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Embodied energy and operational energy evaluation in tall buildings according to different typologies of façade

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Abstract

Although recent studies demonstrate the importance of including the Embodied Energy (EE) in building analysis, only the Operational Energy (OE) is currently taken into account in building energy demand calculation method.
In particular, the EE plays an important role in tall buildings evaluation, because the energy demand increases with building height. Aim of this study was to assess the Embodied Energy in evaluation of different types of tall building façade systems performances along with the Operational Energy, pointing out the importance of taking into account both these aspects.
Within the research activity here presented, 8 glazed envelope typologies, in 5 different climate zones, have been evaluated.

Peer-review under responsibility of KES International.

Keywords: Operational Energy; Embodied Energy; Tall Building; Façade.

1. Introduction

In building energy analysis, the Embodied Energy (EE) is usually not included [1-2-3]. Such exclusion is due to magnitude recognized to Operational Energy (OE), assumed as more significant over the long term. Instead, the

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state-of-the-art recognizes a certain energy impact caused by raw materials extraction as well as by energy consumptions for some building products (i.e. aluminum and steel alloys) [4-5-6].

The findings have revealed 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 [7] the importance of the EE as indicator in the building energy analysis.

In most cases, the use of materials with high energy value, as glass and aluminum, makes the building envelope a main subsystem in global energy demand of EE. Several research studies carried out by Council on Tall Buildings and Urban Habitat (CTBUH) estimate the energy required for façade system equal to 20% of the total EE.

Nomenclature

Ucw	curtain wall thermal transmittance
EE	Embodied Energy
EEi	Initial Embodied Energy
OE	Operational Energy
NRA	Net Rentable Area
CFA	Conditioned Floor Area
UFA	Unconditioned Floor Area
GFA	Gross Floor Area
PED	Primary Energy Demand

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 [8], and the IEA, Evaluation of Embodied Energy and CO2eq for Building Constructions, Annex 57 [9].

The EE is defined as 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).

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. 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. Although that, most of the EE databases [10-11-12] refer to manufacturing and construction stages, while recurring and end-of-life EE are generally considered negligible [13-14].

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

The values of EE have been calculated using the IREEA (Initial and Recurring Embodied Energy Assessment) worksheet tool [15]. This tool is based on the Swiss SIA 2032 [16] technical specification (Grey Energy of Buildings) and its functioning was tested by Master of Science's students enrolled at Politecnico di Torino, Course of Sustainable Architecture. The evaluation refers only to building envelope components. A period of up to 25 years has been examined for EE calculation, considering the energy demand for building envelope maintenance as negligible. The IREEA database refers to Italian data. Such data were used for every analyzed climate zones.

The OE is defined as 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.

In the analysis carried out, the calculated OE considers the PED for heating and cooling. Ventilation and lighting energy demand are not included in the analysis to emphasize the difference of the amount of energy needed to ensure thermal comfort, with different façade technologies. The domestic hot-water energy is not included because it is not influenced by different types of façade.

For OE evaluation, a calculation with a dynamic energy software (IES Virtual Environment) has been performed. Through dynamic energy modelling, real-time detailed simulation of thermal and energy behavior of buildings is permitted. In particular, the real performance of the building envelope can be evaluated, considering every boundary condition: external temperature, solar radiation, natural ventilation, users' behavior, HVAC system.

As explained, EE and OE are both based on the amount of PED. Since the study here described refers only to the initial EE, the latter is considered once immediately after the construction stage (year zero). Instead, the OE takes account of the PED accumulated over the lifetime of the building.

OE is usually measured as the energy per unit Conditioned Floor Area (CFA; MWh/m^2yr) 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.

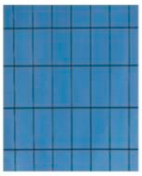
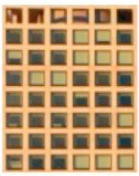
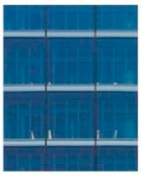
In the analysis carried out, the EE calculation refers only to building envelope components; both EE and OE have been referred to the same Conditioned Floor Area.

3. Case study

On the basis of the previously described definitions and methodological framework, a tall building typical floorplan has been assumed as a case study. It has been analyzed in order to assess the ratio between OE and EE, with different façade system typologies, in different climate zones.

In particular, 8 façade systems, shown in Table 1, in 5 different climate zones, have been analyzed.

Table 1. Analyzed typologies of glazed façade.

Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 7	Type 8
							
Single Skin	Single Skin	Single Skin	Single Skin	Single Skin	Double Skin	Double Skin	Double Skin
Insulated glass, unitized curtain wall	Insulated glass, spandrel panel, unitized curtain wall	triple insulated glass, unitized curtain wall	Insulated glass, spandrel panel, unitized curtain wall	Insulated glass, window wall	Insulated glass int., stratified glass ext., natural ventilation	Insulated glass, ext., stratified glass int., spandrel panel, mechanical ventilation	Insulated glass int., stratified glass ext. operable louvre, natural ventilation
$U_{cw}=1.52$ W/m^2K	$U_{cw}=1.59$ W/m^2K	$U_{cw}=1.14$ W/m^2K	$U_{cw}=1.66$ W/m^2K	$U_{cw}=1.45$ W/m^2K	$U_{cw}=1.10$ W/m^2K	$U_{cw}=1.12$ W/m^2K	$U_{cw}=1.23$ W/m^2K
g-value= 33%	g= 38%	g-value= 33%	g-value= 40%	g-value= 42%	g-value= 12%	g-value= 32%	g-value= 33%
i.e. One WTC, New York (USA)	i.e. Baccarat Hotel, New York (USA)	i.e. Tower Allianz, Milan (Italy)	i.e. 8 Spruce Street, New York (USA)	i.e. 432 Park Avenue, New York (USA)	i.e. The Shard, London (UK)	i.e. Palazzo Lombardia, Milan (Italy)	i.e. Intesa San Paolo, Turin (Italy)

The 5 climate zones have similar latitude and weather conditions and correspond to the following cities.

- Zone A. Turin (Italy)
- Zone B. Frankfurt (Germany)
- Zone C. London (UK)
- Zone D. New York (USA)
- Zone E. Chicago (USA)

The case study is a tall office building typical floorplan, with simplified geometry (50x35x4m). It has an unconditioned core, in which there are the service spaces, and an office open space, with glazed boundary.

The geometry of software energy model is shown in Fig. 1. Two rooms have been added to the model, above and below, to minimize the effect of solar irradiation and heat losses over the floor and the roof, because the only glazed façade is covered by the study.

In order to consider the real building conditions into the model, typical office space internal gains (from people, lights and equipment- 20 W/m^2 in total) and air conditioning system have been implemented. The implemented schedule is 08:00-18:00, from Monday to Friday. The heating system is set on from October the 15th to March the 15th; the cooling system is set on from March the 15th to October the 15th. The air conditioning system is fan coil units, with air-to-water heat pump. The HVAC system efficiency has been considered constantly a value of 3.

In order to consider the users' need to avoid glare in real office spaces with large windows, in case study model shading devices have been implemented. The shadings activation occurs when the window incident radiation is greater than 200 W/m^2.

The weather conditions of the 5 climate zones have been simulated using the IWEC (International Weather for Energy Calculations) database. It consists of hourly data for 12 typical months selected from 20-year data sets and smoothed to provide a continuous one-year long sequence of data. In particular, the used IWEC weather data for the five climate zones are:

- Zone A. Torino IWEC
- Zone B. Frankfurt am Main 106370 IWEC
- Zone C. London 716230 (CWEC)
- Zone D. New York-Central Park 725033 (TMY3)
- Zone E. Chicago-Midway AP 725340 (TMY)

The dynamic energy simulation results are the electricity consumption for space heating and cooling [MWh]. In order to convert the data in PED, the same coefficient (2.42) has been used for every climate zone, referring to Italian current legislation [17].

As regards the case study, for the eight typologies of glazed envelope in the EE calculation the following components have been considered:

- Glass. It includes the glass layers and gas into the cavity, if present.
- Aluminum alloy frame.
- Spandrel panel. An 18 mm width sheet of stainless steel has been used.
- Insulating material. A 150 mm width mineral wool layer has been considered, if present.

In Table 2 an example of EE calculation for a façade system typology is shown.

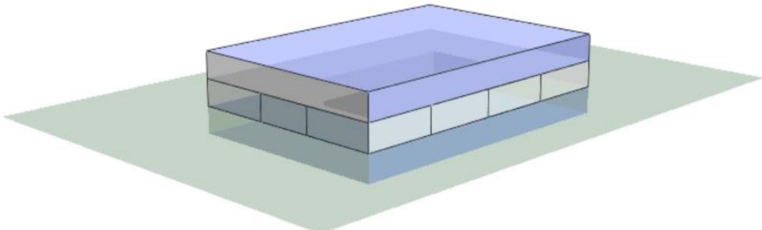


Fig. 1. Geometry of energy model, used for OE calculation.

Table 2. Example of EE calculation. Façade system Type 4.

Single Skin, insulated glass, spandrel panel, unitized curtain wall (i.e. 8 Spruce St., New York, USA)

Function	Type	Thick (mm)	Area (m^2)	Volume (m^3)	Lenght (m)	Density (kg/m^3)	Den. tot (kg/m^3)	EE (MJ/kg)	EE (MJ/m)	EE $_{tot}$ (GJ/m^2)	EE$_{/mq}$ (MWh/m^2)	EE$_{/mq}$ (MWh/m^2) NRA
Vision Panel	Insulated glass	6+6	6	0,072	/	2500	180	39,8	/	7,164	1,99	1353,16
Frame	Alluminium	/	/	/	15	/	/	/	1139,58	17,0937	4,75	3228,72
Spandrel Panel	Stainless steel	18	6	0,108	/	7800	842,4	17,02	/	14,337648	3,98	2708,15
Insulating material	Mineral wool	10	6	0,6	/	150	90	14,69	/	1,3221	0,37	249,72
Tot. module	/	/	/	/	/	/	/	/	/	/	11,09	7539,75
Dim. module	/	/	12	/	/	/	/	/	/	/	0,92	628,31
m^2 NRA	/	/	1500	/	/	/	/	/	/	/	/	**0,42**

4. Results

In order to compare different façade system technologies in different weather conditions, the same case study model has been used. So the analysis results are not referred to a floor unit, but they are expressed in MWh.

The results of EE and OE calculation, for the 8 façade system typologies, are shown below.

The Fig. 2 illustrates the results of EE calculation. As it can be seen, the façade component that mainly affects the case study EE is the aluminum frame.

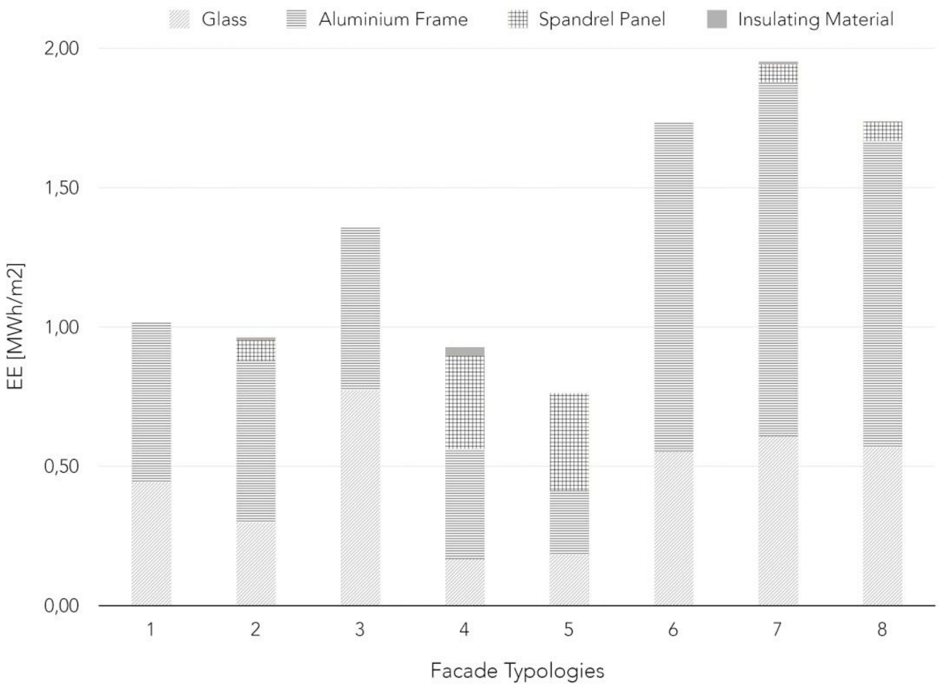


Fig. 2. Results of EE calculation, for the 8 façade system typologies

The monthly results of OE calculation are shown in Fig. 3. In particular, the histograms show the amount of OE [MWh] during one year, with reference to two typical façade systems: Type 1, which is a single skin façade (light grey bars) and Type 6, which is a double skin façade (dark grey bars). Among the results achieved in the analysis the paper shows the OE values referred to the mentioned typologies since they have the most different kind of glazed systems and the most different thermal and energy performances (e.g. U-value and g-value).

Despite the differences in terms of featuring and performances, the trends – according to climate zones B - C and D - E - are similar, even if as expected Type 1 has greater yearly energy need.

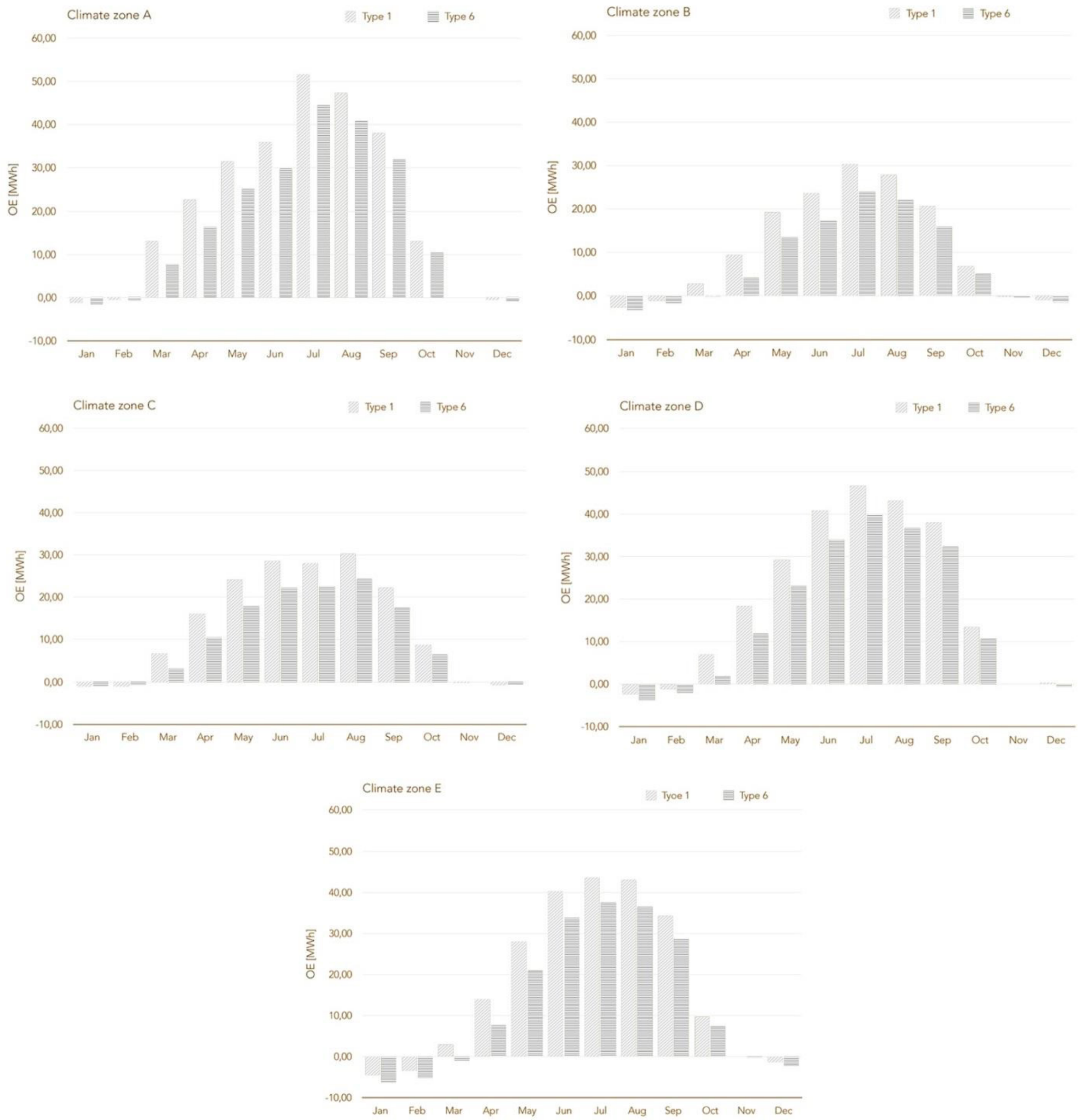


Fig. 3. Monthly results of OE calculation in 5 climate zones. Two façade system typologies: Type 1 - single skin façade (light grey bars) - and Type 6 - double skin façade (dark grey bars).

As regard the sum of EE and OE, the reference period of analysis plays an important role, in results evaluation. The EE and OE values have been normalized according to three periods: 1 year; 10 years; 25 years. In Fig. 4 and Fig. 5, for each climate zone, the three periods are compared. The graphs illustrate the results of the 8 analyzed façade systems. For As it displayed, the double skin façade types are more advantageous than the single ones, referring to a period of time of more than 10 years.

Consistently to the explained above assumptions, the EE is not related to the case study geographical location. The value given by the sum of EE and OE differs a lot for the different climate zones taken into account. In Fig. 6 the sum of EE (the light grey bar) and OE (the dark grey bar), is shown for the 5 analyzed climate zones.

On the whole the OE has a greater impact over a period of 25 years (an average of 70% of the total energy need). The lowest value (OE + EE) refers to Type 4 (single skin with spandrel panel) this is due to the larger opaque surface (60% of the total envelope surface). Concerning the EE the lowest values, refers to Type 4 and Type 5 (single skin – window wall) since the the materials used for opaque elements have generally a smaller energy impact.

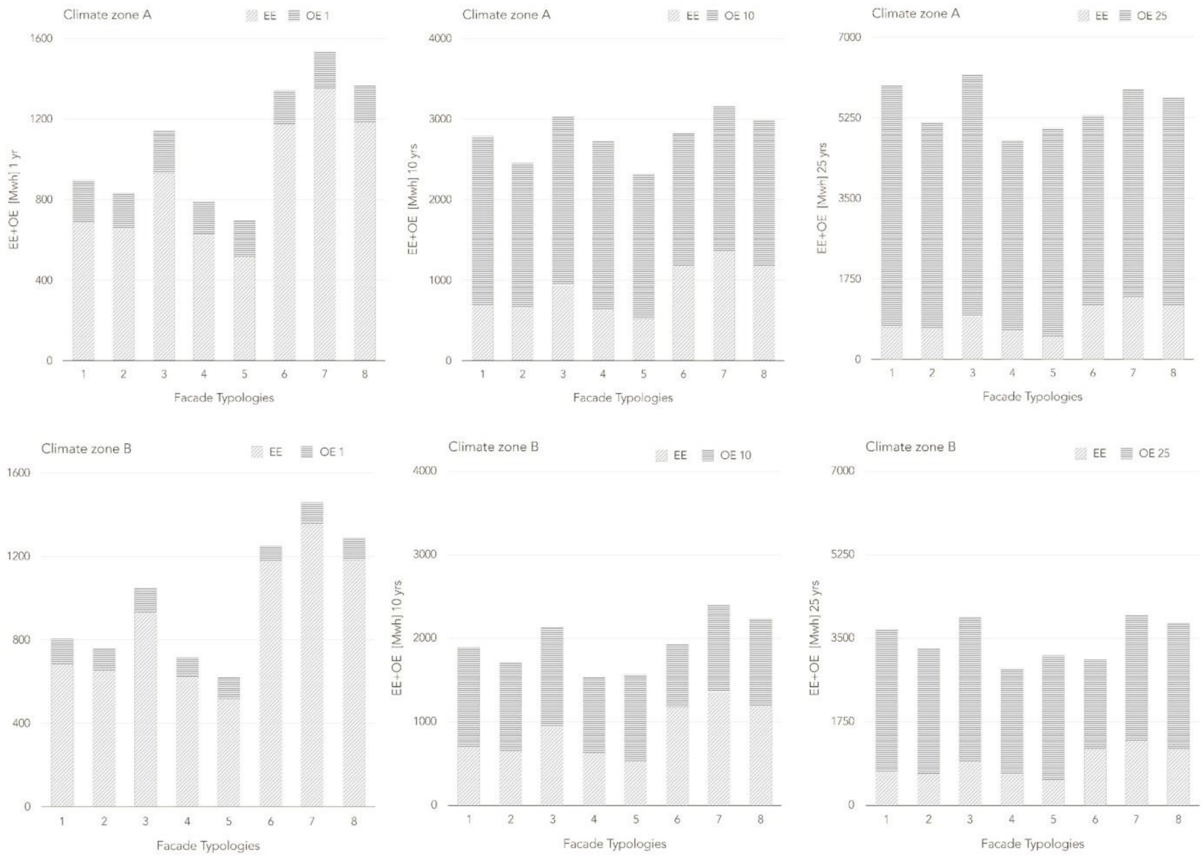


Fig. 4. Sum of EE (light gray bars) and OE (dark grey bars) for the 8 analyzed façade system Types, with reference to three periods of time: 1 (first column), 10 (second column) and 25 years (third column). The graphs refer to the different climate zones. Above: Turin; below: Frankfurt.

Fig. 5. Sum of EE (light grey bars) and OE (dark grey bars), for the 8 analyzed façade system typologies, with reference to three periods of time: 1 (first column), 10 (second column) and 25 years (third column). The graphs refer to the different climate zones. Form above: London; New York; Chicago.

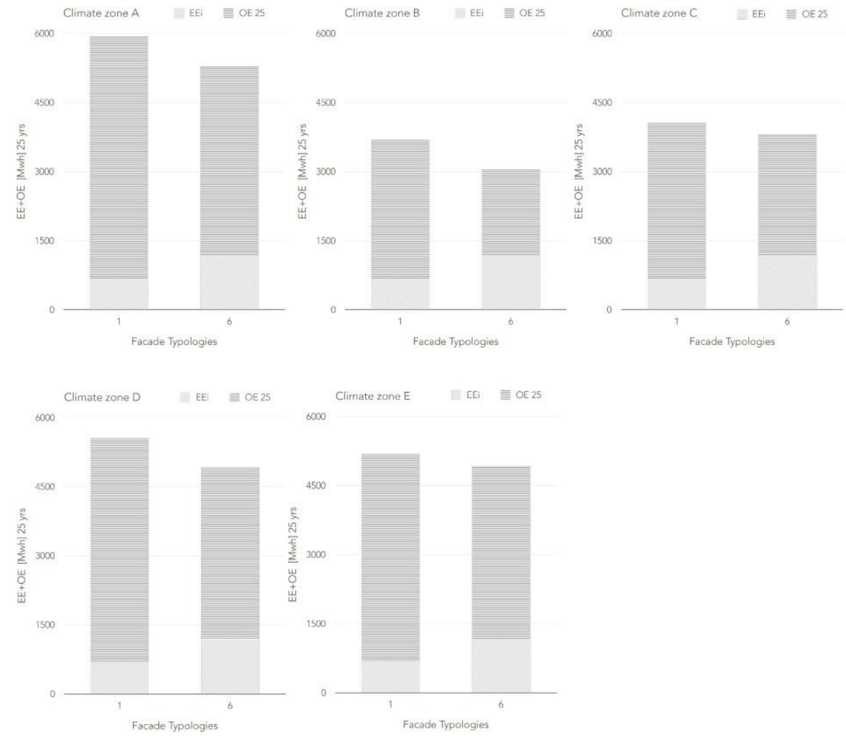


Fig. 6. Sum of EE (light grey bars) and OE (dark grey bars), in 5 climate zones. Two façade system typologies: Type 1 - single skin façade; Type 6 - double skin façade. Period of reference: 25 years

5. Discussion

The paper shows some results obtained from an assessment of the mutual relevance between EE and OE. The OE has a huge energy impact that requires to be balanced by the implementation on renewable sources for thermal needs.

In the OE assessment the climate zone becomes a primary aspect to be considered. The same façade technology generates values of OE depending on the climatic context. Façade solutions that require a higher initial energy, as double skins technology, should be carefully considered in relation to climatic characteristics of the site. Although, in terms of OE, double skin systems involve lower energy requirements in all analyzed climate zone. In climate context, as B (Frankfurt) and C (London), where there is a lower variation of average annual temperatures and summer temperatures are cooler, double skin systems appear to be more efficient.

According to literature review, the study shows the certain significance of the EE. The incidence of EE – after 25 years - for the case study analyzed can reach up to the 35% of the PED (climate zone B - Frankfurt).

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. Future works should be addressed in studying the carbon dioxide emissions associated to embodied energy in building materials.

6. Conclusions

Comparability between OE and EE appears to be a relevant issue in order to get to a broader building energy analysis. Although the paper focuses the study only to a portion of the total building systems that usually featuring the tall buildings, the relevance of the EE is never negligible.

The energy analysis should consider some boundaries (such as the database availability and the data quality for the EE calculation) and implement the study in order to improve the assessment. Some assumptions in the study have been taken into account (e.g. the reference time period). A lack of a standardization is an aspect to be considered specially in order to develop by the end of 2020 harmonized methods and procedures for Nearly Zero Energy Building [18].

On the whole a further analysis needs to be implemented. For instance, the OE should encompass a wider number of energy needs, such as: the lighting energy demand which is strongly related to the glass performances of the building envelope. Replacement of materials and components over the building life cycle could change the EE values. Further scenarios should be considered according to the most probable replacement frequency of materials used for the typologies analyzed. In some cases, the EE might be double.

Future studies may expand the methodological framework in order to assess the energy analysis to other building life cycle stages, including the impact caused by construction and final disposal.

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