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Embodied energy versus operational energy in a nearly zero energy building case study

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Abstract

Currently in the NZEB energy demand calculation method the Embodied Energy is not included, despite the state-of-the-art recognizes a relevant energy impact caused by raw materials extraction as well as components manufacturing, product final assembly and transportation. Aim of this study was to assess the Embodied Energy in a NZEB case study along with the Operational Energy, pointing out the importance of taking into account both these aspects since the earliest design stage.
Within the research activity here presented, for accounting the EE, a worksheet was developed and implemented with over 65 materials taken from a database carried out by the authors, in order to encourage designers to properly manage these issues.

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Keywords: Nearly Zero Energy Building; Operational Energy; Embodied Energy; Design Tool

1. Introduction

In recent years a consistent legislative framework aimed at significantly improving the energy efficiency of European building stock, i.e. the Energy Performance of Buildings Directive (EPBD) [1], the Energy Efficiency Directive (EED) [2] and the Renewable Energy Directive (RED) [3], has been set out.

Particularly relevant is the EPBD Recast stating that new buildings occupied by public authorities and properties have to be Nearly Zero Energy Buildings (NZEBs) by December 31, 2018 and that new buildings have to be NZEBs by December 31, 2020. International Standards and National Building Codes are thus required to duly take into account these goals, identifying commonly agreed definitions and methodologies to estimate the building energy analysis. Both these aspects are not yet standardized and this un-ambiguity represents one of the most important

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issue to be faced. According to the EPBD Recast a NZEB is a building that has a very high energy performance with nearly zero or very low amount of energy required to be covered - to a very significant level - by energy from renewable sources, including renewable energy produced on-site or nearby.

Usually in the NZEB calculation method the Embodied Energy (EE) is not included. Such exclusion is due magnitude recognized to Operational Energy (OE) assumed as more significant over the long term, despite the state-of-the-art recognize a certain energy impact caused by raw materials extraction as well as by energy consumptions for some building products (e.g. aluminum and steel alloys) [4-5-6].

A literature based discovery method was adopted to analyze 38 research works consisting of 206 cases. The study compares the EE with Operational Energy OE of buildings [5]. The findings reveal that most EE calculations were based on different stages of life cycles for the energy analysis in buildings. As a result the comparison was often problematic. So far the impact of EE of the construction materials is frequently ignored since the life cycle energy analysis of buildings is a complex process. Furthermore, methods and tools for calculations can vary widely and the data availability is rather partial.

On the whole, scientific literature shows the need for appropriate analysis metrics and weighting systems to properly characterize NZEB and the importance of the EE as indicator in the building energy analysis.

The aim of this study was to assess if EE is a valuable indicator that should be included in building energy analysis along with OE and if they can be both taken into account at an early design stage.

Within the research activity here presented, for accounting the EE, a worksheet was developed and implemented with over 65 materials taken from a database carried out by the authors, in order to encourage designers to properly consider these issues.

Nomenclature

BIM	Building Information Modeling
CFA	Conditioned Floor Area
EE	Embodied Energy
EEi	Initial Embodied Energy
EEr	Recurring Embodied Energy
HDD	Heating Degree Days
IFC	Industry Foundation Classes
LCA	Life Cycle Assessments
NZEB	Nearly Zero Energy Building
OE	Operational Energy
PED	Primary Energy Demand
REER	Renewable Embodied Energy Ratio
RER	Renewable Energy Ratio
UFA	Unconditioned Floor Area

2. Definitions and methodology

The EE and OE assessment here presented was carried out considering the International Energy Agency (IEA), Solar Heating & Cooling Program, Task 40, Annex 52 [7], and the IEA, Evaluation of Embodied Energy and $CO2_{eq}$ for Building Constructions, Annex 57 [8].

They provide the following definitions concerning a building throughout its life:

- Initial EE i.e. the primary energy demand required for off-site and on-site building processes including raw materials extraction, components manufacturing, products final assembly and transportation.
- Recurring EE i.e. the primary energy demand required in refurbishing and maintaining the building over its life cycle.

- Operational Energy i.e. the primary energy demand required in heating, cooling, lighting and powering services in the building.
- End-of-life EE i.e. the primary energy demand required for the building final disposal.

The energy measures in the various stages of a products life are often related to a "cradle-to-grave" approach [4]. The importance to assess a building over its life cycle refers to the need to implement closed-loop cycles in the construction sectors. Although the cradle-to-grave approach (or consistent with circular economy principles the "cradle-to-cradle" approach) is recommended for a proper and full energy assessment, most of the EE databases [9-10-11] refer to manufacturing and construction stages while recurring and end-of-life EE are generally considered negligible and it is often justifiable to ignore them [12-13].

Due to the data limitations to performing the EE of products over their life cycle, in the case study herein presented, the EE was calculated taking into account in a first phase the "cradle-to-gate" and the "cradle-to-site" processes. The "cradle-to-gate" EE was assumed as the Primary Energy Demand (PED) until the product leaves the factory gate. The "cradle-to-site" EE is the PED until the product reaches the construction site.

In the analysis carried out, in a second phase, the periodic EE was taken into account in order to analyze its impact and highlight its influence, thanks to a preview study carried out by the authors [11].

Furthermore the paper was intended to calculate the materials' Renewable Embodied Energy Ratio (REER). REER is the ratio between the EE from renewable sources and the total EE. It is indicated as a percentage and it can be used as criteria in the materials selection process.

There are some peculiarities concerning OE and EE that deserve to be highlighted. Although EE and OE are both based on the amount of PED, EE is commonly considered once immediately after the construction stage (year zero) especially when the analysis refers only to initial EE, whereas OE accumulates over the lifetime of a building.

OE is usually measured as the energy per unit Conditioned Floor Area (CFA; kWh/m^{2}yr) while EE is calculated taking into consideration the total mass of materials required for the building construction (kWh/kg or MJ/kg).

In order to harmonize EE and OE values, it is therefore necessary to both annualize EE and express it on the basis of a floor surface unit; this implies making assumptions 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).

Based on these premises, the study was carried out in compliance with the MINERGIE® definitions and labels [14]. Minergie Institute has set out several building energy efficient standards. The Minergie-A and Minergie-ECO standards were adopted as references in the assessment procedure. Minergie-A and Minergie -ECO are two rating systems that are used for new and refurbished low-energy-consumption buildings. They are defined consistently with NZEB certification. Both take into account OE and EE. The OE considers the energy demand for heating, ventilation and hot-water production. 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 [15]. With regards to EE two different mandatory requirements are provided, respectively: i) Minergie-A=50 kWh/m^{2}yr; ii) Minergie-ECO=30 kWh/m^{2}yr. The EE value encompasses two EEs, both of which refer to CFA [16]. The former includes the building envelope and the partitions. The latter involves building services (e.g. the EE of the heating systems). The EE is annualized according to the lifetime of the building expected by the main standard (50 years). Optionally, Minergie-ECO sets out a broader analysis by including building systems that refer to un-conditioned spaces.

2.1. A tool for EE related performance metrics

The EE calculation is often problematic. The available free-software cannot be easily implemented by users (e.g. BEES® model) thus only a limited amount of materials can be assessed in the building energy analysis. Other tools, such as those enable to carry out a Life Cycle Assessment are extremely time consuming and they require specific expertise [9]. In order to overcome the mentioned constraints, according to MINERGIE® Certification (A and ECO), it was developed and implemented a worksheet tool: IREEA (Initial and Recurring Embodied Energy Assessment). IREEA enables to quantify the EE for any class of building. Particularly it is based on the Swiss SIA 2032 technical specification (Grey Energy of Buildings).

IREEA makes possible to evaluate: 1) the initial EE value of each building systems (e.g. floor systems, wall systems, etc.); 2) the initial EE value of the window frames and glazing systems; 3) the simplified initial EE of building services; 4) the recurring EE based on the replacement cycles of material and components; 5) the potential variation of the building's estimated life time; 5) the total EE of a building.

IREEA assesses if specific materials and components have a considerable EE impact in the early design stage in order to allow some replacements.

The tool initially was developed as an excel file. Its functioning was tested by Master of Science's students enrolled at Politecnico di Torino, Course of Sustainable Architecture.

Currently a standalone web-based version is under development. It will enable to export and read data files in IFC (Industry Foundation Classes) format, common to several BIM (Building Information Modeling) software.

The software was designed keeping in mind two key features: a simple and intuitive user interface and the integration of a database that provide instant accessibility of materials EE.

IREEA is structured in three main datasheets: 1) input; 2) building systems; 3) results.

In the *input datasheet* users must enter data concerning the building features, such as: the project name; the building use or the building uses; the surface of each building systems [m^2]; the building expected life time [years]; the floor surface unit to assume as reference [m^2] (e.g. if the EE is measured per CFA or UFA); the life cycle stages to take into account (e.g. assessment of EEi or assessment of EEi + EEr).

The *building system datasheet* focuses on data insertion about materials and components used for drawing up the building systems. The datasheet requires to filling out the input cells with data concerning properties of materials used in the analyzed system. By laying down for each material selected: density [kg/m^3], thickness [m] and number of replacement cycles [n], through the database available, the datasheet provides the total EE value for the building system [MJ/m^2] and the share of EE from renewable resources [MJ/m^2]. A pie chart shows automatically the renewability index [%] based on ratio between EE from renewable resources and total EE. Fig 1 (a).

The *result datasheet* provides the EEi [MJ/m^2] and the EEr [MJ/m^2] values with regards to whole building. The datasheet specifies also the annualized EE expressed on the reference floor surface unit [kWh/m2yr]. Furthermore, it shows, automatically two pie graphs. The former concerns the REER [%]; the latter refers to the ratio between EEr and EEi [%]. Finally, according to life cycle of building set out [50 years], the datasheet assesses if the EE fulfill the requirements of MINERGIE® Certification (A or ECO). Fig 1 (b)

A printable version of results obtained is available.

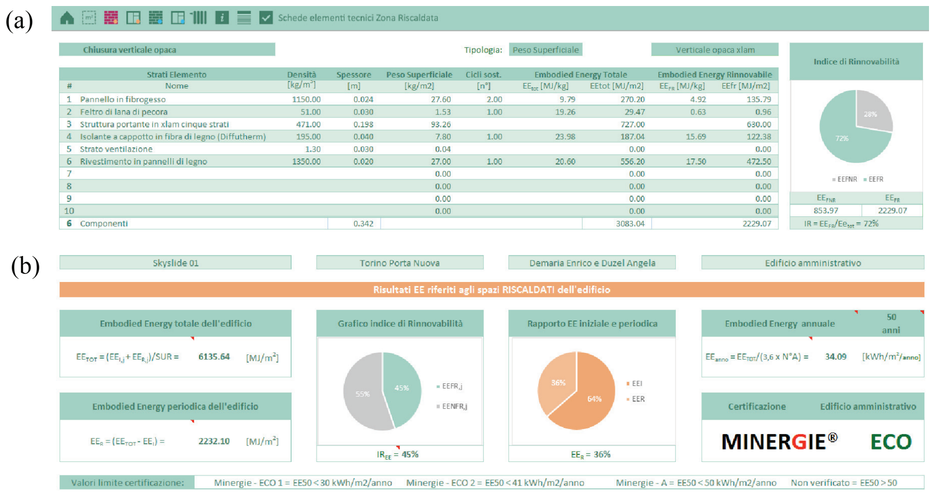


Fig. 1. (a) Building systems' sheet of IREEA; (b) the summary of the results section.

3. Case study

On the basis of the previously described definitions and methodological framework, a building project with different technical innovation levels, building assemblies and materials was assumed as a case study and it was analyzed in order to assess the ratio between OE and EE and monitoring the IREEA functioning. The case study, named Skyslide tower, is an office building (Fig.2) and it is located in the City of Turin (Lat. 45.30°N, Long. 7.40°E, Italian climate zone E). The Heating Degree Days (HDD) are 2617. The mean annual solar radiation is about 4700 MJ/m^2.

Fig. 2. The case study Skyslide.

The building is located near Porta Nuova railway station, an urban area undergoing a thorough renovation process. The skyscraper that rises above the underground station, includes two below grade floors for the shopping mall and 25 above grade floors of administrative offices and panoramic restaurant.

Strict environmental guidelines, asking for Reduction, Reuse and Recycling of materials drove the design process. These 3R issues have therefore supported the concept from the very beginning, contextually with energy efficiency strategies. The Skyslide tower was thus designed to be an energy efficient building, through the adoption of strategies aimed at reducing the heat transmission through the building envelopes and at exploiting and controlling solar gains. The double façade that characterizes the building envelope plays a thermodynamic role. The façade, hosting integrated PV panels, allows: to providing a high coverage of shading in the summer months; to reducing the cooling demand; to producing the on-site renewable energy. The main building features are displayed in Table 1.

Table 1. Reference building features.

Building features	Skyslide project
Building type	Office building
Gross Conditioned Floor Area (CFA)	22.160 m^2
Useful floor area	19.046 m^2
Number of stories above ground (conditioned)	25
Average floor-to-floor height	3,5 m
Surface area-to-volume ratio	0,29 m^{-1}

The design process defined eight different technological solutions, summarized in Table 2 according to three main variables: the structure of the building, the energy sources used for the materials production and the Italian U-value limits [16]. As far as the structure is concerned two solutions were identified: the former was an Xlam building reinforced by Steel Beams structure (XSS). The latter was a usual structure mixed in Concrete and Brick Blocks (CBS).

As regards the energy sources used for the materials production, in the study were selected materials with different Renewable Embodied Energy Ratio such as natural solutions with high REER, like wood fiber/cellulose flakes insulation and recycled wood panels cladding (XSS_A and CBS_A) and mineral/synthetic solutions with low REER, like rock wool insulation, aluminum window frames and steel cladding (XSS_B and CBS_B), Fig. 3.

Regarding the glazing systems two options were considered: wooden frame windows (XSS_A and CBS_A) and aluminum frame windows (XSS_B and CBS_B). Both options mounted a double selective low-e glazing filled with argon. Due to the minimal difference of U-value (mainly related to glazing) it was assumed the same U-value for both the solutions (U_w= 1,05 W/m^{2}K).

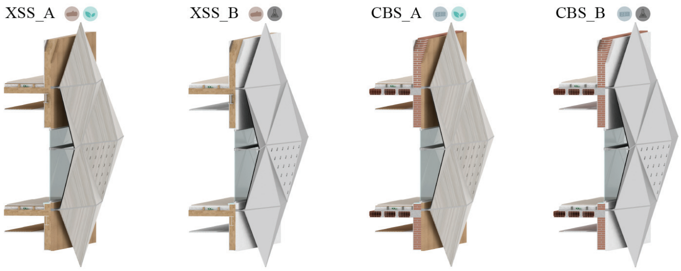


Fig. 3. The main different technological solutions.

For the last variable the U-value was defined according to the minimum values to be achieved respectively in 2015 and 2019/21 (2019 for public buildings): 2015 (XSS_A_U_{2015} and CBS_A_U_{2015} / XSS_B_U_{2015} and CBS_B_U_{2015}); 2019/21 (XSS_A_U_{2021} and CBS_A_U_{2021} / XSS_B_U_{2021} and CBS_B_U_{2021}). Details are provided in Table 2.

The Skyslide project was therefore designed to be a building that complies with the mandatory and current energy efficiency requirements of the whole system building envelope –building services (representing the conventional building, assumed as the reference case). Moreover, in order to obtain a Nearly Zero Energy Building, the energy behavior was assessed assuming a coverage of energy from renewable sources on-site (photovoltaic) equal to 80%,

Table 2. Building envelope and building service performances.

Structure	Xlam Steel Beams (XSS)				Concrete and brick blocks (CBS)			
Energy sources for materials production	High REER (XSS_A)		Low REER (XSS_B)		High REER (CBS_A)		Low REER (CBS_B)	
Italian U-value limits [W/m^{2}K]	2015 (A_U_{2015})	2021 (A_U_{2021})	2015 (B_U_{2015})	2021 (B_U_{2021})	2015 (A_U_{2015})	2021 (A_U_{2021})	2015 (B_U_{2015})	2021 (B_U_{2021})
Wall system	0.28	0.24	0.28	0.24	0.27	0.24	0.28	0.24
Roof system	0.24	0.21	0.24	0.21	0.23	0.21	0.22	0.20
Floor system	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23
Average value	0.25	0.27	0.25	0.27	0.24	0.22	0.24	0.22

3.1. Boundaries in the building energy analysis

The study considers as PED: i) the extraction off combustible fossil fuels such as coal, oil, and natural gas extracted from a stock of finite resources; ii) their transformation into secondary energy sources; iii) their transport iv) the useful energy supplied. Based on these assumptions kWh primary energy per year was used a reference unit for the building energy analysis [kWh/m^2yr].

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

- *Boundaries in the life cycle*: EE was calculated considering raw material extraction, raw material refining, component manufacturing, off-site building-system assembly (EEi) and component replacements during the use of the building (EEr).
- *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.
- *Boundary towards geography*: Common conversion factors were set out for EE and OE. These factors were taken from available databases [9-10-11] 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. When data did not refer to the Italian mix, Western Europe Countries energy mix was used for the calculation.
- *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. The EE was initially calculated taking into account materials used for CFA. In a later stage materials were considered both material used for CFA and UFA. The solar heating, the PV systems and thermal plants were omitted in the EE calculation.

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

- The EE calculation refers to the initial EE, and the recurring EE. In particular, the estimation procedure refers to upstream processes. Both direct and secondary data concerning the materials and components used.
- The OE calculations were performed according to Italian standard UNI TS/11300 [17], taking into account heating, ventilation, cooling, and hot-water production.

3.2. Results

With regard to OE values for the eight different scenarios, since the results are very similar being mainly related to the U-values, an average PED was assumed as shown in Fig.4. The conventional building, without the on-site renewable energy production, has an average PED of 72 kWh/m^2yr, whilst the Nearly ZEB building, with a RER of 82%, have a PED of 18 kWh/m^2yr. The cooling system (PED C) represents the most important voice of the energy balance (38,16 kWh/m^2yr) with an incidence of 53% on the global value, followed up by the heating system (PED H) accounting for the 24% (17,82 kWh/m^2yr) and the equipment for ventilation (PED V), lighting (PED L) and domestic hot water (PED W) with a 23% (16,02 kWh/m^2yr).

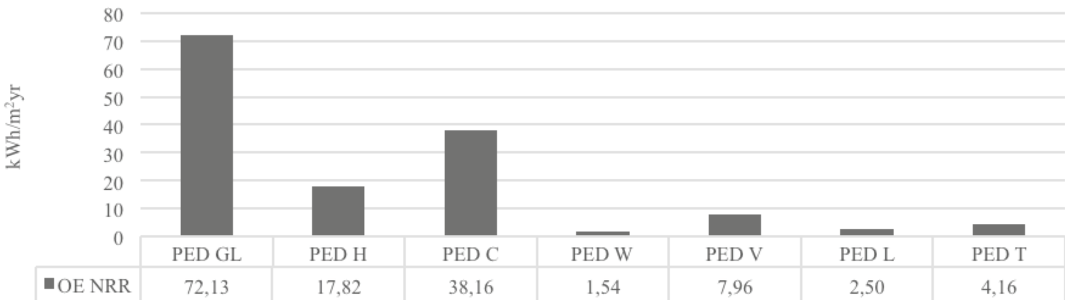
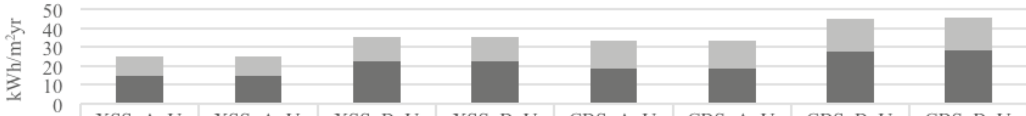


Fig. 4. Operational Energy values normalized to CFA (kWh/m2yr).

In the energy analysis the EE values are noteworthy. In the worst scenario (CBS_B_U_{2021}) a maximum PED of 27,82 kWh/m^2yr is obtained for the initial Embodied Energy (EEi) which becomes 45,35 kWh/m^2yr if the recurring Embodied Energy (EEr) is added. Considering the EEr value there is an average increased of the total EE value of 41%, as shown in Fig. 5. Based on the EE data the best scenario is the XSS_A_U_{2015}, with Xlam structure and natural materials. The worst-case scenario is the CBS_B_U_{2021} with traditional masonry and synthetic materials. An incidence of 46% related to the materials, corresponding to 20 kWh/m^2yr, was thus obtained.

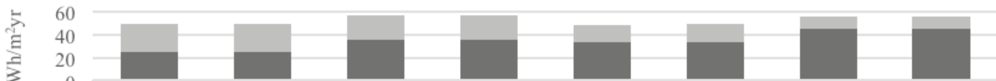


	XSS_A_U 2015	XSS_A_U 2021	XSS_B_U 2015	XSS_B_U 2021	CBS_A_U 2015	CBS_A_U 2021	CBS_B_U 2015	CBS_B_U 2021
EEr	10,33	10,48	13,19	13,28	14,43	14,40	17,41	17,53
EEi	14,27	14,42	22,05	22,14	18,70	18,61	27,70	27,82

Fig. 5. Initial and Recurring Embodied Energy values normalized to CFA (kWh/m2yr) refers to materials used in the conditioned spaces.

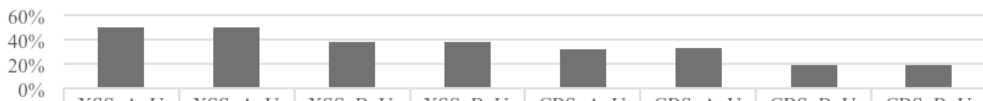
The Renewable Embodied Energy Ratio (REER) was calculated in order to study the impacts of energy sources used in the initial and recurring EE. The Xlam (XSS_A and XSS_B) based technology shows the higher total EE (Fig. 6) but it has the higher REER too (50% and 38%). The REER varies in range between 19% - for the scenario with traditional masonry and synthetic materials - and 50% - for the scenario with Xlam structure and natural materials. By deducting the EE from renewable resources (EE_{RR}) and focusing the analysis on the EE from non-renewable resources (EE_{NRR}) the histogram shows that the higher impact in terms of fossil fuels depletion is due to CBS_B scenarios. The higher EE value (EE_{RR}+EE_{NR}) is 57,13 kWh/m^2yr (XSS_B_U_{2021}) and the best scenario is the CBS_A_U_{2015} with a EE_{NRR} of 48,72 kWh/m^2yr. On the whole the REER ratio is a valuable indicator for a comparison among materials and technologies. It enables an immediately assessment in terms of energy impact. It might be helpful in the early design stage by laying down threshold values within the international standards and in NZEB assessment.

(a)



	XSS_A_U 2015	XSS_A_U 2021	XSS_B_U 2015	XSS_B_U 2021	CBS_A_U 2015	CBS_A_U 2021	CBS_B_U 2015	CBS_B_U 2021
EE RR	24,61	24,90	21,60	21,71	15,59	16,26	10,58	10,64
EE NRR	24,61	24,90	35,24	35,42	33,13	33,00	45,11	45,35

(b)



	XSS_A_U 2015	XSS_A_U 2021	XSS_B_U 2015	XSS_B_U 2021	CBS_A_U 2015	CBS_A_U 2021	CBS_B_U 2015	CBS_B_U 2021
REER	50%	50%	38%	38%	32%	33%	19%	19%

Fig. 6. (a) Embodied Energy from renewable (EE RR) and not renewable resources (EE NRR); (b) Materials Renewable Embodied Energy Ratio for the eight different scenarios.

Finally, by comparing the two energy components (OE and EE) of the analyzed buildings, conventional and Nearly ZEB, it can be noticed the different EE's incidence on the total amount.

In the conventional building, the solution without the production of on-site renewable energy, has an impact on the total PED (EE+OE) ranging between 25% (24,61 of 95,65 kWh/m^{2}yr) and 39% (45,35 of 117,46 kWh/m^{2}yr), Fig. 7 (a). In the Nearly ZEB solution, instead, the EE's impact is totally different, varying between 57% (24,61 of 42,85 kWh/m^{2}yr) and 71% (45,35 of 63,61 kWh/m^{2}yr) of total building's PED, Fig. 7 (b).

For the analyzed case study, moving from a conventional building to a Nearly ZEB, the average incidence of EE rises from 32% to 67%.

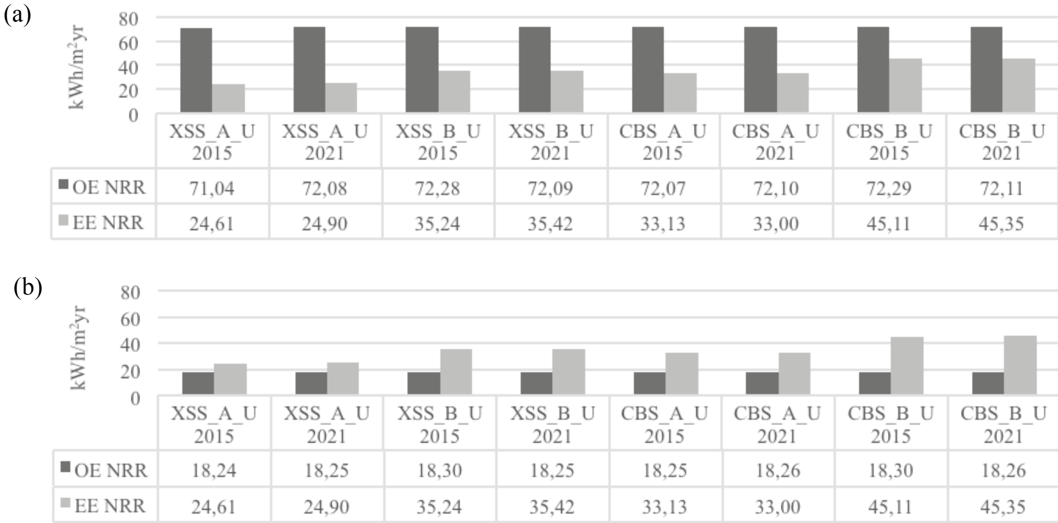


Fig. 7. (a) Annualized Operating Energy and Embodied Energy values normalized to CFA (kWh/m2yr) of the traditional solutions; (b) Nearly ZEB solutions.

4. Discussion

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, OE has a huge energy impact that requires to be balanced by the implementation on renewable sources for thermal needs and electricity feeds. According to literature review the study shows the growing significance of EE. The incidence of EE in the building energy analysis accounts in some cases 50% of the whole PED. However, it must be provided an extra PED if was taken into account the end-of-life EE.

Consistent with debate [4, 6, 11, 13, 18] about the importance of assuming a life cycle perspective, the case study has highlighted the importance of estimating EE at an early stage of the design process, in addition to the impacts and potential long-term consequences of using different construction materials.

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.

According to the results obtained from the case study, it can be asserted that the threshold limits of the MINERGIE® certification (30 e 50 kWh/m^{2}yr) can be easily complied even when synthetic materials are employed and the recurring EE is taken into account.

In the future the NZEB implementation need to be addressed by the choice of a proper balance metrics and weighting system. So far only few countries have introduced requirements pertaining to EE, mainly due to the lack of national and agreed EE databases for building materials.

Furthermore, a weighing scale among energy analysis factors requires to be investigated. In the future, a broader analysis will be carried out, according to the data availability, in which end-of-life EE will be included.

Finally, the discussions about EE and OE should be extended to Embodied Carbon (dioxide emissions). Current legislation within European Countries aims at Zero Emission Buildings, mainly through an OE minimization [18].

Similarly, to what was demonstrated through the building energy analysis carried out on the case study, achieving zero carbon dioxide emissions could lead to an increased EE of building. Future works should be addressed in study the carbon dioxide emissions associated to energy that is embodied in the building materials.

The study should encompass the sequestration of carbon within some products, such as wood based materials, and the emission (or sequestration) of carbon dioxide through chemical reactions during the production of materials such as cement i.e. the carbonation of concrete [11].

5. Conclusion

In recent years European and national legislations have emphasized the energy efficiency in use stage. It is important – according to ecological and sustainable principles – to design building with a life cycle approach.

Designers and technicians should therefore consider the EE along with the OE as indicator to minimize the non-renewable raw materials extraction and exploitation.

In order to help designers and other stakeholders have been developed tools for reducing EE. These tools need to be implemented and the methodologies they are based on refined, including e.g. the embodied carbon and underpinning the correlations between EE and OE values.

Currently in order to reach the NZEB qualification it is more righteous considering only the OE and aiming at its complete fulfillment. It is nonetheless evident that a new index of energy rating considering the EE amounts is needed for a more comprehensive evaluation of buildings energy impact.

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