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Life cycle assessment of energy efficient buildings

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Abstract

Life Cycle Analysis applications in the construction sector are growing due to the increased importance of embodied components in low energy buildings. In this study, standard building reference scenarios were compared with highly efficient building typologies, classified as low-energy or nearly Zero Energy Buildings. Energy consumptions were simulated starting from validated models while uniform assumptions, such as materials to be included, stages to be considered and coefficients of impact to be applied, were made for the LCA. The results show how the enhanced energy efficiency in the examined buildings and the reduction of their operational non-renewable primary energy requirement correspondingly causes a decrease of their life cycle non-renewable energy requirement, Cumulative Energy Demand and Global Warming Potential. A high potential in the reduction of non-renewable operational primary energy and GWP was found (until a maximum of 89% for the energy and 88% for the emissions). However, due to the shifting of impacts to the embodied components, the achievable life cycle reduction of non-renewable primary energy and emissions is lower (respectively 60% and 63% for the best performing retrofit). The benefit on life cycle CED is even lower due to the energy transition to renewables.

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Keywords: Life Cycle Analysis; LCA of whole buildings; Energy efficiency; Renewable energy; Low-energy buildings

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1. Introduction

In the last decades, the attention to energy and environmental issues has been growing quickly. The reduction of energy consumptions is boosted by climate change issues and the need to reduce greenhouse gas emissions. The Paris Agreement, signed in December 2015, sets an ambitious target to limit climate change imposing to keep the global temperature rise, within this century, below 2 °C compared to pre-industrial levels and hopefully equal to 1.5 °C.

In developed countries, the building sector is responsible for a large share of greenhouse gas emissions and their reduction can bring to a significant cut of the environmental impacts. In Europe, for example, the primary energy demand of the building sector is about 40% of the total while the constructions are responsible for the 36% of the global greenhouse gas emissions [1].

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A large part of the building stock in Europe is quite old and built without any regulation about energy efficiency; consequently, its energy consumptions are very high and, sometimes, very simple energy efficiency precautions can have a strong impact on the reduction of environmental burdens [2,3]. The census of 2011 [4] shows that more than 80% of the Italian buildings stock was built before 1991, when the reference law on energy efficiency was promulgated, and that the 64% was erected before 1976, when the first law aiming at reducing the energy consumptions in buildings was published. These buildings can be in very bad or critical maintenance conditions, even according to the opinion of their users. The potential energy saving that can be obtained from their retrofit is very high [5–7] even if there are sometimes normative or technical impediments: complexity in the façade design, presence of thermal bridges, environmental or technological constraints.

For new constructions, instead, high energy performances are required: following the Energy Performance of Buildings Directive — EPBD Recasts [8] all new constructions realized in Europe after 2020 should be nearly Zero Energy Buildings (NZEB). This standard implies not only a very good energy efficiency performance of the building systems but also an adequate coverage of the consumptions by local renewable energy generation.

The increase of the energy efficiency performances and the installation of new energy systems inevitably causes the introduction of additional equipment and plants and extra materials that increase the Embodied Energy (EE) and Embodied Carbon (EC) of buildings. The consequence can be a burden shifting of the energy demand or of the environmental impacts from one life cycle phase of the building to another: whereas the impacts of the operational stage are reduced, and sometimes also close to zero, the environmental burdens linked to the production and maintenance stages are amplified [9,10].

Within this framework, the traditional approach that is focused on the reduction of operational burdens should be overcome considering the whole life cycle of the buildings [11]. Within this perspective, the Life Cycle Analysis (LCA) can be a helpful tool and its potential should be deeper explored for future applications regarding the building sector.

This paper fits into this line of research comparing some ideal and real case studies to verify the whole environmental effectiveness of some building typologies and of some recurrent energy retrofit interventions.

2. State of the art

The application of LCA in international research literature about buildings is growing rapidly [12].

Several LCA studies demonstrate that the use phase of a building is responsible for the mayor contribution to the largest part of environmental impacts [13]. According to [14] the incidence of the use stage, as measured by the Cumulative Energy Demand (CED), is 77% for a detached house and 85% for an office building, while the construction stage weights respectively 21% and 14%.

Cuéllar-Franca and Azapagic [15] calculated the Global Warming Potential (GWP) contribution of use phase to be equal to 90% for a semidetached house located in the United Kingdom; [16] evaluated an incidence of 80%–90% of the operational energy consumption for high rise office buildings; according to [17] the use stage accounts for 93% of total warming potential of a residential dwelling. [18], considering six categories of environmental impact (acidification potential, human toxicity, depletion of abiotic resources, climate change, terrestrial eco toxicity and ozone depletion), confirmed that the use phase is the most critical stage accounting approximately for 80%–90% of the total life cycle burdens of residential dwellings located in Catalonia.

Although there is hardly a reference because of the lack of standardized benchmark values, the reduction of energy consumptions is an important task since it is clear from literature studies that the use phase is generally the most impactful in traditional buildings [19,20]. The effect of the retrofit is generally to reduce consumption while increasing the embodied energy. In low energy constructions the impacts of the construction phase can therefore become more relevant for the minimization of the global life cycle burdens. The incidence of the use stage in life cycle analysis decreases when a low energy building is considered and, at the same time, the embodied components acquire more importance accounting for about the 50% of the total CO_2 emissions [21]. Ramesh et al. [22] also stressed on how the energy incorporated into traditional buildings is between 10% and 20% while in buildings with low energy consumptions it is about 45%.

The question turns to be whether the burden shifting has a positive overall consequence on the life cycle or not.

Blengini and Di Carlo [23,24] tried to answer the question analyzing a standard detached house whose winter heat requirement was reduced from 109 to 10 kWh/m^2 y: the retrofit had a positive LCA outcome but, while the operational energy was reduced by a factor of 10, the overall life cycle energy was only cut by a factor of

Table 1. LCA stages included in the analysis.

LCA stage	Description	Stages included
A1	Raw material extraction and processing	✓
A2	Transport to the manufacturer	✓
A3	Manufacturing process	✓
A4	Transport to the building site	✓
A5	Installation in the building site	✗
B1	Use	✗
B2	Maintenance	✗
B3	Repair	✗
B4	Replacement	✓
B5	Refurbishment	✗
B6	Operational energy use	✓
B7	Operational water use	✗
C1	Demolition, de-construction	✓
C2	Transport to waste treatment facilities	✓
C3	Waste processing	✓
C4	Disposal	✓
D	Reuse, recovery or recycle potential	✗

2.1. Ramesh et al. [22] performed an interesting review on literature data about embodied, operational and life cycle energy for 73 buildings with different construction materials, located in different parts of the world and with both residential and office functions. The analysis showed that decreasing the operational energy means also decreasing the life cycle energy of the buildings with offices showing higher energy demands in both indicators. This kind of relationship was also supported by other authors [25,26]. However, the data reported do not distinguish between renewable (PER) and non-renewable (PENR) primary energy, displaying generic indicators on embodied and operational energy requirements. This work tries to give a uniform methodology for the comparison of some case studies: a distinction between PENR and PER is guaranteed and also GWP was included in the LCA outputs considered.

3. Material and methods

3.1. Life Cycle Analysis

The methodology used for the Life Cycle Analysis follows the Product Category Rule (PCR) for buildings published by [27]. Table 1 shows the LCA stages that are included in this work. Concerning the end-of-life, the possible benefits deriving from the substitution of virgin materials with recycled ones were neglected: only stages C1–C4 were modeled.

Eq. (1) defines the total non-renewable primary energy (PENR) that is obtained from the addition of the operational non-renewable energy ($PENR_{op}$), with the embodied non-renewable energy ($PENR_{emb}$) and with the end-of-life one ($PERN_{eol}$). The latter are defined as the sum of the PERN of every single material and component (n) normalized for their useful life (l) and for the gross internal surface of the building (S).

Eq. (2) introduces the total renewable primary energy (PER) that is defined in a similar way as the previous non-renewable component. The operational part (PER_{op}) is calculated as the sum of the renewable energy used by the heat pumps and of the energy produced by solar thermal or photovoltaic systems that is self-consumed by the building.

Eq. (3) reports the Cumulative Energy Demand (CED) as the sum of PENR and PER.

Eq. (4) defines the total fossil Global Warming Potential (GWP_f) of the building. The second term of the sum can be considered the embodied carbon (EC) of the building. Biogenic carbon was not considered in the calculations since only fossil emissions were accounted.

$$PENR = \frac{PENR_{op}}{S} + \frac{\sum_{i=1}^{N} PENR_{n,emb}}{Sl} + \frac{\sum_{i=1}^{N} PENR_{n,eol}}{Sl} \tag{1}$$

$$PER = \frac{PER_{op}}{S} + \frac{\sum_{i=1}^{N} PER_{n,emb}}{Sl} + \frac{\sum_{i=1}^{N} PER_{n,eol}}{Sl} \tag{2}$$

$$CED = PENR + PER \tag{3}$$

$$GWP_f = \frac{GWP_{f,op}}{S} + \frac{\sum_{i=1}^{N} GWP_{f,n,emb}}{Sl} + \frac{\sum_{i=1}^{N} GWP_{f,n,eol}}{Sl} \tag{4}$$

The values of operational/embodied energy and of operational/embodied carbon are normalized for gross internal surface of the building (S). The values of operational energy are referred to a single year and are supposed to remain constant for the whole study period, that, following the PCR about buildings, can be considered equal to 50 years. Every value of embodied energy/carbon of each building material or embedded component is normalized for its reference useful life (l): 100 years for load bearing structures, 50 years for secondary structures (such as insulation layers or roof covering), 35 years for windows, 20 years for energy systems. The functional unit (FU) considered is therefore the inverse of the product between the gross internal surface and the useful life of every single component (1/m^2 y). Transportations distances are supposed equal to 100 km and are covered using light commercial vehicles fed by diesel.

In case of renewable energy integration, only the energy that is self-consumed by the building was accounted in the LCA calculations. The photovoltaic electricity that is eventually exported into the national energy grid was reported separately. The most updated national primary energy and emission factors were used for the calculations [28]. SimaPro [29] was employed for the LCA calculations.

3.2. Energy modeling

An energy model of the reference configuration for each considered building was created within the software DesignBuilder [30] or using a semi-stationary code. The results obtained about the energy consumptions were adapted to the real bill data following two methodologies:

- the methodology established by the ASHRAE Guideline 14 [31] for the dynamic models,
- the methodology introduced by [32] for the semi-stationary models.

As concerns the first method, the parameters Mean Bias Error (MBE) and Coefficient of Variation of Root Mean Squared Error (CV(RMSE)) were calculated to validate the energy model using the following equations.

$$\boldsymbol{MBE} = \frac{\sum_{i=1}^{N} (\boldsymbol{M_i} - \boldsymbol{S_i})}{\sum_{i=1}^{n} \boldsymbol{M_i}} \tag{5}$$

$$\boldsymbol{CV\,(RMSE)} = \frac{\sqrt{\sum_{i=1}^{N} \frac{(\boldsymbol{M_i} - \boldsymbol{S_i})^2}{\boldsymbol{N}}}}{\sum_{i=1}^{N} \boldsymbol{M_i}} \tag{6}$$

where, Mi and Si are respectively the measured and simulated values during the month i, N is the count of the number of values involved in the calculations. The model is considered calibrated if the MBE is between ±5 and the CV(RMSE) ranges ±15.

The second methodology is based on the comparison between the annual energy consumptions of the generators of the building and the simulated values: the model is adapted modifying the weather input data, the internal heat gains, the scheduling hours of the systems and the temperature setpoints until the best correspondence between simulated and monitored values is reached.

The operational energy consumptions of the supposed configurations were simulated starting from the calibrated model and considering different retrofit solutions.

3.3. Case studies

Three case studies were chosen: a university test building, a residential complex and a school. They have different characteristics in term of function, construction typology, energy consumptions. In order to perform a comparative assessment, different configurations were supposed for each case study, considering as the reference configuration the real building, whose energy consumptions were monitored.

Fig. 1. The test building of the University of Trento.

3.3.1. A university test case

The building is located in Trento and used for university activities such as exhibitions and experimental campaigns. Fig. 1 shows a picture of the building. The gross internal surface of the building is equal to 89 m^2 and it has a lightweight wooden load-bearing structure and a concrete foundation with inverted beams. The envelope is very well insulated with values of thermal transmittance that are below the current limits recommended by the Italian legislation: 0.117 W/m^2 K for the vertical walls, 0.149 W/m^2 K for the roof and 0.132 W/m^2 K for the ground floor. High performance triple glass windows were also installed with a global U-value equal to 0.91 W/m^2 K. The building is completely fed by electricity and a reverse air-to-water heat pump guarantees the heating and cooling requirement. The emission systems are underfloor radiant panels working at 35 °C for the heating and fan coils for cooling. The performances of the heat pump declared in the technical sheets, measured at the full load and at the compressor rating frequency, are: Coefficient of Performance ($COP_{7\text{-}35}$) equal to 4.54 and Energy Efficiency Ratio ($EER_{35\text{-}7}$) equal to 3.03. The heat pump is oversized, as it often happens to guarantee instant Domestic Hot Water (DHW), and the frequent operation at a capacity lower than the nominal one causes a degradation of the performances. The electrical energy requirement is partially covered by a 3.5 kW photovoltaic system.

One reference building was defined varying the insulation thicknesses until a value of 0.62 W/m^2 K for the walls, 0.49 W/m^2 K for the roof and 0.45 W/m^2 K for the ground floor: only insulation thicknesses were lowered until a value representative of the average north Italian building stock while maintaining unaltered all the other envelope components. Triple glass windows were substituted with double glass ones (global U-value equal to 1.67 W/m^2 K). The PV system was removed, and a gas boiler with an efficiency of 90% was inserted to provide heating to the internal spaces. Radiators working at 80 °C were supposed as the emission bodies. The cooling requirements were covered using split systems ($EER_{35\text{-}7}$=2.9).

3.3.2. "Le Violette" residential complex

"Le Violette" is a social housing complex located in Foligno (heating degree days equal to 1899) with a gross internal surface of 951 m^2. The complex has three levels above the ground hosting a total of twelve apartments (simplex and duplex) of internal surface between 71 and 90 m^2 (see Fig. 2). An underground level is used for garages. The building has a reinforced concrete load bearing structure with infill walls built using brick blocks. The floor and roof have a masonry structure. The envelope was designed to meet the current legislation on energy efficiency in force in Italy [33]: the walls are insulated with EPS and wood fibers (U-value equal to 0.3 W/m^2 K), the roof is characterized by a thermal transmittance of 0.32 W/m^2 K. Attention was also given to the exposition with large windows (U-value of 2 W/m^2 K) equipped with solar shadings inserted in the south facing facade. The flat roofs are characterized by green covering while the picked ones are used to install solar thermal and photovoltaic panels (10.4 kW). A radiant underfloor heating is guaranteed in every apartment and it is powered by a centralized geothermal heat pump, that also furnishes cooling and DHW. The geothermal heat pump has a heating power of

Fig. 2. "Le Violette" residential complex.

59 kW and uses glycolic water as energy carrier fluid; the declared $COP_{0\text{-}35}$ is equal to 4.43, the $COP_{0\text{-}50}$ is equal to 3.07 while the $EER_{27\text{-}7}$ is 5.85. The energy measuring and accounting is separated for every apartment.

The reference construction has reduced envelope properties: the U-value of the walls is 0.429 W/m^2 K, the flat roofs have a more traditional tile covering and a U-value of 0.476 W/m^2 K while insulation in slabs towards unconditioned spaces was not considered. The photovoltaic system was removed, and traditional autonomous gas fired boilers with an efficiency of 0.9 were installed in every apartment with radiators as emission systems. The cooling requirements are covered using split systems ($EER_{35\text{-}7}$=2.9) while external sun-shadings were moved away.

3.3.3. A school in Turin

The last case study is a school (I.T.I.S. Giuseppe Peano), located in Turin and built in the 1940s. The gross internal surface of the building is equal to 3466 m^2. The main front of the school develops for 17 m along the surrounding streets (see Fig. 3) with a detached gym closing the inner side of the courtyard in the center. Since the construction was built in absence of legislation about energy efficiency in buildings, its envelope and energy systems have very poor thermal performances and efficiency. The load bearing structure is formed by two layers of brick blocks separated by an air cavity that is not insulated (U-value equal to 1 W/m^2 K). The picked roof is over the attic that is not heated: its floor has a non-insulated concrete structure lightened with hallow bricks. The windows are principally made with a single glass and a wooden frame (U-value equal to 5.46 W/m^2 K). Only heating and DHW are provided to the building with a generation system composed by two pressurized double flame gas boilers of 1860 kW of total installed power. The distribution system has six independent circuits with on–off regulation and radiators as emission bodies. The lighting is guaranteed by fluorescent lamps.

Fig. 3. The school I.T.I.S. Giuseppe Peano in Turin.

Different retrofit scenarios have been already supposed for this case study [32,34]

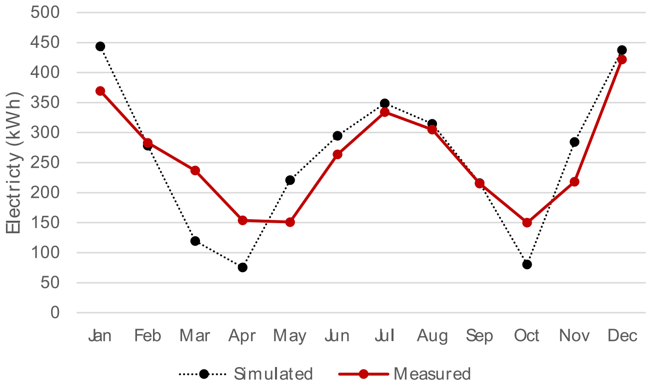

Fig. 4. Case study at the University of Trento: monthly electricity demand of the building (simulated against measured values).

- Cost-optimal solution (cost-opt): this scenario is defined after a cost optimal analysis performed by [32] to find the retrofit interventions to be implemented in order to reach the minimum global cost of the retrofit. The interventions identified are: insulation of the external walls, insulation of the surfaces towards the spaces that are not heated, insulation of the roof, installation of a 40 kW of photovoltaic system, substitution of lamps with more efficient fluorescent ones and introduction of control systems for environmental temperature and for lighting.
- Solution compliant with the Ministry Decree of 26 June 2015 (DM 2015): the D.M. 26 June 2015 [33] is the current Italian law in force about energy efficiency in buildings. In order to meet the requirements of the Decree, the interventions selected were: installation of heat pumps, solar collectors (6 m^2) and photovoltaic panels (60 kW of peak power) to respect the renewable energy coverage recommended; increase of the insulation of external walls, ground floor and substitution of the windows with 6-12-6 Low-E argon filled PVC framed ones to respect the limits about thermal transmittance of the envelope; installation of external movable shading systems in fabric.
- Electric NZEB solution (NZEB 1): compared with the previous one, the NZEB 1 has a higher insulation of the envelope, an increased photovoltaic surface (80 kW) and LED lamps in substitution of the fluorescent ones installed in the current building.
- Biomass NZEB solution (NZEB 2): compared to the NZEB 1, NZEB 2 is characterized by the substitution of the heat pump with a 231 kW biomass boiler, coupled with an accumulation system of 5780 liters capacity.

4. Results

4.1. The building prototype of the university of Trento

An energy model of the building was created in DesignBuilder to simulate the energy requirements of the supposed baseline configuration. The model was calibrated considering the real functioning of the systems (24/24 h in 7/7 days) and against the monthly energy consumptions of the building obtained from monitoring (see Fig. 4). An MBE equal to −0.4% and a CV(RMSE) equal to 1.9% were obtained and so the model can be considered calibrated. If the heating and cooling systems are always on, the monitored energy requirement is equal to 19 kWh/m^{2}y for heating and 17 kWh/m^2 y for cooling [35]. The PV production results equal to 44 kWh/m^2 y and it is able to annually balance the electricity requirement of the building. The non-renewable and renewable primary energy demand result respectively equal to 74 and 83 kWh/m^2 y. The results about the energy requirement of the reference "baseline" configuration are displayed in Table 2.

As it can be noted from Fig. 5, the supposed baseline has a higher non-renewable primary energy demand even if a burden shifting is observed. While in the reference building the operational cumulative energy requirement represents the 77% of the total, the current construction is characterized by 63%. The embodied component acquires a significant role in the determination of the total even for GWP (see Fig. 6) with a share of 45% for the real NZEB construction.

Table 2. Case study of the University of Trento: operational renewable and non-renewable energy requirement and related GWP of the real and reference building.

	PENR (kWh/m^2 y)	PER (kWh/m^2 y)	GWP (kg CO_2eq/m^2 y)
Reference building	194	8	49
Heating	*160*	*0*	*37*
Cooling	*30*	*7*	*11*
Lighting	*3*	*1*	*1*
Real building	74	83	27
Heating	*37*	43	*13.5*
Cooling	34	39	12.5
Lighting	*3*	*1*	1

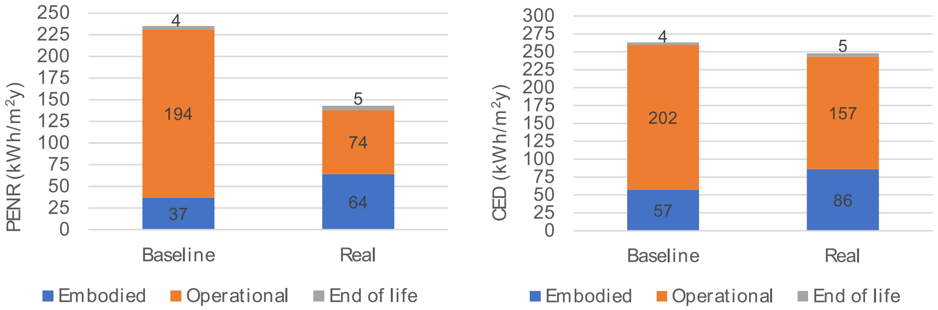

Fig. 5. The case study of the University of Trento: PENR and CED for the supposed baseline and the real building.

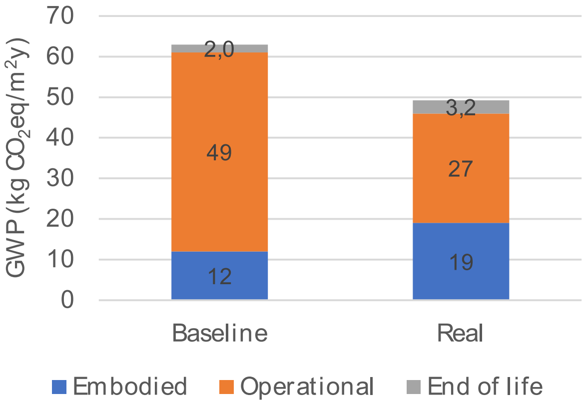

Fig. 6. The case study of the University of Trento: GWP (fossil) for the supposed baseline and the real building.

The NZEB transformation of the "common practice" baseline building reduces the PENR, CED and GWP of the construction resulting in a favorable intervention from an energy and environmental perspective. A reduction of 62% is found for the operational PENR and of 45% for the operational GWP. Considering the life cycle impacts, instead, the reduction is lower and corresponds respectively to 39% and 22%. Finally, very similar values are obtained for the CED of the two configurations.

4.2. *Le Violette residential complex*

A good knowledge of the building characteristics was derived from previous studies [36]. The building was modeled in DesignBuilder considering a typical scheduling of the energy systems to determine the energy requirement of the real and baseline configurations. The schedules were determined from statistical data about the hours of operation of the heating and cooling systems in the area [37]: the heating is on from 6 a.m. to 8 a.m. and from 5 p.m. to 11 p.m. while cooling is turned on in the afternoon for 4 h a day. 50 daily liters/person were supposed for DHW requirements and LED lamps were simulated for artificial lighting. As far as lighting, a value between 500 and 200 lux was guaranteed on the basis of the functions of the inner areas. The temperature setpoints were 20 °C for heating and 26 °C for cooling. The thermal properties and the materials used for the envelope components and energy systems were obtained from the executive engineered drawings of the building, from the technical sheets of the manufactures and from site inspections during the construction works.

The dynamic simulation gave an electricity requirement of 5.5 kWh/m^{2}y for heating, of 5 kWh/m^{2}y for DHW, of 2.2 kWh/m^{2}y for cooling and of 8.5 kWh/m^{2}y for lighting and appliances and it can be considered a low energy house. The non-renewable primary energy requirement is 41 kWh/m^{2}y while the renewable primary energy requirement is equal to 42 kWh/m^{2}y. The data about the operational primary energy demand of the real and of the reference building are shown in Table 3.

Table 3. Le Violette case study: operational renewable and non-renewable energy requirement and related GWP of the real and reference building.

	PENR (kWh/m^2 y)	PER (kWh/m^2 y)	GWP (kg CO$_2$eq/m^2 y)
Reference building	132	8	35
heating	62	0	15
DHW	38	0	9
cooling	11	3	4
electrical appliances	21	5	7
Le Violette (real building)	41	42	15
heating	11	19	4
DHW	10	13	3.5
cooling	4	6	1.5
electrical appliances	16	4	6

Due to the unavailability of monitored values for the building, it was not possible to perform a calibration of the results against the real energy consumptions data. However, a good agreement is reached between the simulated values and the monitored data of the energy consumptions of some residential NZEBs found in literature [38] and located in north Italy. The NZEBs are all characterized by a very high thermal insulation of the walls (U-value equal to 0.15 W/m^2 K that is higher than the one characterizing "Le Violette"), triple glazed windows (U-value equal to 1 W/m^2 K), heat production by only solar systems (for domestic hot water) or by heat pumps (for heating and cooling), PV systems connected to the national electricity grid; most of them use radiant floors as emissions systems. Considering the range between maximum and minimum values reported in Table 4, "Le Violette" can be classified as a low-energy building since its energy performance is close to the maximum values of the NZEBs. As it can be noted from the breakdown of the energy consumptions, heating and DHW represent the highest contribution followed by electricity for lighting and appliances.

Table 4. Maximum, minimum and average final energy consumption of low energy residential buildings in Italy (kWh/m^{2}y).

		Heating + DHW	Lighting + appliances	Cooling	Total
NZEBs	Max	6.7	9.1	–	15.5
	Average	5.9	6.8	–	12.6
	Min	4.6	3.7	–	9.5
Le Violette	Simulated	10.5	8.5	2.2	21.2

Fig. 7 shows the PENR and CED for the supposed baseline configuration and the real building distinguishing the embodied, operational, and end-of-life contributions. The baseline configuration has a higher operational PERN because the energy demand is mainly guaranteed by natural gas. The real building is characterized by a shifting on renewable energy that starting from the 6% of coverage in the reference building arrives to the 50% of its operational CED. The reduction of the operational PENR results of 69% while the cut of the life cycle is only of 40%; the decrease of the CED is lower: −16%.

A reduction is also obtained for the GWP as displayed in Fig. 8: its results of 57% for the operational component and of 23% for the life cycle GWP. The baseline building is characterized by an incidence of operational emission

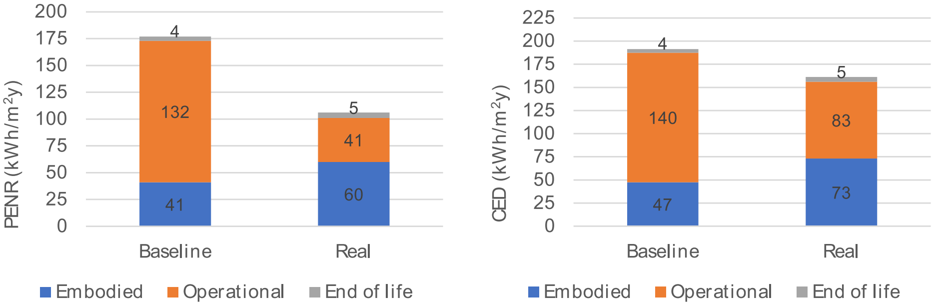

Fig. 7. "Le Violette" case study: PENR and CED for the supposed baseline and the real building.

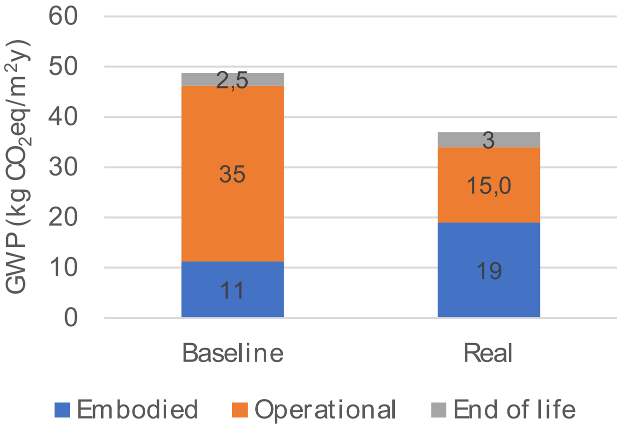

Fig. 8. "Le Violette" case study: GWP (fossil) for every scenario analyzed.

of 72% that is reduced to 40% in the real construction. Similarly, for the CED, the incidence of the operational stage reduces from 73% to 51%.

4.3. The school in Turin

A calibrated energy model was created by [32] considering the real occupancy schedule to simulate the energy demand for each of the retrofit scenarios supposed. The determination of the energy requirement of the building is based on the semi-stationary method introduced by the standard UNI/TS 11300 [39] and it is based on standard climatic data referred to the city of Turin. The calibration of the model returned a maximum percentage deviation between the simulated and real energy consumptions equal to 3.6% [32]: therefore, the model results representative of the real energy behavior of the building. Table 5 reports the results obtained in terms of primary energy and GWP.

A shifting towards renewable energy use was persecuted in the supposed retrofits of the school: a progressive reduction of the PENR characterizing the operational stage of the building can be observed in Fig. 9. It is, however, followed by an increase of the non-renewable primary energy attributed to the embodied components due to the installation of organic fossil insulation materials (EPS), new windows, photovoltaic panels, solar thermal systems, that are all components characterized by a high non-renewable embodied energy. The burden shifting from the use stage to the production stage results in a remodulation of the percentage contribution of the different stages to the total LCA impact: the current building (baseline scenario) has an operational CED corresponding to the 78% of the total while an incidence ranging from 38% to 56% is found in the retrofit solutions. Similarly, the incidence of

Table 5. School in Turin case study: Operational renewable and non-renewable energy requirement and related GWP.

	PENR (kWh/m^2 y)	PER (kWh/m^2 y)	GWP (kg CO_2eq/m^2 y)
Baseline	145.2	11.8	39
heating	*97.6*	*0.4*	*22*
DHW	*0.5*	*0.1*	*0.1*
lighting	*44.5*	*10.7*	*16*
ventilation	*2.6*	*0.6*	*0.9*
Cost-optimal	58	12	18
heating	*30*	*0*	*6.7*
DHW	*0*	*0*	*0*
lighting	*22*	*9*	*9*
ventilation	*6*	*2*	*2.3*
DM 2015	40	32	21
heating	*15*	*19*	*10*
DHW	*0*	*0*	*0*
lighting	*20*	*10*	*8.7*
ventilation	*5*	*3*	*2.3*
NZEB 1	23	28	14.5
heating	*11*	*16*	*7.6*
DHW	*0*	*0*	*0*
lighting	*9*	*9*	*5.2*
ventilation	*3*	*3*	*1.7*
NZEB 2	15	28	4.5
heating	*4*	*16*	*0.5*
DHW	*0*	*0*	*0*
lighting	*8*	*9*	*3*
ventilation	*3*	*3*	*1*

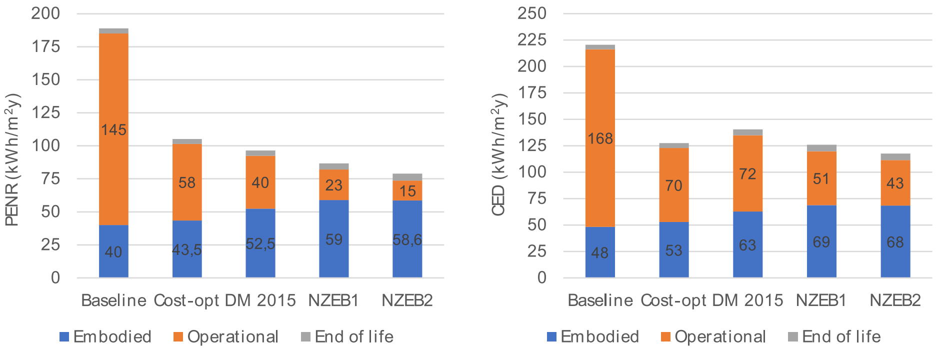

Fig. 9. School in Turin case study: PENR and CED for every scenario analyzed.

operational stage in the total GWP is equal to the 76% in the baseline building while it is between 25% and 60% in the retrofitted scenarios (see Fig. 10).

The retrofit of the building results always to be an environmentally friendly solution for all the supposed scenarios that are characterized by a lower total PENR and GWP in comparison with the baseline. Considering the baseline scenario, a reduction of about 89% of the PENR can be reached by the NZEB2 but a lower value of about 60% is verified for the global PENR. Similarly, for the operational GWP a reduction of 88% is obtained, while it results of only 63% for the life cycle GWP. Due to the energy efficiency measured applied, a comprehensive reduction is obtained also for the CED that is about halved by the NZEB2 (−48%).

5. Discussion

LCA results are subjected to a lot of uncertainties and literature results rarely report uncertainty analyses of their outcomes. For the case studies analyzed it was impossible to perform such evaluations because the largest part of the

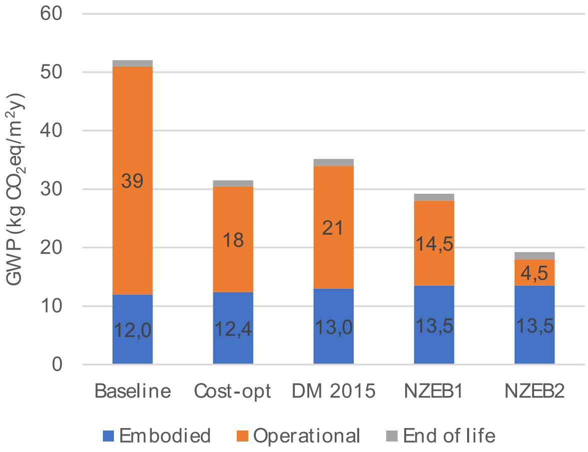

Fig. 10. School in Turin case study: GWP (fossil) for every scenario analyzed.

used data was not characterized by statistical distributions. Three main sources of uncertainty in buildings LCA were detected by [40,41]: parameter, scenario, and model uncertainties. Parameters uncertainties refer to material, energy and other LCA inputs; scenario uncertainties regard the different assumptions that can be done about the boundaries of the system, the functional unit and the allocations methods; model uncertainties concern the transformation factors adopted and the modeling process of the production systems. Moncaster et al. [42] showed however that, when comparing a lot of different buildings, the methodology adopted to perform the LCA is one of the sources of highest influence in results. The high variability in the LCA modeling approaches can be reduced to three main sources of variation: the temporal life cycle stages included, the embodied energy or carbon coefficients used, the physical boundaries of the analysis (e.g. inclusion of only some building parts, such as structural elements and not sub-structures, or inclusion/exclusion of energy exported to the grid by NZEB buildings).

Despite the high uncertainty inside LCA calculations, this work presents a quite uniform methodology for the evaluation of operational and embodied energy-carbon of some case studies: the same impact coefficients and temporal/physical boundaries were adopted. The adoption of the same assumptions in the LCA reduces the heterogeneity of data (e.g. data obtained from different literature sources employing non standardized methodologies can be very scattered) and increases their uniformity and coherence for the research of relations.

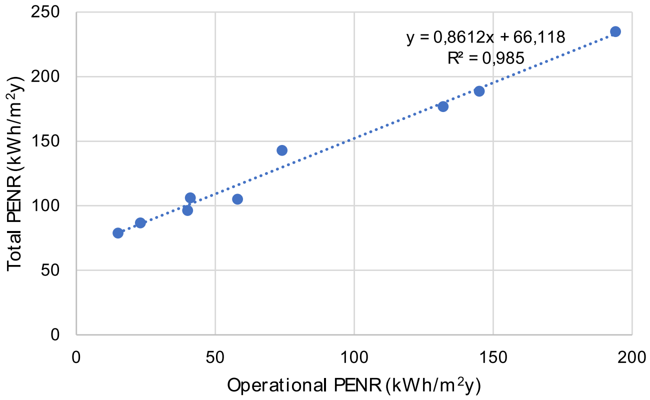

Fig. 11. Total PERN against operational PENR for the analyzed case studies.

Fig. 11 shows the relationship between the operational and the total PENR for all the analyzed case studies. As it can be noted the reduction of the operational PERN causes a reduction of the life cycle one in an almost linear way despite the differences in the functions characterizing the buildings, in the heating and cooling schedules and

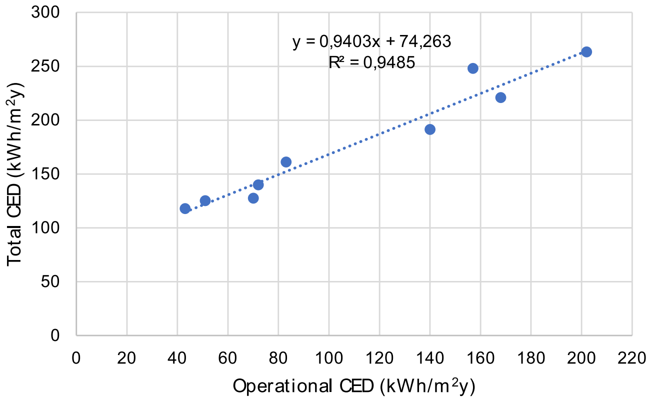

Fig. 12. Total against operational CED for the analyzed case studies.

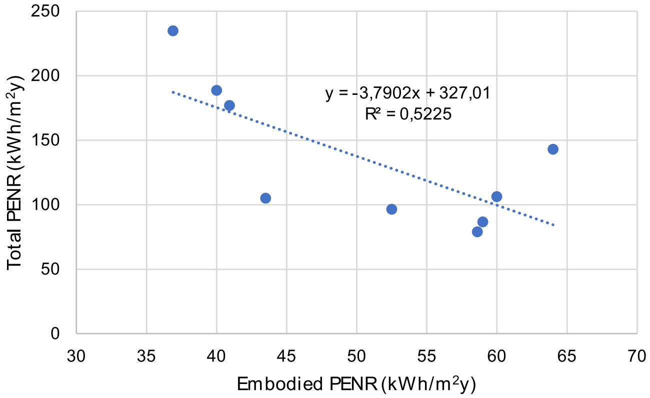

Fig. 13. Total against embodied PERN for the analyzed case studies.

systems, in the typology of energy supply, in the services provided (lighting, electric equipment, . . .), in the type and size of renewable energy systems integrated, and in the envelope performances. A significant linear regression was also found for the relation between operational PENR and CED or GWP (see Fig. 11 and Fig. 12). As already noted by [43], this regression is justified by lower variation of embodied components in comparison with the operational ones: e.g. the maximum increase found for embodied CED is equal to 29 kWh/m^2 y while the operational CED can be reduced of 125 kWh/m^2 y. Similarly, when the maximum increase of the embodied carbon is verified (7 kg CO_2eq/m^2 y), the decrease of the carbon emission during the use stage is equal to 22 kg CO_2eq/m^2 y.

When instead the relation between embodied PENR and total PENR is considered (see Fig. 13), the scattered embodied values found do not permit a good fitting. The high variability of the data about embodied energy can be explained by the different design choices and materials that characterize the buildings. However, the trend that is expected is confirmed: high performance constructions have higher embodied non-renewable energy and lower total PENR due to the reduction of the operational contributions.

A better linear regression is found for the relation between operational PENR and the global GWP (see Fig. 14), but the low number of case studies do not permit a generalization.

The shifting of impacts on embodied components, that acquire more importance in the determination of global impacts of the buildings due to the minimization of the operational ones, does not overcome the benefits deriving from the increased energy efficiency during the use stage. As a matter of fact, if the embodied impacts have an average incidence of 20%–25% in total for the defined baseline scenarios, their contribution can reach more than 60% when considering the NZEB solutions.

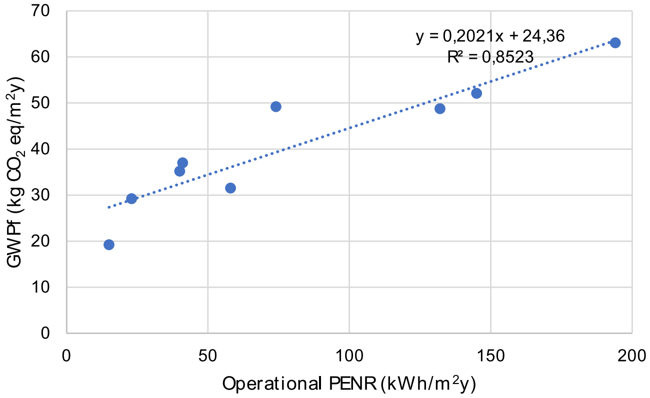

Fig. 14. Cumulative GWP (fossil) against operational PERN for the analyzed case studies.

6. Conclusions

This work showed the importance of considering a life cycle approach when evaluating the real energy and environmental performances of buildings. A very high reduction of operational energy and emissions is achievable from the improvement of the energy efficiency of standard buildings characterized by high non-renewable primary energy consumptions ranging from 132 kWh/m^2 y to 184 kWh/m^2 y.

The implementation of some energy retrofits aiming at improving the envelope thermal performances, enhance the efficiency of the systems and increase the renewable energy coverage brought to a significant reduction of operational energy requirement that also means decrease of the life cycle burdens in all the scenarios considered.

A maximum reduction of 89% for the operational non-renewable energy and of 88% for the operational emissions was found in the best retrofit scenario analyzed.

However, the reduction of operational energy is accompanied by an increase of embodied energy, due to the materials and plants which are necessary to obtain the higher energy performance of the building: when the burden shifting on materials and systems is taken into account, the comprehensive life cycle benefit is lower: respectively 60% and 63% for the PERN and GWP in the best performing retrofit. The decrease is even lower when considering the life cycle CED that arrives to a maximum of 48%.

Nomenclature	
CED (kWh/m^2 y)	Cumulative Energy Demand
COP (–)	Coefficient of Performance
CV(RMSE)	Coefficient of Variation Root Mean Squared Error
DHW	Domestic Hot Water
EER (–)	Energy Efficiency Ratio
FU	Functional Unit
GWP$_f$ (kg CO$_2$eq/m^2 y)	Global warming potential (fossil)
l (years)	Useful life
LED	Light Emitting Diode
MBE	Mean Bias Error
NZEB	Nearly Zero Energy Building
PCR	Product Category Rules
PENR (kWh/m^2 y)	Primary Energy Non-Renewable
PER (kWh/m^2 y)	Primary Energy Renewable
PV	Photovoltaic
R^2 (–)	Coefficient of Determination
S (m^2)	Gross internal surface
U-value	Thermal Transmittance

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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