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Retrofitting of the Italian precast industrial building stock. LCA analysis as decision-making tool

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ABSTRACT

The challenging European goal concerns the achievement of a carbon-free economy by 2050 must necessarily consider the improvement of the construction sector along with the redevelopment of the existing buildings. In fact, according to a European report concerning existing buildings, 80% of the built environment will remain the same by 2050. Nowadays buildings are responsible for 30% of the global final energy consumption and 37% of global energy and process emissions. As regards industrial buildings, they account for 33% of global final energy demand. The research aims to define some effective retrofitting measures to be applied in the existing Italian industrial facilities to improve their both energy and environmental performance. Several redevelopment scenarios and their possible combinations related to external envelope technological solutions and systems are analysed. The different interventions are applied to an existing Italian industrial building chosen as a case study and are compared by Life Cycle Assessment (LCA) analysis considering different environmental indexes (GWP, AP, PERT and PENRT). The calculation of the primary energy demand is also performed. Phase B6 accounts for about 80% of the whole environmental impact calculated considering 20 years as building lifetime. The redevelopment scenarios that foresee the intervention on the external envelope are the most impactful ones in terms of the production phase (A1-A3). Those related to the existing roof are characterised by a significant impact due to the demolition, disposal and landfill of finishing panels made of asbestos. The configurations that include the substitution of the existing heating system with an air-to-air heat pump coupled with renewables to produce electrical energy on-site are the most advantageous ones. The latter make the industrial building carbon-zero thanks to the considerable amount of surplus electrical energy produced on-site. In this case, phase D mostly recovers the environmental impact of the whole life cycle considering the different indexes.

1. Introduction

According to the Global Status Report 2023, nowadays buildings are responsible for about 132 EJ of global final energy consumption, representing 30% of the total (REN21, 2023a). In general, the energy needs in 2022 increased by about 1% compared to 2023 (REN21, 2023b). Moreover, the buildings sector accounts for 37% of global energy and process emissions (United Nations, 2022). In March 2023, the European Parliament approved the updated Energy Performance of Buildings Directive, expecting an improvement in energy efficiency for the existing building stock and phasing out fossil fuels to produce energy. Although the latter is mainly oriented towards residential building, achieving a carbon-free economy by 2050 requires considering all building types and their intended uses. For instance, the industrial sector is one of the most energy-intensive, accounting for 33% of global final energy consumption (REN21, 2023c). Analysing the Italian context, manufacturing buildings account for 22% of the national final energy demand (ENEA, 2022), requiring about 25 Mtep of Italian energy (ENEA, 2023). According to the ENEA (Energy Efficiency National Agency) Report of 2023, the industrial sector has experienced an 8.8% increase in electrical energy consumption compared to 2020 (ENEA, 2023). Moreover, it is notable that only about 2% of the energy needs in Italian manufacturing buildings are met by renewables (International Energy Agency (IEA), 2022). Furthermore, the European Commission highlights that 80% of the existing building stock will not be demolished and will be in use by 2050 (European Commission, 2020). The Italian industrial building stock is mostly characterized by architectural, technological, and structural deficiencies along with inadequate energy performance. Most of the Italian industrial heritage is made of precast-reinforced concrete elements, and this possibly provides several

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critical issues in case of seismic events, as demonstrated in various studies (Belleri et al., 2015; Savoia et al., 2017). Structural deficiencies are mainly related to the columns and their connections to horizontal beams as well as to external walls panels (Menichini et al., 2020). Most manufacturing buildings were constructed before the 1990s when effective energy and environmental regulations were completely missed. Usually, the horizontal or vertical precast concrete panels used for the external walls present a reduced thickness of thermal insulation that results in low thermal performance (Banti, 2024). The same issue applies to roof slabs, in which thermal insulation is completely missed. Moreover, in most of cases, roof stratigraphy is made of fibre cement panels containing asbestos, which must be removed for preserving workers' health. Currently, external envelope components do not meet the requirements of the Italian Energy standard (Italiano, 2015) leading to inadequate internal thermo-hygrometric comfort for workers. Finally, this building type is characterised by low airtightness level due to the properties of the external envelope and high air infiltration resulting in some cases from its intended use (Brinks et al., 2015). The retrofitting of building heritage is undoubtedly a crucial aspect of achieving an energy-efficient and environmentally friendly building environment. In this perspective, the Life Cycle Thinking (LCT) approach can be applied to evaluate the environmental sustainability and suitability of several retrofitting interventions proposed for Italian industrial building heritage. Many authors in the literature implemented this approach to individuate the most suitable structural retrofitting intervention coupled with energy recovery measures (Labò et al., 2022) or to develop decision support tool for defining the best redevelopment intervention while minimising the economic and environmental impacts and energy needs (Zhang et al., 2021; Prabatha et al., 2020). Other research highlights the necessity of including the LCT in the initial phase of the design process to outline the cost- and energy-effective retrofit solutions (Pombo et al., 2019) or to point out the most appropriate building material to use (Tokede et al., 2022). Life Cycle Assessment (LCA) is a method to assess the environmental impact of a building during its life cycle, through the determination of several environmental indicators. Most of the studies concerning LCA analyses retrieved in the literature are mainly focused on residential (Harter et al., 2023; Morales et al., 2023; Luo et al., 2022), office (Luo and Oyedele, 2021; Ramon et al., 2023) and educational building types (Scheuer et al., 2003). The analyses of the environmental impact are sometimes coupled with Life Cycle Cost (LCC) analyses (Ma'bdeh et al., 2023; Luo and Oyedele, 2022) to determine the cost-effective solution. As far as industrial building type is concerned, there is a general lack of studies and research dealing with LCT analyses connected with this specific intended use. By the way, some authors (Chau et al., 2015) highlight that industrial buildings are characterised by a significant environmental impact throughout their life cycle, related to both the operational and construction phases. As for the operational phase, several studies mainly focus on the life cycle assessment of the production process (Alejandrino et al., 2022). Some researchers outline sustainability indices (social, economic, environmental) for industrial building type (Heravi et al., 2015; Fregonara et al., 2017), or define a method to support the initial phase of the design process by evaluating different building components in terms of energy, environmental and cost sustainability (Lee et al., 2016). For instance, Lee et al. (2011) developed a green building rating for industrial buildings to evaluate their performance and sustainability. They compare two different constructive technologies in terms of embodied, operational, and demolition energy. With the same approach, Lombera et al. (San-José Lombera and Garrucho Aprea, 2010) outlined an environmental sustainability index for industrial buildings by combining different non-deterministic variables. According to the previous approach, Marrero et al. outline a method to evaluate small industrial facilities projects to facilitate the designing of eco-efficient constructions (Marrero et al., 2022). Moreover, most studies retrieved in the literature focus on newly built manufacturing buildings. For instance, Rodrigues et al. (2018) performed a gate-to-gate LCA analysis of a new industrial building concluding that the materials are the most influential contributors to environmental impact. In line with the previous results, some authors affirm that 71% of the environmental impact of a low-energy industrial building is related to manufacturing of construction materials, followed by 17% of the operational phase (Tulevech et al., 2018). This study also demonstrates that intervening in systems (lighting and ventilation) can enable the building to achieve net-zero energy demand over its entire life cycle. On the other hand, many authors performed life cycle analysis only considering some building components, without taking into account the building scale analysis. For instance, Shubbar et al. (2021) analysed the energy and environmental performance of an existing industrial building (surface of the ground floor equal to 220 m^2) located in Liverpool, concluding that the installation of PV panels (60 m^2 installed on the roof) can reduce CO_2 emissions during the operational phase by about 16%, and the improvement of external envelope insulation results in decreasing in energy needs and CO_2 emission by about 56%. According to previous research, some authors (Bonamente et al., 2014; Bonamente and Cotana, 2015) investigated the carbon and energy footprint of four different types of prefabricated industrial buildings, concluding that the most impactful category is the operational phase (accounting for 71%) due to the significant energy needs for both lighting and cooling. Furthermore, in the literature, it is possible to find some research comparing different structural solutions to build an industrial building applying a cradle-to-gate approach and considering global warming potential (GWP) and acidification potential (AP) (Lee et al., 2011). Always considering structural solutions and integrating the BIM environment and LCA method, Raposo et al. (2019) conducted an environmental comparison in terms of GWP between precast structural elements for a new industrial building and the installation of seismic reinforcements in an existing building as a retrofitting proposal to avoid demolition and reconstruction. Reisinger et al. (2022) compared different structural alternatives and several enclosures options for an industrial building, performing a parametric optimisation based on different criteria (production layout design, dimensions, load-bearing capacity) to minimise both cost and carbon footprint.

Considering the cited background related to the existing Italian manufacturing building stock and the lack of analyses in the literature focus on buildings with this intended use, this study addresses a significant gap in current research, which often overlooks the application of a LCT approach to manufacturing facilities. As highlighted by the background, existing literature tends to focus on specific issues of existing manufacturing buildings without considering an integrated redevelopment approach or emphasizing the design of new industrial buildings and production process improvements, driven by economic priorities over environmental impact assessment. This research aims to evaluate and compare different retrofitting interventions for existing manufacturing buildings from a life cycle perspective. The redevelopment measures considered mainly address external envelopes, systems and the introduction of renewables. According to the authors' expertise, LCT studies involving integrated sustainable redevelopment are notably absent in the current literature. For the definition of the most suitable improvements, the LCA method is applied considering a representative existing industrial building as a case study.

2. Materials and method

An Italian existing industrial building located in the Tuscany Region (Central Italy) is chosen as a case study. It is exemplary of the most widespread typological variant within the 1950s and 1970s and it represents 65% in the 80s (Banti et al., 2022a, 2022b). The representativeness of the manufacturing building chosen as a case study was determined during previous studies conducted by the authors foreseeing the classification of industrial buildings located in Tuscany Region based on different characteristics. The following parameters were considered to define the different typological variants of the Tuscan industrial building heritage: construction period, urban context, geometry and dimensional data, construction technology for the external envelope, structural solution for the load-bearing structure and systems.

This typological variant is used to define some possible retrofitting measures, outlining the most effective ones from an environmental life cycle perspective. Different redevelopment measures (Table 1) related to the external envelope and system improvements coupled with the installation of renewables to produce on-site energy are evaluated and compared by performing a Life Cycle Assessment analysis. The different retrofitting interventions are considered separately or combined to define the most effective and environmentally friendly options. A summary of the workflow of the applied methodology is detailed in Fig. 1.

For completeness, some considerations are necessary to point out the peculiar characteristics of the different redevelopment measures proposed. The retrofit interventions chosen for this typological variants are selected primarily based on the existing characteristics of the load-bearing structure, external envelope components and systems as well as addressing the previous described issues in the introduction section and the complete lack of installed renewable energy systems. The proposed redevelopment measures for the external envelope are selected based on common practices in proper retrofit design for this building type. The retrofit proposals are lightweight solutions and allow to address the energy issues by complying with the required thermal transmittance in Italy without increasing the vertical loads on existing columns and dynamic actions during potential seismic events.

This building type is usually characterized by low architectural and technological quality, so for instance the proposal intervention W2 also allows to improve the aesthetical quality of the building. The intervention on the roof stratigraphy also involves the demolition of the existing finishing layer made of fibre cement panels containing asbestos, which must be removed according to Italian regulations (Governo Italiano, 1992). Once again, the proposed technological solution allows compliance with the required thermal transmittance for roof components without increasing vertical loads. Additionally, the solution using sandwich panels can easily accommodate the integration of on-site renewables energy systems. Concerning the existing conditioning system, a substitution of the existing gas heaters with an air-to-air heat pump is considered. This kind of intervention is completed by integrating renewables on the rooftop to produce energy on-site. This retrofit proposal allows to overcome issues related to high energy consumption and consequent high level of CO_2 emissions released in the atmosphere (Governo Italiano, 1992) along with guaranteeing increased thermal comfort for workers within the working environment. In one case, the necessary power of the photovoltaic system is considered to guarantee the minimum requirements of current Italian regulation (HP + PV_{min}) (Italiano, 2021). In the other one, the maximum area of PV panels (HP + PV_{max}) is considered installed on the available roof surface to include the possible surplus energy produced in the environmental balance. Finally, as far as artificial lighting improvement, LED installation with light control with two different levels of intensity (on/off) is considered. The latter is chosen compared to the continuous dimming and the solution with 3 levels of intensity because it is characterized by intermediate behaviour in terms of energy needs (Banti and Ciacci, 2023).

The lifetime for the LCA is considered equal to 20 years instead of 50 because the case study is an existing facility built at the beginning of the 1980s. For completeness, a sensitivity analysis using the one-at-time step method is performed related to the variation in transport distance to the construction site for the different materials, considering three different steps of increase (25 km, 50 km and 100 km). Additionally, it explores a variation of the conversion factor for the CO_2 emissions to evaluate possible future scenarios and examines changes in the geometry (1 nave or 3 naves) of the building by varying the quantity of the materials. For the former, the perturbation values are set within a range that the authors consider reasonable to ensure a maximum total distance of 250 km from the construction site. As for the CO_2 emissions conversion factor, the sensitivity analysis is fundamental to consider the variability over time of this parameter, which is primarily based on the Italian energy mix. Over the last 20 years, a 55% decrease is registered in Italy's CO_2 emissions conversion factor. In the context of the United Nations SDGs and considering the significant influence of the operational phase of manufacturing buildings on environmental impact, it is essential to consider the potential reduction over time. Finally, the sensitivity analysis focusing on the quantities of materials considered in the study is necessary to generalize the findings and account for the variability in the geometry of this building type. Typically, this type of building is characterized by an internal layout with 1, 2, or 3 naves.

The life cycle analyses were performed through One Click LCA (OneClick LCA software) exploiting its interoperability with Autodesk Revit (Autodesk, 2022). A Revit BIM model was created in the BIM environment complying with the main geometrical, dimensional and technological features of the sample industrial facility. The interoperability was exploited through the Autodesk Revit plugin OneClick LCA to further perform the Life Cycle Assessment analysis. The materials assigned in Revit and the quantity calculated through the geometrical model were directly associated with materials present in the OneClick LCA database. Moreover, the energy needs of the existing industrial buildings and the retrofitting ones are calculated through Design Builder (Design Builder). In this case the energy model (BEM model) of the

Table 1
Redevelopment measures proposed for the existing industrial building.

Envelope component	Name	Type of intervention	Constructive solution
External Wall + windows	W1	Retrofit of the external walls without demolishing the existing ones	Installation of an internally insulated (rook wool insulation) false wall
External Wall + windows	W2	Retrofit the external walls without demolishing the existing ones	Installation of external sandwich panels (polyurethane insulation)
Roof + skylights	R	Demolition of the external fibre cement panels with asbestos and substitution of the existing roof	Installation of sandwich panels (polyurethane insulation)
System component	Name	Type of intervention	Constructive solution
System + Renewables	HP + PV_{min}	Substitution of the existing heating system and integration with renewables on-site	Installation of a heat pump and PV panels (minimum area)
System + Renewables	HP + PV_{max}	Substitution of the existing heating system and integration with renewables on-site	Installation of a heat pump and PV panels (maximum area)
LED + Light Control	LED + LC	Substitution of the existing lighting system	Installation of LED lighting and related lighting control
Combination	Name	Type of intervention	
External Envelope	COMB1	W2+R	
External Envelope + System	COMB2	R + LED + LC	
External Envelope + System	COMB3	R + HP + PV_{min}	
External Envelope + System	COMB4	R + HP + PV_{max}	
External Envelope + System	COMB5	R + HP + PV_{min} + LED + LC	
External Envelope + System	COMB6	W2+R + HP + PV_{max} + LED + LC	

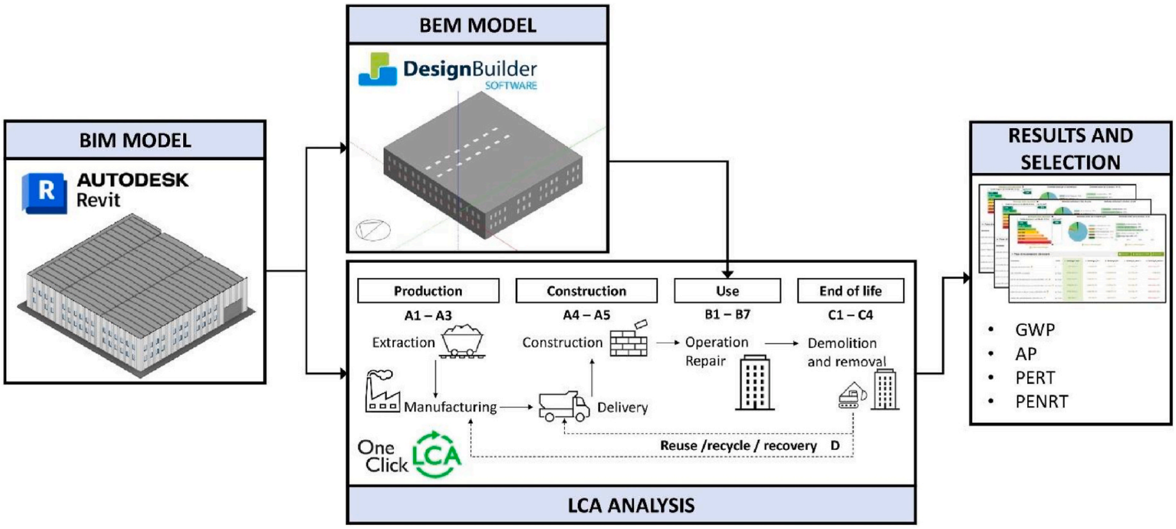

Fig. 1. Workflow of the research method.

building in gbXML format was directly imported from BIM model to the energy simulation software. The properties of the thermal zone are then assigned directly from Design Builder environment. Finally, for completeness, an evaluation of the carbon payback period for the combinations that make the building carbon-zero is performed. As retrieved in the literature (Zhang et al., 2021), it is defined as the ratio between the initial embodied GHG emissions and the annual GHG savings. In this case, the GHG savings is evaluated with the amount of surplus energy produced on-site by renewables.

2.1. Case study building

The analysed industrial building belongs to an existing industrial district in the Casentino Area, in the Municipality of Subbiano, province of Arezzo. This manufacturing building was selected because it is representative of the most widespread building type in the Casentino industrial district, where most of buildings are built using prefabricated reinforced concrete structural solution. The high diffusion of this type of buildings in this area is due to the presence on the territory of companies operating in the heavy prefabrication sector, both in the past and currently. The original project is available for this facility, so the geometrical, structural, and technological details are retrievable in the authentic documentation. Moreover, data needed for energy simulations were collected during different on-site surveys carried out by the authors' research group (monthly energy bills, occupation profiles, working hours, heating generation, and distribution system). This construction was built in 1982 and currently hosts a company working in the production of mechanical components. The facility is characterized by a rectangular shape with a gross area of approximately 1600 m^2 and a volume of about 13600 m^3 (Fig. 2). It is made of two different parts that

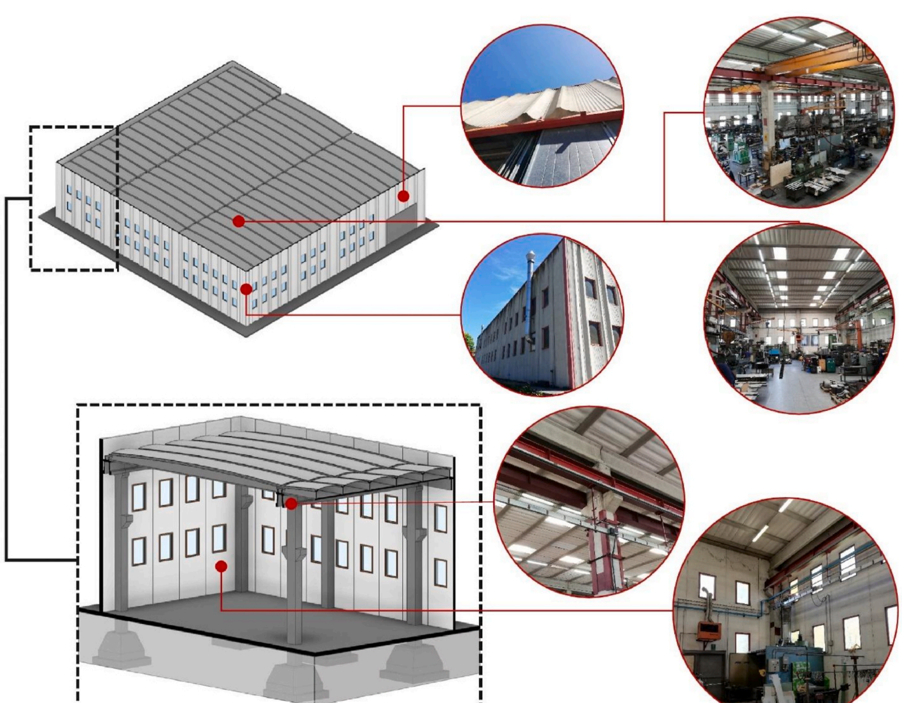

Fig. 2. Case study industrial facility.

are structurally independent. The first part hosts the workshop area, which occupies 90% of the total surface area. It is a single-story double-volume space. It was enlarged with an additional nave in 1996, but this expansion is characterized by the same constructive and technological solutions as the first original block of the building. The second block is a double-story, that hosts ground-level worker locker rooms, archives, and storage, while on the first floor the administrative offices. The industrial facility is composed of three naves (9 m width each) with a total length of 42.80 m and 5 spans of 9 m width for the workshop area and 6 m for the administrative one. The internal height is about 8.5 m for the workshop area, 3.90 m for the secondary rooms, and 3.10 m for the offices.

The precast concrete structure consists of tenon head columns and perimeter H-shaped beams, completed with Y-shaped beams on the roof floor. The external walls are made of two different kinds of precast concrete sandwich panels: plain ones (0.13 m thick) and concave ones with variable thickness within a range from 0.13 m to 0.27 m. Both types are characterized by internal insulation in expanded sintered polystyrene (EPS) with a variable thickness. The roof stratigraphy is composed of fibre cement panels, containing asbestos, with a double insulation layer in glass wool totalling 0.06 cm in thickness. The existing polycarbonate skylights are characterised by the following thermal properties: thermal transmittance = 5.6 W/m^{2}K, solar heat gain coefficient = 0.35, and light transmittance 0.4. The main distinguishing features and thermodynamic properties of the external envelope components are reported in Table 2. Windows are composed of a wired single-glazed pan and metallic frame without a thermal break with the following thermal properties: thermal transmittance = 5.63 W/m^{2}K, solar heat gain coefficient = 0.82, light transmittance 0.5. Regarding the heating system, gas heaters with an efficiency equal to 0.65 are installed in the existing building for the workshop area. As for artificial lighting, the existing fluorescent lamps are characterised by a radiant fraction equal to 42% and a visible one equal to 18%.

Based on the peculiarities of the existing facility, the retrofitting measures (Table 1) detailed in Table 4 were proposed to improve the overall performance of the industrial facility. The main distinguishing features and thermodynamic properties of the external envelope components are reported in the following Table 3.

As regards windows redevelopment, it is coupled with the requalification of the external walls and it foresees the installation of a metal frame with thermal break and glazed portions with the following characteristics: thermal transmittance = 1.2 W/m^{2}K, solar factor = 0.51, light transmittance 0.74. Furthermore, the replacement of the existing skylights is considered, coupled with the improvement of the existing roof. New polycarbonate skylights are characterized by the following properties: thermal transmittance = 1.4 W/m^{2}K, solar heat gain coefficient = 0.62, and light transmittance 0.58.

2.2. Life cycle assessment

For the LCA analysis, the cradle-to-grave approach was applied, as it is the most used boundary condition in similar studies (Anand and Amor, 2017). The LCA analysis includes 4 different phases according to UNI EN ISO 14040 (Ente Italiano di Normazione, 2021): the definition of the goal, the Life Cycle Inventory (LCI), the Life Cycle Impact Assessment (LCIA) and the interpretation of the results (Terán-Cuadrado et al., 2024). The following phases of the method based on UNI EN 15978 (Ente Italiano di Normazione, 2011) were considered: A1-A3 production phase, A4-A5 construction process stage, B4-B5 replacement and refurbishment, B6 energy consumption related to the buildings' operational phase, C1-C4 end-of-life phase, and D1-D4 benefits and loads beyond the system boundary. The functional unit chosen for the LCA analysis is m^2 per gross floor area (GFA). Phases B4 and B5 were considered only for building components with operational life shorter than the building one (20 years). The calculation of phase B6 was coupled with the calculation of the primary energy demand considering the following conversion factors: 1.9 for electrical energy (European Commission, 2023), 1 for electrical energy produced by renewables and 1.05 for natural gas (Italiano, 2015). For the evaluation of the environmental impact the Global Warming Potential (GWP) [kgCO_2eq], the Acidification Potential (AP) [kgSO_2eq], the Total use of Non-Renewable Primary Energy Resources (PENRT) [MJ], and Total Use of Renewable Primary Energy Resources (PERT) [MJ] were calculated. All the indicators were estimated according to the method indicated in the UNI EN 15978 in section (11): calculation of the environmental indicators.

As mentioned before the LCA analysis is performed using OneClick LCA software that complies with UNI EN 15978. The extensive database of this software provides several Environmental Product Declarations

Table 2
Stratigraphy and main properties of the external envelope of the existing case study. In the table half thickness for the insulation materials is used for external walls. For the concave panel, the lowest thickness is considered to represent the worst condition in terms of thermal properties. For the roof stratigraphy, the air cavity thickness is not considered for the calculation of the thermal properties.

	Panel	Layer	Thickness [m]	Thermal conductivity [W/mK]	Specific heat [J/kgK]	Thermal transmittance [W/m^{2}K]	Surface Mass [kg/m^2]	Periodic thermal transmittance [W/m^{2}K]
External wall	Plain panel	Precast concrete panel	0.02	2.07	1000	–	–	–
		Insulation material (EPS)	0.045	0.04	1450	–	–	–
		Precast concrete panel	0.02	2.07	1000	–	–	–
						0.76	107	0.69
	Concave panel	Precast concrete panel	0.02	2.07	1000	–	–	–
		Insulation material (EPS)	0.045	0.04	1450	–	–	–
		Precast concrete panel	0.02	2.07	1000	–	–	–
						0.75	107	0.69
Roof		Fiber cement panel	0.01	0.60	960	–	–	–
		Air	0.55	–	–	–	–	–
		Glass wool insulation panel	0.06	0.046	1030	–	–	–
		Fiber cement panel	0.01	0.60	960	–	–	–
						0.67	37	0.55

Table 3
Retrofitting intervention for existing building. The main characteristics of the external envelope stratigraphy are illustrated as well as ones related to building system redevelopment.

Abbreviation	Layer	Thickness [m]	Thermal conductivity [W/mK]	Specific heat [J/kgK]	Thermal transmittance [W/m^{2}K]	Surface Mass [kg/m^2]	Periodic thermal transmittance [W/m^{2}K]
W1	Plasterboard panel	0.0125	0.31	1000	–	–	–
	Plasterboard panel	0.0125	0.31	1000	–	–	–
	Rockwool insulation	0.08	0.035	840	–	–	–
	Precast concrete panel	0.02	2.07	1000	–	–	–
	Insulation material (EPS)	0.045	0.04	1450	–	–	–
	Precast concrete panel	0.024	2.07	1000	–	–	–
					0.272	145	0.081
W2	Precast concrete panel	0.02	2.07	1000	–	–	–
	Insulation material (EPS)	0.045	0.04	1450	–	–	–
	Precast concrete panel	0.024	2.07	1000	–	–	–
	Metal sheet	0.0006	52	460	–	–	–
	Insulation material (Polyurethane)	0.06	0.022	1599	–	–	–
	Metal sheet	0.0006	52	460	–	–	–
					0.247	118	0.056
R	Metal sheet	0.0006	–	–	–	–	–
	Insulation material (EPS)	0.150	–	–	–	–	–
	Metal sheet	0.0006	–	–	–	–	–
					0.209	15	0.23
Building System							
HP + PV_{min}		Installation of a reversible air-to-air heat pump of 100 kW and flexible photovoltaic panels of 0.128 kWp for 547 m^2					
HP + PV_{max}		Installation of a reversible air-to-air heat pump of 100 kW and flexible photovoltaic panels of 0.128 kWp for 1136 m^2					
LED + LC		Installation of LED with a radiant fraction of 15% and visible one of 15%					

Table 4
Climate data for the energy simulations in the Subbiano Municipality. In the table: HDD means heating degree day, GH stands for global horizontal radiation, Dh means diffuse radiation, Bn means direct normal radiation, Ta stands for air temperature, Td stands for dew point temperature and Ws means wind speed. The climate data are the annual means.

Latitude	Longitude	Climate zone	Heating period	HDD [K/d]	GH [kWh/m^{2}a]	Dh [kWh/m^{2}a]	Bn [kWh/m^{2}a]	Ta [°C]	Td [°C]	Ws [m/s]
43.34°N	11.52°E	D	1st/11–15th/04	2041	1447	629	1496	15	7.9	2.8

(EPDs) for different building components produced in different countries according to the Product Category Rule (PCR) 15804+A1 and +A2 and data points extracted from other recognized databases used for environmental analyses (e.g., Ecoinvent v3.8 and Ökobaudat v2018). Ökobaudat v2018 database is mainly used for end-of-life phase (C1-C4) of materials. Most of the data points set for the LCA evaluation are Italian data, and when it is not possible to choose Italian EPDs, other European locations are selected to proceed with the analyses, considering the best available match. The data points selected for the new construction materials included in the retrofitting measures are detailed in Table A.1 in Appendix A. This Table provides information on the specific materials, their quantities, the environmental impact according to the various indicators and the corresponding sources. As for the functional units for building materials, m^2, kg and m are considered for the external envelope components based on the data retrievable in the available database (OneClick LCA) and single item for systems components.

The materials quantities (bill of quantities – BoQ) are imported automatically from the BIM environment where the existing building and the redevelopment configurations are modelled in accordance with the design drawings. Some authors in the literature (Llatas et al., 2020; Safari and AzariJafari, 2021) highlight that the integration between BIM and LCA can ameliorate the sustainability of the built environment and optimize the choice of appropriate technological solutions, if their integration is considered since the initial phase of the design process.

As for the evaluation of the operational phase (B6) for the GWP index, the conversion factor for the CO_2 emissions for both natural gas and electricity is updated with ones retrieved in the ISPRA (Higher Institute for Environmental Protection and Research) report. For natural gas a conversion factor equal to 1.986 $tCO_2eq/10^3m^3s$ is considered and so 0.1858 $kgCO_2eq/kWh$ (ISPRA, 2023a), while for electricity an emission factor equal to 0.2665 $kgCO_2eq/kWh$ is considered (ISPRA, 2023b). As for the evaluation of the construction process stage, transport phase (A4) values equal to 50 km, 100 km and 150 km are set for building components, massive building components (precast building components) and systems respectively. These distances are considered in the study based on the location of the construction site in Tuscany Region (central Italy) and the availability of nearby material suppliers. When this approach is not possible, the default distances of OneClick LCA database are used as a reference to complete the analysis. Regarding the type of transportation, road transport was chosen for all materials, as it is commonly used in Italy. The data points for the vehicles were directly selected from OneClick LCA database (LCA for European transportation 2017), based on the mass of materials that need to be transported to the construction site.

Furthermore, as it regards the construction and installation process phase (A5), the average construction site impact for temperate and southern climate is selected from the OneClick LCA database, considering the Ground Floor Area (GFA) of the existing building. Finally, when the retrofitting intervention foresees a demolition of an existing building component (e.g., W2) the environmental impact of this demolition is included in the life cycle assessment analysis. In this case, the transport of the waste materials produced on the construction site is also included into the environmental balance.

2.3. Design Builder set-up

The existing manufacturing facility was modelled in the Design-

Builder environment and energy simulations were performed through the Energy Plus engine (Energy Plus). The parameters needed for the energy model (e.g., setpoint temperature, metabolic rate, air change rates and HVAC specifications) were defined for each thermal zone individuated in the existing building following both indications provided by the company itself and Italian regulations for the missing data. The heating setpoint temperature was considered equal to 18 °C as specified by the company hosted in the building. The occupation was set equal to 0.011 people/m^2 and the occupancy time from Monday to Friday, from 8:30 a.m. to 5:30 p.m. During August month the facility was considered closed. As regards the metabolic rate, it was set equal to 167 W/person for the activities related to the company working sector (standing light activity). The natural ventilation flow rate was fixed equal to 0.76 m^3/s considering the formula proposed by UNI/TS 11300–1:2014 (Ente Italiano di Normzione, 2014) for industrial buildings. As far as the external infiltration, a general medium airtightness was set (4 h^{-1}) in the construction panel to consider the real conditions of the external envelope components (Brinks et al., 2015). A sheltering coefficient equal to 0.07 was chosen considering the urban context of the building. Furthermore, as for the conditioning system, the energy simulations were performed considering the simple HVAC method proposed by the software considering an operational time from 7:30 a.m. to 5:30 p.m. To validate the energy model the real gas bills were considered and a comparison with the results obtained by energy simulations was performed. For January the real gas need is equal to 2961 m^{3}s, while in the energy model, 2734 m^{3}s are required. A deviation of less than 10% was registered. For the energy simulation, the half thickness of the insulation material included in the external walls' stratigraphy of the existing buildings was considered to take into account the possible decay of the material that occurred over time.

The considered industrial building belongs to climate zone C (temperate climate) according to the Köppen classification and Italian Climate zone D (Governo italiano, 1993) being characterized by 2041 heating degree-days (HDD). The main climate characteristics of this area are illustrated in Table 4.

3. Results

To better illustrate the results of the research, they are presented in two steps in this section. First, single redevelopment measures are addressed in detail, and then the main results concerning the combination of the different retrofitting interventions are discussed. Fig. 3 illustrates the Global Warming Potential related to the individual redevelopment measures considering the different phases of the entire life cycle (A1-D). Both the building's operational phase (B6) and the recycling and recovery potential at the end-of-life (D) of the different materials and components proved to be particularly significant.

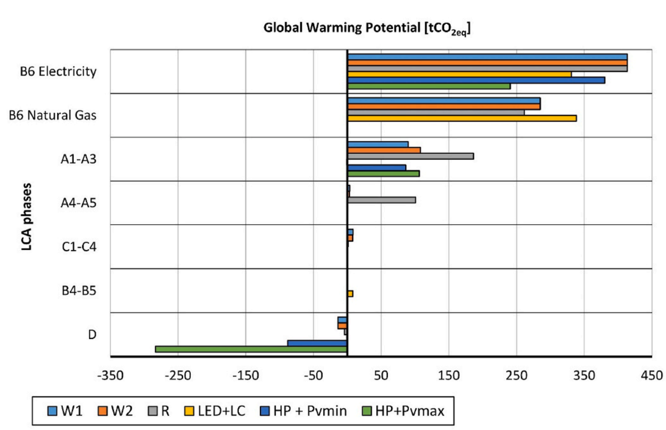

Fig. 3. GWP of the single redevelopment interventions considering the different life cycle assessment phases.

Notably, the B6 phase, relating to the energy consumption of the building during service life, is the most impactful, especially in terms of electricity needs where the production process is also accounted for. Configurations characterised by PV panels with on-site energy production perform significantly better compared to the others, thanks to the renewable source that has a conversion factor of 0 kgCO_2eq/kWh for CO_2 emissions. Furthermore, the graph points out that phase D of retrofitting scenarios foreseeing the installation of a heat pump combined with PV panels is particularly beneficial. Such a result is guaranteed by the amount of surplus energy produced by on-site renewables, which is approximately 15500 kWh/year for the HP + PV_{min} configuration and 282300 kWh/year for the HP + PV_{max} one. If the entire life cycle is considered, the most advantageous configuration is the one including the installation of the highest number of PV panels and heat pump implementation, resulting in a carbon footprint equal to about 63 tCO_2eq. This configuration requires the lowest amount of electrical energy from the public grid (45128 kWh) during the operational phase and it is also characterised by the most advantageous end-of-life stage in terms of surplus energy production, as previously mentioned. Going further, changing the boundary conditions for the LCA analysis and excluding phases B6 and D, phases A1-A3 related to the production process of different materials and components are the most impactful in terms of GWP.

The retrofit configurations R, W2 and HP + PV_{max} are characterised by a significant environmental impact compared to the others. The former (R) exhibits the most impactful phase A because of the demolition of fibre cement panels containing asbestos, their transportation to landfill sites, and their disposal as contaminant material. Their demolition phase alone accounts for 99 tCO_2eq. Retrofitting interventions on roof panels containing asbestos can involve either demolition and subsequent disposal or the encapsulation with special coatings. In this case, the first measure was chosen and analysed because the redeveloping intervention on the roof floor was further coupled with the installation of PV panels. Therefore, encapsulation with coatings was considered less beneficial and inadequate from both technological and construction perspectives. Some studies in the literature, highlight that the management of asbestos panels remains a significant challenge in many countries. The inadequate disposal poses severe risks to human health (Thives et al., 2022).

In the W2 scenario, the increase in GWP is mainly due to the polyurethane insulation in the sandwich panels which accounts for about 57000 kgCO_2eq. In the HP + PV_{max} case, the wider surface area of flexible PV panels (1136 m^2) installed on the roof along with the air distribution system mostly affected the results in terms of GWP, accounting respectively for 36% and 50% for stages A1-A3. The LED + LC solution is characterised by the lowest environmental impact equal to about 8 tCO_2eq at the beginning of the life cycle (A1-A3), but it also involves a substitution phase (B4-B5) that accounts for about 50% of the total amount of A1-B5 phases. Due to the limited lifetime of these components, at least one replacement is needed, considering a building lifespan of 20 years. Generally, the end-of-life stage stands in the whole life cycle for an average of 4% independently from the chosen retrofit solution. In line with this, the transport, construction, and installation phases account for a maximum of 10% of the total A1-B5. These results are valuable for helping the designer during the first phase of the redevelopment projects by prioritizing interventions on existing manufacturing buildings, reducing the overall environmental impact while guaranteeing enhanced indoor thermal comfort within the working environment. The effective retrofit solution in terms of environmental sustainability can be chosen during the decision-making process by comparing possible and various alternatives. Redevelopment interventions on systems and the introduction of renewables are beneficial to reduce the environmental impact of the operational phase while maintaining the required internal setpoint temperature. However, they are characterised by high environmental impact for the construction phase (A1-A3).

For better clarity, Fig. 4 shows the GWP exclusively due to the operational phase (B6) in terms of electricity and natural gas needs for each of the considered scenarios, compared to the current performance of the existing building (namely base case).

Focusing on the GWP due to natural gas consumption, enhancing the thermal properties of the roofing stratigraphy results in a significant reduction equal to about 17%, compared to the existing building. Retrofit interventions on the roof should be preferred over those addressing external walls because of the wider covered surface area. It is worth noticing that the existing roof floor, characterised by low airtightness standards, is made of panels containing asbestos, which must be removed for the protection of human health according to Italian regulations (Italian Government, 2022). Replacing the existing lighting system with an LED one (LED + LC) leads to an increase equal to 7% in GWP because it negatively affects the heating demand due to the reduction of internal heat gains produced by currently used fluorescent lamps. As far as emissions related to electricity demand are concerned, solutions that foresee the installation of PV panels are the most advantageous, because the gas demand for heating is eliminated with the use of the heat pump and consequently the associated carbon footprint. By the way, CO_2 emissions for electrical energy demand to be satisfied by the public grid, are reduced by about 8% for the HP + PV_{min} retrofitting configuration and 42% for HP + PV_{max}.

Figs. 5 and 6 highlight the environmental impact of the single redevelopment solutions in terms of GWP/AP and PERT/PENRT respectively. The results are presented excluding the operational phase (B6) and the benefits and loads beyond the system boundary (D). As expected, as shown in Fig. 5, the retrofit intervention dealing with the roof stratigraphy is characterised by the highest GWP equal to about 188 tCO_2eq. It is worth highlighting that the LED + LC configuration appears to be the most effective one in terms of both Global Warming Potential and Acidification Potential environmental impact. This finding is primarily related to the material quantity required to produce 43 unit of LED lighting. The A1-A3 phases account for 187.795 $kgCO_2eq$ per unit as declared in the EPD (Environmental Product Declaration). The advantageous configuration is also affected by the end-of-life phase of the existing fluorescent lamps (60 units), which only accounts for 26.9 $kgCO_2eq$ per unit. In line with these findings, some authors in the literature points out that recycling fluorescent lamps waste can be beneficial for saving natural resources (Dhawan and Tanvar, 2022) and providing environmental advantages (Viana et al., 2023). This retrofit solution can be considered valuable for industrial building retrofitting projects, as the removal of existing lighting and substitution with LED does not require a significant suspension of work.

By contrast, the solutions with PV panels are characterised by a considerable value of AP, ranging from 0.65 tSO_2eq to 0.75 tSO_2eq for HP + PV_{min} and HP + PV_{max} respectively. This is mainly due to the considerable acidification potential related to the production of the flexible PV panels equal to about 30% of the total impact in both configurations. As for the energy footprint (Fig. 6), considering both total energy from renewables and non-renewables, in line with the previous results, the configuration LED + LC proved to be the most valuable.

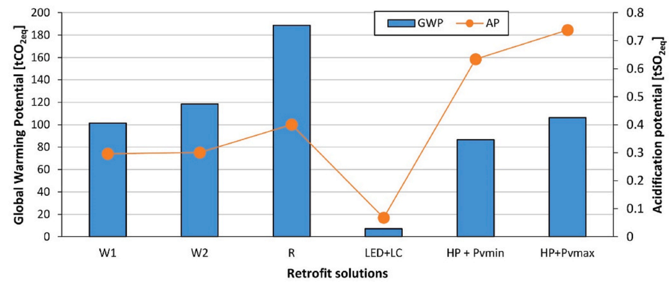

Fig. 5. GWP and AP of different retrofitting interventions.

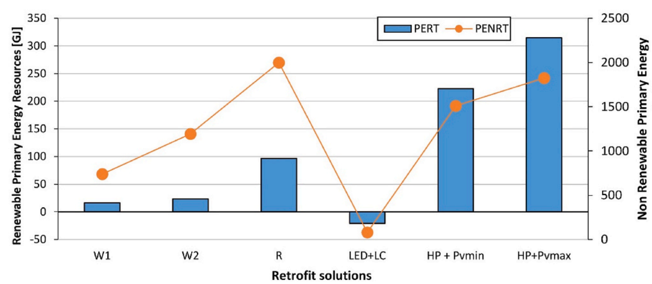

Fig. 6. PERT and PENRT of different retrofitting interventions.

Notably, in this case, the demolition of the existing artificial lighting system has positive results since it seems to present a high recycling potential. The retrofitting measures involving the external walls are all characterised by a considerable value of PENRT, mainly due to the plasterboard panels in the W1 measure and the insulation material for the W2 measure. As regards the R solution, the high impact on the energy footprint is once again related to the disposal and landfilling of asbestos panels. As for configurations including PV panels, the energy footprint is mostly affected by their production phase (A1-A3), with an impact equal to about 167 GJ and 260 GJ for the PERT index and 1460 GJ and 1770 GJ for the PENRT parameter considering HP + PV_{min} and HP + PV_{max} configurations respectively.

In conclusion, based on the different indices previously illustrated and considering the phases A1-B5 as LCA analysis boundaries, the LED + LC retrofit strategy is the most environmentally friendly. By contrast, if both the operational phase (B6) and phase D are included, the installation of the scenario HP + PVmax is the advisable retrofitting measure due to the significant on-site production of surplus energy, which decreases the carbon footprint in terms of Global Warming Potential.

Fig. 7 shows the operational phase (B6) impact for the different combinations (COMB 1–6) of the single retrofit measures considered for the study.

The first combination (R + W2), exclusively focused on the improvement of the entire external envelope, let to the achievement of a

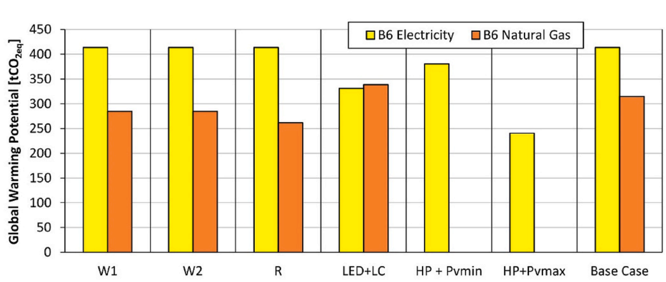

Fig. 4. Global Warming potential for phase B6 due to both electricity and natural gas energy needs. All the single redevelopment measures are illustrated.

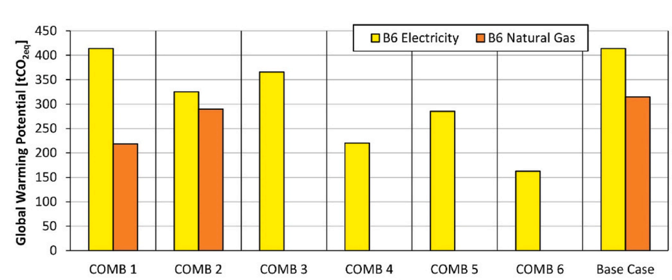

Fig. 7. Global Warming potential for phase B6 due to both electricity and natural gas energy needs. All the combinations are illustrated.

GWP saving of about 30% with respect to the base case. The solution with sandwich panels (W2) was chosen in this case for the redevelopment of the external wall with respect to solution W1 to enhance the building's energy performance and improve its aesthetical quality at the same time. The second combination affects natural gas-related CO_2 emissions to a lesser extent (with a reduction of about 6600 kWh), because coupled with an LED lighting system that reduces internal heat gains. Focusing on the carbon footprint due to electricity demand, the combinations with the widest PV panel coverage are characterised by a reduced impact during the operational phase, confirming the previous results. With combination 6, which includes retrofitting measures for both the external envelope and heating system, it is possible to achieve a 60% electrical energy saving with respect to the base case.

The GWP and AP of various combinations can be demonstrated in Figs. 8 and 9 by setting the analysis boundary conditions to A1-C4. By comparing the outputs reported in these two graphs, the influence of the analysis boundary can be highlighted. This is a direct consequence of considering or not phase D in the environmental analysis.

Combinations 1 and 2 are characterised by the highest environmental impact, mainly due to the production phase of the external envelope components, confirming the results obtained for the single redevelopment measures. Considering also phase D, combinations 4 and 6 allow the industrial building to be carbon zero. The increase in the surface area of PV panels largely offsets the carbon footprint of different redevelopment measures, even though the production phase (A1-A3) of the PV panels increased by about 50%. As for the acidification potential, the combinations allowing on-site energy production once again proved to be the most advisable ones, both considering or not phase D. In the configuration with the widest PV panels surface, the advantage is evident, and the environmental impact is mostly related to the production phases (A1-A3), is once again recovered in terms of tSO_2eq. Further considerations are necessary for combination 5, which foresees roof redevelopment, PV installation and the adoption of an LED system with smart lighting control. Excluding phase D, this configuration is comparable in terms of both GWP and AP impacts with combinations 4 and 6.

Figs. 10 and 11 highlight the total use of renewables and non-renewable energy, respectively. For all combinations, the value of the PENRT is higher than PERT value. Once again, COMB 1 and COMB 2 are the most disadvantageous, while COMB 4 and COMB 6 are the most effective. The latter proved to be the best option to recover part of the energy consumed during the production phase. The last two cited scenarios are characterised by negative values of these indexes: for COMB 4, PERT is equal to −8715 GJ and PENRT to about −1430 GJ. In line with this result, for COMB 6 it is possible to obtain PERT equal to −8971 GJ and PENRT to −3666 GJ. In general, the interventions limited to the envelope components are once again the least environmental-friendly, because of the quantity of materials used and their environmental properties as well as because of the higher energy needs during the operational phase in terms of both electricity and natural gas.

For completeness, the graph in Fig. 12 illustrates the primary energy demand of the industrial building considering the single redevelopment measures and the combined configurations compared to the base case.

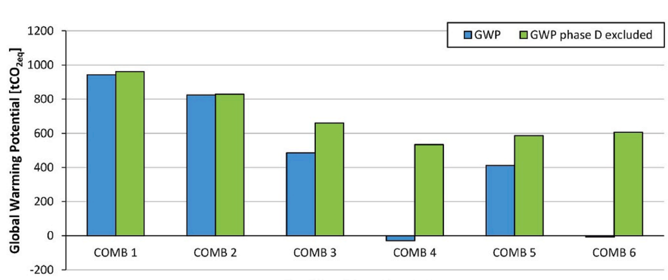

Fig. 8. GWP and GWP (excluded D) of different combinations.

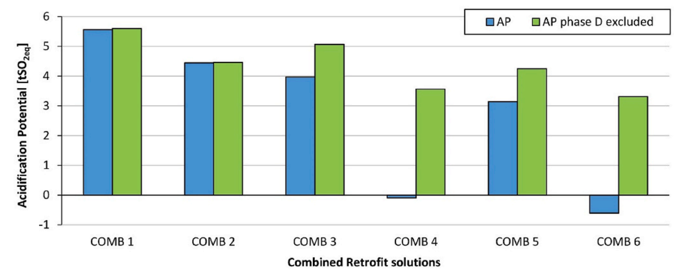

Fig. 9. AP and AP (excluded D) of different combinations.

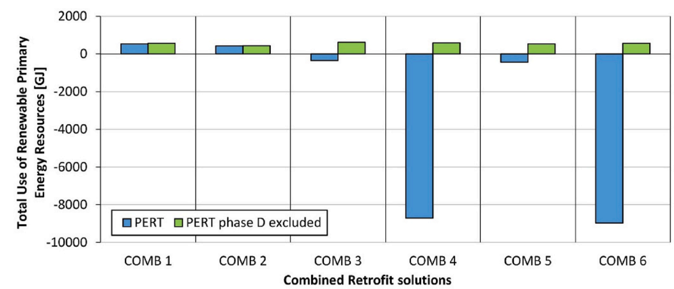

Fig. 10. PERT and PERT (excluded D) of different combinations.

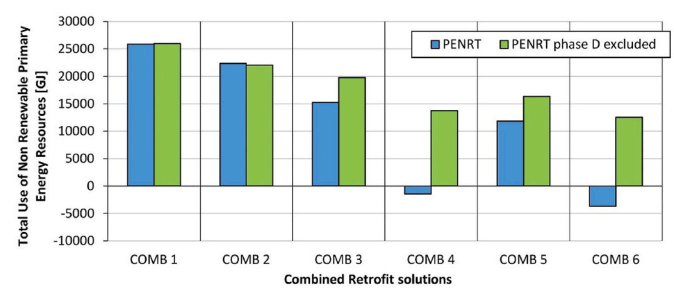

Fig. 11. PENRT and PENRT (excluded D) of different combinations.

As expected, the single redevelopment measure HP + PV_{max} is the most advisable to save primary energy. In this case, there is a saving equal to about 64%. As for single redevelopment measures related to the external envelope, a primary energy saving of 3.5% and 6.5% can be achieved for W2 and R interventions, respectively. According to the previous results related to GHG emissions, COMB 4 and COMB 6, which include energy production by renewables, are the most effective ones. If the former is adopted, the possible primary energy saving is equal to about 89%, while with the latter the redeveloped building can be a zero-energy building.

Based on previous results dealing with carbon and energy footprint and on the evaluation of the primary energy demand, the most suitable effective combinations are COMB 4 and COMB 6. The choice between these two is mainly linked to the building performance that is necessary to obtain in terms of both environmental impact and primary energy demand. Certainly, the former achieves a significant reduction in GHG emissions during the operational phase with lower initial investment cost compared to the latter, because it is necessary to intervene only on the existing roof stratigraphy.

3.1. Sensitivity analysis and carbon payback period

As regards the sensitivity analysis, it is worth noticing that the transport phase (A4-A5) affects the whole life cycle assessment to a lesser extent. Consequently, the perturbation of the data related to the variation in distance for materials transportation to and from the

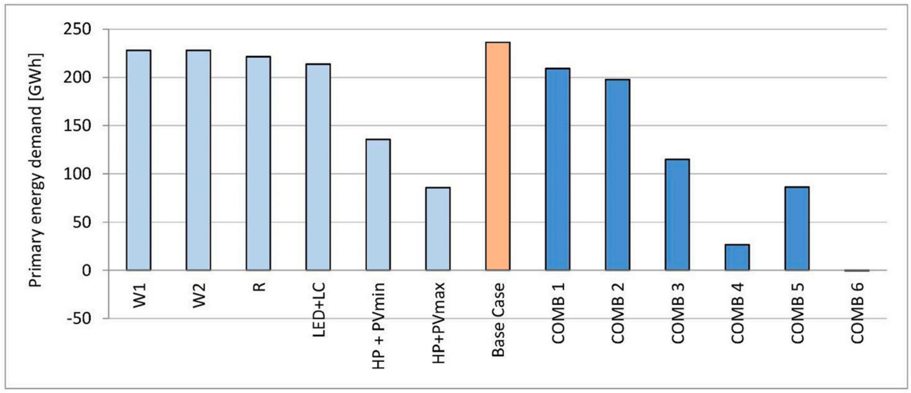

Fig. 12. Primary energy demand for the different retrofitting measures and related combinations.

construction site is not significant for the life cycle assessment of the building. This result aligns with Warrer et al. (Warrier et al., 2024) who state that transportation accounts for 1.5%–2.4% of total GHG emissions.

For construction materials, a variation of 25 km, 50 km and 100 km results in corresponding increase in GHG emissions due to A4-A5 phases equal to 0.075%, 0.12% and 0.21% respectively. The only exception is the demolition, transportation, disposal, and landfill of asbestos in existing roof finishing panels, which accounts for 60% of the entire phase A. As for systems, the influence of distance variations is even less significant, resulting in a total variation of 0.017% for a maximum radius of 250 km (150 km for the starting phase plus 100 km of variation).

These findings about distances transportation are in line with some studies retrieved in the literature. A maximum radius of 300 km is considered as a reference distance to maintain the sustainability of materials supply (Opher et al., 2021).

The consideration of the change in the geometry of the building is necessary because of the variety of geometric configurations found in industrial buildings. It is possible to find 3 different geometric configurations in Italian industrial building stock and facilities are characterised by 1, 2 or 3 naves. The case study analysed features a building with 2 naves. The variation in the environmental impact, limited to phases A1-A3, is directly proportional to the quantities of material needed for retrofitting the building and demolishing existing building components. In this kind of analysis, interventions related to the roof stratigraphy significantly affect the obtained outputs. The GWP increases by about 11.5 % for the demolition of the existing roof and by 4% for the retrofitting intervention R considering a hypothetical building with 3 naves. The intervention on external walls (W2) influences the results to a lesser extent. The introduction of sandwich panels as a retrofitting measure increases the GWP by about 2.6%, while the demolition of existing windows increases it by 0.1% always analysing the 3-nave building. Furthermore, regarding the variation of the CO_2 emissions factor, it is worth pointing out that it exclusively depends on changes in the Italian energy mix. The starting hypothesis is that the Italian energy mix should be improved in the next future, considering the European goal of achieving a free-carbon economy by 2050. The share of energy produced by renewables is expected to increase. Considering the modification in this parameter in the recent few years: from 1990 to 2021 the variation was equal to 309.3 gCO_2/kWh. A decrease equal to 55% was registered for the conversion factor related to the electricity energy vector. If a similar decrease is supposed over the next 30 years, this parameter should drop to 0.1197 $kgCO_2/kWh$. As expected, the same reduction (55%) in terms of electricity-related CO_2 emissions would apply for phase B6 across all combinations. Since phase B6 accounts for an average of 85% with respect to the entire LCA of the industrial building, a reduction of the CO_2 emissions conversion factor is fundamental for buildings with this intended use.

The evaluation of the carbon payback period allows to calculate the number of years needed to recover the initial environmental impact caused by the retrofitting measures. In this case, the evaluation is limited to the combinations that make the building carbon-zero. By considering the amount of surplus electrical energy produced by on-site renewables as the annual CO_2 emissions savings, a carbon payback period is equal to 6.3 years for COMB 4 and 1.3 years for COMB 6.

4. Discussion

The research presented in the paper outlines the environmental impact in terms of GWP, AP, PENRT, and PERT for various retrofitting measures applied to existing Italian industrial buildings. The retrofitting interventions involve both the external envelope and the heating system and were considered singularly and in six possible combinations. The comparison with the base case was evaluated by calculating the operational phase B6 and the primary energy demand. Notably, in the literature, the operation phase is often underestimated or even not included. However, it is essential to consider it when calculating the environmental impact, as its contribution significantly affects LCA analysis, as demonstrated by the results. The process loads, whose weight in terms of energy demand is comparable to that of heating and lighting, as also assessed by (Labat and Attonaty, 2018), were also accounted for in the study. The analysis is conducted considering as a case study an existing industrial facility in Central Italy, which is sufficiently representative of one of the most widespread industrial building types. The study aims to individuate some effective retrofitting solutions for the Italian industrial building stock. As pointed out in the literature, the construction of new buildings is characterised by a GWP up to 128.5 times higher compared to possible redevelopment scenarios (Raposo et al., 2019) and acting on existing buildings is hence recommended. In light of the European goal of achieving a carbon-free economy within 2050, as expected by the Paris Agreement (European Commission, 2015), CO_2 emissions are considered a crucial index when comparing different retrofit scenarios. In line with Bonamente et al. (Bonamente et al., 2014; Bonamente and Cotana, 2015), the operational phase (B6) was proven to account for about 85% of the entire life cycle assessment in terms of global warming potential. Contrails to the previously cited contributions, the research illustrated here includes electrical energy for artificial lighting as well as for production processes in the electricity demand. Considering the results limited to phases A and C, the production phase A1-A3 is the most impactful one in terms of both carbon (GWP) and energy footprint (PENRT and PERT). Opher et al. (2021) highlight that 69% of the carbon emissions occurs from materials production, and Rock et al. (Röck et al., 2020) point out that the production phase accounts for 64% of the total impact. According to the previously cited research, in the case study, the production phase influences the LCA analysis by about 80%.

Considering the entire lifetime of the building and all phases of the LCA analysis, the most environmentally friendly solutions are HP + PVmin and HP + PVmax, due to the considerable advantages related to CO_2 emissions savings in phase D for surplus energy production. By the way, some considerations are necessary considering the life cycle assessment of PV panels highlighting that in the presented case study, the construction process affects the environmental impact more than the disposal phase. First, some authors in the literature affirm that an average of 55% of commercial PV modules are characterised by components that could be recovered (Pascual et al., 2021). Furthermore, according to the analysed case study, Muller et al. (Müller et al., 2006) highlight that the recycling of PV modules can be considered an ecological process, as the environmental impact of recycled components in photovoltaic modules is higher than the burden of recycling. The end-of-life of PV modules is currently a topic requiring continuous technological improvements (Mao et al., 2024), as it presents limitations, as pointed out by some authors in the literature (Ansanelli et al., 2021). The configurations and combinations that foresee external envelope improvements are characterised by the highest environmental impact in terms of carbon footprint with respect to the other interventions. However, an intervention on the external envelope components is necessary because one of the key aspects in making adequate the energy performance of an industrial building is to guarantee an acceptable energy behaviour of the external envelope (Kovacic et al., 2016). For the external wall, 2 technological solutions with dry plasterboard panels (W1) and sandwich panels (W2) are chosen for buildings with this intended use due to their reduced environmental impact in terms of carbon footprint compared to cast-in-place solutions (Teng et al., 2018). Moreover, such solutions avoid the demolition of the existing external wall made of precast concrete panels, which would otherwise negatively affect the environmental impact. Furthermore, these interventions are characterised by low investment costs (Ferreira et al., 2023). By the way, in the literature, most studies on redevelopment interventions for existing industrial buildings focus on retrofitting the roof stratigraphy rather than the external walls (Horan et al., 2020; Espino-Reyes et al., 2020). Lawson et al. (RM et al., 2013) demonstrated that improving thermal transmittance of roof elements leads to greater energy savings compared to increasing the insulation thickness of external walls. In the illustrated research, a primary energy demand saving of about 6.5% is achieved with retrofit scenario R, compared to 3.5% obtained with redevelopment intervention W2.

As regards combinations, COMB 4 and COMB 6 let the industrial building be carbon zero. The production of a significant amount of surplus electrical energy helped recover the considerable CO_2 emissions due to the production phase of the PV panels and the demolition of the existing roof made of asbestos. It is worth pointing out that in this study, the installation of PV panels is always coupled with the redevelopment of the existing roof. The carbon payback period of these two configurations (COMB 4 and COMB 6) which make the building respectively nZEB and carbon-zero, are shorter (ranging from 1.3 to 6.3 years) than the lifetime of the building equal to 20 years. This finding is comparable to other studies in the literature. For instance, Asdrubali et al. (2019) estimate a carbon payback period of 2.8–6.5 years for a school building trough energy improvements. Similarly, Cai et al. (2022) calculate a carbon payback period ranging from 0.9 to 2.3 years for a LEED-certified public library considering CO_2 emissions saving during the building's operation. Roy et al. (2024) highlight a carbon payback period of 0.69–2.15 years for an energy retrofit of roof stratigraphy, considering phase change and insulating materials. The variability in these time intervals is certainly related to the building's intended use, its energy demand during the operational phase and the retrofitting measures adopted.

As outlined by other authors in the literature (Kovacic et al., 2016), it is worth noticing that the Life Cycle Assessment analysis presented in the paper is inevitably affected by the boundary conditions of the analysis, along with the choice of the reference database for materials. The selection of the different EPDs of materials significantly affects the results of the analysis (Opher et al., 2021). The reference database and the different products must be chosen accurately, based on the knowledge of the existing facility and the available information on building components. Designers approaching to a Life Cycle Analysis of an existing building to determine the most effective redevelopment strategy must clearly defined the assumptions of the analysis, including the system boundaries, the life cycle inventory analysis to collect all necessary data, the reference database to identify appropriate data points, and the environmental indicators used to evaluate the environmental impact. These steps are fundamental for properly comparing different retrofitting measures trough LCA analysis and ensuring the robustness and applicability of the findings.

As demonstrated, the inclusion of phase D considerably affects the results across the different indexes, especially for configurations where it is possible to produce a significant amount of surplus electrical energy (HP + PVmin, HP + PVmax, COMB 4 and COMB 6). If phase D is not included in the environmental balance, the scenario LED + LC proves to be the most advisable. According to these results, some authors in the literature point out that the disposal and recycling of not-functioning LEDs results in environmental and economic advantages due to the materials they are made of (Wehbie and Semetey, 2022).

In general, all the proposed redevelopment interventions primarily and directly affect the environmental sustainability of the analysed industrial building. However, significant social benefits for workers can also be observed, particularly through the improvement of indoor thermos-hygrometric conditions, which enhances well-being within the working environment. Moreover, the energy retrofit strategies positively influence energy demand during the operational phase, resulting in reduced operational cost and ensuring economic sustainability. This is also confirmed by other authors in the literature (Weerasinghe et al., 2024).

5. Conclusions

In conclusion, an LCA analysis was performed to determine the most advisable retrofitting measure to be applied to an existing Italian industrial building. As detailed in the text, the chosen industrial building type is one of the most widespread in the Italian context, so the recommended retrofitting measure could be replicable in many similar existing Italian industrial buildings. The research analysed and compared different redevelopment scenarios with measures addressing single component and 6 different combinations concerning both external envelope and systems, also considering the implementation of renewables for on-site electricity production.

The outputs presented are inevitably affected by both the LCA boundary conditions and the materials database available on OneClick LCA.

The analysis of GWP, AP, PERT and PENRT indexes demonstrated that the most promising interventions are COMB 4 (roof + skylights and system + renewables) and COMB 6 (external walls, roof + skylights, system + renewables and LED + lighting control), which make the building nZEB and carbon-zero. These redevelopment measures also allow for the recovery of the environmental impact of the production phase (A1-A3) of PV panels during the building's lifetime (20 years). For instance, COMB 6 is characterised by a carbon payback period equal to 1.3 years, thanks to the amount of surplus energy produced annually by on-site PV panels. To achieve such standards in buildings with this intended use, it is necessary to intervene on both the external envelope and systems, even though the results highlight that the redevelopment of the roof and external walls affects the primary energy demand saving to a lesser extent. In general, redevelopment measures focused solely on external envelope proved to be the less effective due also to the high environmental and energy footprint of envelope components, as well as the considerable carbon and energy footprint associated with the demolition, disposal, and landfill of asbestos panels involving the scenario with interventions on the roof stratigraphy (R).

Regarding systems, it is worth noticing that replacing the existing fluorescent lighting and substituting them with a more efficient lighting system (LED + LC) results in a low carbon and energy footprint during the production phase (A1-A3), even if an increase of GWP occurs during the operational phase (B6). When considering the entire life cycle, phase B6 accounts for 80% of the environmental impact of the industrial buildings, especially when the electrical energy used for production processes is included in the analysis. By contrast, if phases B6 and D are not included in the LCA analysis, the production phase (A1-A3) is characterised by a considerable impact, while the end-of-life stage affects carbon and energy footprint to a lesser extent. Regarding the operational phase, future research could be extended by performing the sensitivity analysis to include the energy needs profiles, corresponding to different production activities and variations in occupation time. This could be a valuable improvement, given the importance of findings related to the operational phase (B6) in the LCA analysis. The main challenge in this context would be obtain accurate information on the actual energy consumption profiles of production activities largely due to the lack of regulations and standardized protocols on this subject. Additionally, acquiring access to the real energy bills of companies is essential to validate the results, but it is subjected to the availability and collaboration of the companies.

Given the various and multidisciplinary challenges associated with retrofitting strategies for manufacturing buildings, the research underscores the importance of an integrated approach to address the complexities of this building type. Designers must consider multiple factors (structural, technological and energy-related) to effectively address all the issues of these facilities. The adoption of redevelopment solutions for both external envelope and systems should be prioritized by the designer during the making-decision process for retrofitting interventions, aiming to enhance energy performance and improve workers' well-being.

It is worth highlighting that the availability of funds for the initial investment cost by commissioners is usually one of the most influential driving-factors in decision making process and it represents one of the main barriers for multiple and integrated interventions in existing buildings. Since economic evaluations are often more relevant than the environmental ones, the evaluation of the cost of the different redevelopment measures should be analysed by performing a Life Cycle Costing (LCC) analysis or by applying an approach based on the cost-optimal methodology. However, the integration of LCA and LCC analysis is currently a challenging problem, as highlighted by some authors in the literature (Lu et al., 2021). This potential integration presents several weaknesses that must be addressed in future research (Schmidt and Crawford, 2018). Combining the evaluation of environmental impact with the calculation of initial investment costs during the early stages of the design process enables more informed decision-making for designers. This approach can lead to not only environmental benefits but also advantages for companies' owners and workers.

Another valuable future development could be the evaluation of the environmental impact of additional retrofitting interventions. The specific case study selected for the research did not require the demolition of existing walls, since their configuration is not posing significant structural issues. Future research could explore the environmental impact associated with the demolition of precast concrete panels of the external walls and extend the findings to other typological variants presenting structural challenges.

Similarly, different system configurations for both generation and distribution systems. Furthermore, the calculation of the carbon footprint of potential storage for electrical energy should be performed to maximise the exploitation of surplus energy produced when solar radiation is unavailable. Finally, with the same approach, the proposed methodology can be applied to different industrial building types to outline the most advisable retrofitting scenario for each. Although this study focuses on a specific typological variant of Italian industrial buildings, many of the proposed retrofitting measures are broadly applicable, including dry technological solutions for external walls and roofs and the integration of renewable resources for on-site energy production. The applicability is primarily due to the consistent characteristics of the manufacturing buildings, as they were all constructed for the same intended use. This is further validated by the results of the sensitivity analysis. The findings confirm that the variations in material quantities and the transport distances within a maximum radius have a relatively minor effect on the overall environmental impact.

CRediT authorship contribution statement

Cecilia Ciacci: Writing – original draft, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Frida Bazzocchi:** Writing – review & editing, Methodology, Conceptualization.

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.

Appendix A

Table A. 1
Environmental impact for new construction materials for retrofitting for production phase (A1-A3).

Material	Quantity	GWP $kgCO_2eq$/ functional unit	AP Total $kgSO_2eq$	PERT Total MJ	PENRT Total MJ	Data points source
Rockwool Insulation (λ = 0.035 W/mK; 25–50 kg/m^3)	1259 m^2	1.2 $kgCO_2eq$/kg	24.46	1638.27	43115.68	One Click LCA 2018; PCR EN 15804+A1; Internally verified; Material composition: BS EN 13162:2008
Steel profiles (0.6 mm; 4.5 kg/m^2)	2058 m	1.49 $kgCO_2eq$/m	6.78	1547.62	43218	EPD 2019 Upstream database: GaBi
Plasterboard panel (6.5–25 mm; 10.725 kg/m^2)	2518 m^2	0.27 $kgCO_2eq$/kg	68.94	12422.96	79398.91	PCR EN 15804+A1; Internally verified; Material composition: BS 1230–1:1985

(*continued on next page*)

Table A. 1 (*continued*)

Material	Quantity	GWP $kgCO_2eq$/ functional unit	AP Total $kgSO_2eq$	PERT Total MJ	PENRT Total MJ	Data points source
Sandwich panel with polyurethane foam core and double steel siding (U = 0.23 W/m^2K; 13.2 kg/m^2; steel thickness = 0.6/0.6 mm (ext/int)	900 m^2	39 $kgCO_2eq/m^2$	105.3	22590	621000	EPD 2021; PCR 2012:01 Construction products and construction services, ver. 2.3; Third-party verified according to ISO 14025; Upstream database: Ecoinvent v3.8
Large polycarbonate roofing elements (20 mm; 3.2 kg/m^2)	28 m^2	37 $kgCO_2eq/m^2$	0.0042	0.058	35.44	EPD 2022; PCR EN 15804+A1; Third-party verified according to ISO 14025; Upstream database: Ecoinvent v3.8
Insulated Glass unit	113.9 m^2	41 $kgCO_2eq/m^2$	27.28	3395.41	84258.63	EPD 2021; PCR EN 15804+A1; Third-party verified according to ISO 14025; Upstream database: GaBi
Compact industrial LED lighting (P = 115 W; 4.34 kg/unit)	43 unit	187.79 $kgCO_2eq$/unit	50.94	9609.04	100806.3	EPD 2022; PCR EN 15804+A1; Third-party verified according to ISO 14025; Upstream database: Ecoinvent v3.8
Lighting management sensors (0.31 kg/unit)	6 unit	3.6 $kgCO_2eq$/unit	0.00046	0.0066	4.08	EPD 2022; Third-party verified according to ISO 14025; Upstream database: Ecoinvent v3.8
Air-to-air heat pump (rooftop mounted; 1546.7 kg/unit; 99.8 kW)	1 unit	11405.07 $kgCO_2eq$/unit	28.21	4982.18	336755.12	EPD 2022; Third-party verified according to ISO 14025; Upstream database: Ecoinvent v3.8
Semi-flexible solar photovoltaic module (PVmax)	1136 m^2	33.6 $kgCO_2eq/m^2$	201.07	178124.8	604920	EPD 2023; Third-party verified according to ISO 14025; Upstream database: Ecoinvent v3.8
Semi-flexible solar photovoltaic module (PVmin)	547 m^2	33.6 $kgCO_2eq/m^2$	96.82	85769.6	291277.5	EPD 2023; Third-party verified according to ISO 14025; Upstream database: Ecoinvent v3.8

Data availability

The authors do not have permission to share data.

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