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Environmental impacts of standard building renovations: City-level extrapolation from a real case study in Spain

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ABSTRACT

The renovation of multi-family buildings aimed at reducing operational energy consumption and improving housing health and safety is a common practice across Europe. However, in response to climate change, the European Union has established ambitious targets for 2050, which require not only reductions in operational energy use but also a significant decrease in embodied energy and CO_2 emissions associated with building renovations.

This study presents a comprehensive analysis of a social housing building in Zaragoza, Spain, which underwent renovation aimed at reducing energy consumption, enhancing indoor environmental quality to improve residents' living conditions. A detailed inventory of materials and construction processes was compiled, and both the embodied energy and CO_2 emissions associated with the renovation phase were calculated and compared before and after the intervention, including an estimation of payback times.

Additionally, the study extends the analysis to the urban scale by selecting buildings with similar characteristics and creating a digital twin using programming tools, in order to assess environmental impacts and payback periods across a broader context.

The results highlight that the renovation works aimed at reducing operational energy—such as façade and roof insulation, window replacement, and system upgrades—account for less than 50% (47.5%) of the total embodied energy of the renovation. In terms of Global Warming Potential, however, this share increases to 74.9%.

Regarding payback periods, the non-renewable Energy Payback Time is 1.35 years at the building scale and 1.12 years at the city scale. For CO_2 emissions, the payback time is 1.62 years at the building scale and 1.35 years at the city scale. These results demonstrate that the renovation—implemented with conventional materials—achieved significant reductions in energy use and emissions. Even greater benefits could be achieved by incorporating materials aligned with circular economy principles. These interventions should also be leveraged to enhance the quality of life of residents by adopting new approaches to adaptability and the reorganization of interior spaces, thereby pursuing optimal functional renewal.

1. Introduction

The European Union (EU) has established the Green Deal, setting a legally binding target of achieving climate neutrality by 2050, defined as net-zero greenhouse gas emissions. This commitment was formalized through Regulation (EU) 2021/1119 [1,2]. As the building sector is responsible for approximately 36 % of EU greenhouse gas emissions and 40 % of total energy consumption, it is recognized as one of the largest contributors to climate change [3]. To date, the European energy policies are focusing on improving the energy performance of buildings and

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promoting the use of renewable energy during the operational phase [4]. The implementation of these regulations results in lower energy consumption during the building's operational phase, operational energy, used to maintain comfort inside the dwelling primarily through heating, cooling, and hot water production systems. In addition to operational energy, the energy consumed during the entire life cycle of a building also includes embodied energy—the energy required to obtain the materials and equipment that constitute the building during its production, transport, construction, final demolition, and disposal [5].

Recognizing this broader impact, recent European policies encourage a life-cycle approach, addressing both operational and embodied energy. In the revised Energy Performance Building Directive (EPBD 2024), in addition to measures aimed at reducing operational energy in both new and existing buildings, there are mandatory measures to reduce embodied energy—but only for new buildings [4]. This limitation is highly significant given that Europe's existing building stock is predominantly old: 86 % of residential buildings in Southern Europe, 83 % in Central and Eastern Europe, and 81 % in North-Western Europe were built before 1990. Moreover, 85–95 % of today's buildings will still be in use by 2050 [4–6]. Consequently, these buildings must undergo renovation to reduce operational energy, as mandated by the EPBD.

However, if renovation strategies focus exclusively on operational energy reduction—as is largely the case today—there is a substantial risk of contradicting the EU 2050 climate-neutrality objective. Although the use phase typically dominates life-cycle energy demand, accounting for approximately 80–90 % of total impacts [7], prioritising only this stage overlooks the growing relevance of embodied energy and emissions. In fact, renovation measures often involve material-intensive interventions, meaning that embodied energy and emissions associated with retrofit works can become a dominant share of the building's total life-cycle energy [8]. Therefore, to achieve the established global goal, it is necessary not only improving the performance of new buildings, but also addressing both operational and embodied energy in the renovation of the existing building stock, since it accounts for a significant share of total energy use in the sector [9]. Current efficient building practices for transforming the existing building stock include passive interventions, such as enhancing building envelope insulation (e.g., façades, roofs, and windows), and active measures, such as implementing system controls or installing renewable energy systems to conserve energy to reduce energy consumption [10]. While these approaches can significantly reduce operational energy, they also introduce material flows whose embodied impacts must be assessed to avoid carbon payback delays or unintended emissions increases.

The European Commission identifies minimizing the environmental footprint of buildings—through resource efficiency, circularity, and transforming parts of the construction sector into carbon sinks—as one of the key principles guiding renovation toward 2030 and 2050 [6]. Circular-economy strategies alone can reduce materials-related life-cycle greenhouse gas emissions by up to 60 % [11].

It is essential to consider not only the individual buildings but also the urban scale when assessing the contribution of cities to climate change and decarbonization efforts. Cities consist of highly heterogeneous building stocks in terms of age, geometry, and material composition which must be taken into account when shifting between scales of analysis. This broader perspective enables a better understanding of the implications of different urban contexts and the morphologies of which they are composed [12].

It is essential to consider not only the individual buildings but also the urban scale when assessing the contribution of cities to climate change and decarbonization efforts. Cities are complex systems in which highly heterogeneous buildings, land uses, open spaces and populations coexist, which makes a direct translation from the building to the urban scale far from straightforward. In this context, the emerging ecosystem of open data enables new perspectives on urban analysis [13], as different datasets can be combined to construct digital models of the city that support decision-making, albeit with important limitations [14,15]. These models may integrate data sources specifically designed for environmental assessment (e.g. land surface temperature, permeability or vegetation indices) together with others originally created for others purposes, such as cadastral records (taxation), which contain detailed information on the building stock but require careful interpretation before they can be used to assess renovation potential.

In Spain, residential buildings are responsible for a great part of energy consumption during the operational phase, due to the obsolescence of its building stock [16]. Deep renovations, which usually focus on reducing energy consumption during this phase, typically involve insulating the thermal envelope (facades and roofs), replacing windows, and upgrading heating and domestic hot water systems [17]. These renovations can be initiated by building occupants, with or without public financial support. In the context of social housing, they are often promoted or subsidized by public administrations. The refunded EPBD 2024 requires Member States to systematically renovate public buildings, ensuring that they achieve high energy efficiency standards, and establishes that all new publicly owned buildings must be zero-emission as of 2028 [4]. The Municipal Society Zaragoza Vivienda (SMZV), is a public company that implements the houses policies in the city of Zaragoza [18]. SMZV, which is responsible for the management, maintenance, and rental of public housing, owns properties dedicated to social housing rentals intended for vulnerable families. In addition to promoting the renovation of its own buildings, SMZV has also managed subsidies for the renovation of privately owned buildings since 2006 [19]. Despite public buildings representing only around 10 % of the building stock, they consume large amounts of energy [20], with its consequent Greenhouse gas (GHG) emissions. This issue is particularly relevant in social housing, since these dwellings must provide adequate comfort and habitability for their residents, many of whom experience energy poverty and cannot afford high utility bills [21]. Social housing is often located in older buildings affected by obsolescence, which undermines the quality of life of their occupants [22,23]. In fact, ensuring comfort in social housing represents a major challenge both for residents and housing managers [24]. In addition, public buildings, including social housing, are not only major energy consumers but are also expected to play an exemplary role [4]. These dwellings, often very old and obsolete, frequently fail to meet the minimum comfort standards required by their occupants. The rehabilitation of these dwellings offers an opportunity not only to improve comfort and energy efficiency but also to adapt housing to the current needs of residents. This includes functional adjustments of older units to better accommodate new family structures and the redesign of interior spaces to meet evolving lifestyle requirements, thereby enhancing the residents' habitability.

To date, these renovations have focused exclusively on reducing operational energy during the use phase of the building [25]. However, given the growing importance of considering embodied energy, it is relevant to assess the environmental impacts of these types of renovations—both at the building scale and in terms of their broader implications at the city level.

Embodied energy refers to the total amount of energy required to produce, transport, and dispose of a material or product, accounting for all stages of its life cycle, from raw material extraction to end-of-life management [7]. Life Cycle Assessment (LCA) is a widely recognized methodology for evaluating the environmental impacts associated with all stages of a product's life cycle. Global Warming Potential (GWP) quantifies the contribution of different greenhouse gases to overall emissions, expressing their impact in terms of carbon dioxide equivalents ($CO_{2\text{-eq}}$) over a specified time horizon [26]. While LCA has been extensively applied to new construction projects, its application to building renovation remains comparatively limited in the existing scientific literature.

The existing literature on building energy retrofit has largely emphasized improvements in operational energy performance, whereas comparatively fewer studies have adopted a comprehensive life cycle perspective that accounts for the embodied impacts of renovation interventions. Several studies have examined the feasibility of cost-optimal and carbon–neutral refurbishment strategies, yet most rely on hypothetical scenarios and do not analyse the real-life implications of actual renovation projects. For example, Panagiotidou et al. [27] evaluate a real building case using hypothetical retrofit scenarios selected from archetype-based statistical analyses, applying Life Cycle Costing (LCC) but not LCA, leaving the environmental implications of the interventions insufficiently characterized. Similarly, Galimshina et al. [28] investigate cost-effective retrofits for two multifamily buildings in Switzerland, showing that replacing heating systems is the most influential measure; and Ferreira et al. [29] analyze cost-optimal effective renovation solutions to achieve net-zero energy in a multifamily building in Portugal. However, these studies share common limitations: they do not study real interventions, they do not analyse the full life cycle impacts, and do not disaggregate results by intervention package making it difficult to attribute environmental benefits or burdens to specific retrofit actions. Although identifying cost-effective retrofit pathways to approach net-zero energy is undoubtedly valuable, it is equally important that renovation strategies achieve the greatest possible reductions in energy demand in order to align with current energy-efficiency priorities and long-term decarbonisation objectives [2].

A second line of research has examined whether existing buildings in Mediterranean climates can achieve life cycle carbon neutrality. Stephan et al. [30] study a real apartment building in Lebanon and evaluate a hypothetical deep retrofit aimed at achieving net-zero life cycle energy and greenhouse gas emissions. Using the Australian EPiC database to quantify embodied impacts, they conclude that achieving full neutrality requires extensive deployment of photovoltaic systems and, ultimately, disconnection from the national grid. Likewise, Panagiotidou et al. [31] found that achieving carbon neutrality in a Greek retrofit requires significant improvements to—or isolation from—the existing electricity infrastructure. While these works provide valuable insights, they do not reflect typical European renovation practices, nor do they quantify the contribution of individual retrofit components. In Spain, several studies have examined the renovation of typical residential buildings, particularly multifamily blocks constructed before 1990. Las Heras et al. [32] conducts an analysis assuming different insulation thicknesses in order to determine the optimal envelope configuration to achieve nearly zero-energy building (nZEB) performance in southern Spain. Similarly, Pombo et al. [33] evaluates a multifamily building in Madrid using both LCC and LCA across various hypothetical retrofit scenarios. While these studies provide useful insights into potential renovation strategies, they rely on simplified or idealised assumptions and do not reflect the complexity of real renovation projects, which involve a wide range of materials and interventions beyond insulation thickness and window replacements.

Beyond the Mediterranean context, several works have analysed renovation strategies using LCA, though their building typologies and constructive systems differ substantially from those common in Europe and Spain. Amoruso et al. [34] assess hybrid renovation and extension strategies for mid-rise timber buildings in Korea, integrating environmental and economic assessments through parametric modelling. Mohammadpourkarbasi et al. [35] compare EnerPHit standards with conventional retrofits in UK detached single-family houses using natural materials. They report carbon payback times below five years, but the building type and renovation standard are not common in Southern European contexts. Apostolopoulos et al. [36] evaluates a real multifamily building retrofit in Greece certified under the Passive House Premium standard, obtaining a 3.5-year payback. Although the reductions achieved are significant, the intervention does not represent a conventional renovation scenario but rather an exceptional deep-retrofit case.

A smaller but important number of studies analyse real renovation projects, although they typically focus on operational energy and omit the full life cycle perspective. Grinham et al. [37] conduct a net-zero carbon retrofit of a university building in the United States, designed as an experimental prototype rather than a typical renovation. D'Agostino [38] develops a highly detailed, calibrated dynamic energy model of a renovated shopping mall in Italy, adjusting real energy consumption data to meet ASHRAE calibration thresholds and calculating operational energy and CO_2 savings under six retrofit scenarios. While the methodological accuracy is noteworthy, the study explicitly leaves LCA integration for future research. Other studies examine different hypothetical retrofit scenarios for buildings with uses other than residential. Ascione et al. [39] analyse the renovation of an educational building in Italy towards nZEB performance but limit the assessment to the use phase, without considering embodied impacts associated with construction materials and systems. González-Prieto [40] explores different hypothetical retrofit scenarios for a real office building with cultural heritage protection. These are therefore hypothetical scenarios, not an actual executed renovation

At a broader scale, several works have evaluated renovation strategies at the urban level. Mastrucci et al. [41] estimate the carbon footprint of multiple hypotetical retrofit scenarios across the residential stock of Luxembourg, demonstrating the relevance of coordinated city-wide approaches. Monzón-Chavarrías et al. [42] and García-Pérez [12] apply a building-by-building model using GIS, LiDAR, and DSM data to assess energy and environmental implications using LCA methodology of façade retrofits in Barcelona. Although these studies provide valuable insights for large-scale planning, they rely on idealised scenarios and require extensive prior data that is not always available, and they do not track the specific contribution of individual renovation measures. Pacheco-Torres et al. [43] propose a model linking urban density to embodied energy associated with neighbourhood-scale retrofits, highlighting the importance of urban form. However, this line of research does not provide detailed insights into the life cycle performance of specific, real renovation projects.

In light of the existing literature, several research gaps remain insufficiently addressed and highlight the need for further investigation. First, there is a clear lack of studies analysing real, successfully executed renovation projects, despite the fact that real construction works involve a much broader set of materials and processes than those typically represented in theoretical or scenario-based studies. Actual renovations include numerous material-intensive tasks beyond the common focus on façade insulation, roof insulation, and window replacement, and therefore provide a more accurate basis for life-cycle assessment. Second, current LCA studies on building retrofits rarely include a disaggregation of environmental impacts by work packages, limiting the ability to identify which interventions contribute most to embodied impacts or operational savings. Third, there is a shortage of research examining conventional renovation strategies applied to the most representative building typologies in Southern Europe—namely, multifamily residential buildings constructed before 1990—despite their prevalence and high renovation potential. Fourth, no studies have been identified that extrapolate the results of a detailed, data-driven LCA of a real renovation to the urban scale, which would provide valuable insights into the aggregated impacts of widespread renovation actions. Finally, for these representative cases, the energy payback time (EPBT) remains underexplored, even though it is a key metric for understanding the balance between embodied burdens and operational gains.

Based on these identified gaps, the objectives of this study are as follows:

1. To quantify the life-cycle environmental impacts of a real multifamily building renovation using a detailed LCA approach. This renovation represents a typical intervention currently carried out in Southern Europe, aimed at reducing operational energy demand, and is assessed through a comprehensive inventory of all materials and processes involved in an actual construction project.

2. To disaggregate environmental impacts and energy savings by renovation work packages, allowing the identification of the most influential intervention components.
3. To extrapolate the results of the analysed renovation to the urban scale, evaluating the potential aggregated impacts of implementing similar interventions across comparable buildings in the city.
4. To calculate the EPBT by integrating both embodied energy and operational energy savings achieved through the renovation.

The novelty of this study stems from its empirical and highly detailed assessment of a real renovation project, rather than a hypothetical scenario. By compiling a comprehensive life-cycle inventory of all materials and processes involved, the study provides a level of accuracy rarely present in renovation LCAs. Furthermore, the disaggregation of impacts by work packages offers new insights into the specific contributions of each intervention. The urban-scale extrapolation of the results extends the relevance of the analysis beyond a single building, while the calculation of the energy payback time (EPBT) for a conventional renovation of a representative Southern European multifamily building provides a valuable empirical benchmark. Together, these contributions offer a novel and robust perspective that supports more informed and effective decarbonisation strategies for the existing building stock.

2. Theory and calculation

1. The scheme of the methodology is shown in Fig. 1. First, a multi-family building deeply renovated with the goal of reducing the energy demand and the energy consumption was selected and studied. This model of renovation can be extrapolated to other similar buildings.
2. Select a real case study (Reference Building). Case study analysis.
3. Constructive inventory. An in-depth study of this building was carried out, making a specific inventory of all the materials and processes involved in the renovation.
4. Environmental impact assessment is calculated according to LCA methodology: embodied energy and CO_{2eq} emissions during the rehabilitation phase.
5. Energy calculation to obtain your operational energy. Operational energy has been obtained with the energy performance certification (EPC) of the buildings.
6. Energy amortization and payback.
7. Extrapolation from the building level to the urban scale.

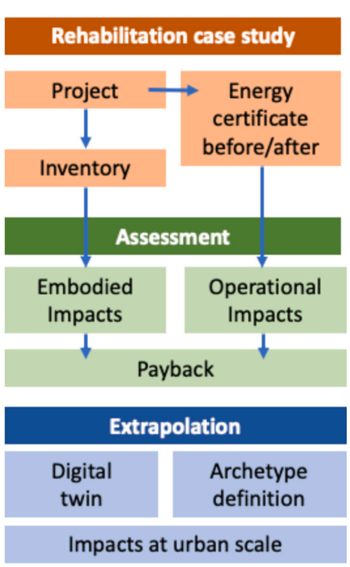

Fig. 1. Scheme of the used methodology.

2.1. Calculation of functional units for extrapolation

6.2. In order to extrapolate from the archetype, work has been carried out using programming notebooks that allow the selection of different constructive and functional characteristics of the buildings from the Cadastral Dataset, thus obtaining a dynamic sample. The article presents a possible extrapolation whose parameters are adjusted by iteration through direct observation.
6.3. Calculation of the environmental impacts of the sample of similar buildings: embodied energy, CO_{2eq} emissions during the rehabilitation phase.
6.4. Comparison of embodied energy with operational energy of these buildings to obtain payback and results, with and without photovoltaic panels.

3. Case study

A case study of a multi-family residential building is selected, where an energy renovation was carried out with the aim of reducing energy demand and consumption. The intervention performed on this building is a very common type of intervention in multi-family residential buildings in Spain. This case study is chosen because there is access to the execution project, and interviews have been conducted with the actors involved in the renovation, providing extensive information about the work carried out.

The case study involves a building located in the historic center of Zaragoza, Spain. This building belongs to the public company Sociedad Municipal Zaragoza Vivienda (SMZV), which is responsible for actions related to renovation and housing in the city. SMZV owns residential buildings that it renovates to offer as social rental housing. In the year 2022, it promoted and financed the energy renovation of a social residential building, achieving an improvement in its energy performance during the usage phase. This intervention consisted of energy renovation of the building envelope, modernization of its installations and interior renovation of residential units making it a model of renovation that can be extrapolated to other similar buildings.

The building, located in the historic center of Zaragoza, was constructed between 1988 and 1990. It is not listed as an heritage building and consists of 8 flats, 8 storage rooms, and commercial spaces distributed over five floors above ground and a basement. Before the intervention carried out by SMZV, the building was unoccupied and awaiting its reactivation.

The characteristics of the plot are summarized in Table 1 and shown in Fig. 2. The main facade faces north and opens onto main street.

3.1. Building description

The original building was designed to accommodate rental apartments in the historic center of the city. It comprises a total of eight units, with each floor containing two flats of four bedrooms each. The ground floor and basement were primarily allocated for commercial or workshop spaces, as well as for the main entrance and shared services for the residential units. Each apartment also has a designated storage room located in the basement. The total living area of the building is 635.56 m^2, while the gross floor area amounts to 792 m^2, resulting in a ratio of heated living space to gross floor area of 20.2 %. All apartments are through-units with dual orientation; however, due to the narrowness of

Table 1
Plot characteristics.

Plot characteristics	
Plot area	327 m^2
Street frontage	13 *m*
Depth	24.7–28.7 *m*

Fig. 2. Plot situation.

surrounding streets and courtyards, natural sunlight reaches very few rooms. Fig. 3 presents the typical floor plan and Fig. 4 shows pictures of the before and after the renovation.

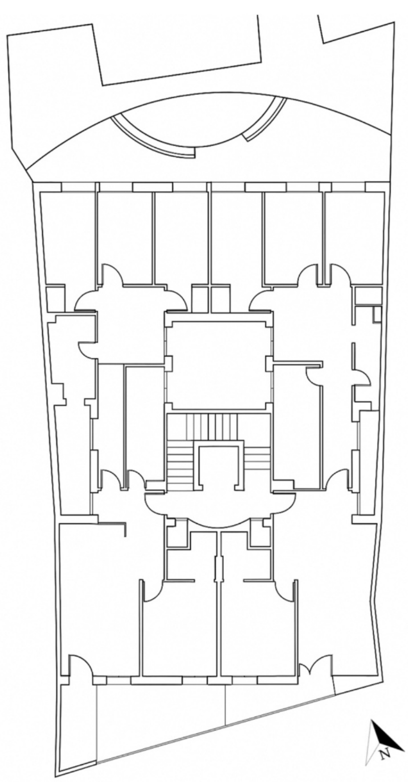

Fig. 3. Floor type of dwellings in the case study building.

3.2. Technical characteristics

The renovation of the building aimed to restore habitability and comfort conditions to a previously vacant structure, making it suitable for rental purposes. The interventions focused on two main aspects.

First, improvements were carried out to enhance the safety and habitability of the residential units. These included replacing interior flooring with insulated underlayment, applying new paint finishes, reintegrating structural volumes, and installing new interior carpentry elements such as doors.

Second, measures were implemented to reduce heating energy consumption by decreasing overall energy demand. This was achieved through the enhancement of the building envelope's thermal insulation and the system replacement. These actions required additional complementary works, such as the creation of a new utility room (previously nonexistent) and the substitution of certain façade elements which, despite being in good condition, could not be preserved due to the integration of new insulation layers.

Although the real project also included an upgrade of the building's electrical system, this particular intervention is not considered within the scope of the present study.

Habitability is a broad concept. In this renovation, the habitability and comfort of residents were enhanced in several ways, including improving the building's structure, installing new interior joinery and flooring, and adding air conditioning where none existed previously.

The constructive intervention is shown in Table 2.

3.3. Green warning Potential and embodied energy

The environmental impact assessment of the selected renovation interventions is calculated according to LCA methodology ISO 14040 [44], EN 15978 [45] and EN 15804:2014 [46]. As it is a renovation, this work incorporates new materials and replaces others. In the case of new products, a "cradle to site" approach was used, this includes the

Fig. 4. Before and after the renovation.

manufacture of the products (A1-A3 stages), transport and installation in the building (A4-A5 stages). The use phase of the building (stages B4-B6) is also included and the demolition, deconstruction, and final disposal of replaced elements (stages C1-C4) are encompassed (Fig. 5).

The environmental implications of the materials, energy and transport involved in the system were simulated using SimaPro 9.4 software [47] and the ecoinvent 3.8 database [48]. The methods selected for the calculation of environmental impacts have been two: Recipe 2016 for the calculation of GWP throughout a horizon of 100 years and Cumulative Energy Demand (CED) [49].

Data quality and system boundary assumptions were explicitly addressed to ensure transparency and reproducibility of the life cycle assessment. Primary data were collected for all material quantities and construction processes directly from project documentation and on-site records, while secondary data for environmental profiles were obtained from the ecoinvent 3.8 database implemented in SimaPro. Due to the limited availability of Environmental Product Declarations (EPDs) for all renovation materials, generic datasets were predominantly used, complemented by EPD-based data when available for key construction products. Overall, the inventory can be considered to have medium-to-high data quality, with a predominance of primary activity data combined with well-established secondary background data.

Transport (module A4) was modelled using standard ecoinvent assumptions for road freight transport, applying average distances representative of regional supply chains in Spain. Installation processes (A5) and demolition activities (C1) were included based on project-specific measurements and standard machinery datasets. End-of-life scenarios (C2–C4) followed conventional assumptions for construction and demolition waste management, including transport to treatment facilities, recycling where applicable, and landfill disposal for non-recyclable fractions.

Potential benefits and loads beyond the system boundary (Module D) were excluded from the analysis. This choice was made to avoid speculative assumptions regarding future recycling rates and substitution credits and to ensure a conservative and comparable assessment of the renovation impacts. Fig. 4 illustrates the system boundaries and life-cycle modules included in the study.

The useful life of the elements has not been taken into account in the presentation of the results, since the total impacts are presented. But it should be clarified that the lifetimes are not the same, for example the building typically has a useful life of 50 years as reported in other studies [30], however the photovoltaic system is normally about 25 years and the air conditioning equipment about 15 years.

ReCiPe 2016 method in Life Cycle Assessment (LCA) is a well-established impact assessment approach and covers a wide range of impact categories (17 mid-point categories), offering a holistic view of the potential effects on the environment. Midpoint indicators focus on single environmental problems, including climate change, resource depletion, and toxicity, thereby supporting more informed and effective decision-making for sustainability.

The Cumulative Energy Demand (CED) characterizes the direct and indirect energy use over the life cycle of a good, service, or product [50], providing separate primary energy from renewable and non-renewable sources. The CED method is valuable for providing a general overview of the energy-related environmental impacts throughout a product's life cycle and for conducting initial comparisons between individual products. In this study, it has also been used to estimate the energy payback of the building renovation.

The environmental impact assessments are shown to the renovation actuation as a whole including demolition and construction works, according to project's measurements and budget. There is an exhaustive detail of all the actions carried out, the environmental impacts are assigned and presented by actions which are divided into 5 packages: demolition, facade, roof, masonry, windows and systems.

A complete inventory of all the materials and machinery used in the project is carried out, obtaining the information from the project and the interviews. Appendice 1 detailed the inventory of this building retrofit. In this renovation, 74,107.12 kg of materials and 656.07 kWh were used (without systems) during renovation works.

3.4. Operational energy

Operational energy has been obtained with the EPC of the buildings. The EPC has been done using the CE3X software, valid according [51]. The EPC provides us with the energy performance of the buildings, before and after the renovation. Specifically, it gives us the Non-Renewable Primary Energy Consumption (NRPEC) and CO_2 emissions. Using the step coefficients published in [52], we obtain the final energy consumption and the primary energy consumption. Before the renovation, the building was equipped only with heating, and air conditioning was added after the renovation.

The study is based on EPCs as they are a standardized and mandatory

Table 2
Constructive solutions before and after the renovation. The letter (E) indicates that this measure contributes to the building's energy efficiency or is necessary to achieve it.

	Original state	Renovated state
Demolition		Necessary demolition to create a new service room for centralised building systems. Ceilings and floors. (E)
Façade	Double-leaf ceramic brickwork 12 cm finished with mortar and paint. 6 cm fiberglass insulation. Ceramic brick partition wall 9 cm. Interior plastering and finishing.	Add External Thermal Insulation System (ETICS) of 12 cm mineral wool adhered with mortar. (E)
Windows	The windows are casement, some with fixed parts, made of anodized aluminum (without thermal break) and double-glazed glass. The kitchen windows are sliding. With Roller blinds are present except in kitchens, corridors, and bathrooms	Replace existing windows with high-performance aluminum and double-glazed glass. (E)
Roof	Sloped roof over ceramic brick partitions spaced 100 cm apart, finished with curved cement tiles on tongue-and-groove boards. Fiberglass insulation blanket, 6 cm thick, was installed on the horizontal roof slab (concrete joists).	On top of the existing insulation, 30 cm thick blown rock wool insulation (type Rockin). In the utility room to be constructed in the attic space: 20 cm of XPS insulation on the existing floor slab, followed by a polished concrete floor with quartz. (E)
Masonry	Slab thickness of 28 cm, with terrazzo flooring laid using mortar.	High-density rock wool insulation will be installed over the terrazzo flooring in two layers, each 15 mm thick, type ROKSOL E 525, followed by the installation of laminate flooring. (E) Interior finishes of housing, repair of blind openings, trim and touch-ups. Include the finishing of carpentry openings and wall painting with gypsum plaster, replacement of interior flooring, installation of suspended ceilings, wall tiling, surface painting, volume reconstruction using epoxy adhesive, repair of shutter openings with polyurethane foam and plasterboard, and installation of artificial stone sills.
Systems	Individual heating by electric radiators No cooling systems Domestic Hot Water (DHW) is produced by individual electric heaters.	Centralised heat pump installation producing heating and cooling energy (cooling/heating capacity 22.4/25 kW), 8 indoor units and 300 l inertia tank (E). DHW centralized system consisting of two heat pumps (E). Photovoltaic (PV) system installation on the south roof consisting of 28 PV panels, of 350 Wp located on the roof of the building, 55 m^2 of solar area (E).

tool for buildings across European countries, ensuring that this research can be easily replicated. Operational energy could also be assessed through dynamic simulations or on-site measurements, which would be equally valid; however, such approaches would require dedicated studies, consuming significant time and making replicability more challenging. Furthermore, the analysis uses EPCs calculated with the same tool before and after the retrofit, which makes the results self-comparable and allows for detecting improvements following the renovation. Many recent scientific studies rely on EPCs to evaluate the energy performance of buildings during their operational phase [53–55].

3.5. Energy payback time

The energy amortization/payback is the number of years required to recover the energy consumed to manufacture the components (i.e., the total embodied energy of all renovation materials and construction processes). In this study, the energy payback time is calculated by relating this total embodied energy, quantified through a detailed life-cycle inventory and the Cumulative Energy Demand (CED) method, to the annual operational energy savings achieved after renovation.

Calculating the energy payback allows assessing the advisability of carrying out renovations. It helps optimize financial investment, particularly public funds, while improving the quality of life of residents, who are often affected by energy poverty, and minimizing the environmental impact of these interventions. For this purpose, the energy saved each year has been estimated based on the data of the building's Energy Performance Certifications (EPC) before and after the renovation.

Energy payback time (EPBT) is the amount of time that an energy technology takes to deliver the amount of energy required over its life cycle. In the case of the retrofitting of the building, it will be the years necessary for the energy saved due to the retrofitting to compensate for the primary energy needed to extract the materials, produce, manufacture, transport and install all the components and equipment on site (EE: embodied energy). EPBT is calculated following eq.1.

$$EPBT = \frac{EE}{E_{bef} - E_{aft}} \quad (1)$$

Where E_{bef} and E_{aft} are the yearly primary the energy consumption before and after the retrofitting of the building (kWh/y) and EE the embodied primary energy (kWh).

The calculation of the energy payback time (EPBT) in building renovation projects based on life cycle assessment is subject to significant uncertainties arising from multiple sources. Key uncertainties include the accuracy of embodied energy data for materials, the reliability of operational energy savings estimates, and the influence of user behavior and building operation over time. Variability in input data, such as material properties, energy prices, and future energy mixes, can substantially affect EPBT results, [56–58]. The energy performance gap (the difference between predicted and real energy use) can lead to systematic underestimation of payback periods if not properly accounted for, often resulting in anticipated savings being significantly higher than those realized in practice [57,59]. In this research, a robust collection of data has been carried out on all the materials that have entered the construction site. Although this is not without multiple uncertainties, the amount of primary data entered into the model increases the reliability of the results. However, the data from the use phase has been obtained from the building's energy certificates and could need to be validated with measured data in the future.

Furthermore, the calculation of EPBT in building rehabilitation is subject to several important limitations that must be taken into account. First, future grid decarbonization pathways can significantly alter the carbon intensity of operational energy, meaning that static assumptions about grid emissions may misrepresent long-term environmental benefits or payback periods [60,61]. Second, photovoltaic (PV) system degradation over time reduces energy output, which, could lead to underestimation of the actual payback period [62]. Third, reporting EPBT as a single deterministic value fails to capture the inherent uncertainties in key parameters such as future energy prices, technology performance, and policy changes [63,64]. Finally, the use of static simulation models or fixed input assumptions can result in overly optimistic payback estimates, as real-world performance often diverges from modeled predictions due to factors like user behavior, climate variability, and system maintenance [64]. These limitations highlight the need for transparent reporting and explicit acknowledgment of uncertainties in EPBT calculations for building rehabilitation projects.

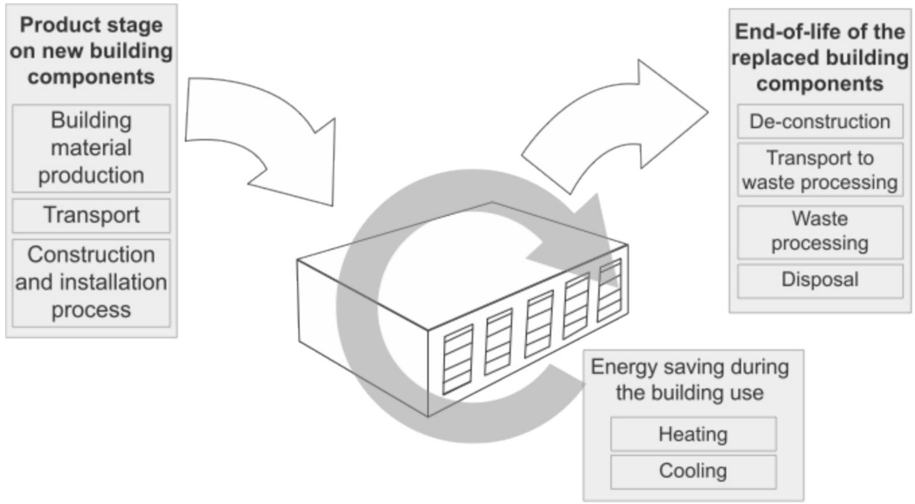

Fig. 5. System boundaries and life-cycle modules included in the assessment.

Despite the inherent uncertainties and limitations in calculating the EPBT for building rehabilitation projects, it remains highly advisable to perform this calculation. EPBT provides a clear and quantifiable metric to assess the effectiveness of renovation measures in reducing energy consumption and environmental impact over the building's life cycle, supporting informed decision-making and prioritization among alternative strategies [65]. Moreover, integrating EPBT into project assessments encourages the adoption of life cycle thinking, which is essential for aligning building renovations with broader sustainability and decarbonization goals [63]. Ultimately, the EPT serves as a valuable benchmark for comparing interventions, guiding policy, and justifying investments, [65,66].

3.6. Extrapolation to city scale

3.6.1. Functional units

Different functional units have been defined for each package of action because the works are extremely different in nature, and using specific units for each of them allows a more granular and accurate representation of the associated environmental impacts (Table 6). The environmental results for the façade package have been calculated with respect to one m^2 of the building's façade (744.70 m^2); the roof package concerning one m^2 of roof (304.94 m^2); the package referring to the windows relating to one m^2 of the surface area of the windows of the building (104.96 m^2); heating and cooling installations packages with respect to one m^2 of living area (635.56 m^2); and finally demolition, masonry and the photovoltaic installation with respect to one m2 of gross floor area (792.00 m^2).

The different functional units have been adapted to match the structure of the Spanish Cadastre [67], so that façade area, roof area, window area, constructed area and living area can be directly retrieved or derived from cadastral records, facilitating the extrapolation of the results to similar buildings in the city of Zaragoza and, more broadly, in other municipalities and countries that provide open cadastral data under the Inspire Directive framework.

3.6.2. Search buildings with similar characteristics in the city

The in-depth study of this building is taken as an archetype for extrapolation to other buildings of similar characteristics in the city. The open data provided by the *Dirección General del Catastro* [67], harmonised under the Inspire Directive [68], allow to characterise the building stock in terms of construction data (year of construction, construction quality, dates of refurbishment, total floor area, height of the building) and function data (uses of the building, number and surface area of the dwellings, etc.). In addition, geospatial information makes it possible to obtain other geometric data (roof surface, façade or party wall surface, etc.) which are used to calculate the functional units defined in Section 2.5.1. However, cadastral information, which is essentially two-dimensional and plan-based, does not provide some relevant variables for environmental assessment at building level, such as the actual construction materials of the envelope, the detailed orientation and solar exposure of each façade, the structural capacity of the roof to support PV systems, or socio-demographic data such as the number of occupants per dwelling. Recent research has begun to complement cadastral records with additional sources such as LiDAR data [69,70], which help to define real building volumes and roof slopes, or detailed photogrammetry, which can support the identification of construction materials [71]; however, these datasets are not yet systematically available and their coverage is often limited, which constrains their applicability for large-scale urban analyses. In this context, relying on cadastral data ensures a high degree of replicability and transferability to other municipalities operating under the Inspire Directive framework, while the reference building is used as a detailed archetype to infer representative values for non-observable parameters and to bridge the gap between the building and city scales).

This study develops a geospatial dataset that integrates construction, function and spatial information into a unified digital model twin. By using programming notebooks and querying our database, we identify buildings with similar characteristics at the city scale. Specifically, the digital model allows us to retrieve buildings in the city of Zaragoza that share comparable features.

1. The characteristics chosen to select the typology that defines similar buildings in the city of Zaragoza are the followings:
2. Buildings built between 1980 and 2007 (included).
3. Dominant residential use and at least 15 % of the building use is residential.
4. Roof surface greater than 50 m^2, and less or equal than 400 m^2.
5. The enveloping surface is between 10 m^2 and 5,000 m^2.
6. Between 6 and 15 dwellings.
7. Residential gross floor area, between 500 m^2 and 2,000 m^2.

The reference building provides representative values for parameters that cannot be obtained from the Cadastre, such as the window-to-wall ratio (WWR), the configuration of the pre-retrofit heating and domestic hot water systems, and the specific energy demand per square metre. The WWR of the reference building (23.06 % ratio of window area to total façade area) is therefore applied to all selected buildings to estimate their window surface from the cadastral façade area, as a necessary modelling assumption in the absence of detailed information on openings at the urban scale. In a similar way, the photovoltaic installation designed for the reference building is used to parameterise the urban extrapolation: the environmental impacts of the PV system correspond to an array of 28 panels with a total area of 55 m^2, calculated with respect to the gross floor area of the building. For each building in the sample, the area of panels is obtained by maintaining the same ratio between PV area and gross floor area as in the archetyp (Eq.2):

Api = Agi x Ap/Ag (2).

where is the gross floor area of building, is the PV area in the reference building and its gross floor area. If the required PV area is smaller than the available roof area (derived from the Cadastre), the building is assumed to install PV and both embodied and avoided impacts are accounted for; otherwise, no PV installation is considered on its roof. This procedure allows a consistent treatment of PV at city scale, while acknowledging that feasibility is assessed only on the basis of roof area and archetype-based ratios, without explicitly modelling structural constraints or detailed solar access.

3.6.3. Energy payback of the sample

A comparison is made between the embodied energy and the operational energy to obtain the payback period for the renovation of these types of buildings. This payback period has been calculated in two ways: first, assuming that none of the buildings have photovoltaic panels installed on the roof; and second, assuming that photovoltaic systems have been installed in those buildings where roof surface area allows for it, as discussed in Section 3.6.2.

4. Results and discussion

4.1. Green warning Potential and embodied energy in reference building

The breakdown of the results in action packages allows the identification of the stages and building installations with greater environmental relevance, providing information on possible improvements. It also shows the environmental loads embodied in the energy systems, providing valuable information that can be compared with the impacts avoided in the use phase due to equipment replacement.

Table 3 and Fig. 5 present airborne emissions of Global Warming Potential (GWP) of reference building, which is the GHG evaluated in terms of $kgCO_2$ equivalent emissions according to ReCiPe 2016 considering a time horizon of 100 years and the involved primary energy evaluated with the Cumulative Energy Demand (CED) method (MJ). The values indicate the environmental impacts due to the manufacture and installation of all components in the reference building. The results include the management of waste generated during construction and commissioning. The GWP emissions amount to 85,497 $kgCO_{2eq}$ and a CED of 1,717,736 MJ.

As shown in Fig. 6, the packages contribute between 24.9 % of GWP emissions in the case of masonry and 0.3 % in the case of demolition. However, when considering embodied energy, the masonry package accounts for more than 50 % of the total energy needed (50.4 %), while the roof package has the lowest embodied energy, contributing only 7.2 % and demolition with 0.3 %.

Table 3
Environmental results of Reference Building. Global Warming Potential (GWP) and Cumulative Energy Demand (CED) of the renovation.

Packages	Embodied energy (MJ)	GWP (kg CO_2 $_{eq}$)
Demolition	5,717	230
Façade	335,324	20,739
Roof	124,090	16,588
Masonry	865,024	21,267
Windows	146,795	9,514
Systems (Total)	240,787	17,159
– Heating, Cooling and DHW. Without PV installation	78,389	8,614
–PV installation	162,397	8,545
TOTAL	1,717,736	85,497

The masonry works dominate the embodied energy mainly due to the plasterboard included in the false ceiling. It accounts for 51.1 % of the energy consumed in the entire masonry package and more than 25 % of the total embodied energy. Paint and varnish account for 14.8 % of the masonry package and more than 7 % of the total.

The complete package involving the retrofit of the façade, roof, and windows accounts for 35.2 % of the total embodied energy, while the replacement of building systems represents 8.5 %. However, by analyzing the materials and processes required for each package, as detailed in Appendix 1, Table A1, more accurate results can be obtained. Fig. 7 provides a summary of this information. For the façade package, the thermal insulation applied to the façade (ETICs) accounts for 95.4 % of the embodied energy and 96.4 % of the GWP of the entire façade package. Less than 5 % of the impact is due to additional works required to renovate the façade. In the case of the roof package, the situation is the opposite: thermal insulation represents only 30.6 % of the total embodied energy and 23 % of the GWP. This is because, in the case study, additional works such as installing a metal walkway to improve building safety were necessary, and this walkway alone accounts for 33.04 % of the EE. For masonry works, the thermal insulation included represents only 1.45 % of the embodied energy of the entire package. The window package is considered to contribute entirely to reducing operational energy. Based on these data, it can be stated that the impact of thermal insulation applied to the envelope represents 21 % of the embodied energy and 36 % of the GWP, while other works required for the retrofit of façade, roof, and masonry account for 56 % of EE and 33 % of GWP. When considering windows, which directly influence the reduction of energy demand, the materials that directly contribute to reducing energy demand (thermal insulation of the envelope and windows) represent 30 % of EE and 47 % of GWP. The remaining impact corresponds to works necessary to ensure safety, quality, and habitability during the retrofit. Breaking down the systems, the highest share of EE and GWP is attributed to the photovoltaic system, representing 50 % and 67 %, respectively.

4.2. Operational energy in reference building

EPC provides data of non-renewable primary energy consumption (NRPEC) and CO_2 emissions during the usage phase, before and after the renovation. Using the pass factors published in [32], the final energy and the total primary energy consumption have been obtained (Table 4).

The typical renovation of the building envelope is easily extrapolated to other similar buildings. However, the convenience to install photovoltaic (PV) panels depends on the orientation and the shadows of each building. To facilitate the extrapolation to other similar buildings in the city, the results differ between renovation done using PV panels and without them. For this purpose, the electric energy obtained from the PV panels has been calculated to obtain the energy consumption in both cases.

In the pre-retrofit state of the building, 81.3 % of the NRPEC and CO_2 emissions during the use phase were attributable heating, while cooling accounted for 2.45 % and domestic hot water (DHW) for 16.25 %. After the retrofit, 63,05 % of the NRPEC and CO_2emissions during the use phase were attributable heating, while cooling accounted for 8,2% and domestic hot water (DHW) for 28,75 %. After the retrofit, the greatest improvement was achieved in heating consumption, with a reduction of 93.3 %, followed by DHW with 84.7 %. Although the improvement in cooling was smaller, it was still significant at 71.4 %. Overall, a global reduction of 91.4 % was achieved. In the scenario without PV installation, the overall improvement would be 85 %.

According to the EPC, the heating energy demand before the retrofit was 223.6 kWh/m2·year, and solely through envelope improvements it was reduced to 44.8 kWh/m2·year, representing a 79.96 % savings

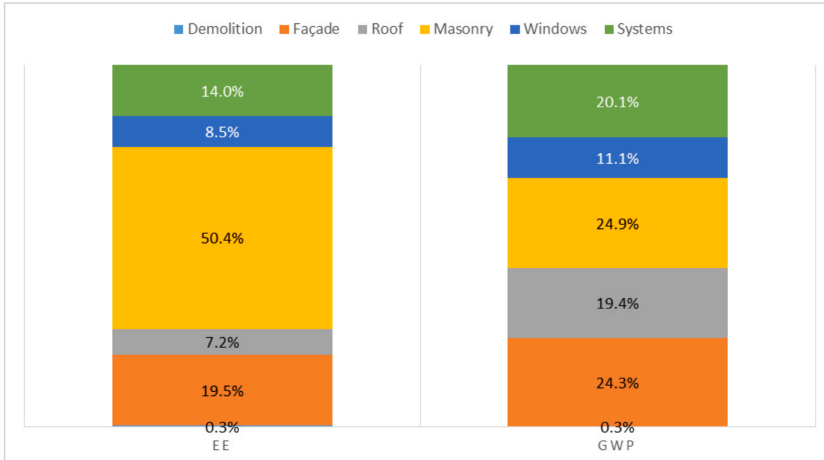

Fig. 6. Percentage of Global Warming Potential (GWP) emissions and Embodied Energy (EE) by packages in Reference building.

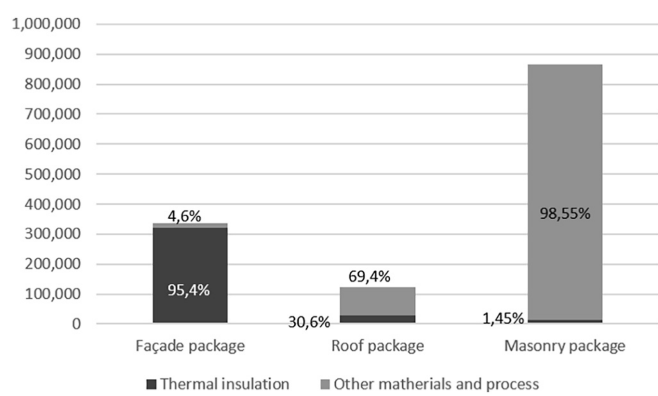

Fig. 7. Percentage of Embodied Energy (EE) by packages in Reference building.

Table 4
Energy performance of the Reference building according to Energy Performance Certification (EPC) and pass factors. NRPEC: non-renewable primary energy consumption.

	Before renovation	After renovation (with FV)	After renovation (without FV)
NRPEC (kWh/m^{2}y)	537.6	46.3	–
- NRPEC heating (kWh/m^{2}y)	437	29,19	
- NRPEC cooling (kWh/m^{2}y)	13,16	3,77	
- NRPEC DHW (kWh/m^{2}y)	87,44	13,36	
CO_2 emissions (kgCO_{2eq}/m^{2}y)	91.1	7.8	–
- CO_2 emissions heating (kgCO_{2eq}/m^{2}y)	74,03	4,94	
- CO_2 emissions cooling (kgCO_{2eq}/m^{2}y)	2,23	0,64	
- CO_2 emissions DHW (kgCO_{2eq}/m^{2}y)	14,81	2,26	
Final energy consumption (kWh/m^{2}y)	275	23.54	41.22
Total primary energy consumption (kWh/m^{2}y)	650.77	55.72	97.61

through passive measures, while the remaining 20.04 % is attributable to the replacement of building systems. For cooling, the building's initial demand was relatively low at 13.5 kWh/m2·year, and it was reduced by 28.9 %, reaching 9.6 kWh/m2·year after the retrofit. It should be noted that the information provided by EPCs only allows for the calculation of final energy consumption and the total primary energy consumption that would occur without photovoltaic systems. It is not possible to obtain this data for NRPEC or emissions during the use phase.

By relating the data from Sections 3.1 and 3.2, we observe that the works directly influencing the reduction of energy demand (thermal insulation and window replacement) account for 21 % of the embodied energy (EE) and 36 % of the GWP, while achieving a 77,1% reduction in heating and cooling energy demand.

4.3. Energy payback in the reference building

The primary energy consumption has been obtained from the EPC before and after the renovation. It is calculated by considering only energy from non-renewable sources (NR). The building's primary energy consumption before the renovation was 537.6 kWh/m2y, which was reduced to 46.3 kWh/m2y after the renovation—representing annual savings of 491.3 kWh/m2.

The embodied energy in the materials and systems and the energy needed to carry out the renovation was 1,717,736 MJ of which 88 % (1,513,647 MJ) was non-renewable. Based on these figures, the energy payback time (considering only non-renewable energy) is just 1.35 years.

Similar calculations can be made to determine the time in years required to amortize the GHG emissions generated during the retrofitting of the building. In the energy performance certificates of the buildings, the data of kgCO_{2eq} emitted annually per m^2 of housing are available, which are 91.1 and 7.8 kgCO_{2eq}/m^{2}y before and after the intervention. The payback in terms of GHG emissions is 1.62 years, a value similar to the EPBT (NR).

The energy payback time of the entire intervention, considering non-renewable energy, is 1.35 years for the reference building and in the case of GHG emissions, the payback is 1.62 years. This payback is slightly higher than that reported by [36], most likely due to the amount of materials required to achieve the Passive House Premium standard, and in the case of [35], because of the more adverse climatic conditions.

These results suggest that deep renovations currently being implemented in multifamily social housing buildings are appropriate from a life-cycle perspective, as their payback periods remain below two years. Improving the thermal envelope and upgrading building systems to reduce energy consumption yields very positive short-term outcomes in energy terms, even when using standard, widely applied materials. Regarding interior refurbishment, better results are obtained in terms of

GHG emissions. In both cases, future research could explore the use of alternative materials aligned with circular economy principles.

4.4. Sensitivity analysis

A sensitivity analysis has been conducted to assess the sensitivity of the outputs to input changes. The sensitivity analysis evaluates the influence of a change in an input parameter on the results of a LCA, while other input parameters are held constant.

Several studies in the building sector support the practice of varying environmental LCA inputs by controlled percentage bands (on the order of ± 10–15 %) to assess the robustness of results and to identify which rehabilitation or design assumptions most strongly influence building scale impact indicators [72,73].

In this study, for each package the most critical inputs (model hotspots) have been identified and variated by ± 15 % while the rest remain constant. Table 5 presents the results obtained.

The ETICs (Façade package) is the material input to which the outputs are more sensitive, 3.47 % for GWP and 2.77 % for EE. For all inputs, except for the laminated gybsum borad (masonry), the GWP results are more sensitive to the inputs variations than the EE results.

The inputs for installation systems (Centralised Heat pump and PV system) have very low influence on the impacts change. Concluding, a variation of 15 % in the amount of sensitive input could cause minimal changes in both impact categories, all above 4 %.

4.5. Extrapolation

4.5.1. Obtaining similar buildings in the city of Zaragoza

Based on the characteristics specified in Section 2.6.2 and according to the Spanish Cadastre, Zaragoza has 731 buildings comparable to the case study, which define the typology analyzed in this article. A visual inspection confirmed that these buildings share similar features and are widely distributed across the city. This enables the extrapolation of the building archetype at the city scale, which we refer to as the sample. The reference building serves to define the archetype. Fig. 8 illustrates the location of these buildings within Zaragoza, showing that they are present throughout the entire city. Given that Zaragoza has a total of 25,417 residential buildings, this archetype accounts for 2.57 % of the residential building stock.

The retrofit analyzed in this study is a conventional intervention aimed at improving the thermal envelope and building systems to reduce operational energy consumption. This type of intervention has been widely examined in previous research 252932,33. Therefore, the results obtained are highly relevant for generalizing to other retrofits of multi-family buildings, which represent 68 % of Spain's building stock [74]. Furthermore, a specific typology of multi-family building has been defined, meeting the characteristics outlined in Section 2.5.2 regarding construction year, predominant use, roof surface, envelope surface, number of dwellings, and residential gross floor area. Consequently, the findings can be extrapolated to buildings of similar typology, which account for 25,417 residential buildings in the city (2.57 %).

Table 5
Results for the Sensitivity analysis (%) with ± 15 % input variation.

Package	Critical Input	Indicator	
		GWP	EE
Demolition	Electricity	±0,01 %	±0,01 %
Facade	ETICs	±3,47 %	±2,77 %
Roof	Thermal isolation material	±1,63 %	±0,35 %
Masonry	False ceiling plasterboard	±0,45 %	±3,86 %
Installations	Steel (Centralised HP)	±0.06 %	±0.03 %
Installations	Silicon casted (PV system)	±0.76 %	±0.74 %

Table 6
Functional units (FU) selected of Reference Building to extrapolate to the sample to the city scale.

Packages	FU	GWP (tCO_{2eq}/FU)	Embodied energy (MJ)
Demolition	m^2 of constructed area	0.3	7.2
Facade	m^2 of facade	27.8	450.3
Roof	m^2 of roof area	54.4	406.9
Masonry	m^2 of constructed area	26.9	1,092.2
Windows	m^2 of windows	90.6	1,398.5
Installations: HC and DHW	m^2 of living area	13.6	123.3
Installations: PV	m^2 of constructed area	10.79	205.05

4.5.2. Extrapolation of environmental impacts. Implications at city scale

The functional units calculated for the reference building, as shown in Table 6, have been extrapolated to the sample to the city scale. For this, the environmental impacts of each package are used.

In performing the extrapolation, we assume that all the buildings in the sample have the same heating and domestic hot water (DHW) systems as the sample building (radiators and electric water heater). We obtain the data by differentiating between installing photovoltaic panels and not installing them.

The average operational behavior of the 731 buildings is obtained using the methodology published in [34]. The consumption of non-renewable primary energy is 234.29 kWh/m^2y (usable m^2) and the CO_2 emissions are 48.92 $kgCO_{2eq}/m^2$.

4.5.3. Comparison embodied energy vs operational energy. Savings

With functional units and building characteristics, we obtain the embedded energy and CO_2 emissions due to the renovation of the defined sample.

The gross floor area of these 731 buildings is 572,311 m^2. Considering the relation between heating leaving space and total constructed area is 20,2%, as in the reference study, the heating leaving space of the archetype buildings is 456,704.2 m^2.

Table 7 presents the results of embodied energy (EE), environmental impacts, and operational energy for the 731 buildings at the city scale because of the renovation. In the case of GWP, two scenarios are distinguished: with and without photovoltaic (PV) systems. The EE and GWP has been calculated in two ways: first, assuming that none of the buildings have photovoltaic panels installed on the roof; and second, assuming that photovoltaic systems have been installed in those buildings where roof surface area allows for it, as discussed in Section 3.6.2.

Fig. 9 illustrates the percentage contribution of each renovation package to the total impact. For embodied energy, more than half (57.23 %) is attributed to masonry. Windows, façade, and PV systems each account for approximately 10 %, while installations and roofing contribute around 5–6 %. The lowest share of embodied energy is associated with demolition (0.38 %).

Regarding GWP, the package with the greatest impact is again masonry, although it represents only about one-third of the total (30.02 %), followed by roofing at 18.64 %. Windows, façade, PV, and installations each contribute approximately 12–13 %, and—similarly to embodied energy—demolition has the lowest impact, at just 0.33 %.

4.5.4. Energy payback at city scale

Once the environmental impacts and results for the building archetype at the city scale were obtained, the energy payback period of the renovation was calculated. The total primary energy consumption of the building stock before renovation was 297,209,392.23 kWh/y, which was reduced to 25,447,556.80 kWh/y after renovation with PV. This represents an annual energy saving of 271,761,821.12 kWh/y. The embodied energy associated with renovation amounts to 1,092,177,380

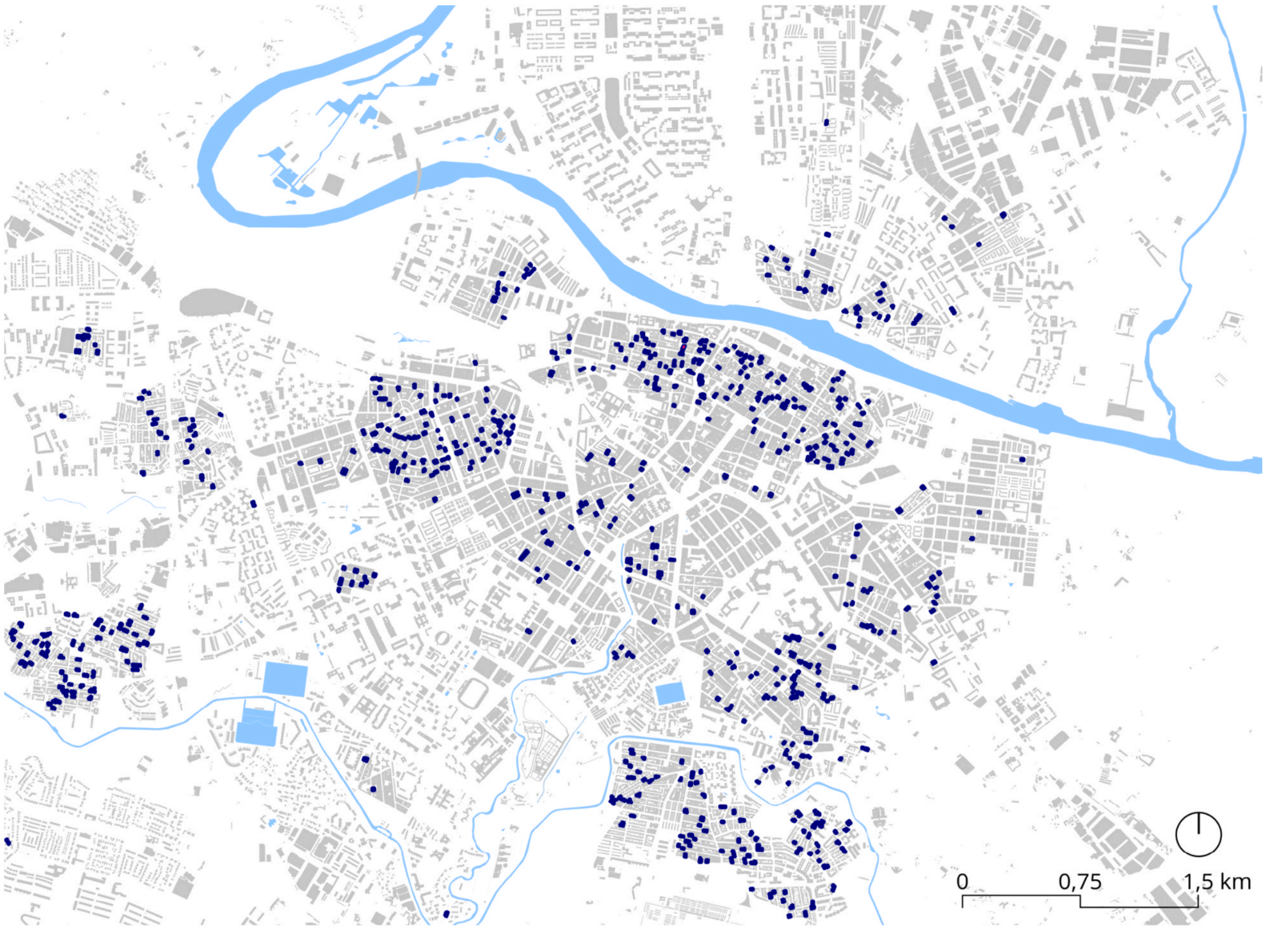

Fig. 8. Sample of 731 residential buildings with similar characteristics of our building reference in the city of Zaragoza.

Table 7
Energy performance of building archetype at the city scale using extrapolation.

Total EE, EO and GWP (sample at city scale) Embedded energy (EE)(MJ)	
Total EE (with FV panels)	1,092,177,380
Total EE without FV panels	974,825,009
Global warning Potential (GWP) (tCO_{2eq})	
Total GWP (with FV panels)	51,289.24
Total GWP without FV panels	45,114.0
EO: Total primary energy consumption (kWh/y)	
Before renovation r	297,209,392.23
After renovation (without PV)	44,578,896.96
After renovation (with PV)	25,447,558.02
Savings by year (with PV):	271,761,834.21
CO_2 emissions during use ($kgCO_{2eq}/m^2y$)	
Before renovation	91,1 $kgCO_{2eq}/m^2y$ x 456,704.2 m^2 = 41,605,752.62 $kgCO_{2eq}/y$
After renovation	7.8 $kgCO_2/m^2y$ x 456,704.2 m^2 = 3,562,291.2 $kgCO_{2eq}/y$
Savings by year:	38,043,461.42 $kgCO_{2eq}/y$

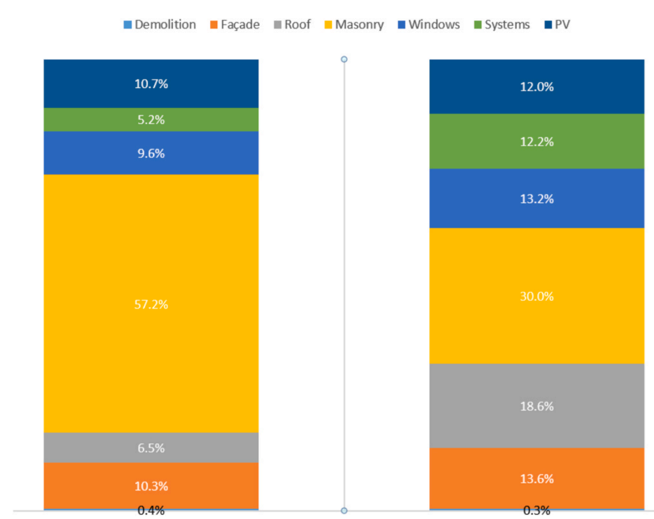

Fig. 9. Embodied Energy and GWP of building archetype at the city scale by packages.

MJ. Therefore, the energy payback period for the renovation of the 731 buildings at the city level is 1.12 years.

The CO_2 emissions of the building stock before renovation were 41,605,752.62 kCO_2eq/y, which was reduced to 3,562,291.2 kCO_{2eq}/y after renovation. This represents an annual energy saving of 38,043,461.42kCO_{2eq}/y. The CO_2 associated with the renovation amounts to 51,289.24 tCO_{2eq} with PV. Therefore, the GWP/GHG payback period for the renovation of the 731 buildings at the city level is 1.35 years.

Similarly to the calculation of the payback period for the individual building, the energy payback at the urban scale is also less than two years. The results vary slightly because this extrapolation considers buildings of the same typology according to the criteria set out in Section 2.5.2, using the functional units described in Table 6. In this way, although the buildings share the same typology, the façade area, roof area, constructed area, or living area varies from one to another. The extrapolation to the urban scale in this study is valuable because it does not assume that all buildings are exactly the same; rather, it accounts for their specific characteristics and dimensions to obtain more accurate city-scale values.

5. Conclusion

This study presents a comprehensive life-cycle assessment of a real, executed energy renovation of a multifamily social housing building in Spain and extends the analysis to the urban scale. By focusing on an actual rehabilitation project rather than on hypothetical or archetype-based scenarios, the research provides robust empirical evidence on the environmental performance of typical renovation practices currently implemented in Southern Europe.

One of the main contributions of this work is the detailed analysis of a real renovation process, based on a complete inventory of materials and construction activities. This approach captures the full complexity of renovation works, including not only the thermal insulation solely. The present study considers energy-efficiency measures but also the complementary interventions required to ensure safety, habitability, and functional upgrading. This level of detail is rarely achieved in the existing literature, which often relies on simplified assumptions or idealized scenarios.

A second key contribution is the disaggregation of environmental impacts by intervention packages. This breakdown provides valuable insights into the relative importance of different renovation actions and enables the identification of priority areas for environmental optimization. The results show that the masonry package is the largest contributor to embodied energy (50.4 %) and a significant source of Global Warming Potential (24.9 %). This impact is mainly driven by the plasterboard used in the false ceiling, which alone accounts for 51.1 % of the embodied energy of the masonry package and approximately 25 % of the total embodied energy of the renovation. These findings highlight the substantial influence of interior refurbishment works, which are often overlooked in energy-focused retrofit assessments.

In contrast, the packages aimed at improving the thermal envelope—façade and roof insulation—together with window replacement account for 35.2 % of the total embodied energy, while the replacement of building systems contributes an additional 8.5 %. The remaining share of impacts corresponds to works that, although not directly related to energy efficiency, are necessary to upgrade the building to current standards of safety, health, and habitability. When considering exclusively the measures that directly reduce energy demand—namely thermal insulation of the envelope and window replacement—these represent approximately 30 % of the total embodied energy and 47 % of the Global Warming Potential of the renovation.

Despite their relatively moderate embodied impacts, these energy-related measures deliver substantial operational benefits. Works directly influencing the reduction of energy demand (thermal insulation and window replacement) account for only 21 % of the embodied energy and 36 % of the GWP, while achieving a 77.1 % reduction in heating and cooling energy demand. At the building level, the overall renovation leads to a 91.4 % reduction in operational energy consumption, demonstrating the effectiveness of combining passive envelope improvements with system upgrades. Regarding building systems, the photovoltaic installation is identified as the component with the highest embodied energy and GWP within this package, underscoring the importance of carefully balancing renewable energy deployment with its life-cycle impacts.

Another major contribution of this study is the calculation of energy and emissions payback times (EPBT), both at the building and urban scales. By integrating embodied impacts with operational energy savings, the EPBT provides a clear and robust indicator for decision-making. The results show that the non-renewable energy payback time is 1.35 years at the building scale and decreases to 1.12 years when extrapolated to the city scale. Similarly, the greenhouse gas payback time is 1.62 years at the building scale and 1.35 years at the urban scale. These very short payback periods confirm that conventional deep renovations of multifamily buildings are environmentally justified from a life-cycle perspective, even when standard materials and technologies are used.

Finally, the extrapolation of the results to 731 similar buildings in the city of Zaragoza demonstrates the relevance of scaling up building-level analyses to inform urban decarbonization strategies. The proposed methodology—based on functional units compatible with cadastral data and a digital selection of comparable buildings—offers a transferable framework for other cities and regions. Overall, the findings reinforce the role of large-scale renovation of the existing building stock as a key lever for achieving climate neutrality, while also pointing to the need for future research on circular materials and integrated assessments that combine environmental performance with social and functional outcomes, particularly in the context of social housing.

These interventions, which already achieve optimal energy performance, should also be leveraged to enhance the quality of life of residents by adopting new approaches to adaptability and the reorganization of interior spaces, thereby pursuing optimal functional renewal, especially in the case of social housing. While this study does not directly measure residents' quality of life, the analysed renovation measures are implemented in a social housing context where reductions in operational energy demand and energy costs are strongly associated with improved affordability, thermal comfort stability and reduced exposure to energy poverty, all of which are widely recognised contributors to living conditions.

Habitability is a complex concept that lies between the qualitative and the quantitative. Accordingly, this article focuses on energy- and environment-related quantitative indicators, which can be understood as a necessary baseline to support broader sustainability assessments. As a future line of research, the incorporation of other quantitative (air quality, acoustics, accessibility) and qualitative (comfort, well-being, satisfaction) dimensions is proposed.

5.1. *Limitations and future research*

This study focuses on the environmental and energy-related performance of a real building renovation, assessed through life-cycle assessment and energy payback indicators. As such, it does not explicitly address the social and economic consequences of the renovation measures, which are particularly relevant in the context of social housing. As a limitation, aspects such as investment costs, affordability, impacts on rents or household expenses, and changes in occupants' comfort, well-being, and energy poverty have not been quantitatively assessed. Future research will therefore extend this work by incorporating a socio-economic analysis of renovation strategies, including life-cycle costs and social indicators, in order to provide a more comprehensive evaluation of the consequences of building renovation measures and to better support decision-making by public administrations.

Despite these positive results, the study presents several methodological limitations that should be acknowledged. First, the urban-scale analysis relies on cadastral data that are essentially two-dimensional, which do not provide key variables such as construction materials, detailed façade orientation and solar access, roof structural capacity or socio-demographic information; as a result, several parameters (e.g. window-to-wall ratio, pre-retrofit systems and PV configuration) must be inferred from a single archetype building and applied to the whole sample. Second, the feasibility of photovoltaic installations at city scale is assessed only on the basis of available roof area and archetype-based ratios, without explicitly modelling structural constraints or detailed solar access, which may lead to an under- or overestimation of the real

PV potential. Third, the energy payback time is calculated as a deterministic metric, without explicitly propagating the uncertainties associated with embodied data, operational performance, future grid decarbonisation or user behaviour.

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CRediT authorship contribution statement

Marta Monzón-Chavarrías: Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jorge Sierra-Pérez:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Sergio García-Pérez:** Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Silvia Guillén-Lambea:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation.

Declaration of competing interest

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

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Data availability

No data was used for the research described in the article.

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Glossary

CED: Cumulative Energy Demand
CO_2eq: Carbon dioxide equivalent

DHW: Domestic Hot Water
EE: Embodied energy
EPC: Energy Performance Certifications
EPBD: Energy Performance Building Directive
EPBT: Energy payback time
ETICS: External Thermal Insulation System
GHG: Greenhouse gas
GWP: Global Warming Potential
LCA: Life Cycle Assessment
NR: Non-renewable sources
NRPEC: Non-renewable primary energy consumption
PV: Photovoltaic
SMZV: Municipal Society Zaragoza Vivienda