Integrated Approach to Assess the Energy and Environmental Payback Time of Buildings Refurbishment: A Case Study

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Abstract

The design of nZEB buildings, as well as the implementation of retrofit interventions in existing structures, are essential tools for reducing energy consumption in buildings and increasing decarbonization of the building sector. To describe the effectiveness of a retrofit intervention, in addition to the analysis of the benefits in terms of costs and energy savings, an environmental analysis should also be performed, introducing various indicators, such as energy and environmental payback times. In this article, we considered a residential building located in Montemarcello (Liguria, North-west of Italy) that had been subjected to a refurbishment and an expansion, with the aim of evaluating the energy and carbon savings achievable due to the interventions carried out. The life cycle analysis approach was applied to calculate the environmental payback times. The main purpose of this work is the application of an integrated approach to assess the economic, energetic and environmental convenience of retrofit interventions during the entire life cycle of the building, underlining the importance of considering LCA and environmental aspects to achieve decarbonisation of the construction sector. The results show that energy and environmental payback times are lower than the useful life of the building and of its components, and that LCA proves to be a strategic methodology for studying the problems deriving from global warming and energy supply in the building sector.

1. Introduction

It is well known that the construction sector is nowadays one of the most energy-intensive, and that, in Europe, it is responsible for about 40 % of final energy consumption and 36 % of greenhouse gas emissions, representing about one third of EU energy-related emissions (European Commission, 2020). These emissions arise partly from the direct use of energy from fossil fuels in buildings and partly from the indirect emissions due to the generation of electricity used in buildings.

Although the EU's total greenhouse gas emissions from buildings decreased significantly by 29 % over the period 2005-2019 (EEA, 2021), Member States' emissions should continue declining in the future in order to achieve the EU climate change policy goals. Indeed, to achieve the overall EU target of a 55 % reduction in emissions by 2030, the construction sector would need to reduce its emissions by 60 % (EEA, 2021). For this to happen, the current energy renewal rate of building stock must greatly increase. In this context, to reduce energy consumption and to increase the decarbonisation of the construction sector, the design of nearly Zero Energy Buildings - nZEB (European Parliament and Council, 2010), as well as the implementation of retrofit interventions on existing structures or the selection of materials and building elements with low environmental impact are essential actions to be undertaken. Concerning the embodied burdens, different literature works have already shown that certification with Environmental Product Declarations – EPD (CEN, 2019) – can help in the determination of the environmental performance of building materials, such as insulation (Grazieschi et al., 2021) and windows (Asdrubali et al., 2021).

The implementation of retrofit interventions on existing structures is of additional importance.

However, in order to identify the most efficient and sustainable retrofit intervention, in addition to an assessment in terms of economic benefits, environmental and energy analyses must also be

Part of
Pernigotto, G., Patuzzi, F., Prada, A., Corrado, V., & Gasparella, A. (Eds.). 2023. Building simulation applications BSA 2022. bu,press.
https://doi.org/10.13124/9788860461919

considered, using appropriate indicators, such as environmental and energy payback times (Asdrubali et al., 2019; Asdrubali & Grazieschi, 2020).

Most of the scientific literature reviewed (Ardente et al., 2011; Webb, 2017) focuses on the evaluation of retrofit interventions of existing buildings or on the energy and environmental performances of new constructions. This work presents, on the other hand, a combined intervention that is characterized by the retrofitting of an existing house that involves a new add-on part. These typologies of retrofit interventions, sometimes referred as parasite architecture (Rinaldi et al., 2021), nowadays represent one of the possible architectural solutions for increasing living spaces, indoor comfort conditions and, if necessary, reducing energy consumption (Assimakopoulos et al., 2020).

In particular, a residential building located in Montemarcello (Liguria, North-west of Italy) subjected to a renovation and construction of an extension was considered, evaluating the energy and carbon savings due to the interventions and applying the life cycle analysis (LCA) to calculate the environmental payback times.

Therefore, this work presents the application of an integrated approach for estimating the environmental convenience of some structural and energy redevelopment interventions during the entire life cycle of the building.

The paper is organized as follows: Section 2 describes the materials and methodologies used in this work for the life cycle, energy and economic analysis of the pre- and post-energy requalification study building; in Section 3, the case study is presented; in Sections 4 and 5, the results of the study are reported and discussed, respectively, while in Section 6, conclusions are provided.

2. Materials and Methods

2.1 LCA and Dynamic Energy Simulation

Life Cycle Analysis (LCA) is a methodology that aims at determining the overall environmental impacts of a product or a service during the entirety of its life stages. This analysis addresses a comprehensive evaluation so that it is able to detect burden shifting or a trade-off between life cycle phases or between different categories of environmental impact.

The methodology is standardized at international level by ISO 14040 (ISO, 2006) and 14044 (ISO, 2006). These two standards give a general overview of the phases that every LCA study should follow, defining a framework that is not characterized by a rigid temporal order, but which permits a shift from one phase to another also in reverse order when there is the need for updating or revising the assumptions previously made. The LCA phases individuated by the ISO standards are: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), results reporting and sensitivity analysis.

The LCA application is very useful for identifying the most effective scenario in building retrofit interventions, also starting from the early design stage when there is the need to choose the solution that minimizes the cumulative environmental impacts during the whole life cycle of the construction.

In this work, the aim of the study was to compare the environmental impacts of a building, chosen as a case study, which was subjected to an energy retrofit intervention that also includes an extension of its useful volume, thus a new part. The life cycle environmental burdens of the ex-ante scenario and of the retrofitted solution were compared to confirm the environmental benefit deriving from the intervention proposed.

The functional unit that was chosen for the comparison was equal to the gross internal area of the building. The boundaries of the analysis included the raw material supply (A1), the transportation to the fabrication site (A2), the manufacturing process (A3), the transportation to the construction site (A4), the replacement of materials and components after their useful service lives (B4), the operational energy uses (B6) and, finally, the end-of-life stages (C1-C4).

The "cradle-to-grave" approach is so adopted for the analysis, excluding some stages that are considered negligible for the scopes of the evaluation (see Fig. 1 for more details).

LCA Phases																			
Product Stage			Construction process		Use							End of Life				Benefits and Loads beyond the System Boundary			
Cradle to gate			Gate to site																
Cradle to site																			
Cradle to grave																			
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D			
Raw Materials Supply	Transport	Manufacturing	Transport	Construction and installation	Use/application	Maintenance	Repair	Replacement	Refurbishment	Operational Energy	Operational Water	De-Construction/ Demolition	Transport	Waste Processing	Disposal	Reuse	Recovery	Recycling	Exported Energy

Fig. 1 – Building life cycle stages and related system boundaries - modified from PCR (Wiklund, 2019)

The environmental impacts determined employing the SimaPro software (PRé Sustainability, 2022) were the primary energy non-renewable requirement (PENR), calculated from the Cumulative Energy Demand (Frischknecht et al., 2015) single issue indicator, and the IPCC Global Warming Potential – GWP 100y (IPCC, 2007). Ecoinvent database (ecoinvent, 2021) was used as the background source of data.

The operational energy requirements were evaluated through a dynamic simulation of the building using the EnergyPlus code implemented in DesignBuilder environment (DesignBuilder Software Ltd., 2022).

The assumptions that were made for the development of the LCA are detailed in the following bullet points:

- The useful life of the building (after the intervention) was considered equal to 50 and 100 years, as recommended by the Product Category Rules (Wiklund, 2019) for the compilation of buildings Environmental Product Declarations and other LCA studies (Asdrubali et al., 2019; Asdrubali and Grazieschi, 2020; Blengini and Carlo, 2010). A 100-year lifespan is quite a long time-frame but it permits consideration of the long service life that interventions undertaken with good construction quality generally have.
- The analysis was performed for a rough building, thus external spaces, technical rooms, internal furniture, potable water grids, sewage grids, electrical plants, and any swimming pools were not considered in the evaluation, which was limited to the external envelope, to the internal walls and to energy systems. The consumption of water, DHW, electricity for lighting and household appliances was also excluded.
- Only heating and cooling energy requirements were accounted for in the analysis.
- A complete substitution of the components after their service life was foreseen without fractioning their environmental impacts in case of maintenance of the functionality after the end-of-life of the building.
- Load-bearing structures were supposed to have a service life of 100 years; secondary constructions and insulating materials were supposed to have a duration of 50 years, while for windows it was 35 years; energy systems and plants were modeled with a 20-year life span.
- The transportations means were supposed to be 16-ton trucks (diesel-fueled), while the transportation distance was always considered equal to 60 km.
- Construction and demolition waste material was considered but excavated soils (about 600 m^3) were not accounted for in the evaluation.

2.1 Energy and Carbon Payback Times

The energy and carbon payback time are the two indicators that were considered to describe the effectiveness of the interventions proposed from an energetic and environmental point of view. These two indicators were calculated only for the retrofit intervention of the existing building and for the combined solution. which also includes the realization of the new extension: in fact, the evaluation for the new part was not possible because no ex-ante baseline scenario could be individuated.

The Energy Payback Time (EPBT) is the ratio between the difference of Embodied Energy (EE), after and before the retrofit, and the annual saved energy due to the retrofitting (see Eq. 1).

$$EPBT = \frac{EE_{A1-A4}+EE_{B1-B4}+EE_{C1-C4}}{E_{sav}} \tag{1}$$

The Carbon Payback Time (CPBT) is the ratio between the difference in Embodied Carbon, after and before the retrofit, and the annual carbon reduction due to the retrofitting (see Eq. 2).

$$CPBT = \frac{GWP_{A1-A4}+GWP_{B1-B4}+GWP_{C1-C4}}{GWP_{sav}} \tag{2}$$

The numerators of equations (1) and (2) represent the energy consumptions and the CO_2 emissions due to the construction of the system (stages A1-A4, B1-B4 and C1-C4) and E_{sav} and GWP_{sav} are the annual reductions of PENR consumption and CO_2 emission due to the system operation, respectively.

3. Case Study

The residential complex under study is located in Montemarcello, in the Liguria region (Italy). The building is in a countryside area (226 m a.s.l.) and was built around the year 1930.

According to Italian legislation, the climatic zone of the property is C (on a scale from A to F, where A corresponds to the hottest places and F to the coldest), with a value in degree days between 1400 and 2100 (President of Italian Republic, 1993).

The building was subject to redevelopment and expansion interventions with the aim of ensuring an adequate level of internal environmental well-being and the containment of the consumption of energy and environmental resources. Fig. 2 shows the structural demolition and reconstruction interventions carried out on the property.

Fig. 2 - Demolitions and reconstructions conducted on the study building for the refurbishment and expansion of the building

The ante operam building, with an area of 211 m², consisted mainly of a brick-cement structure with single-glazed wooden windows. The heated space was separated from the roof by an accessible, unventilated and uninsulated attic, while the roof, also not insulated, was made of a brick-cement structure with tile cladding. The floor slab was raised above the ground level on a dry and damp air space. Instead, the infill walls are of the empty box type with a 10 cm thick air gap. Regarding the heating system, this consisted of 2 natural gas boilers with a nominal power of 24.4 kW and heat input between 12.5 and 27.1 kW. The emission system consisted of a radiant floor with copper pipes embedded in a cement screed directly laid on the brick-cement floor, for an overall average thickness determined by means of a span, including the tiles, of 11 cm. Finally, the regulation system included the room thermostat.

The interventions carried out on the building consisted of a major energy renovation, since the intervention involved more than 50 % of the dispersant envelope (Italian Ministry of Economic Development, 2015) and consisted of: the insulation of the floors, the insulation of the walls, the replacement of fixtures, the reduction of thermal bridges, the replacement of the thermal system, the integration of the summer cooling system, the dehumidification of the air during the winter and summer with heat recovery, and finally the remote management of the heating system.

Fig. 3 illustrates some elevations of the building ante operam, inter operam and post operam.

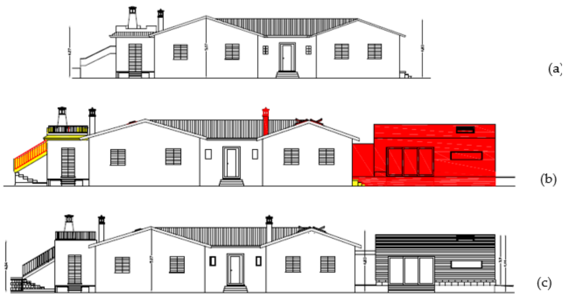

Fig. 3 - Prospects of the studio building ante operam (a), inter operam (b) and post operam (c)

The redeveloped building has a total area of 255 m², including an extension structure of 44 m². In the energy efficiency project, much importance was given to the insulation of the building envelope. In particular, windows with a transmittance between 1.1 and 1.5 W/(m²K) (< 2.0 W/(m²K) of limit value (Italian Ministry of Economic Development, 2015)) and glazed components with a transmittance between 1.332 and 1.687 W/(m²K) were installed. Finally, opaque elements with overall values lower than 0.42 W/(m²K) were obtained, as prescribed by the legislation in force in Italy on the minimum requirements about energy efficiency in buildings (Italian Ministry of Economic Development, 2015).

While the toilets are to be heated with towel-warmer radiators, the heating system of the redeveloped building is of the low-temperature type with radiant floor panels. This system is also capable of cooling in the summer.

The older system was based on a traditional boiler fed by natural gas, with radiators as terminal units and split air-to-air heat pumps for summer cooling. Before the retrofit, the control system was characterized by an on-off termostat installed in the living room, while after the retrofit each room was also equipped with its own thermostat in order to manage and differentiate the temperature independently.

The central heating and cooling system involves the use of a 500-liter boiler (technical water) and an integrated solar thermal circuit, designed to be combined with a single phase heat pump of 10.6 kW.

4. Results

The results showed that the application of energy efficiency measures can bring significant savings in terms of operational non-renewable primary energy consumption and GHG emissions. In particular, the retrofitting of the existing building permitted a reduction of the non-renewable primary energy demand for heating and cooling of 62 % to be obtained, increasing the coverage of renewable energy (see Fig. 4). The overall intervention, on the other hand, produced a reduction of the non-renewable energy demand equal to 60 % if compared with the ante operam situation.

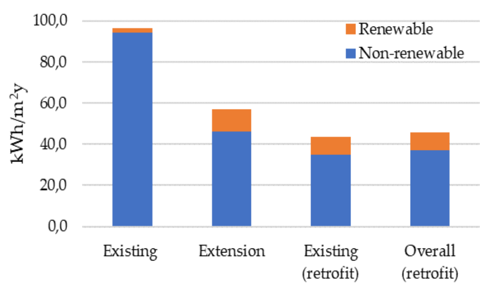

Fig. 4 – Overall annual energy consumptions per square meter for the different scenarios considered (operational energy)

The effort in reducing the operational non-renewable energy demand, however, caused an increase in the embodied impacts due to the introduction of new materials and energy systems. Tables 1, 2 and 3 show the PENR and GWP that characterize the extension, the retrofitted building and the overall combined intervention (composed of the requalification of the existing part and the addition of the new volume).

Table 1 – PENR and GWP of the new extension

LCA stage	PENR (kWh/m^2y)	GWP (kg CO_2eq/m^2y)
A1-A3	21.3	5.78
A4	1.3	0.28
B1-B4	17.0	3.90
B6	41.7	7.90
C1-C4	1.9	1.70

Table 2 – PENR and GWP of the existing part after the retrofit

LCA stage	PENR (kWh/m^2y)	GWP (kg CO_2eq/m^2y)
A1-A3	12.0	2.73
A4	0.3	0.07
B1-B4	12.0	2.51
B6	35.0	6.70
C1-C4	0.4	0.42

Table 3 – PENR and GWP of the overal intervention: retrofit of the existing building and new extension

LCA stage	PENR (kWh/m^2y)	GWP (kg CO_2eq/m^2y)
A1-A3	13.6	3.26
A4	0.5	0.11
B1-B4	12.9	2.75
B6 (post)	36.9	7.04
C1-C4	0.7	0.64

The increase in embedded impacts was relevant and cannot be discarded. Considering the existing construction, for example, the retrofit produces an increment of about 25 kWh/(m^2y) in the embedded PENR that corresponds to 26 % of the initial operational non-renewable energy requirement. Looking at the results for the new extension (Table 1), the embodied components (stages A1-A4 and B1-B4) account for 47 % of the total PENR and 57 % of the life cycle GWP of the building. More-over, if we consider a building lifespan equal to 50 years, the percentage incidence of the embodied components reaches 57 % and 68 % of the life cycle PENR and GWP, respectively, becoming the most important sources of environmental impact.

Fig. 5 displays the overall non-renewable life cycle energy of the scenarios analysed versus its operational component. As can be noted, the increment of the embodied impacts is beneficial, since it is followed by a reduction of the overall life cycle non-renewable primary energy of the building.

The calculation of the energy and environmental payback times (see Table 4) confirmed the environmental advantages of the intervention, showing values that are much lower than the useful life of the building (50 or 100 years are both considered) and of its components.

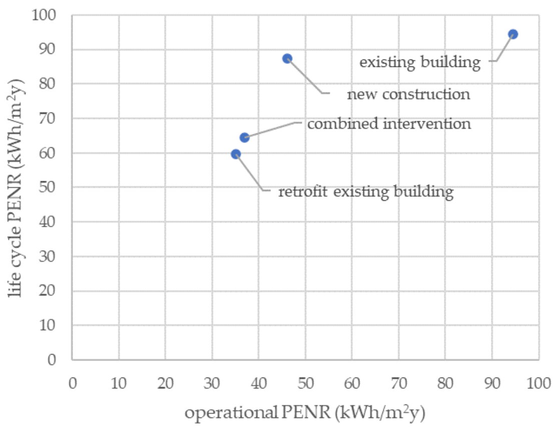

Fig. 5 – Life Cicle-PENR versus operational PENR for the existing building and for the intervetions supposed

Table 4 – Payback times of the overall intervetion

	Payback (months) 100-year life span	**Payback (months) 50-year life span**
	retrofit existing part	
PENR	5	6
GWP	3	4
	combined intervention	
PENR	6	8
GWP	4	6

5. Discussion

The analysis showed that the most sustainable intervention resulted in the energy requalification of the existing part. The addition of the extension results, on the other hand, is a much less competitive solution in the whole life cycle if compared with the retrofit of the old part: the interventions related to the extension, in fact, have a higher PENR in the entire life cycle. This result depends on different aspects:

1. The operational energy requirements of the old construction after the retrofit are lower than the ones of the new built volume. This is linked with the higher S/V ratio and with the higher window-to-wall ratio of the extension.
2. The retrofit definitely involves a lower embodied energy and carbon because only the roof is completely re-built, while external walls and foundations are conserved.
3. The retrofit implies a higher production of construction and demolition waste, but the management of this waste has relatively low environmental impact. In particular, the demolition waste generated was composed of 46.8 tons of mineral materials, 226 kg of metal waste (ferrous material), 361 kg of glass waste and 720 kg of wood waste.

The overall combined intervention is mainly affected by the retrofit of the existing part, albeit still slightly higher than the one concerning only the redevelopment of the existing building. However, it is characterized by life cycle environmental performances that are still very interesting, even if slightly higher than the ones of the most sustainable solution (namely retrofitting only the existing building): the calcuation of the payback times for the overall intervention shows that they are much lower than the service lives of the installed construction materials and components and it confirms the environmental benefit and the compatibility of the solution.

6. Conclusions

The energy and structural refurbishment of existing buildings implies the selection of a series of strategies and solutions.

In order to identify the most sustainable ones from an environmental point of view, it is necessary to take into consideration an integrated approach that also considers the environmental impacts in terms of the energy and carbon that are incorporated in the building materials and components.

In this study, a residential building subject to an energy retrofit, a structural intervention and an extension was analyzed. The energy consumptions of the building were simulated in an EnergyPlus environment, while the overall LCA was performed employing an ecoinvent life cycle database.

Therefore, using the PENR, GWP, EPBT and CPBT indicators, the results for the new construction, for the existing building after and before the retrofit and for the combined intervention were compared.

The results are in accordance with other literature studies regarding single buildings with a residential function. In particular, as already shown by other works (Asdrubali & Grazieschi, 2020; Blengini & Carlo, 2010), the operational PENR can be significantly reduced (from 94 to 35 kWh/(m^2y) in our case study) if an adequate combination of passive and active solutions is designed and implemented. Consequently, in such low energy solutions, the embodied impacts can represent a very significant part of the total impact, even more than 50 %.

The adoption of a life cycle approach therefore proved to be very useful for the evaluation of the overall environmental burdens. It permitted detection of the burden shifting between the operational and production stages that characterizes the energy retrofit interventions or the construction of new energy-efficient buildings. Moreover, the study made it possible to understand the heaviest interventions and the most impacting phases from an energetic and environmental point of view, while underlining that the energy and environmental payback times are much lower than the useful life of the building and its components. Also in this case, the outcomes obtained agree with the results of other literature works (Ardente et al., 2011; Asdrubali et al., 2019). The trade-off turns out to be only temporary, while environmental benefits are obtainable in the long term.

The new add-on volume, which represents the most peculiar aspect of the retrofit intervention, increased the energy requirement and the environmental burdens of the building, also delaying the payback times of the intervention. That is mainly linked to the fact that the two parts were not integrated, but conceived of as separate units. A higher integration between the two could have been more interesting from the environmental perspective, particularly if the add-on volume had contributed to the reduction of the energy requirement of the existing part.

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