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Embodied Energy and Operational Energy assessment in the framework of Nearly Zero Energy Building and Building Energy Rating

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Abstract

The latest energy standards pertaining to buildings mainly focus on the reduction of Operational Energy (OE). The adoption of highly efficient energy production systems as well as of high performance materials is being encouraged more and more in order to achieve the Nearly Zero Energy Buildings target. Several studies have pointed-out that an increasing amount of materials are required in building construction. Their Embodied Energy (EE) can be assumed significant from a life-cycle perspective and in a NZEB approach. The present paper focuses on the assessment of the mutual impact of OE and EE on two residential buildings assumed as case studies.

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Keywords: Life-cycle energy analysis; Embodied Energy; Operational Energy; Building Energy Rating, Nearly Zero Energy Buildings

1. Introduction

Directive 2010/31/CE, which is a recasting of Directive 2002/91/CE [1], represents a general methodological framework for the calculation of the integrated energy performance of buildings and the fulfillment of minimum requirements. The Directive states that all new buildings must be Nearly Zero Energy Buildings (NZEB) by 31

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December 2020. Furthermore, a Building Energy Rating (BER) certificate has to be drawn up for the sale or rental of these buildings. Overall the calculation of an annual building energy demand on its own is not sufficient for a complete NZEB analysis. The energy grids connection through renewable sources integration (e.g. photovoltaic panels) is a mandatory requirement. Finally it has also been recognized that different definitions are possible, according to a Country's energy policy targets and specific conditions [2].

In order to comply with the EU Directive requirements, both NZEB and BER need a method in order to define how a building energy analysis should be carried out [3]. According to the conventional definition, BER refers to the energy that is used for heating, ventilation, cooling and lighting, and it is calculated on the basis of the standard occupancy, while an appropriate national standard is required for NZEB, and no clear legal requirements have been decided on for Europe [4-6].

On the whole, scientific literature shows the need for appropriate analysis metrics and weighting systems to properly characterize NZEB and BER goals. The present paper deals with a study focused on two aspects pertaining such goals. The former is related to indicators that should be included in building energy analysis in a life-cycle approach, with particular attention being paid to Embodied Energy (EE) and Operational Energy (OE). The latter aspect, which is inherent to the methodology framework, demonstrates a correlation between the aforementioned indicators.

2. Definitions and methodology

The EE and OE assessment here presented was carried out considering the definitions provided by the International Energy Agency (IEA), Solar Heating & Cooling Program, Task 40, Annex 52 [7], and by the IEA, Evaluation of Embodied Energy and CO_{2eq} for Building Constructions, Annex 57 [8].

The OE is the annual amount of non-renewable primary energy required for use during the life of a building. OE refers to Primary Energy Demand (PED) for heating, ventilation, cooling, hot-water production and for lighting.

The EE is the amount of non-renewable primary energy required for the extraction of raw materials, their transformation into semi-finished and finished products (initial EE), the replacement processes (recurring EE) and the disposal processes (end-of-life EE). Owing to the lack of data concerning the recurring and end-of-life EEs, most of the EE databases [9-11] refer to upstream processes. In addition, since recurring and end-of-life EE are generally considered of minor importance it is often justifiable to neglect them[12].

Although EE and OE are both based on the amount of PED, EE is only considered once, whereas OE accumulates over the lifetime of a building. Finally, OE is usually measured as the energy per unit Conditioned Floor Area (CFA; kWh/m^2yr).

In order to harmonize EE and OE values, it is necessary to both annualize EE and express it on the basis of a floor surface unit; this implies making assumption on the lifespan of the building and properly managing the EE values calculated for the materials used for both the CFA and the Unconditioned Floor Area (UFA).

The study was carried out in compliance with the Minergie® definitions and labels [13]. The Minergie-A standard was adopted in this paper. Minergie-A is a label that is used for new and refurbished low-energy-consumption buildings that wish to apply for NZEB certification, taking into account both OE and EE.

The OE considers the energy demand for heating, ventilation and hot-water production, while plug-loads and lighting energy demand are not included in the analysis. In particular, the heating demand is assessed according to a quasi-steady state balance, based on the methodology defined in EN ISO 13790.

The EE value encompasses two EEs, both of which refer to CFA [13]. The former takes into account the building envelope and the partitions. The latter includes building technology EEs (e.g. the EE of the heating systems) in the EE calculation. The EE is annualized according to the lifetime of the building expected by the standard. Eventually Minergie-A sets out a broader analysis by including building systems that refer to un-conditioned spaces.

3. Case studies

On the basis of the previously described definitions and methodological framework, two building projects, with different technical innovation levels, building assemblies and Window-to-Wall (WWR) Ratios, were assumed as case studies and analyzed. The case studies, named Case Study 1 (CS1) and Case Study 2 (CS2), are residential

buildings (Fig.1). They are located in the Province of Turin (Lat. 45°N, Long. 7.65°E, Italian climate zone E). The Heating Degree Days (HDD) are 2639 for CS1 and 2952 for CS2. The mean annual solar radiation, which is the same for CS1 and CS2, is about 4700 MJ/m^2. Table 1 shows some building features concerning CS1 and CS2.

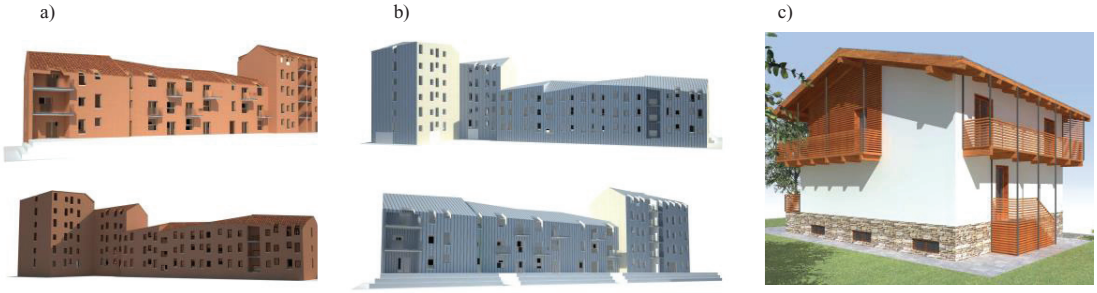

Fig. 1. (a) Case Study 1, option a; (b) Case study 1, option b; (c) Case study 2, option 1.

Table 1. Reference building features for CS1 and CS2 or Features of the CS- and CS- reference buildings

Building features	CS1	CS2
Building type	Multistorey building	Detached house
Gross Conditioned Floor Area (CFA)	2453 m^2	226.89 m^2
Useful floor area	2112 m^2	184.16 m^2
Number of stories above ground (conditioned)	from 3 to 6	2
Average floor-to-floor height	2.7 m	2.7 m
Surface area-to-volume ratio	0.59 m^{-1}	0.62 m^{-1}
Window-to-Wall Ratio (WWR)	16% - 30% - 50%	16%

CS1 and CS2 were originally designed to be energy efficient buildings. Thus the projects were implemented with materials enable to lessen the heat transmission through the building envelopes and to exploit solar gains. Two technological solutions were taken into account in the CS1 design process. The first (CS1_a) was masonry based system (walls, roofs, partitions and floors) with a cladding and insulated envelope (three layers of plaster over rigid polystyrene board insulation). The second (CS1_b) was steel framed building with precast lightweight coating materials (aluminum, galvanized steel and gypsum board) with an aluminum rain screen and insulated envelope made up of high density rockwool.

Two window options were taken into account in the project: aluminum clad windows, identified as W1_A, and wooden windows, identified as W1_B. Both W1_A and W1_B had a double Low_E glazing filled with Argon.

A comparable approach was considered for CS2. Two technological solutions were designed: the first (CS2_a) was a platform framing system made up of laminated timber, and implemented with a wood stud wall, plastered wood siding and rockwool blanket insulation; the second one (CS2_b) featured the same building envelope systems designed for CS1_a, with the exception of the window systems. In this case, recycled (30%) aluminum clad windows (W2_A) and wooden windows (W2_B) with triple Low_E glazing filled with argon were considered in the analysis.

The same window thermal transmittance U_w was assumed for both windows (wooden and aluminum) and the small differences in window performances due to the different frames were neglected (CS1, W1_A and W2_B: U_w= 1.48 W/m^{2}K; CS2, W1_A and W2_B: U_w = 0.98 W/m^{2}K).

The case studies considered materials and technologies aimed at reducing heating, ventilation, cooling and the hot-water energy demand, and intended to obtain A and B energy efficiency ratings for houses (Class A: 27 kWh/m^{2}yr ≤ PED < 44 kWh/m^{2}yr; Class B: 44 kWh/m^{2}yr ≤ PED < 82 kWh/m^{2}yr).

Table 2 displays the CS1 (a and b) and CS2 performances related to the building envelope technologies and building services.

Table 2.Building envelope and building service performances

Building envelopes	CS1		CS2			CS1/ CS2
U-value [W/m²K]	a and b		a	b	Building services	
Wall system	0.16	0.27	0.17	0.19	Heating system [η]	0.8
Roof system	0.23	0.30	0.17	0.19	Cooling systems [COP] [η_{el}]	2.5 2.17
Floor system	0.19	0.23	0.28	0.28	Hot water [η]	0.85
Average value	0.27	0.27	0.22	0.22	Air flow rate n [h^{-1}]	0.5

3.1. Life-cycle energy analysis

The calculation considers the extraction of the non-renewable energy sources, their transformation into secondary energy sources, their transport and the useful energy supplied. Therefore, the kWh primary energy per year was assumed as a *functional unit* for the energy analysis [kWh/m²yr].

The following boundary conditions were significant for the purposes of the study:

- *Boundary in time*: EE and OE were calculated considering secondary data for the 2005-2014 period, and direct data related to Life-Cycle Assessment (LCA) studies carried out from 2007 to 2014. EE was annualized taking into account a lifespan of 50 years.
- *Boundary towards geography*: Common conversion factors were set out for EE and OE. These factors were taken from available databases [9-11] in order to assess the primary energy value of the energy carriers (e.g. natural gas, coal, etc.) and in agreement with the Italy electrical energy mix. If no data referring to the Italian mix were available, the calculation was based on the Western Europe Countries energy mix.
- *Boundary towards systems*: EE encompasses the primary energy value of the material and components used for walls, floors, roofs, windows systems as well as partitions. Other materials used for manufacturing un- conditioned building systems were considered in the EE account in a second stage while EE ascribed to solar heating, PV systems and thermal plants was not included in the assessment.
- *Boundaries in the life cycle*: EE was calculated considering raw material extraction, raw material refining, component manufacturing and off-site building-system assembly.

The energy analysis was conducted taking into account the following cut-off rules:

- The EE calculation refers to the initial EE. In particular the estimation procedure refers to upstream processes. Both direct and secondary data concerning the materials and components were used.
- The OE calculations were performed according to Italian standard UNI TS/11300 [15], taking into account heating, ventilation, cooling, and hot-water production.

3.2. Discussion and results

Figure 2 (a; b) shows the annualized EE and OE values normalized to CFA concerning to an average U-value referred to the CS1 envelope (0.27 W/m²K). EE and OE values reported in the bar chart concern three WWRs (ranging between 16% and 50%) and take into account the two window options (W1_A and W1_B).

As shown in figure 2, the more the WWR ratio increases, the more EE rises, for both CS1_a and CS1_b as well as for W1_A and W1_B. Although in WWR 30% and WWR 50% the building envelope mass (kg) is lower, the EE is higher because of the PED used in the production of glass, aluminum and wood. The difference between the W1_A EE and the W1_B EE is due to the total amount of non-renewable energy sources used in W1_A. In W1_B,

the EE calculation does not include the biomass energy used in the window production and assumed as a renewable energy source.

A noteworthy result is obtained for OE going from WWR16% to WWR30% for CS1_a and CS1_b and for W1_A and W1_B. Despite the wider glazing area, the energy consumption is about 60 kWh/m^{2}yr. Figure 2 shows that CS1_a and CS1_b have different characteristic trends. Such trend variation is caused by the different wall thicknesses considered in the case studies: CS1 = 0.56 m; CS2 = 0.30 m, and, as consequence, it is influenced by the different shading factors. In CS1_a, the windows have a significant recess (measured from the outer envelope layer) compared to the window recess in CS1_b. A greater obstruction index was taken into account in the OE CS1_a calculation, and thus the mutual relationship between heating and cooling for the different WWRs was affected. In CS1_a, the optimal WWR is in the range between 30 to 50 %, showing very similar values. In CS1_b, the best performance is achieved for WWR 30%. Since the window area is increased, the higher cooling loads are no longer balanced with the lower heating loads in the wintertime.

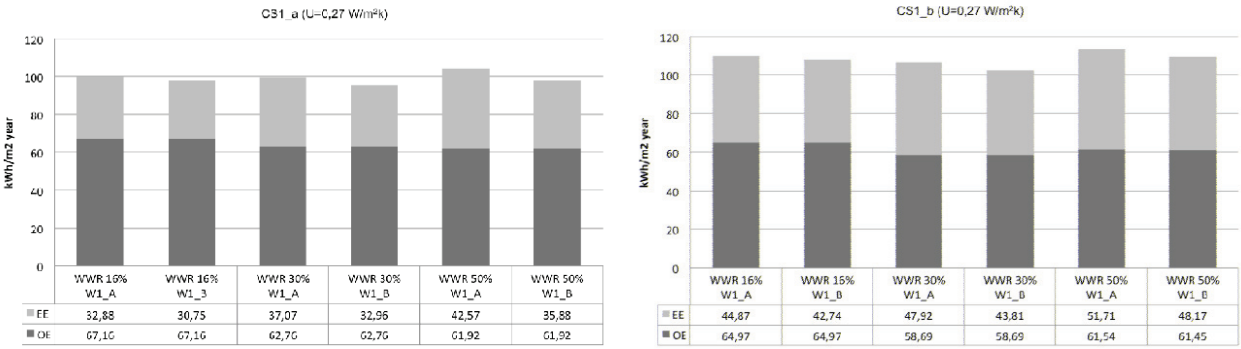

Fig. 2. (a) CS1_a; (b) CS1_b
Annualized Operating Energy and Embodied Energy values normalized to CFA (kWh/m^{2}yr). EE refers to materials used in the conditioned spaces.

When OE is added to EE, the lowest value (95.56 kWh/m^{2}yr) is related to CS1_a, WWR 30%, W1_B, while the highest value (113.25 kWh/m^{2}yr) is associated with CS1_b, WWR 50%, W1_A.

Figure 3 (a; b) shows details of the annualized EE and OE values, normalized to CFA, and referring to the average U-value considered for CS2 envelope (0.22 W/m^{2}K). The EE and OE values reported in the bar chart take into account the two window options (W2_A and W2_B).

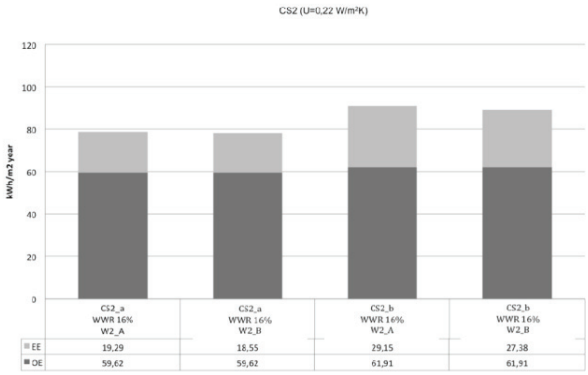

Fig. 3. CS2_a and CS2_b
Annualized Operating Energy and Embodied Energy values normalized to CFA (kWh/m^{2}yr). EE refers to the materials used in the conditioned spaces.

The correlation among CS1 and CS2 values shows that CS2_a has the lowest EE value. This is due to the large amount of wood used for the structure, envelope and partitions. CS2_b is characterized by a higher EE value when compared to CS2_a and by a lower value when compared to CS1_a. The difference between CS2_a and CS2_b is the consequence of the construction systems used (wood vs. masonry). The variation between CS2_b and CS1_a (designed with similar materials) is due to the following reasons: the recycled aluminum fraction used for manufacturing W2_A entails an EE reduction; the triple glazing used in CS2 affecting the OE decrease.

In both case studies, the EE percentage incidence on the total amount of PED falls from a range of 25-34% (CS1_a; WWR 16%; W1_A and W1_B as well as CS2_a; WWR 16%; W2_A and W2_B) to a range of 35-42% (all the other analyzed options). The introduction of EE moves the CS1_a, the CS1_b and the CS2_b energy efficiency rates from Class B to Class C. Only CS2_a remains in Class B.

When the energy analysis adds up the EEs of all the building systems used for both the CFA and UFA, the corresponding value increases. In some options, such as in CS1_a and CS1_b (WWR 50%; W1_A) cases, the EE percentage exceeds the OE by 53-61%.

4. Conclusion

The paper shows some results obtained from an assessment of the mutual relevance between EE and OE. Overall, in order to reach a nearly zero energy condition, EE has an energy impact that requires to be balanced by the implementation on renewable sources for thermal needs and electricity feeds. EE makes it more difficult to achieve the high-efficiency BER suggested in national and local standards. Furthermore, the paper demonstrates the incidence of WWR on the building energy analysis. EE increases because of the use of energy-intensive materials, while the OE calculation is influenced by the solar gain, the shadowing factor and by heat transmission. A weighing scale among energy analysis factors requires to be investigated. In the future, a broader analysis could be carried out, according to the data availability, in which recurring EE and end-of-life EE will be included.

In short, the choice of a proper balance metrics and weighting system should depend on the targets of the political agenda. Only a few countries have so far introduced requirements pertaining to EE. A frequent constraint for various countries is the lack of national and agreed EE databases for building materials.

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