining them and eventually for discarding them. A life cycle energy perspective is needed in order to properly evaluate the full extent of the potential resource use and hence, the life cycle assessment (LCA) methodology comes into play.

LCA is used as a quantitative measure of the environmental impacts caused by human induced processes and resource uses. Building design and operation, being a major driver of these environmental pressures [1], is thus an obvious sectoral area in which to apply LCA in order to identify environmental problems and promote eco-design.

Earlier generations of building life cycle energy studies identify the operational energy in the use stage as being the most dominant process (80-95 %) in terms of primary energy consumption from the building's life cycle as a whole [2][3]. However, contemporary buildings designed for low operational energy requirement have in some cases shown to present embodied life cycle energy of the same magnitude as the operational energy use [4][5].

In a Danish perspective, the operational energy performance of new buildings is regulated through the national building regulation, but no requirements regarding the embodied energy use are currently in place. The 2010 building regulations operate with three different classification levels of a building's operational energy use; the 2010 regulatory minimum requirements, the 2015 low energy class and the 2020 building class. For the 2010 building regulations, the class 2010 is minimum requirement and for the newly introduced 2015 building regulations, the 2015 low energy class is the minimum requirement. Thus, there is a progressive development toward improved operational efficiency of new buildings.

This study investigates how typical structural and technical solutions for contemporary building practice are reflected in the life cycle energy use of a Danish single-family house. Furthermore, the study analyses how typical solutions to comply with the 2010, 2015 and 2020 operational energy requirements differ in life cycle energy use.

2. Method

The process based building life cycle model is based on the standardized EN 15978:2011 methodology for environmental life cycle assessment of buildings. The building life cycle is simplified in the sense that some life cycle stages are omitted. This simplification is further discussed in section 4.

2.1. LCA modeling details

The functional equivalent is a typical Danish single-family house with an expected service life of 100 years and a total gross floor area of 149 m^2.

The included life cycle stages are shown in italic in Table 1.

Table 1. Life cycle stages and modules as defined in the EN 15978:2011. Modules included in current study are in *italic*

<table>
<tr><th></th><th>Life cycle stage</th><th colspan="2">Module</th></tr>
<tr><td rowspan="16">Building life cycle information</td><td rowspan="3">Product stage</td><td>A1</td><td>Raw material supply</td></tr>
<tr><td>A2</td><td>Transport</td></tr>
<tr><td>A3</td><td>Manufacturing</td></tr>
<tr><td rowspan="2">Construction process stage</td><td>A4</td><td>Transport</td></tr>
<tr><td>A5</td><td>Construction, installation process</td></tr>
<tr><td rowspan="7">Use stage</td><td>B1</td><td>Use</td></tr>
<tr><td>B2</td><td>Maintenance</td></tr>
<tr><td>B3</td><td>Repair</td></tr>
<tr><td>B4</td><td>Replacement</td></tr>
<tr><td>B5</td><td>Refurbishment</td></tr>
<tr><td>B6</td><td>Operational energy use</td></tr>
<tr><td>B7</td><td>Operational water use</td></tr>
<tr><td rowspan="4">End of life stage</td><td>C1</td><td>Deconstruction, demolition</td></tr>
<tr><td>C2</td><td>Transport</td></tr>
<tr><td>C3</td><td>Waste processing</td></tr>
<tr><td>C4</td><td>Disposal</td></tr>
<tr><td>Supplementary information</td><td>Benefits and loads beyond the system boundary</td><td>D</td><td>Reuse-, recovery-, and/or recycling potentials</td></tr>
</table>

Scenarios for transport of materials to building site is set at 50 km for all materials in a 20-26 tons Euro 3 truck.

Scenarios for the service life of building materials or components are set according to the guidelines for the Danish LCA tool for buildings, LCAbyg, reflecting average national practice and conditions for different types of building materials and components used in the building. Guiding principles in terms of service life are that structurally important elements are expected to last throughout the building's expected service life of 100 years, surface materials somewhat shorter, and technical and installatory components in the range of 20-40 years. Replacement of materials and components is important to the total impacts from a building in the sense that each time a replacement happens, a new material or component is produced, thus entailing further resource use and emissions to the environment. The replacements are accounted for in integer numbers, i.e. a building material with a service life of 80 years is replaced one time in the course of the building's expected 100-year service life.

Scenarios for the waste treatment process of the building waste are based on current national practice, even though some of these processes are distant in time due to the long service life of the building. Guiding principles in terms of waste treatment scenarios are that mineral materials are crushed for reuse as gravel, wood and plastics are incinerated, glass and insulation materials are landfilled and metallic and technical components are disaassembled and processed for reuse.

2.2. Building model and inventory data

The building model is based on calculation examples for operational energy performance published by the Danish Energy Agency [6]. The examples cover typical technical and structural solutions in fulfilling the operational energy requirements at three different levels of classification: the 2010 standard requirements, the 2015 low energy requirements and the 2020 building class requirement.

The building model, as visualized in Figure 2, is a standard construction with main structural parts (i.e. slab, foundation and external wall) consisting of concrete and the roof structure made of wood. Outer surfaces are brick/tile and inner surfaces are gypsum boards/screed and wooden laminate flooring. Windows are with triple-paned glass and wooden/aluminum frames. The building has a mechanical ventilation system with heat recovery (temperature exchange efficiency of 85 %) and ventilation rate of 0.3 L/s/m^2.

Figure 1. Building model reference [6]

Thermal simulations of the operational energy requirement have been conducted in the Danish BE10 calculation tool [7] as part of the calculation examples [6]. The difference in insulation levels and other measures to reduce energy consumption can be seen in Table 2 for the three variations of the building model. Specific energy profiles for the annual operational energy requirement for the three variations are also displayed in Table 2.

Table 2. Characteristics of the three variations of the building model

Characteristics of building model	**2010**	**2015**	**2020**
Insulation levels (in mm)			
Slab (EPS)	220	370	400
Ext. walls (mineral wool)	190	250	400

Roof (mineral wool) Plinth (EPS)	350 130	400 200	400 200
Other measures Improved airtightness of building envelope Better foundations Improved efficiency of vent. system Photovoltaics (5.0 m^2) Add. Window area (3.8 m^2)	 - - - - -	 + + + - -	 + + + + +
Annual operational energy (kWh/m^2) Electricity District heating	 4 52.4	 2.6 37.8	 0.1 32.8

2.3. Life cycle energy indicators

The LCA impact categories assessed in current study are limited to the total primary energy consumption (PEtot), further differentiated in non-renewable (PENRT) and renewable primary energy consumption (PERT). For the embodied primary energy use, factors from the building material database Ökobau 2013/2015 are used [8][9]. The methodological background for the primary energy factors of this database correspond to the following calculation procedures (see [10]):

- chemical energy from upper or lower heating value
- renewable biomass from energy harvested appraoch, i.e. processes for growing the biomass are not included
- other renwables from the amount of renewable energy needed to produce the amount of energy delivered, thus taking into account the conversion efficiency of the technologies used
- fission energy on the basis of an 451,000 MJ/kg uranium factor

2.4. Background environmental data

The Ökobau 2013 is used as the primary database for environmental data on building materials and components [8]. Where needed, data has been supplemented by data sets from the Ökobau 2015 database [9]. Environmental data for the average Danish district heating and electricity production is taken from the Danish LCA tool for buildings, LCAbyg [11].

3. Results

Figure 3 shows the embodied PEtot of different building elements in the building model at the three levels of building classification. As seen from the figure, the total embodied life cycle energy for a building with a 100-year service life, increases from $3.5*10^5$ kWh to $4.1*10^5$ kWh from the 2010 to the 2020 model. The increase in embodied life cycle energy is primarily caused by more insulation materials in the building as well as a more comprehensive technical system in the 2020 model.

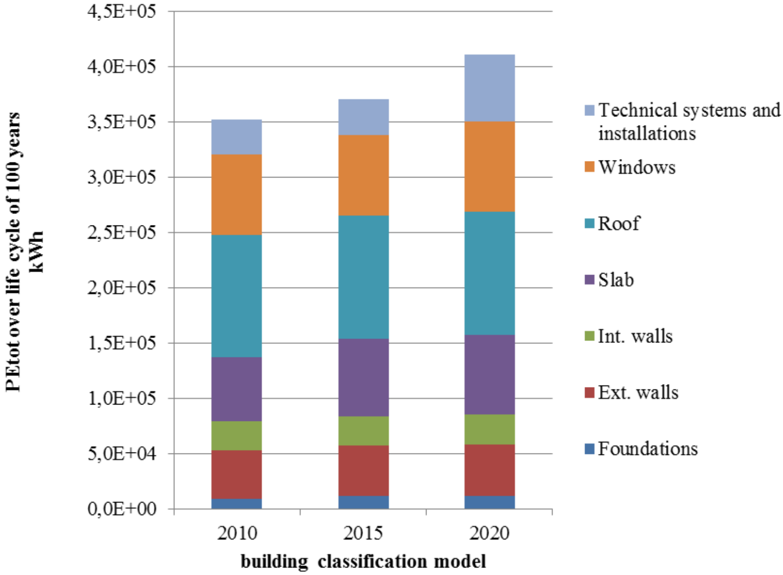

Figure 2. Embodied PEtot of building models over a building life cycle of 100 years

In figure 4, the life cycle energy PEtot of both embodied and operational life cycle processes are shown for the three different building classifications. Notable in this figure is the relatively low contribution from the waste processing and disposal activities (~ 1 % of embodied life cycle energy) as well as the low contributions from the transport of materials to the building site (less than 1 % of embodied life cycle energy). Furthermore noteworthy is how relatively large an impact the replacement of materials has, almost as large an impact as the production stage of the original construction. Naturally, this contribution depends much on the scenarios defined for replacement of materials.

The increasing embodied life cycle energy displayed in figure 4 is amply counterbalanced by the reduction in operational energy from the 2010 to the 2020 building model. Again, a specific use stage scenario is of importance to the results, in this case the scenarios for the energy technology scenarios composing the district heating and electricity grid mixes used for the modeling. An important consideration in this regard is the static modeling applied for this model, i.e. the technology mixes for the energy supplies are assumed static throughout the whole life cycle of the building, when in fact the energy system changes annually due to price fluctuations and technological development. This static approach is further discussed in section 4 of this paper.

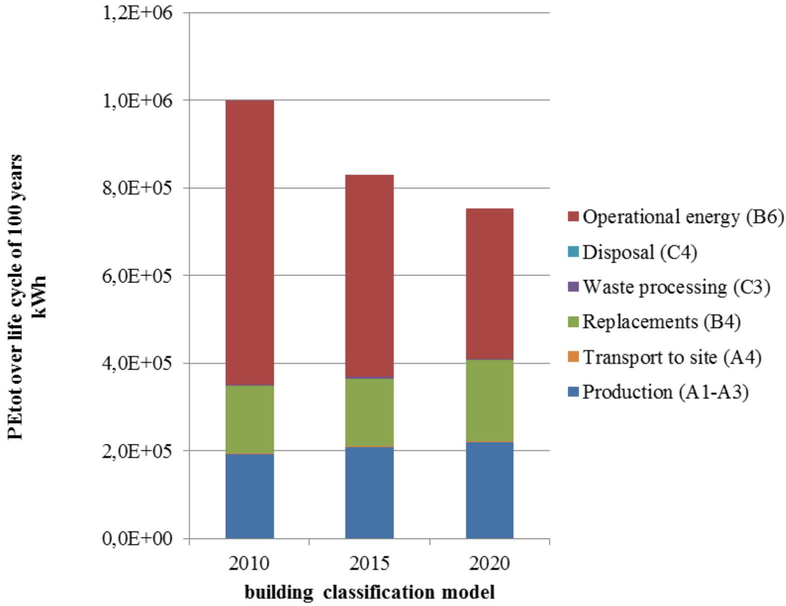

Figure 3. Life cycle PEtot of building models over building life cycle of 100 years

Figure 5 displays the relationships between, on the y-axis, the total life cycle energy use of the building model with a benchmark of 100 % in the 2010 model results. On the x-axis, the figure displays the embodied life cycle energy's share of total life cycle energy use.

The trend for all three categories, PERT, PENRT and PEtot (of which the latter is a total of the former two), is that total life cycle energy is reduced by almost 20 % from the 2010 to the 2015 model and again by additionally 10-20 % point to the 2020 model.

Embodied life cycle energy's share of total life cycle energy increases by almost 10 % from the 2010 model to the 2015 model, and again by 10 % point to the 2020 model. This reflects the earlier mentioned additional use of materials to reduce operational energy use.

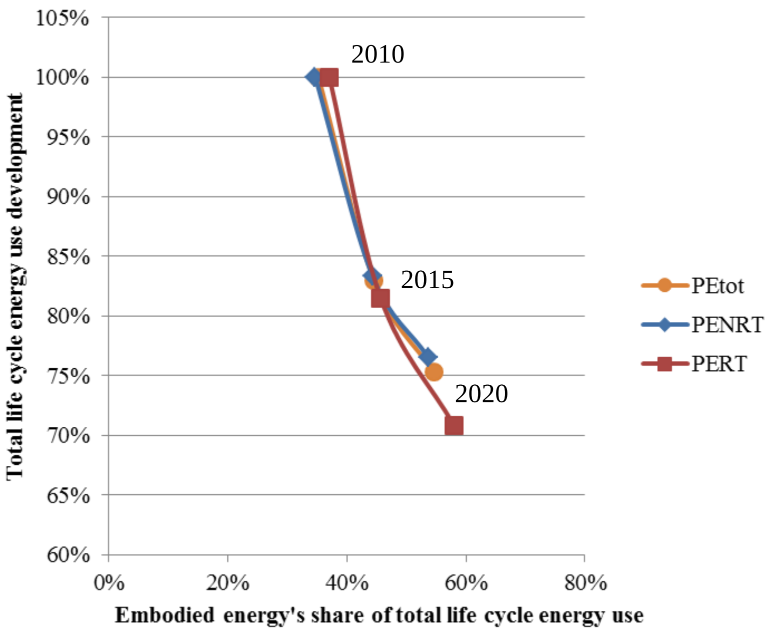

Figure 4. Development of total life cycle energy use and embodied share of this between the three building models; 2010, 2015 and 2020.

4. Discussion

The current study is a simplified study, where only a selection of life cycle stages is included. Thus, the embodied impacts may be somewhat underestimated because relevant processes of e.g. maintenance and construction are left out of scope. However, the excluded processes are commonly regarded as influencing life cycle impact results to a lower degree and frequently left out of simplified assessments [12]. For instance, a case study by Blengini and Di Carlo of a low-energy house in northern Italy identified the construction stage (module A5) as having impacts within the same range as the transport to site of materials (module A4), hence insignificant compared to the production and the use stage [5]. However, the construction process impacts can potentially vary a lot due to the variations for this process, caused for instance by time of year the construction takes place.

When calculating life cycle impacts of a building, the very long service life of the building generally leads to the use stage scenarios being very important to the results obtained. For this case study, a static approach to all elements of the use stage is presumed, even though a 100-year service life span is a very long time in which to apply this status quo-approach to the involved processes and technologies. Some literature highlight the importance to results of dynamic scenario modelling in building LCA [13] [14], but the static approach is widespread within building LCA practice due to the vast amount of uncertainties connected with defining future dynamic scenarios, for instance for changing practice of or changing replacement rates of materials. Furthermore of importance in this regard is the static nature of operational energy scenarios for supply and demand. There is reason in keeping the operational demand static when no changes of the building design are assumed. However, on the supply side of the operational energy, the types and contributing shares of the technologies behind the supply mixes definitely will change with time as fossil fuels are phased out, smart grid systems introduced etc. In this sense it is important to be aware of the contemporary nature of a figure like figure 5. In this figure the actual comparison is based on annual primary energy uses. For the embodied life cycle primary energy, this denounces a 100-year perspective of embodied energy use from production, replacements and end-of-life processes, all divided on 100 years to obtain an annual use of primary energy. For the operational energy use, the numbers in reality reflects a contemporary 2015 picture because this is the year the energy grid mix data is from. Given that the Danish national energy grids in the future will consist of more renewable energy conversion technologies, a figure like figure 5 will change to reflect larger shares of non-renewable primary energy use from the embodied energy use and larger shares of renewable primary energy from the operational energy use.

5. Conclusion

This life cycle energy study of typical structural and technical solutions for a Danish single-family house confirms the importance of the embodied impacts of contemporary low-energy buildings when the whole life cycle of the building is taken into account. A breakdown of the embodied total primary energy use in the building life cycle stages show that the material transport to site as well as the final waste processing and disposal activities are insignificant in comparison with the production of building materials and the use stage replacements. The latter two life cycle stages contribute almost equally for all three operational energy performance models of the house. In terms of building elements, the roof and windows are prominent contributors to the embodied energy use.

The building’s embodied primary energy uses increase with stricter operational energy performance requirements because more insulation and technical equipment is needed in the building. However, the expenditure in embodied energy use is counterbalanced by the savings in primary energy from the reduced operational energy. This holds true as long as the energy scenario for the operational energy is calculated from a static 2015-mix of technologies. However, operational energy from increasingly renewable energy mixes will shift the shares of total impact further towards the embodied impacts of the building. Thus, there is reason in applying a regulatory focus on buildings from a more life cycle based view where embodied impacts are included as part of the initial evaluation of a buildings energy performance. This shift of focus is in line with general European Union concerns of resource conservation and circular economy, although work remains in developing practical and accepted methods for the actual inclusion of embodied impacts from building materials' production and use.

References

[1] United Nations Environment Programme (UNEP), "Building Design and Construction : Forging Resource Efficiency and Sustainable Development," *Sustain. Build. Clim. Initiat.*, no. June, 2012.

[2] R. J. Cole and P. C. Kernan, "Life-Cycle Energy Use in Office buildings," *Build. Environ.*, vol. 31, no. 4, pp. 307–317, 1996.

[3] C. Scheuer, G. a Keoleian, and P. Reppe, "Life cycle energy and environmental performance of a new university building: modeling challenges and design implications," *Elsevier*, vol. 35, no. 10, pp. 1049–1064, 2003.

[4] C. Thormark, "A low energy building in a life cycle—its embodied energy, energy need for operation and recycling potential," *Build. Environ.*, vol. 37, no. 4, pp. 429–435, 2002.

[5] G. A. Blengini and T. Di Carlo, "The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings," *Energy Build.*, vol. 42, no. 6, pp. 869–880, 2010.

[6] Energistyrelsen, "Eksempelsamling om energi." [Online]. Available: http://eksempelsamling.bygningsreglementet.dk/enfamhus_eksempel. [Accessed: 21-Jan-2016].

[7] S. Aggerholm and K. Grau, *Bygningers energibehov : beregningsvejledning*. 2014.

[8] "ÖKOBAU.DAT 2013." German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety.

[9] "ÖKOBAU.DAT 2015." German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety.

[10] R. Frischknecht, F. Wyss, S. Büsser Knöpfel, T. Lützkendorf, and M. Balouktsi, "Cumulative energy demand in LCA: the energy harvested approach," *Int. J. Life Cycle Assess.*, pp. 957–969, 2015.

[11] COWI consulting, "Nye emissionsfaktorer for el og fjernvarme," 2016.

[12] I. Zabalza Bribián, A. Aranda Usón, and S. Scarpellini, "Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification," *Build. Environ.*, vol. 44, no. 12, pp. 2510–2520, 2009.

[13] W. O. Collinge, A. E. Landis, A. K. Jones, L. A. Schaefer, and M. M. Bilec, "Dynamic life cycle assessment: framework and application to an institutional building," *Int J Life Cycle Assess*, vol. 18, no. 3, pp. 538–552, 2013.

[14] F. Rasmussen, H. Birgisdóttir, and M. Birkved, "System and scenario choices in the life cycle assessment of a building – changing impacts of the environmental profile," in *Proceedings of the Sustainable Buildings Conference 2013 - Construction Products and Technologies*, 2013, pp. 994–1003.