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Does embodied energy in windows affect their energy-efficiency ranking?

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Abstract

The energy performance of four alternative low-energy windows for an energy retrofit scenario has been investigated using three methods; a simplified operational energy balance of the windows, a dynamic operational energy simulation on room level, and a total life cycle energy assessment. It is found that the ranking of windows based on the simplified operational energy balance method is very different from the ranking based on dynamic operational energy simulation. Furthermore, it is found that the embodied energy makes up a negligible part of the life cycle energy consumption of window components, and does not alter the ranking of the windows based only on dynamic operational energy simulations.

Keywords: energy use; windows; retrofit; embodied energy

1 Introduction

Minimising the embodied energy in building components is a neglected task in building design as the operational energy of buildings traditionally makes up the predominant environmental footprint. The current development is that legislative requirements are pushing for an increased energy-efficiency in building operation: member countries of the European Union have to tighten their requirement for maximum energy use for building operation every five year [1]. However, as building operation become increasingly energy efficient, the amount of embodied energy of the components increases relatively to the operational energy consumption. An analysis of the total life cycle energy consumption of building components in the building design phase might therefore be relevant to understand the total environmental impact of potential design decisions.

1.1 Total Life Cycle Energy of Building Components

The total life cycle energy (LCE) consumption of a building, often referred to as the Cradle-to-Cradle consumption, overall consists of two components: *embodied energy* and *operational energy* [2]. The embodied energy (EE) is described as the combination of direct and indirect energy sequestered in all phases from the initial Manufacture stage[1], Use stage[2], End of Life stage[3], and any befits and loads beyond[4] the Cradle-to-Grave system boundary. In [2] the embodied energy includes both initial, recurrent and demolition energy, however, in [3] energy expended in the demolition process of the building is regarded as a third separate category beyond embodied and operational energy. Operational energy (OE) is only related to the Use stage of the life cycle and consists of energy expended in maintaining a desired level of indoor environment, i.e. energy for building operation like heating, ventilation and air conditioning.

There are various calculation methods for assessing the total life cycle energy consumption; statistical analysis, process-based analysis, economic input/output analysis and combinations of those [2]. Moreover, there are numerous interpretations of what to include in the analysis of the life cycle energy consumption [4]. Despite the academic discussion on how to conduct an adequate analysis, several practical applicable paradigms for assessing environmental impact (including embodied energy) already exist like e.g. the DGNB, LEED, BREEAM, and the HQE international building certification schemes [5]. However, these certification schemes all conform to different rules and standards and make use of already established life cycle inventory (LCI) databases and environmental product declaration (EPD) databases on different levels to enable the analysis.

The fraction of embodied energy in a total life cycle perspective of a building may vary a lot. Ibn-Mohammed et al. [6] provides an overview of the balance between embodied and operational carbon emissions in a selection of buildings and infrastructure worldwide where the embodied energy contribute to everything between 2-80% of the life cycle emissions. Thormark [7] reports that embodied energy can account for up to 40-60%, and that the choice of material alone can decrease building embodied energy by approximately 10-15% for conventional buildings and up to 17% in a considered low-energy building. Ramesh et al. [3] reports that using materials with a low amount of embodied energy instead of conventional materials (such as steel, concrete etc.), the total amount of embodied energy for a building can be reduced by approximately 30-50%, and even up to 55% if recycled materials are used.

In practice, it is however relevant to question whether such rather costly and general life cycle assessment (LCA) analysis is useful to the individual building project. In the design situation, LCA analysis might be valuable if it can provide information that could change design decisions, e.g. if LCA has

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[1] Raw material extraction, transportation to factory, manufacture, and transportation to site before assembly
[2] Maintenance, refurbishment, but not operational energy consumption
[3] Deconstruction, transportation, waste processing, and disposal
[4] Reuse, recovery, and recycling

considerable influence on the ranking of specific building components in terms of their total LCE consumption.

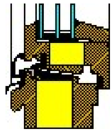
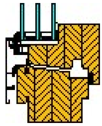
1.2 Scope of paper

This paper features an analysis that ranks four different low-energy windows for a retrofit scenario based on their energy-efficiency. Initially, the windows are ranked according to the output from two different methodologies for calculation of operational energy performance. Later, it is investigated whether embodied energy has any influence on the ranking of the windows.

2 Method

It is assumed that the windows in an existing dwelling have no remaining lifetime and is to be replaced. Four windows with the technical properties listed in Table 1 are therefore ranked according to their operational energy consumption to select the most energy-efficient retrofit solution. The operational energy is calculated in two different ways to investigate the impact of calculation method on the ranking of the windows: 1) a simple energy balance methodology called E_{ref}, which is used for energy labelling of windows in Denmark [8], and 2) a dynamic building energy simulation of the four windows with offset in a specific retrofit case using the software IDA ICE [9]. The embodied energy in the windows is then calculated using environmental product declarations (EPDs) from the Institut Bauen und Umwelt e.V. database [10] and added to the operational energy consumption calculated in the dynamic simulations to investigate whether inclusion of the embodied energy in a life cycle assessment rearranges the ranking of the windows. No energy-economic considerations are made.

Table 1 – Window product properties. Material data and technical lifetime from EPDs in the IBU database (Institut Bauen und Umwelt e.V.).

Parameter	Unit	3-pane wood	3-pane wood/alu	3-pane PVC	2-pane PVC
Cross-sectional view					
g_g-value	-	0.61	0.61	0.50	0.60
U_g-value	W/m^2 K	0.64	0.64	0.70	1.10
U_f-value	W/m^2 K	0.73	1.16	1.10	1.40
Frame fraction	-	0.34	0.30	0.20	0.20
g_w-value	-	0.40	0.43	0.40	0.48
U_w-value	W/m^2 K	0.73	0.89	0.90	1.30
Technical lifetime	Years	40	50	50	50

2.1 Simplified Operational Energy Calculation

Energy labelling of windows in Denmark is based on a simple heat balance methodology considering only the net energy gain (heat gain minus heat loss) of the window during the heating season, defined as E_{ref} – the reference energy consumption. E_{ref} is always calculated for a standard size window (1.23 x 1.48 m) using the standard glazing of the specific window manufacturer (which usually is not solar coated glazing). The formula for E_{ref} is:

$$E_{ref} = 196.4 \cdot g_w - 90.36 \cdot U_w \quad (1)$$

, where g_w is the solar heat gain coefficient (SHGC) of the window and U_w is the heat transfer coefficient of the window. The constants in (1) are derived from the Danish design reference year (DRY) according to the method explained by Duer et al. [8]. Notice that E_{ref} does not consider the actual size and orientation of the specific window, solar shading from surroundings, or any effects due to dynamic fluctuations of boundary conditions. An E_{ref} calculation is therefore not a statement regarding the actual energy performance of a specific building zone. The intention of E_{ref} is to make a simple and standardised calculation methodology for comparison of operational energy performance of different window products.

2.2 Advanced Operational Energy Calculation

The operational energy performance of a specific retrofit case when replacing the windows with the windows listed in Table 1 is calculated using the software IDA ICE [9]. The case is a 66.8 m^2 living room in a single-family house from the early 1970'ies (see Figure 1) located in Copenhagen, Denmark. The living room has three outside-facing facades with a total of seven windows all measuring 1.23 x 1.48 m. The total window-to-floor area ratio is 0.19. Room height is 2.4 m from floor to ceiling. The energy performance of the living room is simulated for all windows in Table 1 with the orientation according to Figure 1 (south) and when rotated 180° (north) to test whether the orientation of the windows influences the ranking of the windows.

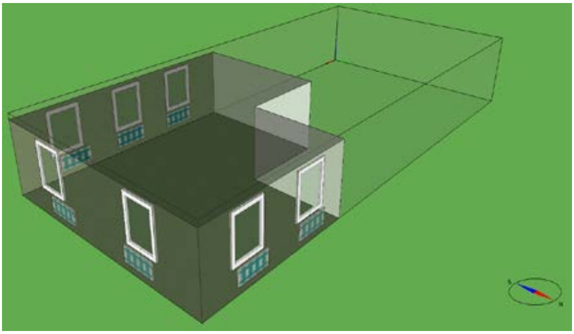


Figure 1 – 3D image and floor plan of living room in single-family house simulated in IDA ICE software. Green hatched area in the floor plan is the living room used for analysis.

The house construction is comprised by an external brick wall (U-value = 0.47 W/m^2K), roof construction (U-value = 0.34 W/m^2K), ground slab (U-value = 1.03 W/m^2K) and internal lightweight concrete walls. Minor thermal bridges (psi-value = 0.05 W/m K) are included to account for insulation leaps near brick-brick, brick-concrete and window/door connections. Windows are modelled with the properties listed in Table 1 using the advanced window modelling option in IDA-ICE, which take into account that the U_w-value varies due to weather conditions. This effect has a significant impact on the simulation results, especially for windows with two-layer glazing [11]. The average air change rate due to infiltration is 0.35 h^{-1}. The house is heated by district heating supplied radiators placed under each window (maximum power is 1000 W at a supply/return temperature of 55˚C/45˚C). The living room is equipped with 50 W lighting, 150 W equipment and two occupants with a 1 Met activity level. In weekdays people are not present from 8 am to 3 pm. From 3 pm to 5 pm one person is present. At all other hours, including weekends and holidays, both persons are present. The indoor thermal environment is governed by a heating set point of 21˚C. The resulting thermal environment does not exceed an indoor air temperature of 26 ˚C at any point during year for the four different windows, neither facing south nor north.

2.3 Embodied Energy in Windows

The assessment of the embodied energy of the four windows in Table 1 is based on a LCI analysis for each window available in EPDs [10]. The EPDs are produced in accordance with current product category rules in ISO 14025 [12] and EN 15804 [13]. The assessment of the embodied energy includes the following system boundaries: Manufacture (phase A1-A5), Use (phase B2-B5) and End of Life (phase C1-C4), but not Reuse (phase D). Included in the embodied energy estimation is also energy sequestered in replacement parts during the lifetime of the window product. Currently, the EPD's include a replacement of glazing (once in lifetime), seals (twice in lifetime) and fittings (once in lifetime). Only non-renewable energy resources are included.

2.4 Life Cycle Energy Calculation

The life cycle energy performance of the four windows is considered the amount of consumed energy (embodied and operational) during a 50 years reference lifetime (length of longest living window cf. Table 1). The life cycle energy consumption in the reference lifetime is thus calculated as:

$$LCE_{ref} = \left(OE_x + \frac{EE_x}{L_x}\right) \cdot L_{ref} \qquad (2)$$

, where *LCE* is the life cycle energy consumption in the reference lifetime in kWh, *OE* is the operational energy consumption in kWh /year, *EE* is the embodied energy in kWh, and *L* is the lifetime in years. Indices *ref* and *x* denote the reference scenario and the considered scenario, respectively.

3 Results

The E_{ref} net energy gain (see section 2.1 for details) of the four windows listed in Table 1 is shown in Figure 2. The two PVC windows (PVC2 and PVC3) have negative net energy gains whereas the triple-glazed wood window (Wood3) and the triple-glazed wood/aluminium window (Wood/Alu3) provide positive net energy gains to the room.

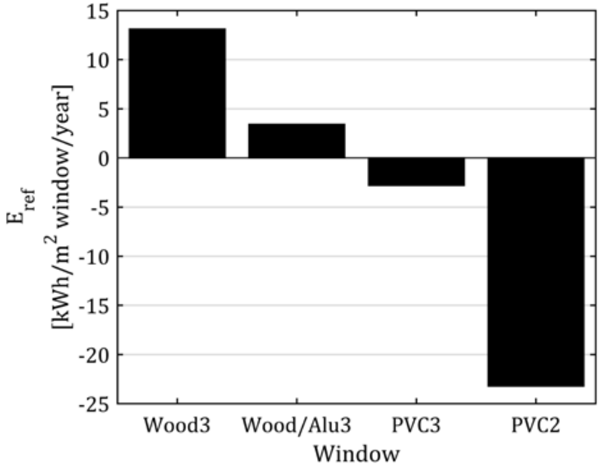


Figure 2 – Net energy gain (E_{ref}-value) of the four windows listed in Table 1. Ranking (best to worst): Wood3, Wood/Alu3, PVC3, and PVC2.

Figure 3 depicts the annual operational energy use of the living room for the four window retrofit options according to the advanced energy calculation described in section 2.2.

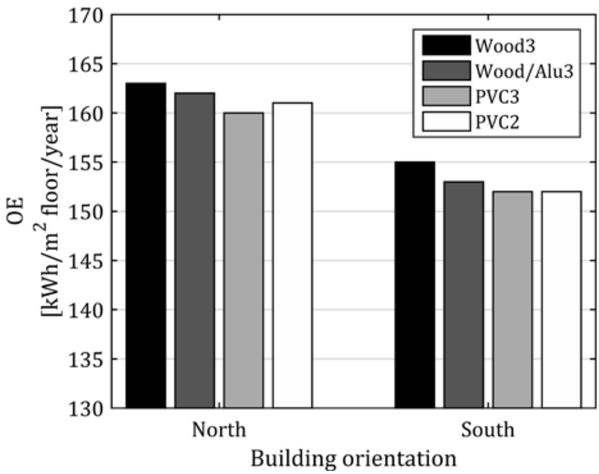


Figure 3 – Operational energy (OE) based on dynamic building energy simulations. Ranking (best to worst): PVC3, PVC2, Wood/Alu3, and Wood3.

According to E_{ref}, the most energy-efficient window is the triple-glazed wood window (Figure 2). However, the same window proves to be the "worst" window when ranking according to the more advanced dynamic simulations (Figure 3). This is the case for both room orientations. The triple-glazed PVC window, which has a negative E_{ref}-value, proves to be the "best" performing window in the dynamic simulations. In fact, even the double-glazed PVC window outperforms the triple-glazed wood window and the triple-glazed wood/aluminium window due to a higher heat gain of the double-glazing – even to the north.

The embodied energy of the windows is shown in Figure 4. The plastic windows – both the triple and double-glazed windows – have a larger amount of embodied energy compared to the two wood-based windows when summing the individual life cycle contributions.

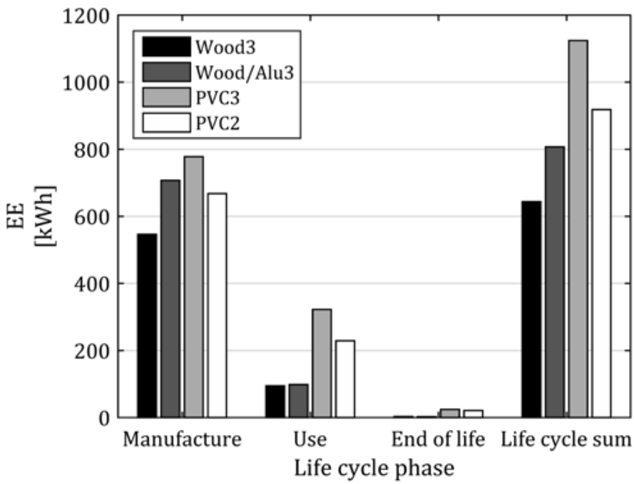


Figure 4 – Non-renewable embodied energy (EE). Operational energy (OE) in the Use stage is omitted.

Figure 5 depicts the life cycle energy consumption attributed to the four window retrofit options according to the description in section 2.4. The embodied energy make up between 0.1-0.2% of the total life cycle energy consumption. Comparing Figure 3 and Figure 5, it is evident that considering the embodied energy does not alter the ranking of the windows leaving the triple-glazed plastic window (PVC3) to be the best ranking window even though it has the largest amount of embodied energy.

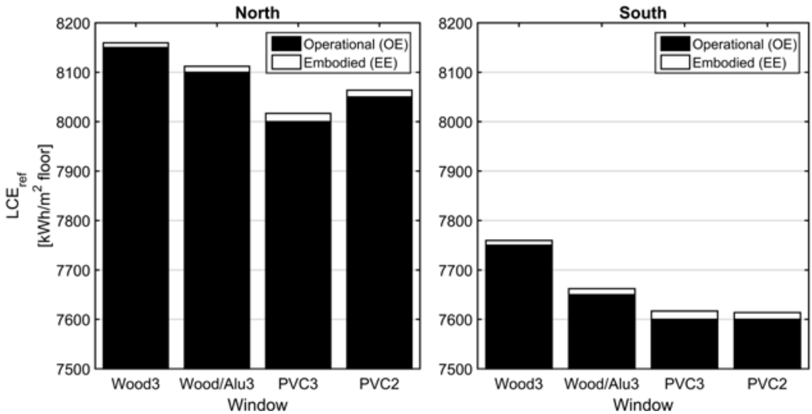


Figure 5 - Life cycle energy (LCE) during a 50 year reference lifetime. Ranking (best to worst): PVC3, PVC2, Wood/Alu3, and Wood3.

4 Conclusion

The energy performance of four different low-energy windows (a triple-glazed wood window, a triple-glazed wood/aluminium window, a triple-glazed PVC window and a double-glazed PVC window) has been assessed with the aim to identify the most energy-efficient solution for a retrofit scenario. The performance has been investigated using three different methods: 1) a simplified operational energy balance method (E_{ref}), 2) a dynamic operational energy simulation on room level, and 3) a life cycle energy assessment including the embodied energy of the windows. Assuming that the results from the dynamic operational energy simulations are representing the true performance of the windows, the following conclusions are drawn:

- To select windows for building retrofit according to an E_{ref} ranking of the energy-efficiency is not necessarily accurate. Instead, the appropriate choice of windows must rely on an analysis of the specific building retrofit case on room level.
- Taking the embodied energy into consideration in a total life cycle energy consumption analysis does not alter the ranking of the windows based only on dynamic operational energy simulations.
- The amount of embodied energy in the windows only makes up approximately 0.1-0.2% of the total life cycle energy consumption. Calculating the embodied energy of window components prior to design decisions in a retrofit scenario therefore seems futile.

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