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Volumetric Add-On Retrofit Strategy with Multi-Benefit Approach toward Nearly Zero Energy Buildings Target

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Abstract: Around 35% of the total housing stock of the European Union is more than half a century old. The shortage of funds for new construction, combined with rapidly changing economic, social, and technological factors, has led to significant obsolescence. Additionally, this situation makes it difficult to satisfy the owners' energy, functional, and socio-economic needs. This research aims to develop an innovative retrofit approach that brings multiple benefits to assessing retrofit designs for social housing, with specific emphasis on volumetric envelope additions toward the nearly zero energy buildings target (nZEBs). To achieve the purpose of this study, the research through design methodology was chosen. The research methodology consisted of two phases: design and simulation. First, the design phase focused on re-designing and retrofitting social housing to address various aspects of the functional requirements in developing rational solutions. Second, the simulation phase focused on computational modeling and analysis of energy performance to assess the nZEBs target. The results show that the use of high-efficiency Heating, Ventilation, and Air Conditioning (HVAC) systems and improved material envelopes cut electricity consumption use by 43% and primary energy use by 40% compared to the base case. Photovoltaics (PV) production can meet the total electricity demand for six months. This approach can encourage residents and tenants to actively participate in the retrofit process and increase the real estate value of buildings through improvements in energy efficiency and housing function.

Keywords: retrofit; nearly zero energy buildings (nZEBs); energy efficiency; building envelope; housing function; social housing

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Citation: Khazaee, M.; Hosseinzadeh, S.; Khorrami, S.; Astiaso Garcia, D.; Ricci, M. Volumetric Add-On Retrofit Strategy with Multi-Benefit Approach toward Nearly Zero Energy Buildings Target. *Sustainability* **2024**, *16*, 5822. https://doi.org/10.3390/ su16135822

Academic Editor: Ali Bahadori-Jahromi

Received: 16 May 2024
Revised: 30 June 2024
Accepted: 3 July 2024
Published: 8 July 2024

1. Introduction

According to the European Commission (2016), about 35% of the housing stock in the European Union (EU) is more than 50 years old [1]. Empirical research has revealed that older dwelling buildings, particularly those over 50 years old, demonstrate lower energy efficiency than newer buildings [2,3]. Also, the age of housing buildings plays an important role in determining their value dynamics, with older vintages potentially diverging from replacement prices due to factors such as physical deterioration and land values [4]. Understanding these processes is necessary for addressing energy efficiency issues in aging residential structures.

Energy efficiency barriers have a significant impact on social housing, particularly those built in the EU between the 1960s and 1980s for the working class. These residential blocks frequently face material durability issues and technical deficiencies, resulting in low energy efficiency and environmental consequences. The challenges have an impact on the building's operational expenses as well as the economic and health conditions of its occupants. Especially impacted are low-income and socially disadvantaged tenants, who face high exposure to energy poverty and limited access to fair energy policies [5].

Furthermore, due to the high carbon costs of new construction, retrofitting existing buildings is considered a more environmentally friendly approach. According to studies, retrofitting the existing buildings can significantly reduce energy demand by up to 81.5% and offer 30% cost savings compared to new construction [6,7]. Additionally, the retrofitting of existing buildings can result in significant reductions in energy usage and carbon emissions and meet sustainability goals [8].

Numerous research studies have examined retrofitting existing buildings using various approaches, focusing on motivators, effects, and surrounding circumstances. For example, Yoshino [9] identified five key elements that influence actual energy use in buildings: requirements for Indoor Environmental Quality (IEQ), occupant behavior, energy systems, temperature, and the building envelope. These factors enable reliable quantitative assessments of energy-saving measures, policies, and techniques. In a different study [10], a novel methodology was used to determine the optimal energy retrofit strategy after a year of monitoring. After identifying multiple schemes for energy-efficient building retrofitting, this study used simulation, comparison, and analysis to determine the best scheme. In certain investigations, the impact of contextual conditions was considered. Fotopoulou [11] assessed the energy performance of façade extensions and their retrofit potential in various climatic situations, showing that façade additions are an effective way to achieve zero energy in existing buildings across different climates. In an another study [12], energy retrofits for balconies as exterior components were investigated. The goal was to convert balconies into ventilated sunspaces during the winter to utilize solar gains and reduce heat loss.

Other research has focused on multiple aspects influencing retrofit strategies in a more comprehensive setting. As shown in [13], which examined the impact of architectural design on energy performance in retrofit solutions, it is essential to connect a building's energy retrofit with its fundamental architectural principles. Retrofit solutions suggested by [14] applied both active and passive design methodologies in the retrofit of residential buildings for elderly populations, based on user needs and energy benefits. Moreover, retrofitting's energy and financial components are equally crucial. Assimakopoulos [15] emphasized that volumetric add-on options can maximize comfort while minimizing financial impact. Additionally, Ferrante [16] offered methods for assessing the techno-economic viability of simulating the energy renewal process in residential complexes.

Finally, some urban research has focused on the regeneration of vulnerable neighborhoods by replacing the envelope of existing social housing with structural–architectural systems to provide new technological and spatial features [1].

This paper presents a novel viewpoint on retrofitting social housing. It creatively uses a multi-benefit integrated approach to assess retrofit potential, encompassing features of internal functionality and user preferences beyond energy efficiency and the nearly zero energy concept. This study is noteworthy for its innovative approach to retrofitting, focusing on adding extra volume to improve both volumetric and spatial restrictions. Furthermore, this study suggests a future-focused design solution framework for building owners and stakeholders, concentrating on the financial viability of future retrofits. Finally, this study employs research through design methodology, which holistically integrates energy efficiency improvements with enhancements in functionality and user preferences, providing a comprehensive framework for the retrofit of social housing.

This study aims to develop an innovative, multi-benefit approach to analyzing retrofit designs for social housing, focusing on volumetric envelope additions to achieve nearly zero energy building targets and increase real estate value. The following objectives will help achieve this aim:

1. Develop design concepts and solutions for unit typologies to improve functionality and user preferences.
2. Analyze the feasibility of integrating volumetric solutions with existing building unit typologies.

3. Evaluate the energy efficiency improvements achievable through volumetric envelope additions to achieve nZEBs target.

This paper is structured as follows: Section 2 presents a literature review, covering nZEBs, context, and the multi-benefit retrofit approach. Sections 3 and 4 describe the case study and the materials and methods, respectively. Following those, Section 5 focuses on the analysis and results of the design and simulation phases, as well as on evaluating the retrofit model in terms of the nZEBs target. Subsequently, the Section 6 compares the results with the existing literature and explores the broader implications.

This work was developed based on the Reinventing Cities C40 student competition, which focused on social housing challenges in the Ciutat Meridiana of Barcelona.

2. Literature Review

2.1. Nearly Zero Energy Buildings (nZEBs)

The United Nations Framework Convention on Climate Change (UNFCCC) has set two targets for carbon reduction in buildings. By 2030, all new or renovated buildings must achieve net zero targets in operations, along with a minimum 40% reduction in embodied carbon. By 2050, all buildings must attain the net zero carbon target throughout their life cycle [17]. Recent progress in sustainable cities has popularized the concept of nearly zero energy buildings (nZEBs), zero energy buildings (ZEBs), net zero energy buildings (NZEBs), and net zero carbon buildings (NZCBs) [18].

One of the most relevant targets for reaching energy efficiency is the nearly zero energy buildings (nZEBs), which are now mandatory for new and renovated buildings in the EU. This requirement is prescribed by the Energy Performance of Buildings Directive (EPBD) 2010/31/EU in Art. 9: "Member States will ensure that: (a) by 31 December 2020, all new buildings are nearly zero-energy buildings; and (b) after 31 December 2018, new buildings were occupied and owned by public authorities are nearly zero energy buildings". The directive also introduces a numerical indicator of primary energy use, expressed in kWh/m^2 per year [19].

The primary energy factors used to determine primary energy use may be based on national or regional yearly average values and may consider relevant European standards [20]. Changes in retrofitting, renovation, and refurbishment can improve energy performance or decrease the energy demand. According to the EPBD and the European Economic Community (EEC), the most effective means to attain energy efficiency is through the integration of on-site renewable energy sources [21].

2.2. Context

Barcelona's ambitious goals of reducing emissions by 45% and achieving carbon neutrality by 2050 indicate a transition toward sustainable heating and ventilation practices. The city has experienced eight heat waves in the past three decades, with the most affected regions concentrated around Ciutat Meridiana and Nou Barris. Increased temperatures present health risks beyond just heat waves, leading to impeded healing at night. Vulnerability assessments show that neighborhoods near Ciutat Meridiana and Nou Barris are among the worst hit due to factors such as age, building energy usage, vegetation, and socio-economic indicators [22].

The Ciutat Meridiana neighborhood is located in the Nou Barris district of Barcelona, Spain. The construction of social housing in Ciutat Meridiana started around the early 1970s and continued until the late 1990s (Figure 1). The region needed more housing for its increasing population and immigrants who came after World War II, which led to high urbanization rates in Catalonia and Spain. Consequently, projects were developed to create mass housing areas like Ciutat Meridiana. The neighborhood has historically been characterized by long-term poverty and socio-economic problems, such as low-income levels for its residents. The area has faced a housing crisis and has seen a high number of housing evictions [23,24].

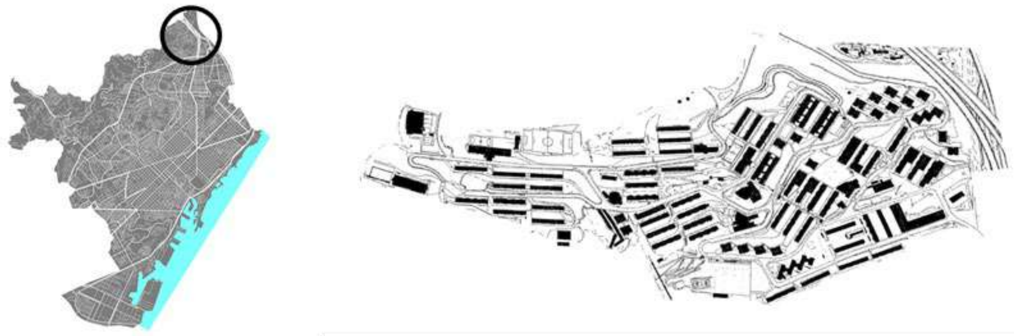


Figure 1. Geographical location of Ciutat Meridia in Barcelona (**left**), Ciutat Meridia neighborhood (**right**).

The challenges of Ciutat Meridiana can be categorized into three aspects: Energy challenges, demographic challenges, and socio-economic challenges.

- Energy Challenges

The social housing energy problem in Ciutat Meridiana revolves around poor energy efficiency, which has resulted in rapidly increasing utility bills, leading to eventual energy shortages. This situation must be remedied, as it affects the cost of living and the lifestyle of the residents. The findings from studies [25,26] show that 87% of households struggle with utility bills. These issues deepen social inequalities and socio-economic challenges.

- Demographics Challenges

Demographics in Ciutat Meridiana present contrasting challenges. On one side, elderly-dominated neighborhoods foster close-knit relationships among native residents, but they are vulnerable due to their heavy reliance on non-contributory pensions. Additionally, socio-spatial issues are more complex due to accessibility challenges. On the other hand, Ciutat Meridiana has youthful demographics, but unemployment rates and low socio-economic conditions make them more vulnerable [27].

- Socio-economic Challenges

Ciutat Meridiana's economic growth has faced several problems, significantly influenced by the 2008 real estate crisis. This crisis left many people unemployed, and many houses empty, thereby worsening the housing and economic issues. The history of Ciutat Meridiana reflects the city's urban complexity. It was planned in the 1960s on unsuitable land without any infrastructure and isolated from the rest of Barcelona, so it encountered different challenges compared to other areas. In the 1980s, people began migrating elsewhere for a better life. Misleading mortgage deals targeting immigrants became prevalent during the 2008 crisis, drawing immigrants seeking cheap credit to purchase homes. Despite being labeled as an eviction capital, Ciutat Meridiana has remained resilient due to its tight community bonds [27].

Real estate owners can often sell their homes for more than the original purchase price. They benefit from any appreciation in the value of products or assets (such as stock market values) without suffering. Thus, when white households began to move into wealthier areas, the once-booming neighborhoods with relatively low populations started to experience a longer-term negative cycle. Richer families then left these damaged communities for more affluent ones, where, at a higher cost, they could still enjoy these social advantages. A neighborhood like Ciutat Meridiana underwent a complete transformation within five years. In 2001, only 5% of its inhabitants were foreign settlers. By 2006, this number had increased to 40% foreigners [28].

2.3. Multi-Benefit Approach of Retrofit

Since meeting the needs of stakeholders is of utmost importance, a multi-benefit approach was chosen for this research. This approach is a strategy aimed at achieving multiple positive outcomes across various domains or sectors through a single initiative or intervention. It investigates whether different elements within a system are interconnected, thereby enabling optimization through the identification and linking of processes [29].

Several studies have emphasized the significance of a multi-benefit approach to energy-efficient techniques for lowering costs, minimizing environmental consequences, and improving public health. Faberi [30] presented the referee tool to assist decision-makers and stakeholders with energy efficiency planning, taking a multi-benefit approach. In another study, Thema [31] discovered that more than half of the energy cost savings are related to the multiple impacts of energy efficiency efforts. These impacts include reduced air pollution, decreased energy poverty, and positive economic effects. Furthermore, Harris-Lovett [32] evaluated mixed-method approaches to promote strategic planning for environmental management by recognizing stakeholder agreements and achieving multiple benefits. This strategy ensures that different aspects within a system are interconnected, enabling optimization through the identification and connection of processes, and ultimately addressing the diverse needs of stakeholders.

On the other hand, many practical experiences have tried to find a design strategy for the diverse challenges of social housing. Alejandro Aravena emphasizes progressive development to solve a variety of social and economic issues by using a creative approach to social housing, which is represented by projects such as Villa Verde. By enabling the initial building of necessary infrastructure, this approach allows residents and homeowners to gradually extend their homes as their financial situation improves. Comparatively, participatory design has been used in Elemental's projects in Chile and Mexico to address housing affordability and community integration [33].

Regarding the context analysis and aim of research, the requirements of this approach can be categorized into two types, which can be seen in Figure 2.

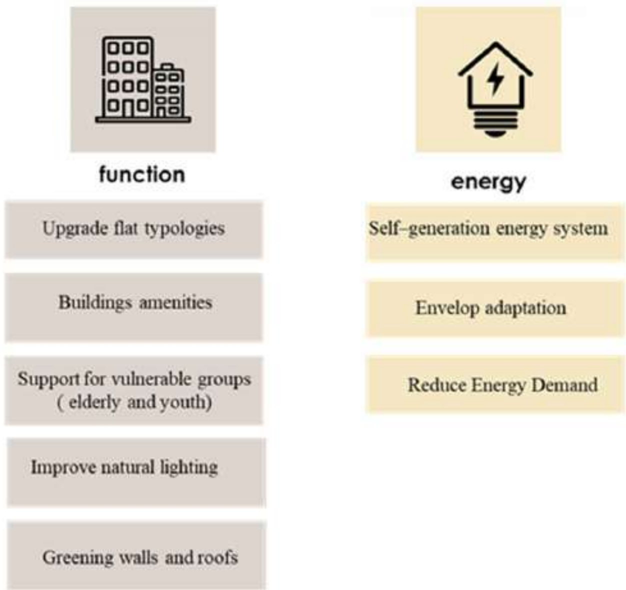


Figure 2. Multi-benefit approach of retrofit (author).

- Energy Requirements

To meet energy demands, it is necessary to integrate or replace existing systems with advanced prefabricated and plug-and-play high-performance envelope and HVAC systems. Additionally, different kinds of "envelopes" can be added, such as additional volumes with extra space, sunspaces, more terraces, or galleries that create a transitional zone between the existing envelope of the building and the external climatic conditions.

Incorporating additional structures at the rear of buildings and employing natural-based solutions, like green roofs and walls, have implications for both building energy efficiency and microclimatic regulation.

- Functional Requirements

Addressing user needs, particularly in façade add-ons, is crucial. Potential add-ons aim to satisfy end-user needs and increase attractiveness, even among sectors typically reluctant to change, such as elderly inhabitants. Examples include balconies and loggias for small individual gardens. Moreover, expanding units in multiple directions can accommodate demographic changes in family structure and address financial challenges or potential evictions.

3. Case Study Description

The case study is in Plaza Roja, the neighborhood center where the first urban regeneration programs were implemented in 1994. Social housing apartments face numerous challenges [24]. This block was chosen due to its ample surrounding space for expansion retrofitting, and it also represents the neighborhood's social housing, changes in family structure, and financial challenges or potential evictions (see Figure 3).

Figure 3. Geographical location of case study in Ciutat Meridia, Barcelona.

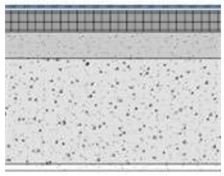
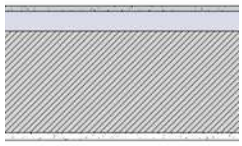
The building comprises six floors, with commercial stores on the ground floor and a total of 40 residential units spread across the upper five floors. Each residential unit covers an area of 80 square meters. It features four distinct façades: the main façade faces Roja Square in the south, while the side façades are oriented to the north, and the remaining façades overlook the east–west side(see Figure 3).

The building's load-bearing walls are constructed using 150-mm-thick hollow bricks, a prevalent construction method in Spain from the 1950s to the 1970s [34]. The floors consist of reinforced concrete, high-alumina cement, and precast concrete infill blocks. The façade is made of 150-mm-thick hollow concrete blocks without insulation or air gaps. Further details about the building are summarized in Table 1.

Table 1. Building envelope materials (author).

Description		Elements
	Concrete, sand/cement screed—20 mm Hollow concrete block—150 mm Gypsum wall board—150 mm	Exterior walls
	Plaster—12.5 mm Hollow concrete block—100 mm Plaster—12.5 mm	Interior walls

Table 1. *Cont.*

Description	Elements
Clear single glass—3 mm	Glazing material
 Brick, engineering, soldier course—5 mm ARDEX_AR_300—5 mm Rigid insulation—40 mm Concrete, sand/cement screed—50 mm Concrete, cast in Situ—200 mm Plaster—12.5 mm	Floor roof
 Concrete, sand/cement screed—10 mm ARDEX_AR_300—40 mm Concrete masonry, floor block—100 mm Gypsum wall board—15 mm	Floor

4. Materials and Methods

To achieve the goal of this research, which was to adopt a multi-benefit approach in the retrofit of social housing, it was critical to use a research methodology that can cover both functional and energy aspects. Because these aspects require various procedures, the research through design methodology was selected. This approach provides a holistic framework for investigating novel solutions that enhance the energy efficiency of social housing while also improving its functionality and user preferences.

Recent studies have focused on integrating design techniques and empirical research to address complex challenges in retrofit solutions. Prochner [35] investigated the use of research through design in developing sustainable retrofit solutions for existing buildings, highlighting the importance of design processes and stakeholder engagement for successful outcomes. Furthermore, Sdei [36] emphasized the role of computational modeling and analysis in optimizing energy performance and functional requirements by studying the application of simulation-driven design methodologies in retrofit strategies. These studies have enhanced the research through design methodology by demonstrating its applicability in retrofit strategies, offering valuable insights into combining design innovation and empirical research to tackle sustainability challenges in the built environment.

Regarding the type of research methodology, two phases were adopted, including the design phase and the simulation phase (see Figure 4).

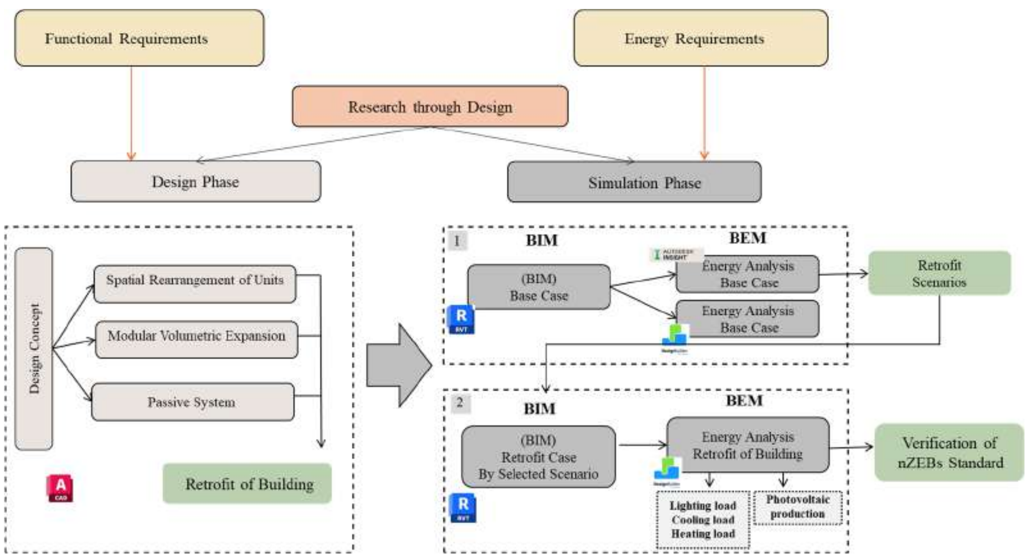


Figure 4. Flowchart of research methodology (author).

- Design Phase

The focus of the design phase was to develop a novel concept specifically adapted for the retrofit of the research case study. This design concept must address a wide range of architectural solutions while also providing multiple advantages to the occupants. The following three considerations were taken into account during the development of the design concept:

1. Functional Consideration: This involves altering the spatial arrangement and ensuring functional flexibility to meet the changing needs of the residents.
2. Structural Consideration: This includes structural expansion through volumetric additions to support necessary alterations and enhancements.
3. Environmental Considerations: This involves implementing passive design solutions to increase energy efficiency and create a sustainable living environment.

- Simulation Phase

To support the design phase, computational modeling and simulation tools were employed. The simulation phase focused on a broad range of research to measure and manage the nZEBs objective. Two energy analysis software programs, Autodesk INSIGHT and Design Builder v6, were selected to effectively manage and coordinate Building Information Modeling (BIM) and Building Energy Modeling (BEM). Autodesk INSIGHT calculated the total energy consumption for retrofit scenarios, while Design Builder v6 validated the Autodesk INSIGHT results and simulates energy consumption and production to meet nZEBs target. The simulation process includes two steps:

1. Initially, an energy analysis was performed in Revit 2024 , and the analysis model was transferred to Autodesk INSIGHT for energy calculation. Various retrofit options, including building materials, HVAC systems, and glazing, shading, and photovoltaic systems, were investigated, and the most suitable option was chosen. Next, the BIM of the retrofit case was revised.
2. The next step involved creating a simulation scenario in Design Builder v6 by importing a gbXML file from Revit 2024. The retrofit case was simulated based on various loads such as heating, cooling, and lighting, as well as energy production, which was achievable by installing a photovoltaic system on the roof. Finally, the requirements to meet nZEBs standards were checked.

5. Analysis and Results of Case Study

5.1. Design Phase

By addressing various challenges within the residential sector, such as energy poverty, high rates of home evictions, demographic vulnerabilities, and the growing proportion of elderly and youth residents, the concept of Green Growing Units was introduced. This concept aims to resolve these financial and social challenges.

Many retrofit case studies have shown that economic feasibility and high investment costs are the two primary economic barriers. Furthermore, many owners perceive the economic feasibility of retrofits as problematic or, at the very least, doubtful [37]. As a result, finding a solution to this conceptual challenge is critical. Alejandro Aravena, the recipient of the 2016 Pritzker Award, introduced an innovative approach to address multifaceted socio-economic challenges in social housing. He advocated for an incremental strategy where governments initiate the construction of “half a good house”, allowing residents to gradually enhance their dwellings as their financial situations improve [33].

Inspired by this idea, the project focuses on the concept termed Green Growing Units (see Figure 5). This concept is pivotal due to the predominantly low-income demographics of the area, underscoring the significance of enabling household expansion within social housing developments. Consequently, additional fixed structures can be seamlessly integrated into and interconnected with existing buildings, facilitating individual unit extensions and the gradual expansion of homes autonomously. This concept promotes sustainable community development and enhances residents' well-being. The process involves the following (refer to Figure 6):

1. Inserting new structures to add volumetric capacity.
2. Adding amenities, such as new lifts connected to existing stairs.
3. Providing a base structure for each unit to expand and grow according to their needs.

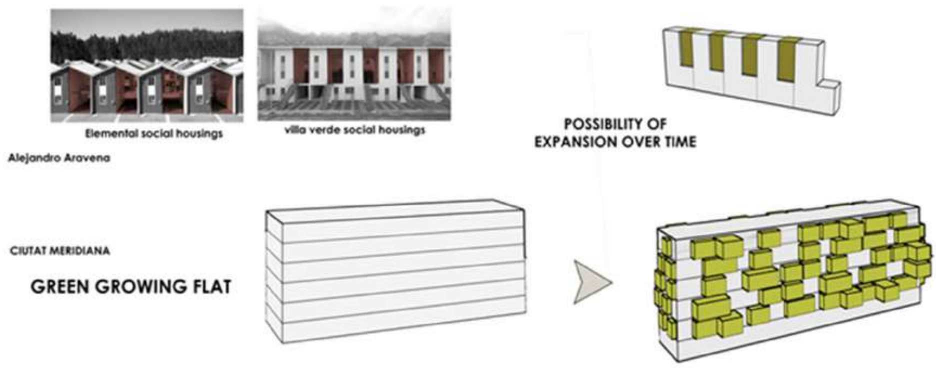


Figure 5. "Green Growing Units" concept inspired by Alejandro Aravena's social housing approach (author).

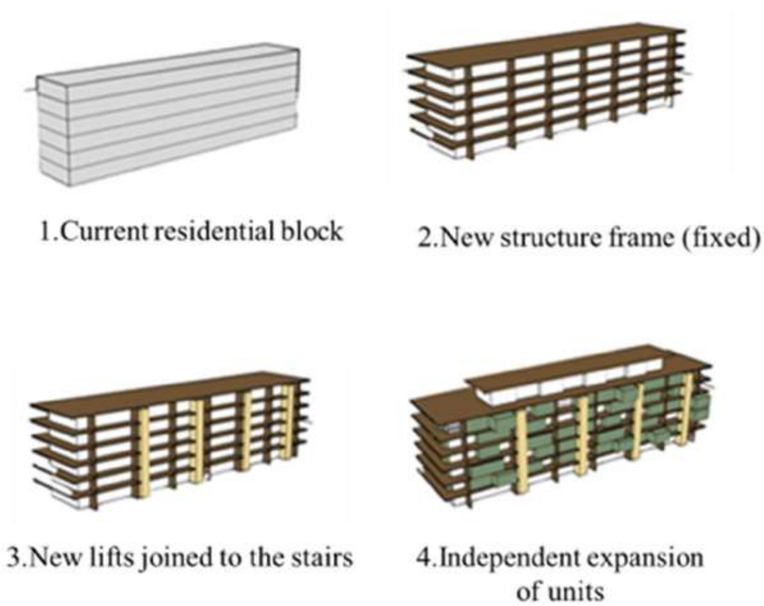


Figure 6. Design concept process (author).

5.1.1. Typological Diversity

The existing residential complex lacks diversity in its typology, with uniform units that do not cater to the diverse needs of residents. Its spatial division is inadequate, and certain areas are improperly positioned. Recognizing the demographic changes of residents, with an increasing proportion of elderly and young individuals, it is important to enhance the typology of residential units and their interior spaces with minimal alterations. As illustrated in Figure 7, the new typologies comprise the following:

Type 1: Expanding units in two or three directions, depending on where the unit is located within the complex.

Type 2: Separating the dwellings into two distinct entities and creating separate additions for each unit.

Type 2 is especially suitable for units facing potential eviction due to financial challenges or requiring expansion to accommodate changing family structures. This strategic intervention aims to enhance the functionality and usability of residential spaces to better serve the diverse needs of the community.

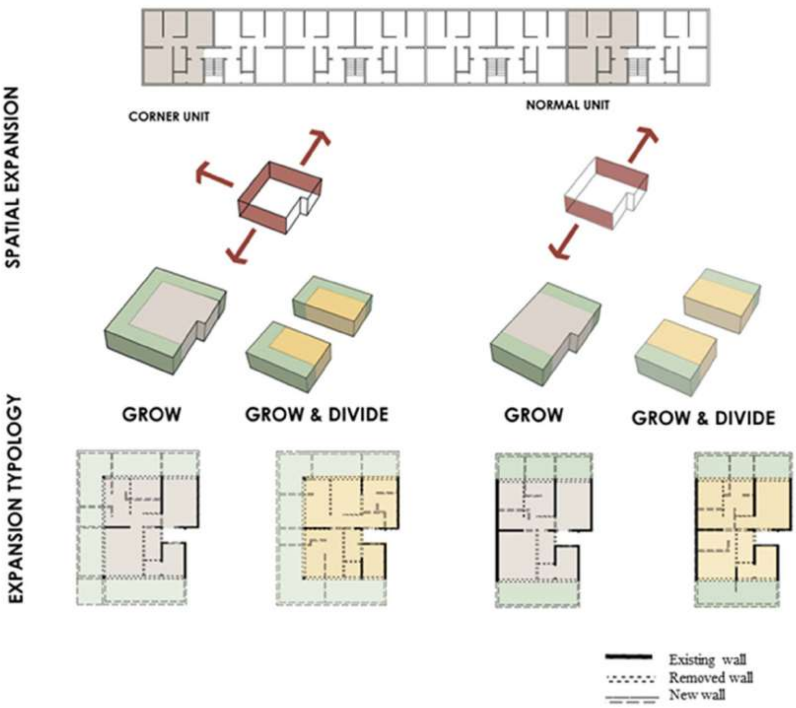


Figure 7. Proposed typology of block (author).

5.1.2. Functional Consideration

To solve inappropriate spatial arrangements within the unit, adjustments were made to the layout. This included relocating the living room to the south side, adjacent to the kitchen, and connecting it to a sunspace and terrace. The other side of the unit was allocated for the remaining rooms. To enhance the functional flexibility and accommodate demographic changes among residents, separate access was provided to one of the rooms. This room can serve as a home office or a suite suitable for elderly individuals or young couples in a family (see Figure 8).

Figure 8. Spatial arrangement: existing type (**left**), and proposed type (**right**) (author).

5.1.3. Structural Consideration

Providing a structural framework for individual retrofits allows owners to make improvements at their own pace and within their financial means, reducing upfront costs and the risk of eviction. This fosters a sense of ownership and empowerment within the community while promoting sustainable and affordable housing facilities. The structural steps of the retrofit include (refer to Figure 9):

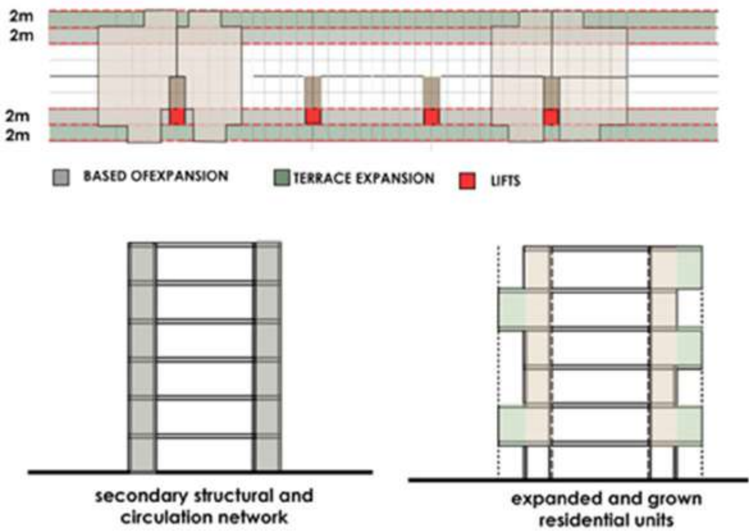


Figure 9. Structural expansion (author).

1. First, the technical system and secondary structural frames were developed along with the skeleton, forming the basis of the growth of "living spaces". This step can be developed without disturbing the lives of the residents.
2. Second, each homeowner can remove their unit's envelope from the primary structure and then expand their units autonomously. Moreover, they have the option to insert hanging terraces into their units.

Exoskeletons provide external structural support for existing buildings, reinforcing them against seismic forces and improving overall stability [38]. This intervention enhances the safety and resilience of social housing. Moreover, cross-laminated timber (CLT) was chosen for the new structural material. Because it is a sustainable and renewable material with excellent prefabrication capabilities, it can be easily manufactured into prefabricated panels or modules, offering versatility in construction and assembly [39].

5.1.4. Environmental Consideration

To enhance the building's greenery, we focused on the terraces hanging from the new structure. These terraces serve as suitable platforms for implementing passive systems, such as sunspaces and green walls, especially on the south side. Additionally, the terraces feature portable shading panels to regulate sun radiation and enhance terrace privacy. This is crucial since many current unit terraces are often covered, mainly due to the religious beliefs of the residents (see Figure 10).

Extensive green walls were installed on the two sides of the façade without openings. Moreover, the roof was transformed into a green roof, providing a communal space and improving social interaction within the community (refer to Figures 11 and 12).

Figure 10. Implementation of passive systems on the terrace.

Figure 11. South façade of retrofit by Revit 2024.

Figure 12. Axonometric of retrofit by Revit 2024.

5.2. Simulation Phase

5.2.1. Energy Performance of Base Case

The data from Revit 2024 were exported in the gbXML file format through an analytical model to apply the Autodesk INSIGHT Analysis Plugin. Subsequently, the gbXML file was used in the Design Builder v6 for energy simulation. The primary energy of the base case that was calculated by the Design Builder v6 is 275.38 kWh/m^2 per year. This amount of primary energy demonstrates that heating and room electricity account for the highest percentage of energy consumption. The HVAC system is solely utilized for heating purposes (refer to Figures 13 and 14).

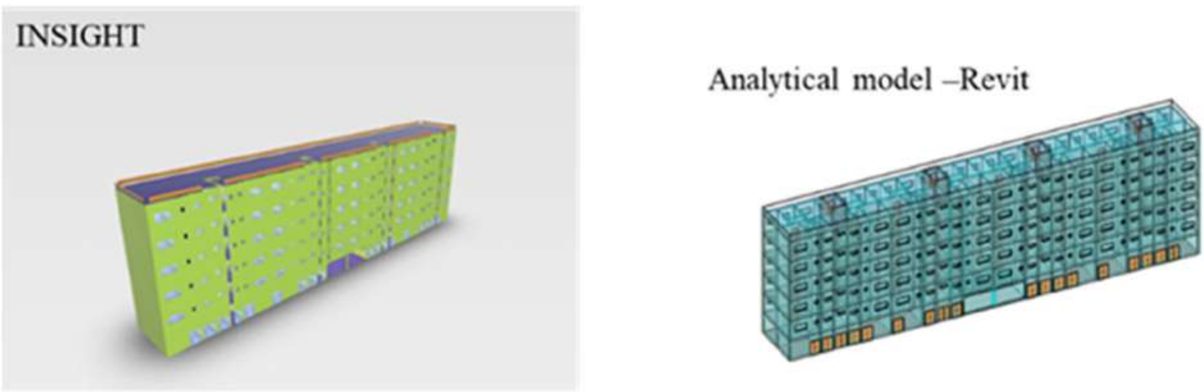
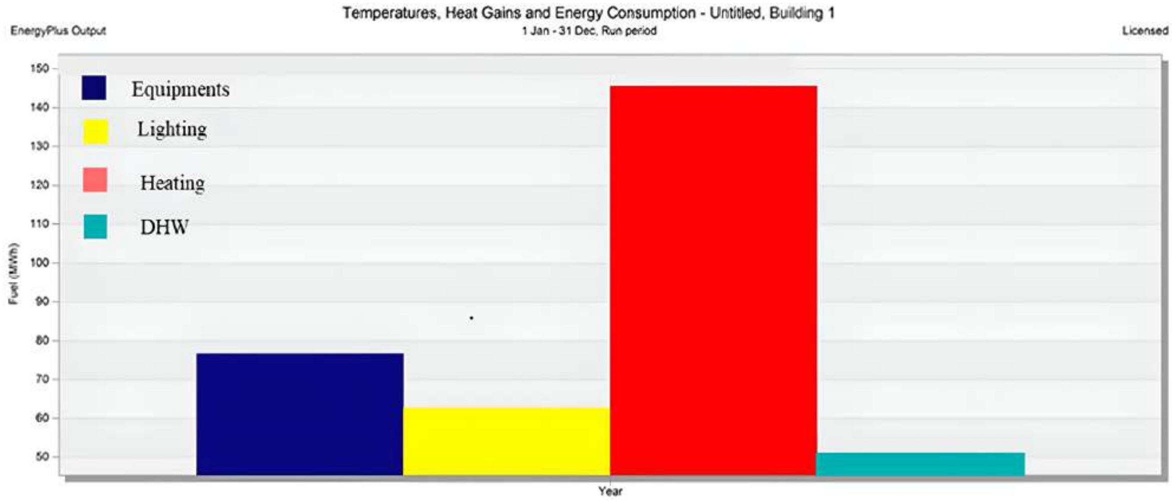


Figure 13. Energy analysis of the base case by Autodesk INSIGHT.



Site and source energy

	Total Energy [kWh]	Energy Per Total Building Area [kWh/m²]	Energy Per Conditioned Building Area [kWh/m²]
Total Site Energy	305,423.00	80.76	80.76
Net Site Energy	305,423.00	80.76	80.76
Total Source Energy	104,483.44	275.38	275.38
Net Source Energy	104,483.44	275.38	275.38

Figure 14. Energy analysis of the base case by Design Builder v6.

5.2.2. Retrofit Scenarios

The Catalan government and municipal building authorities have published building codes to determine the minimum energy demands for the shells of buildings [34].

Different retrofit scenarios were derived from the Autodesk INSIGHT analysis. The wall and roof constructions were analyzed to replace the existing solutions. Additionally, the external windows were examined by installing new models and necessary shading equipment based on the building's orientation. A sunspace was also added to the south terrace. The analytical results focused on reviewing these scenarios and their effects on thermal comfort. Moreover, the impact of technical factors on reducing energy consumption and the utilization of renewable energy were examined (Figures 15 and 16).

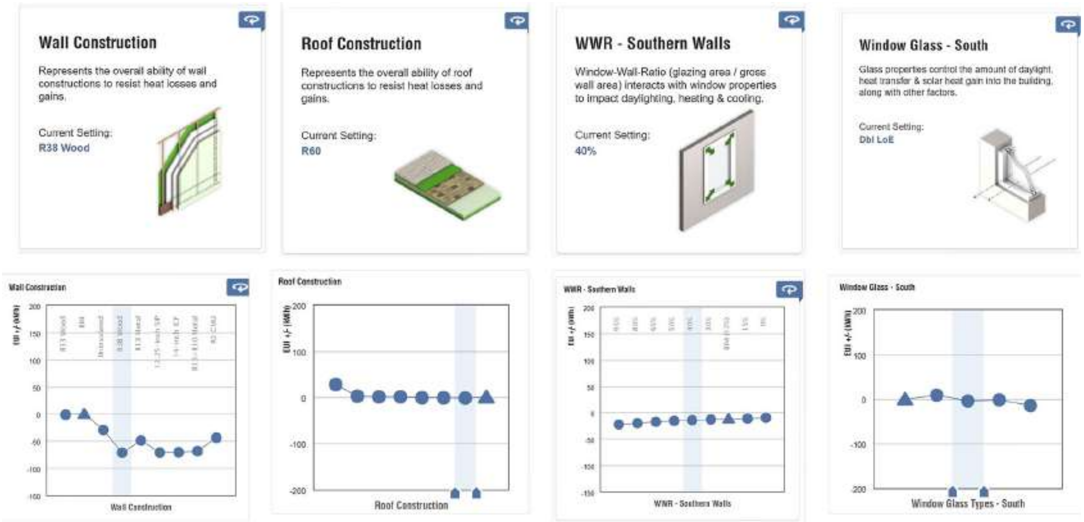


Figure 15. Adding insulation (roof and walls), changing window glasses, and adding window shades.

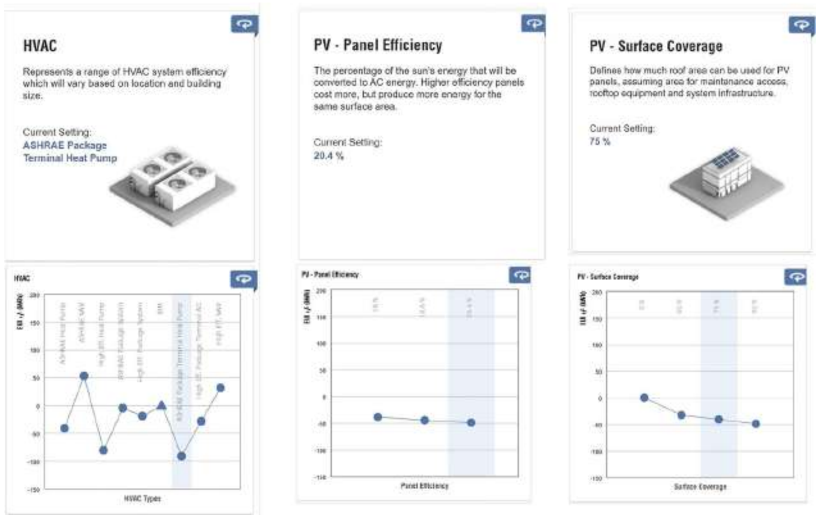


Figure 16. Changing HVAC systems, and using PV cells.

5.2.3. Retrofit Envelop Material and HVAC Systems

The scenarios created by the Autodesk INSIGHT software were used to guide the material selection for this retrofit project. This tool allows for a thorough assessment of materials based on a variety of parameters, including mechanical qualities, durability, sustainability, and cost-effectiveness.

Table 2 lists the thermophysical parameters of the selected scenario. The thermal conductivity was calculated based on improvement scenarios provided by Autodesk INSIGHT. Glass fiber batt insulated cross-laminated panels (X-LAM) were chosen for their effectiveness in nZEB building demonstration (U = 0.1545 W/(m^2K).

Double-glazed windows with low emissivity (Low-E) and spectrally selected materials were also considered. The roof was also included in the renovation scope to increase the overall energy efficiency (U = 0.0857 W/(m^2K). In terms of HVAC systems, Pastore [40] mentioned that heat pumps are the most energy-efficient equipment. Therefore, heat pumps are preferred for heating and cooling to provide year-round comfort. Although installation costs are higher, heat pumps can save money in the long run due to their energy efficiency. Given the characteristics of HVAC systems, it is critical to use photovoltaic systems to provide on-site electricity. A photovoltaic system was chosen for the social housing Ciutat Meridiana due to its reasonable efficiency (15%), reliability, and long lifespan of crystalline silicon cells, which are a cost-effective choice for low-income residential areas, requiring minimal maintenance, primarily periodic cleaning, and occasional inspection to ensure optimal performance. The system's southeast orientation and 36° tilt optimize solar exposure, enhancing energy production to approximately 135 MWh/year, and significantly offsetting the building's energy consumption (see Table 3).

Table 2. Retrofit envelope materials (author).

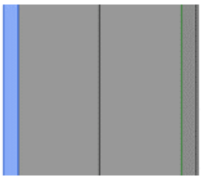
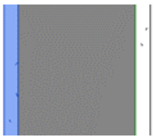
Description		Elements	
	Gypsum wall board—16 mm Cross-laminated panels—89 mm Fiberglass batt—89 mm Gypsum wall board—16 mm Paint: generic, primer, acrylic latex—1 mm	R-38 wood frame wall (U = 0.1545 W/(m^2·K))	Exterior walls
	Plaster—12.5 mm Hollow concrete block—100 mm Plaster—12.5	R-15 plus R-5 insulation wood studs (U = 0.3520 W/(m^2·K))	Interior walls
Double glazing—1/4 in thick, green/low-E (e = 0.1) glass (U = 1.9873 W/(m^2·K), SHGC = 0.36)		Glazing material	
	Carpet—7 mm Carpet padding—12 mm Plywood—15 mm Fiberglass batt—80 mm Glue-laminated timber—150 mm Reflective insulation—25 mm Plaster—12.5 mm	R-60 wood frame roof (U = 0.0857 W/(m^2·K))	Floor roof
	Acrylic-based waterproof—1 mm Vapor control layer Fiberglass batt—140 mm Vapor control layer Glue-laminated timber—150 mm	R-15 board insulation any cover (U = 0.3463 W/(m^2·K))	Floor

Table 3. Technical consideration of HVAC systems and PV systems (author).

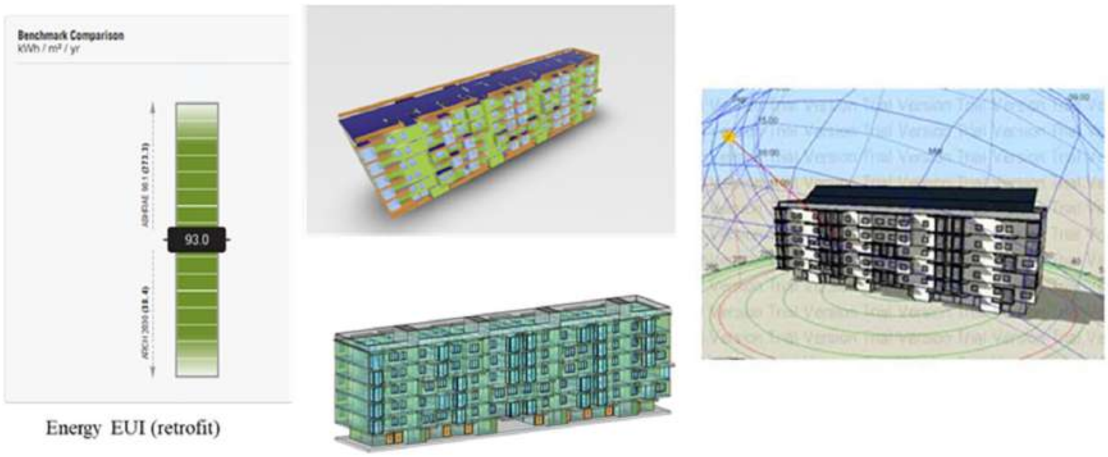
Technical Specifications	
Heating: Heat pumps Heating system seasonal SCOP: 3.5	Weather compensation 1 November–31 March 7:00–11:00 and 18:00–22:00 Set point temperature: 22 °C (residential), 20 °C (commercial)
Cooling: Heat pump compressors Coolin system seasonal SCOP: 4.5	15 May–15 September 6:00–8:00 and 18:00–23:00 Set point temperature: 24 °C (residential), 26 °C (commercial)
DHW: Heat pump compressors Delivery temperature: 65 °C	1 January–31 December (no August, Christmas holiday) Consumption rate: 1.3 L/m 2 day Set point temperature of DHW tank: 55 °C
Photovoltaic system Cell type: Crystalline silicon cells Cell efficiency: 15% N. modules: 365 Total PV area: 528 m^2	RES Orientation: South-east Tilt angle: 36 ° Availability all year

5.3. nZEBs Target Verification

Goenaga-Pérez [41] cited the minimum building requirements for Spanish nZEBs classification, including a limit on non-renewable primary energy. This limit is set by the Spanish technical construction code and usually demands half the maximum starting power. For nZEBs in Spain, the energy consumption threshold must not exceed 100 to 120 kWh/m^2 per year. This requirement aims to increase energy efficiency, reduce carbon emissions, and promote sustainable development as a part of the EU's effort to combat climate change.

To evaluate the nZEBs target, a retrofit simulation was carried out. Figures 17 and 18 show the yearly energy needs for the main services. The primary energy needed is 112.2 kWh/m^2 per year (the total source energy (160.5 kWh/m^2) minus the net source energy (48.29 kWh/m^2)). Based on the classification of nZEBs in Spain, this result meets the nZEBs target requirements. Specifically, the heating demand decreased by more than 75%, and the total electricity consumption dropped by 43% due to improved indoor conditions and the application of high-efficiency HVAC systems. The lighting demand increased slightly due to volumetric expansion and an increase in the building's area. The primary energy decreased by 40%, even though two new services, cooling and ventilation, were added compared to the base case.

Figures 19 and 20 show that over six months, PV production can satisfy the energy requirement. From March to June, the proposed configuration resulted in a surplus of electricity production that could be transmitted to the grid. During July and September, there was a balance between energy consumption and PV production. However, in the middle of summer and the last three months of the year, the energy needs of buildings exceeded PV production and had to be supplemented by the grid.



Site and source energy

	Total Energy [kWh]	Energy Per Total Building Area [kWh/m²]	Energy Per Conditioned Building Area [kWh/m²]
Total Site Energy	216,063.09	58.29	58.29
Net Site Energy	87,728.75	22.86	22.86
Total Source Energy	594,959.44	160.50	160.50
Net Source Energy	179,023.58	48.29	48.29

Figure 17. Results of the retrofit from Autodesk INSIGHT and Design Builder v6.

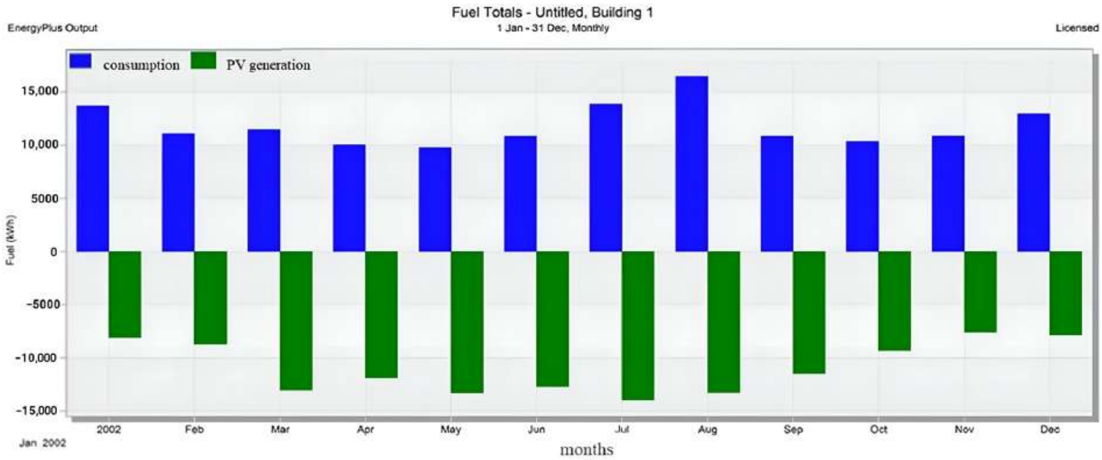


Figure 18. Electricity consumption and PV generation of retrofit case.

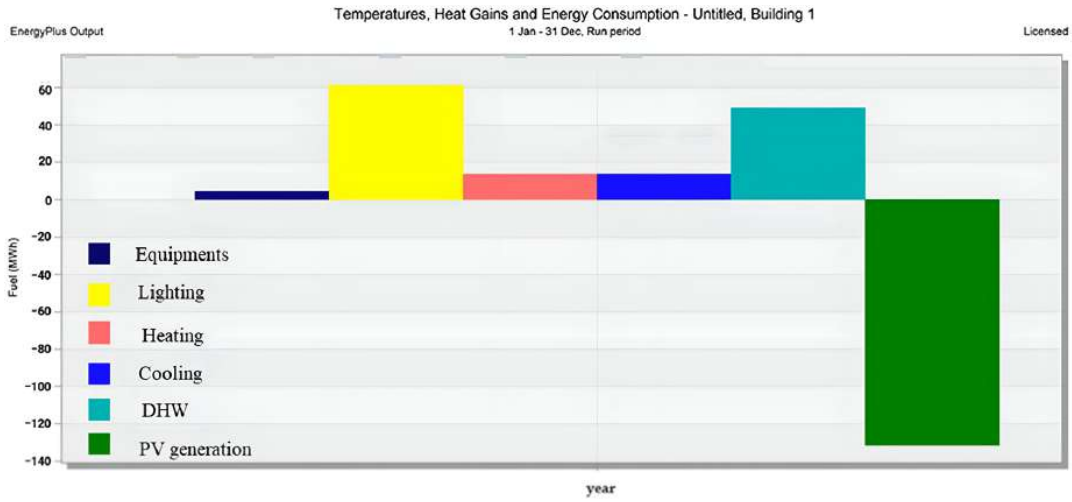


Figure 19. Electricity consumption and PV production.

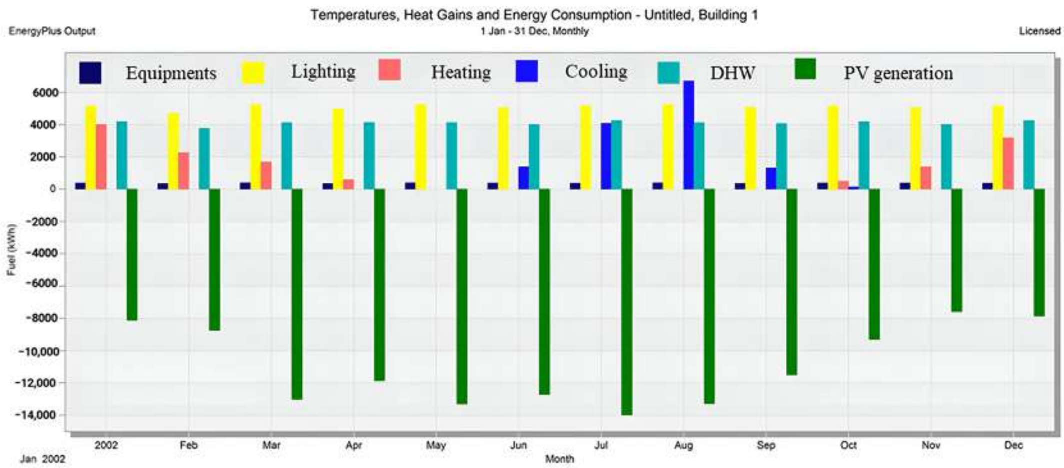


Figure 20. Annual electricity consumption and PV production.

6. Discussion

6.1. Comparison between Results and the Existing Literature

The purpose of this research was the development of a multi-benefit retrofit framework to improve energy efficiency and functionality to meet nZEB targets. The design phase findings support functional improvement through volumetric expansion and the redesign of unit typologies. This approach is similar to the previous studies that applied volumetric expansion to some or whole parts of the façade, such as terraces and sunspaces [15], different combinations of terraces, sunspaces, and extra rooms [42], and the expansion of habitable spaces [1]. Also, passive system strategies were employed to enhance the energy efficiency, similar to the research by Jin et al. [14]. In addition to these interventions, this study added redesigned unit typologies to meet the diverse needs of the residents.

Furthermore, the results of the simulation phase support the nZEBs goal, indicating significant gains in energy efficiency. The primary energy consumption was reduced to 112.2 kWh/m^2 per year, meeting the Spanish criteria of 100–120 kWh/m^2. This is similar to the study by D'Agostino et al. [43], which achieved primary energy reductions of 110 kWh/m^2 per year in Mediterranean climates. This study also showed a 75% reduction in heating demand and a 43% reduction in the total electricity consumption by applying high-efficiency HVAC systems and improving building insulation. These align with earlier research revealing major reductions in energy consumption, including up to 72% in primary energy consumption [44], 65% in heating demand [15], 30–50% in heating, and 35% in total energy consumption [45].

The performance of our PV systems, which meet the building's energy needs for six months of the year and generate surplus electricity from March to June, aligns closely with findings from other studies on PV systems' efficiency in similar Mediterranean climatic conditions. For example, the study by Assimakopoulos et al. indicated that PV systems could cover up to 50% of annual energy needs, with surplus generation during the spring and summer months [15].

6.2. Broader Implications

Nia [46] mentioned that the main challenges in retrofitting social housing for energy efficiency are the low rate of collaboration and participation of homeowners with other stakeholders, and the high costs of retrofitting for social housing residents. This research addresses these challenges by focusing on a multi-benefit retrofit framework.

This study is beneficial to a wide range of stakeholders. Higher-level stakeholders, such as municipalities and policymakers, can adopt this retrofit framework to increase the real estate value on a building scale and raise the percentage of nZEBs on an urban scale to meet the 2030 climate targets. They can offer financial incentives, like local government subsidies. Other stakeholders, such as residents and homeowners of multi-family social housing, can make improvements gradually and within their financial means. This retrofit model can reduce upfront costs and the risk of eviction. This approach fosters a sense of ownership and empowerment within the community while promoting sustainable, affordable housing.

The proposed multi-benefit retrofit framework can be scalable and applicable to multiple contexts beyond the EU. It is particularly relevant for social housing in situations where the spatial configuration of the current house does not meet the diverse needs of the residents and the homeowners cannot afford to buy a better house. Additionally, it addresses residential units whose owners are at risk of eviction or leaving their homes due to economic problems. In these cases, the multi-benefit retrofit framework offers attractive solutions for them. Homeowners can choose either the expansion model or the division-expanding model based on their family's social and economic needs, providing flexibility in retrofit types. They can also gradually retrofit their units by using local government subsidies. Moreover, this retrofit framework can be applied in many cities that have a Mediterranean climate to cover most of their energy needs through PV systems.

The retrofit framework has constraints that may affect its practicality. To successfully apply the suggested retrofit framework, it is important to analyze and resolve the restrictions. The engineering team of the retrofit project should evaluate the technical considerations of the existing structure to ensure it can support the new secondary structure without causing damage or instability. Moreover, it is important to consider sufficient space around the building to allow for volumetric expansion in one or more directions. Regarding the gradual process of retrofitting, relevant actions should be considered to minimize the discomfort in the lives of the residents. Finally, the retrofit project may require permission from municipal authorities and other relevant organizations due to the expansion of the units and volumetric additions.

Financial challenges are significant limitations to social housing retrofit projects. However, the multi-benefit retrofit framework can address these issues effectively. This retrofit framework allows for gradual implementation and budgeting over time, reducing the upfront construction cost. Generally, the financial issues of the retrofit project can be divided into two categories: shared and individual costs. Shared costs are structural and HVAC system installation during the initial phase of retrofit. This cost can be distributed among all homeowners, with financial incentives, including local government subsidies, assisting in funding this stage. On the other hand, individual homeowners are responsible for the cost of their unit retrofit and renovation, which they can schedule based on their financial capabilities over time.

7. Conclusions

The need to improve existing buildings for energy and functionality has highlighted various issues in social housing. This study proposes a framework for retrofitting that uses the multi-benefit approach to achieve the nearly zero energy building target.

This paper addresses the problems and challenges faced by low-income and vulnerable people in social housing, focusing on energy, functionality, and socio-economic issues. The research through design methodology was selected to achieve the aim of the research. The design phase focused on redesigning and volumetric additions to improve functionality and usability. The "Green Growing Units" design concept emphasizes the integration of new structures to allow individual units to gradually expand over time, independently of other units. The simulation results demonstrate that the suggested retrofit falls within the range of the Spanish nZEBs categorization restrictions. Primary energy consumption fell by 40% compared to the base case, and PV production can supply the electricity demand for half of the year.

Finally, further studies should focus on several key areas: the structural and technical feasibility of volumetric retrofits, the economic assessment and profitability of optimal retrofit solutions, and the development of community engagement strategies in social housing retrofits using a human-centered approach. These areas are critical to achieving long-term, cost-effective, and community-supported retrofits.

Author Contributions: Conceptualization, M.K., S.H., and S.K.; Methodology, M.K., S.H., S.K. and M.R.; Software, M.K. and S.K.; Validation, M.K.; Formal analysis, M.K., and S.H.; Investigation, M.K., S.H., and S.K.; Resources, M.K., and S.H.; Data curation, M.K.; Writing—original draft, M.K., and S.K.; Writing—review & editing, S.H., and M.R.; Visualization, M.K., S.K., and S.H.; Supervision, S.H., D.A.G. and M.R.; Project administration, M.K., D.A.G., and M.R.; Funding acquisition, S.H., D.A.G., and M.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflict of interest.

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