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Balancing Construction and Operational Carbon Emissions: Evaluating Neighbourhood Renovation Strategies

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Corresponding Author:	Miguel Hernandez-Valencia, B.Arch, MSci, Phd Universidad de Sevilla Instituto Universitario de Arquitectura y Ciencias de la Construcción Sevilla, Sevilla SPAIN
First Author:	Javier Garcia-Lopez, B.Arch, MSci, Phd
Order of Authors:	Javier Garcia-Lopez, B.Arch, MSci, Phd
	Miguel Hernandez-Valencia, B.Arch, MSci, Phd
	Jorge Roa-Fernandez, B.Arch, MSci, Phd
	Emilio Mascort Albea, B.Arch, MSci, Phd
	Rafael Herrera-Limones, B.Arch, MSci, Phd
Abstract:	Compliance with the global decarbonisation commitments set out in Horizon 2050 undoubtedly involves optimising the conditions of the housing stock. In this respect, the planned actions on housing blocks in the southern countries of the European Union, most of which have become obsolete, hold the key for the achievement of such compliance. This research strives to demonstrate the suitability of intervention strategies at district scale. For this purpose, an innovative methodology that combines open data, Geographic Information Systems (GIS), Urban Energy Modelling (UBEM), and Life Cycle Assessment (LCA) is proposed and tested in a case study, whilst considering several renovation and new-building hypotheses. As a novel approach, this study concurrently analyzes greenhouse gas emissions arising from both use-related energy consumption (operational carbon footprint) and the construction process (embodied carbon footprint). This dual perspective provides added value to the results obtained, as it offers a more comprehensive representation of reality. Based on the results from the LCA and UBEM models, this study unveils the entire impact of residential energy use combined with either the carbon footprint of initial refurbishment or that of new buildings. The UBEM simulation model has therefore been validated with reference methods while embodied energy is accredited with environmental product declarations (EPD). The results show that, for the 2050 horizon, not only can renovation hypotheses applied extensively reduce the cumulative emissions of construction and operational energy use by up to 47% from the baseline, but also the new-building alternatives can impact 30% more than can the ‘no intervention’ hypothesis. It is concluded that comprehensive renovation combined with renewable-energy strategies present a higher potential than do new buildings as future decarbonisation strategies in urban regeneration processes. This new methodology seems especially suitable for obsolete neighbourhoods with a repetitive building typology. It can be widely implemented in other residential districts, thereby providing the stakeholders involved with data-driven support for the design of policies regarding future energy, housing, and urban regeneration. The case study analysis reveals that total emissions, encompassing both embodied and operational aspects, are lower for retrofitting existing buildings when compared to new construction, even up to the horizon of 2050. Remarkably, this preference for retrofitting persists even as far as 2100. The study underscores the critical importance of upgrading the existing residential stock, particularly focusing on outdated residential neighborhoods constructed between 1951 and 1980, in order to achieve the ambitious

	goal of net-zero greenhouse gas emissions by 2050.
Suggested Reviewers:	Belinda Lopez-Mesa, B.Arch, MSci, Phd Full professor, Universidad de Zaragoza belinda@unizar.es Researcher in the field of energy efficiency and sustainability in residential buildings, spezialized in characterization of fuildings stocks and full scale renovations policies
	Rufino Javier Hernandez-Minguillon, B.Arch, MSci, Phd Full professor, Universidad del País Vasco rufinojavier.hernandez@ehu.eus Expert in field and teaches at the doctorate program in Energy Efficiency and Sustainability in Engineering and Architecture
Opposed Reviewers:	

Universidad de Sevilla
Dr. Miguel Hernández Valencia
Avenida Reina Mercedes, 2
Sevilla 41012
mhvalencia@us.es

Editor-in-Chief
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Dear Dr. Editor,

We are pleased to submit the revised manuscript titled **"Balancing Construction and Operational Carbon Emissions: Evaluating Neighbourhood Renovation Strategies"** for your consideration in Journal of Building Engineering.

Based in the results from LCA and UBEM models, the study unveils the entire impact of residential energy use combined with the carbon footprint of initial refurbishment or of new buildings. The energy simulation of the UBEM model, once calibrated with reference methods, provides aggregate energy consumption and embodied energy results, but also specific results for every building for each intervention scenario analysed. Embodied energy and emissions for intervention hypotheses is accredited with environmental product declarations (EPD).

Our research endeavors to demonstrate the viability of intervention strategies at the district scale. To achieve this, we propose an innovative methodology that integrates open data, Geographic Information Systems (GIS), Urban Energy Modelling (UBEM), and Life Cycle Assessment (LCA). We rigorously test this approach in a case study centered around the residential district of San Pablo in Seville, Spain. San Pablo, constructed in the 1960s, comprises 3,887 flats across 357 residential buildings, with a density of 154 dwellings per hectare.

Drawing from the results obtained through LCA and UBEM models, our study unveils the holistic impact of residential energy consumption, considering both the carbon footprint of initial refurbishment and that of new buildings. The UBEM model, once calibrated using reference methods, provides aggregated energy consumption and embodied energy results. Additionally, it furnishes specific insights for each building within various intervention scenarios. Our findings are further substantiated by environmental product declarations (EPD) that validate the embodied energy and emissions associated with different intervention hypotheses.

Notably, our results reveal that, for the 2050 horizon, extensive renovation scenarios can significantly reduce cumulative emissions from construction and operational energy use by up to 47% compared to the baseline. Moreover, these renovation strategies outperform new-building alternatives by an additional 30% when compared to the 'no intervention' hypothesis. We conclude that comprehensive renovation, coupled with renewable energy strategies, holds greater potential for future urban decarbonization than new construction.

The interdisciplinary nature of our research aligns well with the focus areas of the prestigious **'Journal of Building Engineering'** journal, presenting a novel, cross-cutting, and highly topical approach. Furthermore, we affirm that the authors have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Thank you for considering our manuscript, and we look forward to your feedback.
Sincerely,

Javier García-López, (B.Arch, MSci, Phd)
Miguel Hernández-Valencia, (B.Arch, MSci, Phd) email: mhvalencia@us.es
Jorge Roa-Fernández, (B.Arch, MSci, Phd)
Emilio J. Mascort-Albea, (B.Arch, MSci, Phd)
Rafael Herrera-Limones, (B.Arch, MSci, Phd)

Affiliation: Instituto Universitario de Arquitectura y Ciencias de la Construcción, Escuela Técnica Superior de Arquitectura, Universidad de Sevilla, Spain.

Highlights

- Carbon footprint assessment at district-scale with buildings resolution, using UBEM & LCA open tools and data.
- Innovative methodology for assessing operational and construction energy with results expressed in CO_2 emissions.
- Case-study demonstrates retrofitting buildings is a better solution for decarbonisation than building new ones.
- Full envelope renovation with PV energy reduces 50% carbon emissions of obsolete neighbourhoods by 2050.
- Strategy to identify, define and assess interventions for obsolete neighbourhoods decarbonisation.

Balancing Construction and Operational Carbon Emissions: Evaluating Neighbourhood Renovation Strategies

Javier García-López[a], Miguel Hernández-Valencia[b*], Jorge Roa-Fernández[a], Emilio J. Mascort-Albea[b], Rafael Herrera-Limones[a]

[a] Universidad de Sevilla. Escuela Técnica Superior de Arquitectura. Departamento de Construcciones Arquitectónicas 1. Instituto Universitario de Arquitectura y Ciencias de la Construcción. Avenida de Reina Mercedes 2, 41012 Sevilla, España [javigalo@ us.es; jroa@us.es; herrera@us.es]

[b] Universidad de Sevilla. Escuela Técnica Superior de Arquitectura. Departamento de Estructuras de Edificación e Ingeniería del Terreno. Instituto Universitario de Arquitectura y Ciencias de la Construcción. Avenida de Reina Mercedes 2, 41012 Sevilla, España [mhvalencia@us.es; emascort@us.es]

* Corresponding author: mhvalencia@us.es

Abstract

Compliance with the global decarbonisation commitments set out in Horizon 2050 undoubtedly involves optimising the conditions of the housing stock. In this respect, the planned actions on housing blocks in the southern countries of the European Union, most of which have become obsolete, hold the key for the achievement of such compliance.

This research strives to demonstrate the suitability of intervention strategies at district scale. For this purpose, an innovative methodology that combines open data, Geographic Information Systems (GIS), Urban Energy Modelling (UBEM), and Life Cycle Assessment (LCA) is proposed and tested in a case study, whilst considering several renovation and new-building hypotheses.

As a novel approach, this study concurrently analyzes greenhouse gas emissions arising from both use-related energy consumption (operational carbon footprint) and the construction process (embodied carbon footprint). This dual perspective provides added value to the results obtained, as it offers a more comprehensive representation of reality. Based on the results from the LCA and UBEM models, this study unveils the entire impact of residential energy use combined with either the carbon footprint of initial refurbishment or that of new buildings. The UBEM simulation model has therefore been validated with reference methods while embodied energy is accredited with environmental product declarations (EPD).

The results show that, for the 2050 horizon, not only can renovation hypotheses applied extensively reduce the cumulative emissions of construction and operational energy use by up to 47% from the baseline, but also the new-building alternatives can impact 30% more than can the ‘no intervention’ hypothesis. It is concluded that comprehensive renovation combined with renewable-energy strategies present a higher potential than do new buildings as future decarbonisation strategies in urban regeneration processes.

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outdated residential neighborhoods constructed between 1951 and 1980, in order to achieve the ambitious goal of net-zero greenhouse gas emissions by 2050.

Keywords

Sustainable urban regeneration; Geographic Information System; Urban Modelling Interface; decarbonisation; residential energy consumption; open data

Abbreviations

EEC: Energy Efficiency Certificate
EPD: Environmental Product Declaration
CPR: Construction Products Regulation
DHW: Domestic Hot Water
HVAC: Heating, Ventilation, and Air-Conditioning
LCA: Life Cycle Analysis
GIS: Geographic Information System
GWP: Global Warming Potential
GWP-total: Total Global Warming Potential (kg CO_2 eq)
NZEB: Nearly Zero-Energy Building
PENRT: Total use of Non-Renewable Primary Energy resources (MJ)
PV: Photovoltaic
UBEM: Urban Building Energy Model
UMI: Urban Modelling Interface (MIT Sustainable Design Lab)
WWR: Window-to-Wall Ratio
ZEB: Zero-Energy Building. Carbon neutral

1. Introduction

Article 2 of the 2015 Paris Agreement (United Nations Climate Change Conference 2015 - COP21) aims to maintain the global average temperature at 1.5°C below the pre-industrial levels at the end of the 19th century. This objective recognises that achieving this temperature would significantly reduce the effects of climate change. In order to reach this goal, it is necessary to reduce greenhouse gas emissions by approximately 55% by 2030 compared to 1990 levels, and to achieve net-zero greenhouse emissions by 2050 [1].

Faced with this global challenge, as well as with the Global Goal 11, ‘sustainable cities and communities’ of the UN 2030 Agenda, sustainable urban regeneration of obsolete residential neighbourhoods is a key aspect. This issue encompasses the social, economic, and environmental principles of sustainability, with particular impact on the southern regions of the European Union, including Portugal, Italy, and Greece. In Spain, where the case study of this research originates, 49.14% of the main dwellings (which function as habitual residences) are pre-1981, and 38.27% of the total number of dwellings were built between 1951 and 1980. Of the total number of principal dwellings, only 2.53% were built between 2011 and 2020 [2]. In order to meet the net-zero greenhouse emission targets for Horizon 2050, it is a priority to improve the existing residential stock, especially those buildings constructed between 1951 and 1980.

The development of energy plans and policies requires research into decarbonising the residential stock and analysing potential climate change scenarios. Predictive models, such as bottom-up engineering models, can be utilised to estimate the residential energy consumption of a building or group of buildings [3]Using this estimate, it is possible to predict the progress towards the targets regarding reducing greenhouse gas emissions, and to conduct exploratory analyses to evaluate the impact of various mitigation strategies. Urban Building Energy Modelling (UBEM) is an emerging discipline, which, over the last decade, has developed tools and strategies for energy simulation at district scale in highly populated environments [4,5] Through the comprehensive and massive analysis of the energy consumption of buildings during their use phase, numerous factors can be considered, such as urban fabric, building morphology, boundary conditions, typological diversity, building design, and climate.

Reinhart and Cerezo-Dávila (2016) provide an overview of the contributions made to this discipline and establish the main actions required for the creation of energy models in urban sectors [5]. Moreover, in recent years UBEM-based research has increased in both quantity and quality [[6–8], and has established a challenging and innovative framework [9]. Likewise, the most relevant case studies include those using a combination of Urban Modelling Interface (UMI) and Geographic Information System (GIS) tools for the energy modelling of neighbourhoods in Boston [10], Lisbon [11], and Dublin [12].

Validation methods and the simplifications assumed by the models also constitute a key factor in understanding the fundamentals of the various UBEM strategies. One major development in this field involves the initiative of the International Building Performance Simulation Association (IBSPA) for the development of a district-scale energy model (DESTEST) [13,14]. It aims to adapt validation methods for Building Energy Modelling (BEM) tools based on the Building Energy Simulation Tests (BESTEST) of the International Energy Agency (IEA) [15]. Through this process, a series of standard buildings simulated with different calculation engines define a range of values between which the tools to be validated should lie. However, it is also important to point out that there is currently no commonly accepted international standard for UBEM metrics [7]. For the present case study, the validation and calibration of UBEM models in Spain is proposed by adapting the methodology based on confidence bands similar to BESTEST [16], through the proposed standard for the official authorisation of tools for the energy certification of buildings [17].

Furthermore, and as proposed in this research, in the exploratory analysis of time projections of refurbishment scenarios, the calculation of the energy included in the refurbishment processes must also be incorporated into the estimation of the previous consumption by means of the Life Cycle Analysis (LCA) of the actions.

For the calculation of Nearly Zero-Energy Buildings (NZEB), operational energy is incorporated, but embodied energy is usually excluded [18]. In residential buildings in Southern Europe, embodied energy represents approximately 25% of operational energy over a service life of 50 years [19]. Moreover, the reduction of operational energy due to technological advances in installations is leading to an increase in the ratio of embodied energy to operational energy in new residential buildings [20].

As Seyedabadi (2023) has pointed out, there is a need for LCA studies applied at neighbourhood scale [21]. Along these lines, research combining LCA and GIS methodology shows the possible strategic impacts of including LCA methods for policy development at urban scale in cities such as Barcelona (Spain) [22]. Another study links BIM-LCA-GIS tools by establishing an Eco-Efficiency Matrix, oriented towards the evaluation of the sustainable development of an area of tall buildings in the city of Quito (Ecuador) [23]. The validation of this type of method is based on the LCA of a cradle-to-site approach. This environmental impact analysis includes production, transport to the construction site, and installation in the construction processes. To this end, the data of the construction systems applied in the retrofitting are obtained from the Environmental Product Declarations (EPD) of each of the retrofitting scenarios considered. The EPDs have been developed according to the European standard EN 15804.

Following the approach made to the research topic, it can be stated that hardly any research references comprehensively address UBEM and LCA strategies for the assessment of the impact of the carbon footprint in residential developments. Likewise, this type of work seldom considers district-scale retrofitting as a priority strategy over new construction. Furthermore, the validation of the results of UBEM models is generally carried out using reference models, without incorporating real consumption values at neighbourhood scale that would allow the model to be calibrated.

Given the aforementioned context, this study develops and applies a methodology for the assessment of energy consumption and greenhouse gas emissions of various residential refurbishment scenarios at district scale, and calculates the effects of the energy incorporated in the interventions and the operational energy use up to the 2050 horizon. This research aims to facilitate decision-making regarding possible residential retrofitting strategies by considering the impact of the carbon footprint in each case, both during the intervention and during the use phase of retrofitted buildings. To this end, the proposed methodology combines GIS, UBEM, and LCA tools to assess the effects of the different intervention hypotheses. This is carried out through the calculations performed by the Urban Modelling Interface (UMI) open tool, developed by the Massachusetts Institute of Technology (MIT) Sustainable Design Lab [24], which enables the energy consumption and CO_2 emissions derived from the construction processes to be obtained, as well as the consumption and emissions from the activities of the various residential user profiles.

The development of this applied research has made it possible to estimate the energy consumption and greenhouse gas emissions of a neighbourhood over time, and to integrate data and results relating to the use of housing facilities, as well as integrating those of the construction processes and systems applied in retrofitting. The results obtained enable an integrated analysis of use and renovation, thereby making it possible to assess the effectiveness of solutions aimed at improving the health and comfort conditions of the inhabitants, with the goal of achieving net-zero greenhouse emissions in 2050.

Moreover, the study uses only open data and tools for its development, which enables replication in other alternative locations and for various exploratory scenarios. The method also integrates the validation of the model of useful and embodied energy consumption with benchmarks and real data.

Lastly, the compatibility of the study with the UBEM.IO platform [25] fosters the sharing of results with other studies being carried out in widely differing contexts, thereby contributing towards the creation of knowledge and transfer on the decarbonisation of buildings.

To illustrate the research approaches, a case study of an obsolete residential housing estate in Southern Europe from the period 1951-1980 has been selected. Obsolete residential neighbourhoods present common characteristics that justify the development of a specific methodology, based on prominent levels of urban vulnerability and the repetition of construction solutions and residential typologies belonging to the large peripheral urban developments of European cities, which are characteristic of the second half of the 20th century [26,27].

In order to comply with the vulnerability indicators proposed by the methodology, the A and B neighbourhoods of *Polígono de San Pablo* in Seville (1964-1966) were selected (Figure 1). These neighbourhoods contain approximately 4,000 dwellings of low-income households, mostly located in linear blocks of 5 floors with two dwellings per floor. The construction of the dwellings was massive and serial, using repetitive construction systems: reinforced concrete structure, double brick façades with air cavity without thermal insulation, metal carpentry with single glazing, and flat roofs without thermal insulation.

Figure 1. Comparison of the study area: year 1977 (left) and year 2023 (right). Source: REDIAM, 2024 [28]

Consequently, the main objective of the research involves the design of a methodology to assess retrofitting and decarbonisation scenarios at district scale in obsolete residential neighbourhoods. This is in line with the Net-Zero 2050 emission targets.

After an introductory presentation (Section 1), the article describes the development of the methodology applied to the case study of neighbourhoods A and B of Polígono San Pablo, located in Seville (Section 2). The results obtained have made it possible to specifically evaluate the energy consumption and carbon footprint up to the year 2050 (Section 3) for these two neighbourhoods. The discussion of the results (Section 4) is organised based on the main topics of the research and evaluates the suitability and replicability of the methodology designed for these obsolete neighbourhoods. Finally, the conclusions (Section 5) reflect on the relevance of the results in defining appropriate energy rehabilitation criteria, which contribute towards a better allocation of energy and economic resources in vulnerable neighbourhoods.

2. Material and methods

The objective of this study is to define and test a methodology to assess energy consumption and carbon footprint at district scale, in extensive retrofitting scenarios of obsolete residential neighbourhoods, using open data and GIS, UBEM, and LCA tools. This method integrates the analysis of energy consumption and greenhouse gas emissions due both to the use and to the construction processes of refurbishment. The three main phases of the proposed methodology are presented below (Figure 2).

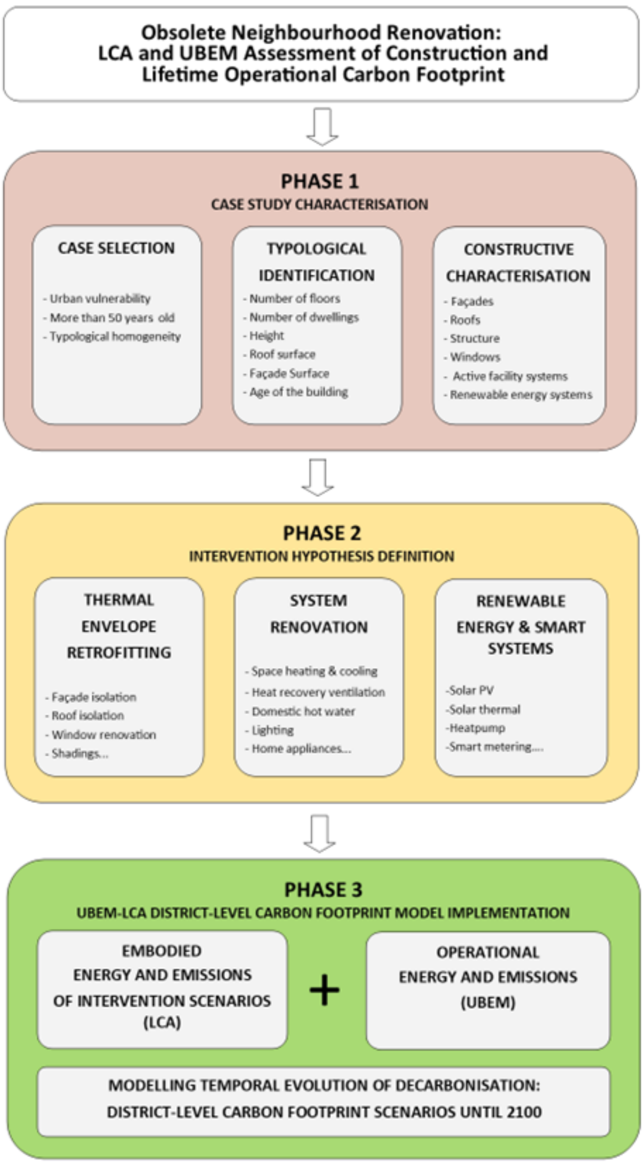


Figure 2. General methodology schema

2.1. Phase 1: Characterisation of the case study

This phase involves a process of selection and technical characterisation of a case study that complies with the necessary conditions for the application of the method. The work area must verify the conditions of an obsolete residential neighbourhood, based on a set of indicators related to the current state of the building. Subsequently, the architectural identification and characterisation of those representative building-types is to be carried out using GIS and open data.

2.1.1. Case study selection: obsolete neighbourhood

To select the case study, open data was collected from the catalogue of the National Statistics Institute (Instituto Nacional de Estadística, INE) [28], which provides information on the state of the buildings. Geospatial analyses carried out using GIS have made it possible to obtain indicators relating to the vulnerability, age, and typological definition of the dwellings.

Urban vulnerability: The Catalogue of Vulnerable Neighbourhoods in Spain (CBVE) [29] helps to define one of the fundamental criteria for the selection of case studies. A vulnerable neighbourhood consists of an urban area of a certain homogeneity and urban continuity with an approximate population of between 3,500 and 15,000 inhabitants. In this residential area, at least one of the three Basic Indicators of Urban Vulnerability (IBVU) related to educational attainment, housing, or unemployment exceeds a vulnerability benchmark [30]

- **Housing more than 50 years old:** An age of more than 50 years is established as an indicator of obsolescence for the selection of the neighbourhood. In Spain, this reference date is taken as the date of entry into force of the Regulations on Thermal Conditions in Buildings (Norma Básica de Edificación NBE-CT-79) [31], which specify minimum technical requirements aimed at saving energy and achieving minimum conditions of habitability and thermal comfort.
- **Typological homogeneity:** This is a characteristic of obsolete residential neighbourhoods. These urban developments correspond to actions carried out over a brief period, less than 10 years, with projects based on mass production. Thus, architectural types (double bay, linear block, two dwellings per communication nucleus, cross ventilation, double orientation, number of floors) and construction types (double brick façades with air chamber without insulation, flat roofs without insulation, metal frames with single glazing) are repeated in each neighbourhood. Typological homogeneity is identified with the concept of urban cluster and allows the definition of extensive rehabilitation solutions, which facilitates the application of the same solution to all the buildings in a neighbourhood.

In accordance with the aforementioned criteria, if the neighbourhood meets the above conditions, we call it an obsolete residential neighbourhood and the application of the designed methodology is feasible.

2.1.2. Typological identification

Using GIS tools and open databases, representative parameters of the buildings in the neighbourhood are determined: number of floors, number of dwellings, height, roof surface, façade surface, and age of the building. These parameters are employed to define the typical buildings that represent all the buildings in the neighbourhood.

2.1.3. Constructive characterisation

A bottom-up methodology is applied, based on data obtained *in situ* from a representative building in the neighbourhood. The collection of data on this sample of buildings enables the calculation models to be calibrated and, therefore, the obtained results to be validated.

2.2. Phase 2. Definition of intervention hypothesis

The concept of extensive renovation refers to renovation interventions that can be applied to the broad range of dwellings in a neighbourhood and not only to isolated buildings, in order to ensure a better allocation of resources in vulnerable neighbourhoods. Renovation scenarios aim to reduce energy demand, consumption, and carbon footprint and to improve energy efficiency, to provide ‘on site’ renewable energy, while, at the same time improving the comfort conditions of the users.

Building envelope renovation scenarios are defined for which the implementation is feasible for the totality of dwellings in the neighbourhood. Interventions on the interior of dwellings and individual renovations of individual active facility systems are generally excluded as they fall outside the scope of the extensive retrofit concept. Each scenario must incorporate the characteristics of the existing building systems and of each of the refurbishment proposals. Therefore, variations of the models are necessary for the energy and carbon footprint assessment of each proposal.

2.3. Phase 3. UBEM-LCA district-level implementation

In the following, the UBEM-LCA application process on the existing building stock and on the different renovation scenarios is presented. With a bottom-up engineering model, and at district scale, the aim is to evaluate, the emissions and operational energy consumption and the embodied energy of the renovation scenarios [3]. The results obtained enable the evaluation of the temporal evolution of decarbonisation scenarios.

The LCA and operational energy modules of the UMI tool of the MIT Sustainable Design Lab [24] are employed for the calculation. The UMI tool enables the final energy consumption of buildings during their use (operational energy) to be attained, as well as the embodied energy and CO_2 embedded in the construction processes (life cycle assesment). The results obtained by both applications in combination lead to an evaluation with a time projection of energy consumption and carbon footprint up to 2050, in coherence with the Net-Zero 2050 emission targets.

A typical data science process model, known as OSEMN [32], has been implemented to estimate emissions during the use phase of the dwellings. The graphical representation of the process is included in Figure 3, where phases, tasks, and intermediate results are laid out in columns.

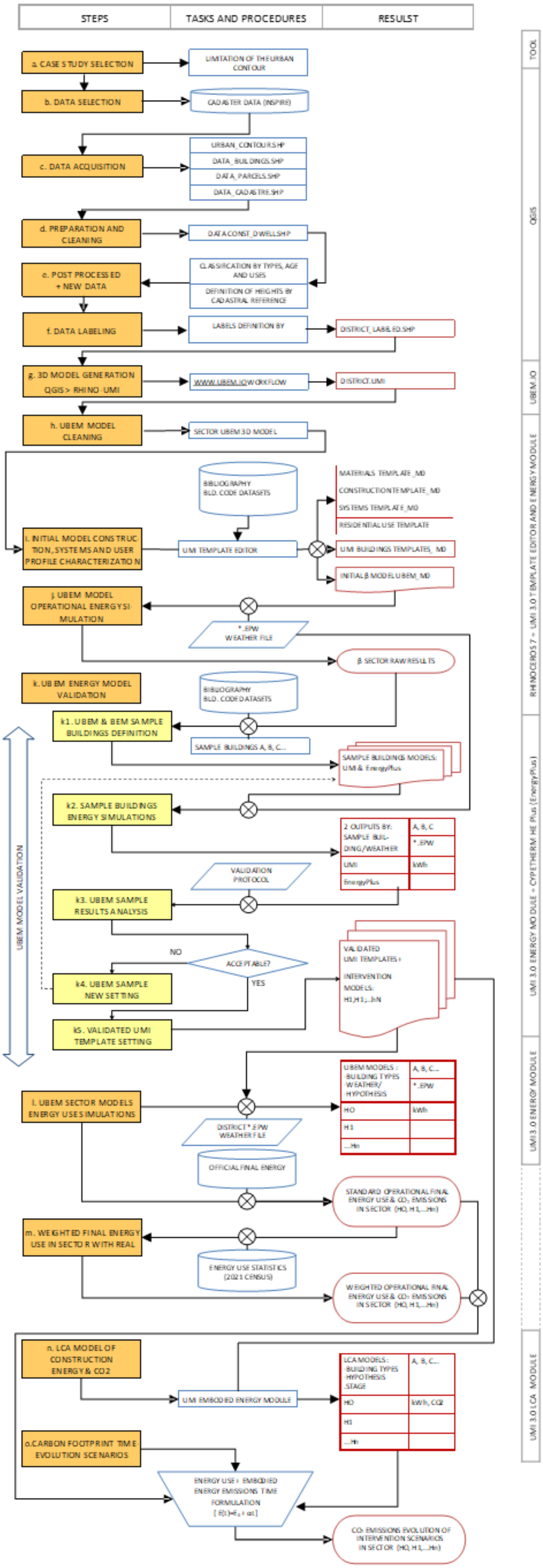


Figure 3. Phase 3 workflow: Carbon footprint of district-level embodied and operational energy modeling

2.3.1. Operational energy and emissions (UBEM)

Our proposal starts by obtaining open data from the cadastre in GIS format. Subsequent to cleaning and preparation, the data must be categorised in terms of typology and age, and assigned to a specific "building type". The next step is to transform the GIS information into a three-dimensional UBEM model using the online tool UBEM.IO developed at the MIT [33]. The three-dimensional model of the buildings, where each building is identified by its cadastral reference and a specific building type, is processed with the Rhinoceros tool, using the UMI v.3.0 plugin interface [34]. Each building type is assigned a building template that includes the dimensional characterisation, construction, facilities, and use profile, as well as the embodied energy and CO_2 of the components of the retrofitting scenarios. The climate file is then linked in EPW format, obtained from the PVGIS database [35] for that location. Each intervention scenario requires its own UMI model, which incorporates the variations in the building elements (thermal envelope) and architectural elements (PV roofs) specific to each scenario.

After this set of steps, the results of the first H0 model can be obtained, and the data of the standard building in UBEM can be compared with that of the BEM EnergyPlus database that represents the same building casuistry. Through the adoption of the criterion of confidence bands [36], the UBEM model can be adjusted by modifying the operational and system conditions of the UMI templates to fit the confidence bands defined in the BESTEST-derived reference method.

2.3.2 Embodied energy and emissions of LCA intervention scenarios

Following the validation of the UBEM model, simulations can be carried out and the energy consumption results of the operational and energy phases can be extracted as can the CO_2 incorporated with UMI's energy and LCA modules.

2.3.3 Evolution of decarbonisation scenarios

Lastly, in order to obtain the results relating to the temporal evolution of the various decarbonisation scenarios, the results must be processed, by transforming the final energy consumption into CO_2 emissions in accordance with the official pass-through coefficients. Similarly, the emissions incorporated in the construction phase must be computed to reveal the evolution of the emission scenarios. This is carried out by considering the initial emissions and those differredover time according to the simulations of each scenario.

3. Results

3.1. PH01: Description of the case study proposal

Polígono San Pablo is a district of Seville consisting of more than 8,800 dwellings that belong to the III National Housing Plan (1961-1976). Neighbourhoods A and B form part of the first phase, executed between 1964 and 1966, and include some 4,000 dwellings [37,38]. The Spanish Housing Union (Obra Sindical del Hogar) built the neighbourhood, together with the National Housing Institute (Instituto Nacional de Vivienda) and the Seville Town Planning Department (Gerencia de Urbanismo de Sevilla). The methodology developed in the previous section is applied below.

3.1.1. Neighbourhoods A and B of Polígono San Pablo (Seville, Spain)

These constitute a representative case of obsolete residential neighbourhoods, included in the CBVE of Spain 2011 that are over 50 years old (1964-1966). There is a repetition of the construction systems utilised in all the dwellings: reinforced concrete structure, double brick façades with an air chamber without thermal insulation, flat roofs without thermal insulation, and metal window frames with single glazing. Furthermore, the main architectural type is a 5-storey linear block with 10 dwellings per block [39].

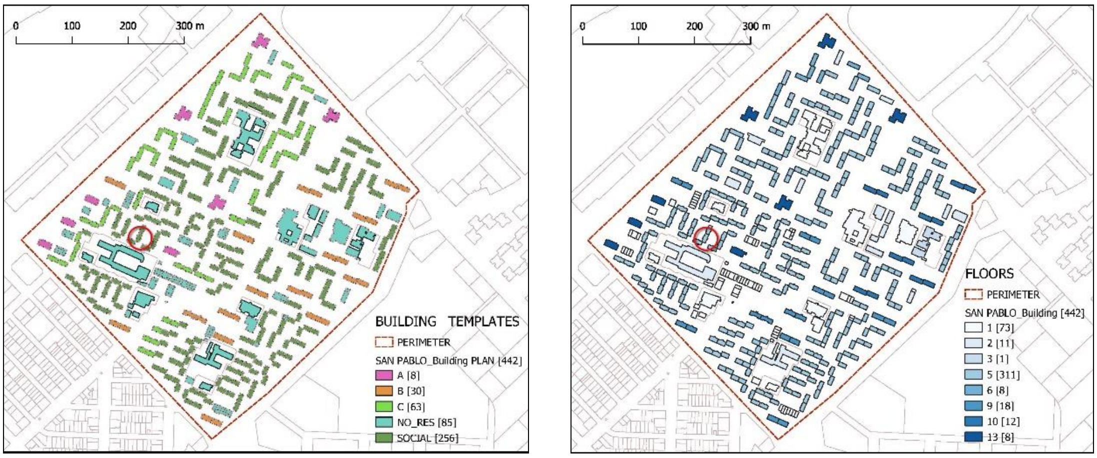
3.1.2. Building typological identification

The representative data of the buildings has been obtained from open databases of the Cadastre Headquarters of the Spanish Government (*Sede de Catastro del Gobierno de España*) [40], and includes the number of floors, number of dwellings, height, roof surface and façade surface. The typical buildings of the neighbourhood are identified, for which differentiated templates of construction characteristics are developed (Table 1).

Table 1. Statistics of buildings and dwellings in the neighbourhood

Category	Blocks	%	Floors	Dwellings per floor	WWR %	Built Area m²	Rooms	Type	Dwellings	%
1st Category A1	4	0.90%	13	3	24.67 %	80/200	4 & 5	Tower	146	
1st Category A2	4	0.90%	13	2	24.67 %	80/200	4 & 5	Block	96	
TOTAL A									242	6.22%
2nd Category B1	12	2.71%	10	2	17.71 %	60/125	3 & 4	Block	195	
2nd Category B2	18	4.07%	9	2	17.71 %	60/125	3 & 4	Block	291	
TOTAL B									486	12.50%
3rd Category C1	8	1.81%	6	2	13.44 %	50/80	3 & 4	Block	72	
3rd Category C2	55	12.44%	5	2	13.44 %	50/80	3 & 4	Block	534	
TOTAL C									606	15.58%
Social Category	256	57.92%	5	2	15.41 %	50/60	3	Block	2,555	
TOTAL Social									2,555	65.70%
TOTAL RESIDENTIAL	357	80.77%							3,889	100.00%
Non-residential	85	19.23%	1-3	-	-				-	
TOTAL BUILDINGS	442									

The neighbourhood is made up of 442 building blocks (Figure 4), with a housing density of 154 dwellings per hectare. Of these, 80.77% are residential buildings. The height distribution of these residential buildings corresponds to the categories and building typologies. Of the 3,889 dwellings counted, 81.28% correspond to the 'C' or 'Social' categories. Dwellings within these two categories have less built area and are of lower quality according to the design regulations. The sample residential building used as a baseline for the constructive characterisation corresponds to this category.



(a) (b)

Figure 4. Building categories (a) and number of floors (b). The location of the sample building is indicated

3.1.3. H0: Constructive characterisation of building types

To extrapolate the constructive characterisation to the rest of the neighbourhood, data was gathered from a representative sample building. In this case, a 5-storey linear block with 10 dwellings located at 1, Saeta street (37°23'35.3"N 5°58'05.5"W) was considered (Figure 5). The collection of data on this building model enables the calibration of the calculation models used, and therefore the validation of the results obtained.

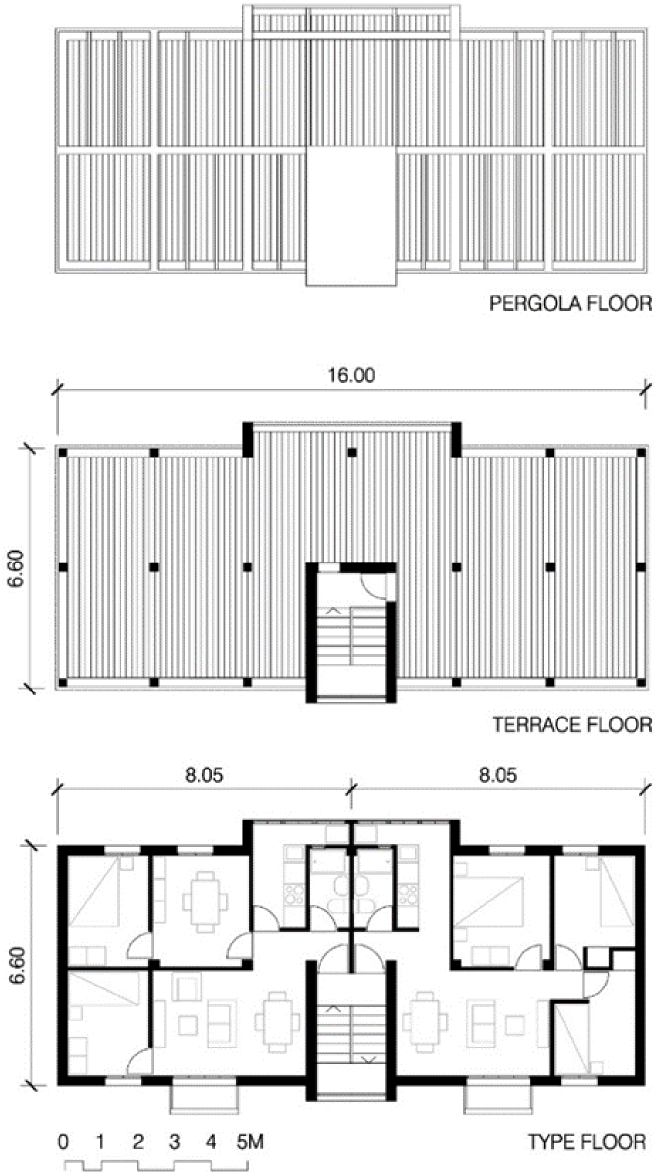


Figure 5. Plans of representative sample building located at 1, Saeta street (Seville, Spain)

Prior to its construction, in 1954, the Technical Standards for Limited-Income Housing (*Ordenanzas y Normas Constructivas de las Viviendas de Renta Limitada*) [41] were drawn up in Spain. The principles set out in these norms have a strong typological, functional, and hygienic basis, and clearly delimit the minimum built and usable areas per category.

These internal standards were designed to be a guide for the drafting of projects and they contain a series of non-innovative construction recommendations that sought to standardise systems, to provide an immediate economy of resources, and to guarantee at least a minimum level of health and safety of the dwelling. In the San Pablo project, these standards are translated into the construction systems (Table A1).

Since all the residential buildings correspond to the same construction period, the building characterisation used for the GIS-UBEM-LCA predictive models has been carried out with 4 templates corresponding to the 4 categories of building types. The templates differ in the percentage of openings in the façade. Each building, in the model, will be assigned a certain template that includes the constructive characterisation, the thermal systems, and the use profile with which it will be modelled. Annex A includes the construction, structure, and installation features of the current state (H0).

3.2. PH02: Characterisation of proposed interventions

In accordance with prior case study analysis, a set of intervention strategies was designed, that combines envelope renovation actions and renewable energy systems contribution. Due to the lack of collective MEP, HVAC, and DHW installations, no renovation systems are considered, nor are any interventions inside the dwellings, since these are generally excluded from the ‘extensive retrofit’ concept. Consequently, five intervention hypotheses (H1, H2, H3, H4, and H5) have been designed: four with common low-impact, extensive energy-rehabilitation solutions with minimal influence on domestic use, and a fifth scenario based on new construction.

3.2.1. Constructive definition of intervention hypotheses: H1, H2, H3, H4, and H5

For this study, technical data for material and system characterisations has been retrieved from official building datasets [42] and openly available Environmental Product Declarations (EPD) of real construction systems of supplying companies. In the same way as in a real architecture renovation project, data was acquired from certified records in professional way. This enabled the validation of the physical properties of the materials, and also that of the embodied energy and GWP emissions throughout the construction process for the LCA analysis.

Environmental Product Declarations are issued in accordance with the EN ISO 14025 standard. The International EPD System operates in accordance with ISO 14025, ISO/TS 14027, ISO 14040, ISO 14044, and ISO 14067. For construction products, this EPD programme also complies with the European standard EN 15804 (A1 and A2) as well as with ISO 21930. For all EPDs used in this research, the Construction Products Regulation (CPR), which consists of a set of specific rules for the development of environmental declarations, is EN 17213:2020.

- **H1. Injection of rock wool insulation in the air chamber (1A).** As mentioned above, building envelopes in the 1960s in Spain were insulated with only an airtight air chamber. Hypothesis H1 proposes the incorporation of injected mineral wool foam in the existing air chambers. This type of action can be carried out from inside the building and requires almost no auxiliary means nor incurs any inconvenience to users.
- **H2. Replacement and improvement of the exterior carpentry (2A).** This intervention scenario envisages a two-stage development. The first stage consists of the removal of the existing carpentry in the openings with its corresponding contribution of CO_2 and energy consumption. The second stage involves the installation of new carpentry. For this reason, fields C1-C4 and D corresponding to removal and recycling are incorporated.
- **H3. Improvement of roof insulation (3A+3B).** For this hypothesis, the installation of an insulation system is proposed, based on 50x50 cm two-layer prefabricated tiles, formed of a layer of 50 mm high-density EPS-type insulation material and a top surface of 35 mm mass concrete. For this purpose, two EPDs have been combined: that of extruded polystyrene insulation and that of precast concrete slabs, measured per tonnes of product.
- **H4. Installation of photovoltaic solar panel systems on roofs (4A+4B).** This intervention scenario also envisages a two-stage development. The first stage consists of a support structure of metal profiles that establishes a shading plane 3 m from the roof to maintain the use of the roof while also generating a support for solar panels. The second phase consists of the installation of photovoltaic panels. The functional unit for which LCA data is obtained is 1 watt peak for a period of 25 years. A value of 430 watt peak (average between 420 and 440 Wp provided by the manufacturer) and an area 1.82 m² is considered for each panel. For the second stage, all usage scenarios occur in Spain and are based on the product characteristics.
- **H5. Completely new construction.** To complete the comparison of results, a totally new building construction of an equivalent neighbourhood with current construction characteristics and conventional systems is envisaged. No demolition energy and emissions of existing reference buildings is taken into account. The construction and systems used in this fifth hypothesis are shown in Annex A.

3.2.2. Constructive characterisation of intervention hypotheses

For H1, H2, H3, and H4, the basic characteristics of the different systems are also defined as the thermal transmittance of the assembly, its density, and its thickness. These values are incorporated into the UBEM UMI templates for further calculations. This transmittance data complies with the limits stipulated for the thermal envelope according to Table 3.1.1.a of the CTE-DB-HE1 [43]. Physical characteristics of intervention hypotheses H1, H2, H3, and H4 are detailed in Annex A.

3.2.3. CO_2 emissions and energy consumed in the Life Cycle Scenarios

The units of the data extracted from each EPD to be transferred to the LCA module of UMI are:

- GWP-total = Total Global Warming Potential (kg CO_2 eq).
- PENRT = Total use of non-renewable primary energy resources (MJ).

From each scenario, the following data has been selected for inclusion in the UMI templates:

- A1-A3: Product stage. A1 Supply, A2 Transport of raw materials to the factory, and A3 Product manufacturing. In UMI Embodied Carbon and Embodied Energy.
- A4: Transport to site. In UMI Transportation Carbon and Transportation Energy.
- A5: Construction and commissioning. In UMI Assembly Carbon and Assembly Energy.

The B1-B7 stages of use that correspond to the operational period have been disregarded due to their low influence on the results. In addition to the C1-C4 and D stages corresponding to the end-of-life, the retirement and recycling stage has been considered in the Hypotheses where relevant. The functional units of all products are converted into square metres for their incorporation into the templates.

For the assessment of the scenario of new buildings, an estimated total emission value of GWP=400 kg CO_2/m², based on the built-up area, was used (Table 2). This data has been obtained in accordance with the studies developed for buildings with similar characteristics to those of this case study, that were located in Spain in Andalusia (385 kg CO_2/m²) [44] and in Madrid [45].

Table 2. Emission data for Carbon and Energy consumed in the various life cycle stages extracted from the EPDs

Hypothesis				PRODUCT A1-A3 Embodied		TRANSPORT A4 Transportation			CONSTRUCTION A5 Assembly	
				Carbon GWP	Energy PENRT	Carbon GWP	Distance	Energy PENRT	Carbon GWP	Energy PENRT
	Element		Coef.	kg CO_2-eq	MJ	kg CO_2-eq	km	MJ	kg CO_2-eq	MJ
H1	1A	m²	1.43	2.19E+00	4.18E+01	1.40E-01	460	2.16E+00	1.15E-01	2.20E+00
TOTAL		m²		2.19E+00	4.18E+01	1.40E-01	460	2.16E+00	1.15E-01	2.20E+00
H2	2A	m²	1.00	1.83E+02	1.93E+03	1.27E+00	400	1.68E+01	1.24E+00	1.89E+01
TOTAL		m²		1.83E+02	1.93E+03	1.27E+00	400	1.68E+01	1.24E+00	1.89E+01
H3	3A	m²	1.47	3.78E+00	5.59E+01	3.81E-02	250	4.20E-01	1.91E-01	2.82E+00
	3B	m²	1.00	1.29E+01	1.44E+02	6.36E-01	212	8.90E+00	4.76E+00	7.02E+01
TOTAL		m²		1.66E+01	2.00E+02	6.74E-01		9.32E+00	4.95E+00	7.30E+01
H4	4A	m²	0.02	1.64E+01	2.52E+02	1.06E-01	40	1.40E+00	1.51E-05	2.26E-04
	4B	m²	0.55	9.07E+01	1.05E+03	7.02E+00	2500	1.03E+02	6.47E-03	9.71E-02
TOTAL		m²		1.07E+02	1.30E+03	7.12E+00		1.04E+02	6.49E-03	9.73E-02

Element	Description
1A	50 mm MW injection in chamber, density 50 kg/m3, λ= 0.035 W/m.ºK
2A	PVC window with triple glazing (12/12/6/12) U= 0.73 W/m² ºK
3A	XPS 50 mm 50 x 50 cm roof tile density 32 kg/ m³, λ=0.034 W/m.ºK.
3B	35 mm 50 x 50 cm precast concrete tile 84 kg/m²
4A	Auxiliary structure Metal frame 20 Kg/m²
4B	Photovoltaic Panel, area=1.82 m² SPICN6(LAR)-66-420-440 Wp

3.3. PH03.1: Results of energy consumption and CO_2 emissions in the renovation phase

For the present study, the energy incorporated in the baseline scenario HO, corresponding to the current state of the buildings, is zero. Although emissions have obviously occurred in the past during the construction and use of the buildings, the study only computes future emissions for the various intervention scenarios. As explained in the methodology, the results obtained with the UMI LCA module and post-processing are included in Table 1 of Annex B and represented in Figure 6. The vertical axis represents, in logarithmic scale, the emissions of each of the intervention models considered, both those of renovation and that of a new plant, in the initial phase prior to the use of the buildings.

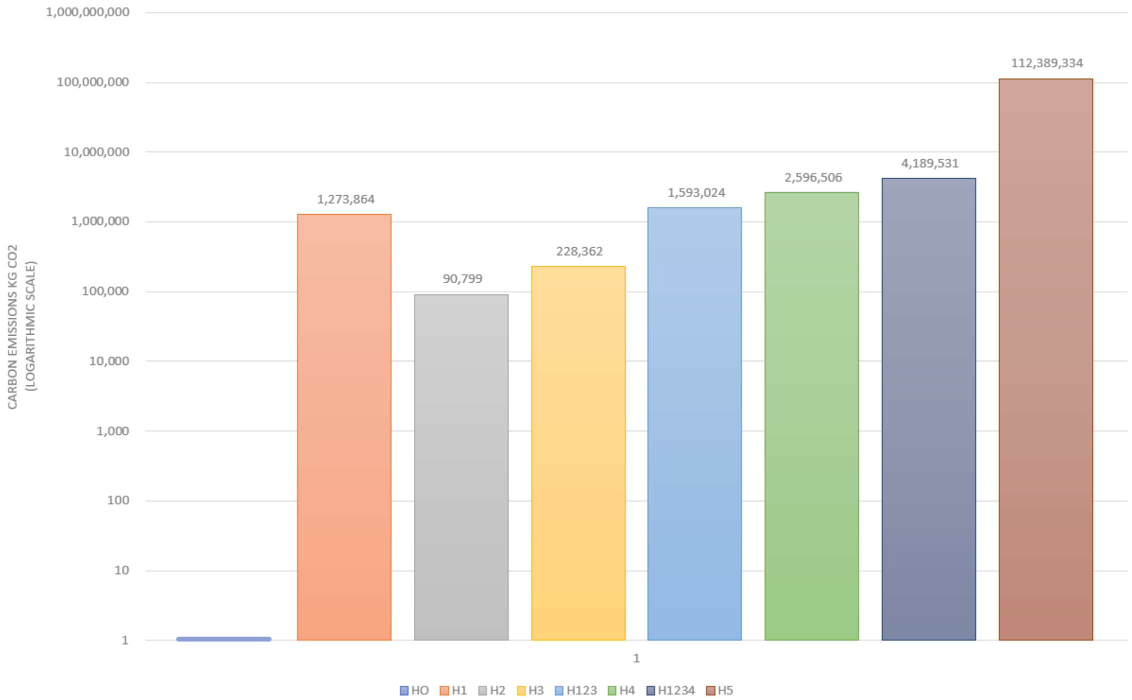


Figure 6. LCA carbon emissions of renovation versus new-building construction phase. GWP in kg CO_2 eq emissions of intervention hypothesis in logarithmic scale

3.4. PH03.2: Results of operational energy consumption and CO_2 emissions

A first step in the calculation of energy consumption and emissions during the lifetime phase is the calibration of the model. To this end, and as described in the methodology, the UBEM model of the sample building has been calibrated according to the results of the BEM model of the same sample building.

3.4.1. Validation of the UBEM model with BEM

Figure 7 represents the sample building model in the BEM calculation tool (Cypetherm HE Plus v23.1, with EnergyPlus™ engine) and in the UBEM model (UMI 3.0). In the validation protocol, the admissible confidence margins according to the reference procedure [36] are ±15% of the demand and ±12.5% of the heating and cooling consumption. Furthermore, the validation results are shown in Table 3.

Figure 7. Aerial view and energy models of the reference sample building in BEM and UBEM tools for the validation test

Table 3. H&C demand and consumption assessment of the reference building

kWh/m²·year	BEM EnergyPlus	UBEM UMI	Deviation %	Max. dev. %	Does UBEM fit BEM?
Heating demand	69.17	64	7.5	±15.0	YES
Cooling demand	42.84	45	-5.0	±15.0	YES
Heating consumption	27.70	25	9.8	±12.5	YES
Cooling consumption	23.80	25	-5.0	±12.5	YES

3.4.2. Operational energy consumption results of the UBEM models of the intervention hypotheses

The characterisation of the energy model of the neighbourhood in the UBEM tool has been carried out and has created various models (UMI bundles) that include changes in the technical and material characteristics of each intervention hypotheses over the current state H0. For each intervention option and on the same reference climate file (EPW reference PVGIS), a dataset of results was obtained that includes the final energy consumption of the entire sector, and that of each of the 357 residential buildings, and also the data disaggregated into its various components (heating, cooling, lighting, etc.). Figure 8 represents the difference in energy consumption before and after the full renovation of the envelopes. The information obtained has been transferred from UMI to a GIS using the cadastral reference as the link identifier.

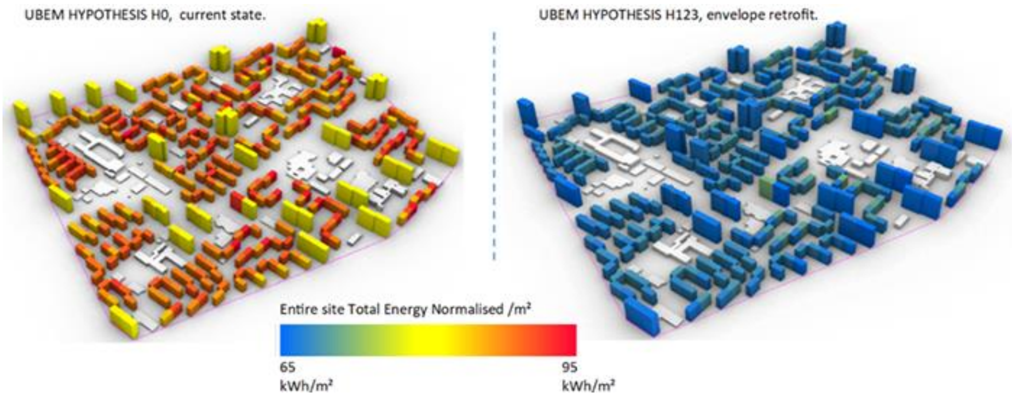


Figure 8. UBEM model overview in Rhinoceros 7 and UMI 3.0 plugin interface. Operational energy consumption kWh/m² output. Intervention H0 vs. H123. Falsecolor scale

3.4.3. Standard operational emissions of the intervention hypothesis

Once the model has been validated, the consumption and emissions associated with the intervention scenarios, under standard operating conditions, are obtained. Table 2 in Annex B shows the results of the final operational energy consumption of the scenarios modelled in UMI and their associated emissions under standard conditions of use of air-conditioning, lighting, hot-water, and equipment services.

By discounting the consumption of lighting and appliances from the previous model, Table 3 in Annex B shows the operational final energy consumption of the scenarios and the associated emissions for air-conditioning and domestic hot-water services, in accordance with the EEC metrics for energy efficiency of European buildings (2010/31/EU Directive) and the Spanish national regulation (RD 235/2013) on the energy performance of buildings [47].

3.4.4. Weighting of simulated operational consumption with local statistics on actual consumption

The following table contrasts the results of the statistical analysis with the results using the GIS tool (Figure 9). These are expressed per percentile of consumption per dwelling from the UMI model and from the consumption recorded in the 2021 housing census for this district [46]. This results in an adjustment ratio of 0.5220 for the consumption calculated with UBEM under standard conditions to the actual consumption of households in that area.

Percentile %	**Census 2021** kWh/Dwl	**UMI UBEM H0** kWh/Dwl	**Bandwidth**	**Census 2021** kWh	**UMI UBEM H0** kWh	**Weight factor**
	A	B	C	A x C	B x C	
10	1,096	4,664	0.125	137	583	
25	1,780	4,829	0.250	445	1,207	
50	2,686	5,019	0.250	672	1,255	
75	3,789	5,391	0.250	947	1,348	
90	5,079	8,317	0.125	635	1,040	
		TOTAL	1	2,836	5,432	**0.5220**
				X	Y	X / Y

Figure 9. Operational energy consumption weighting factor from current census EUI per household

The adjustment factor in the previous section is applied across the board to the aggregated consumption results of the sector, for the various intervention scenarios, and for lifetime operational emission scenarios of the buildings (Figure 9).

3.4.5. Estimation of actual operational energy use and emissions of the intervention scenarios

Emissions are summarised in Table 4 of Annex B. On the other hand, Figure 10 shows the results of standard (H0*) and weighted (H0) consumption for the base case, per use, compared to reference values [[47,48].

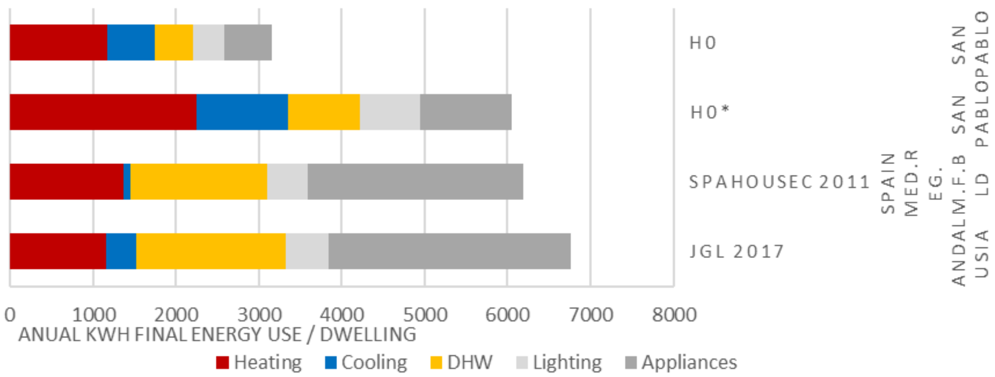


Figure 10. Results of final energy use per service per dwelling in sector and references

Lastly, Figure 11 summarises the emission rates per built area of the lifetime operational hypothesis from Tables 2, 3, and 4 in Annex B.

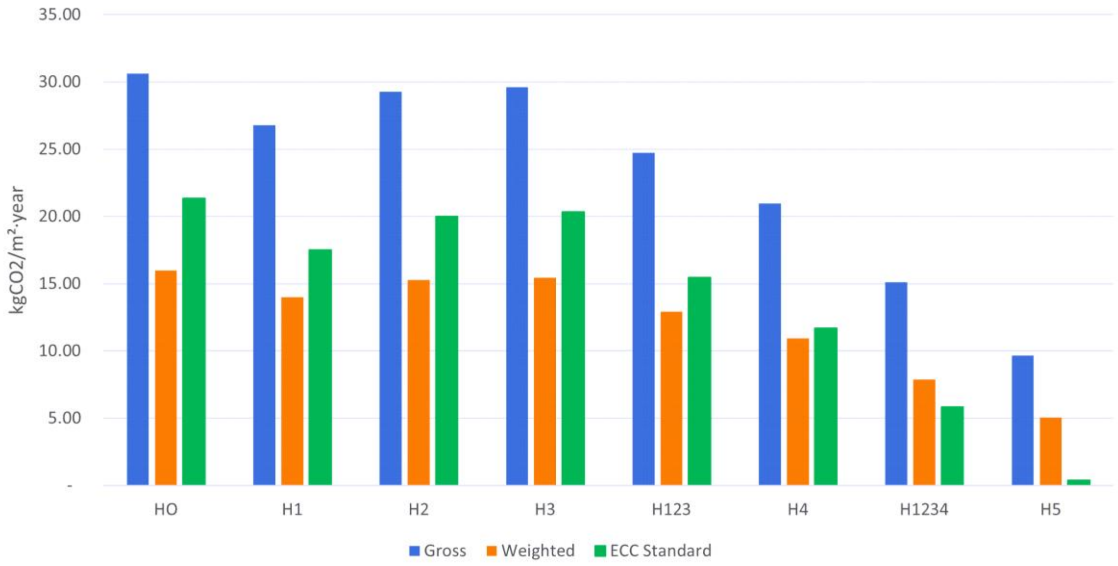


Figure 11. Annual gross, weighted, and EEC standard operational emissions of intervention hypothesis per built area

3.5. PH03.3: Construction and lifetime carbon emissions

Once the weighted/calibrated annual consumptions have been obtained, it is possible to make a projection of the emissions associated with the various intervention scenarios. Time-dependent CO_2 emissions of the whole sector are adopted as the best indicator. It has been assumed that the impact of the energy and emissions of the interventions occurs at the first instant (year 0). Consequently, Figure 12 shows construction and weighted lifetime emission scenarios. This helps to estimate gross global warming potential emissions in equivalent kg CO_2 for each subsequent year until 2100.

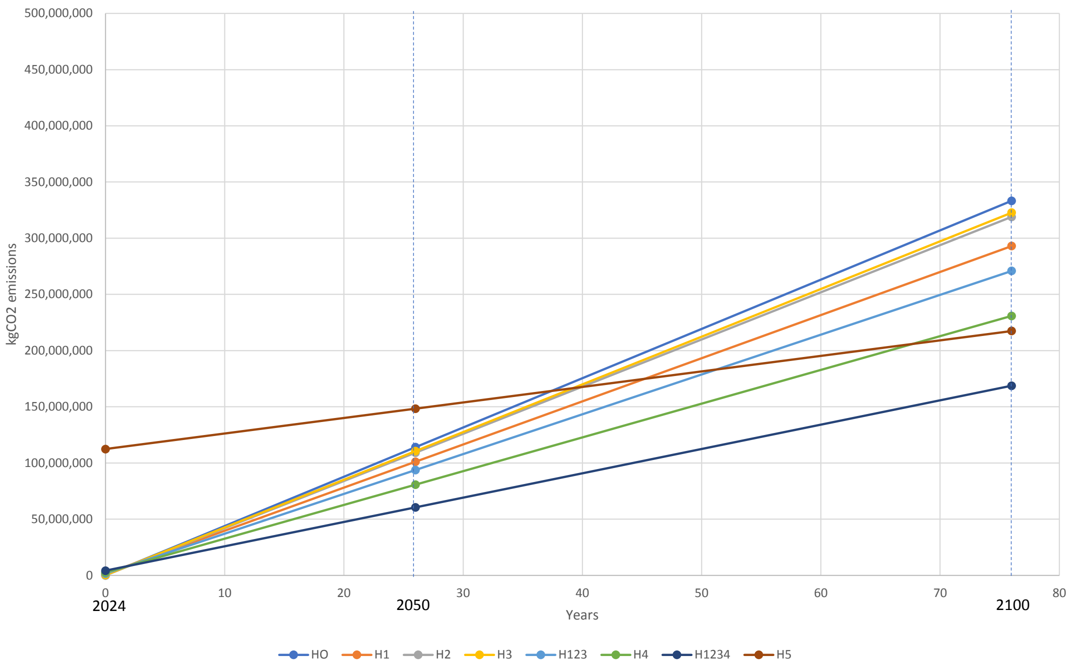


Figure 12. Evolution of the weighted lifetime operational and embodied CO_2 emission scenarios until 2100

Furthermore, Figure 13 plots the evolution of the emissions of the HVAC and DHW services during their lifetime, in accordance with the EEC framework.

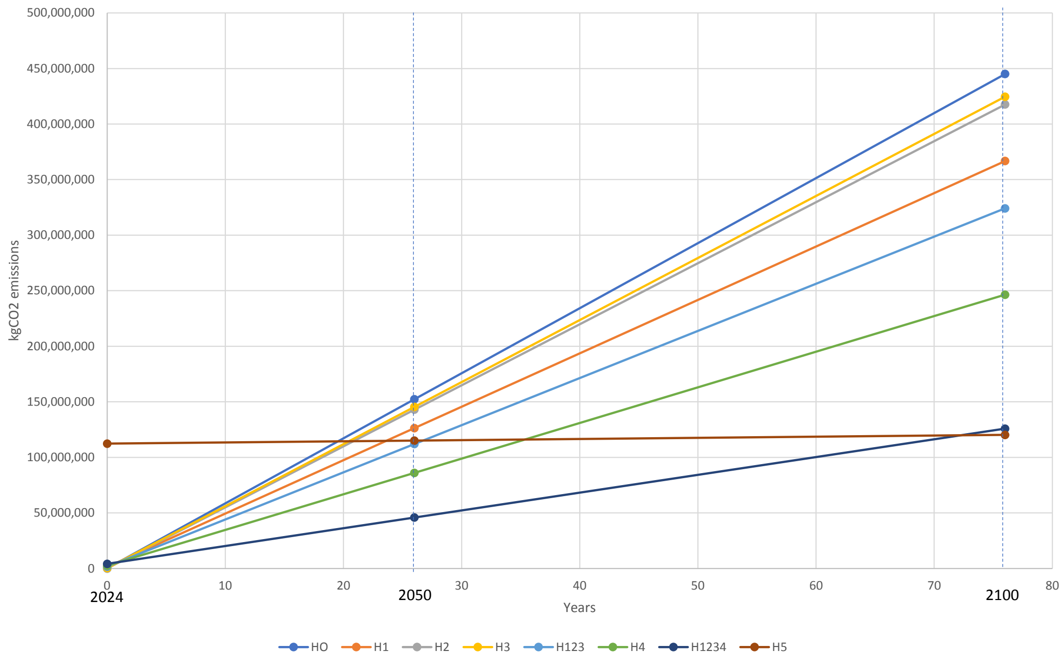


Figure 13. Evolution of the EEC standard lifetime operational and embodied CO_2 emission scenarios until 2100

From this evolution chart of EEC scenarios, it is found that interventions incorporating integral envelope retrofitting and/or PV, H3, and H4, reach the 30% threshold of CO_2 emission savings for access to Next Generation EU funding.

4. Discussion of results

This section addresses the analysis and discussion of results shown in Section 3. In accordance with the objectives of the study, the discussion focuses on Phase 3, and includes the LCA results for the renovation hypothesis carbon footprint, the lifetime operational energy, and the UBEM emission results. It concludes with the analysis of the evolution of the decarbonisation scenarios obtained.

4.1. Analysis of PH03.2: Renovation carbon footprint

The EPD is an open data source to assess the LCA of the manufacturing, transport, and construction processes. The described methodology enables the aggregated embodied energy to be accounted for together with the GWP CO_2 equivalent emissions of every intervention hypothesis defined in Phase 2. Although the results are shown aggregated at district scale, they have been calculated individually for every building in the district with the LCA module of UMI v.3.0.

From among the intervention scenarios, as can be observed in Figure 6, the incorporation of cavity insulation (H1) represents a significant increase compared to the other renovation actions on roofs or windows. It can be explained not only because H1 has a higher embodied energy (see Table 2) but also because it has been applied to a greater area. Nevertheless, the scenario referring to a new building has an impact on CO_2 emissions almost 100 times higher than the renovation of the façade and 27 times higher than the complete renovation with PV.

4.2. Analysis of PH03.2: Operational carbon footprint

According to the methodology, the UBEM workflow requires a first model calculation to run the calibration process. Once the validation condition is verified (see Table 3), the level of accuracy of the model can be considered as acceptable according to the reference protocol established. However, it should be remembered that, as stated in the reference literature [5] by Reinhart and Cerezo-Davila (2016),“an UBEM is not a BEM”, as long as the same level of accuracy is not sought. Nevertheless, in the present case study, it has been possible to verify an accuracy comparable to that which would be required of it as a proposed EEC calculation method submitted for official approval [36]. As seen in Figure 8, the UBEM outputs are individualised for each building in the sector. Energy use is sensitive to building orientation and sun exposure, as well as to construction templates for each hypothesis model simulated.

In order to analyse energy use results it has been necessary to establish two different metrics. The first metric includes all energy uses (weighted with local statistics) and is intended for research on its environmental effects. The second metric only accounts for services included in the EEC framework (HVAC & DHW), and is applied to comply with technical/administrative requirements for public aid programs towards comprehensive rehabilitation.

4.2.1. Gross lifetime final energy use and carbon footprint

According to the results (shown in Table 2 of Annex B), a combined comprehensive retrofit with PV (H1234) can reduce the real carbon footprint of the sector by 50%, while the new-building option reaches a 69% reduction. This can be explained by the enormous differences in the solutions for construction standards versus those for renovations, but it also lies in the improved efficiency of the equipment and installations, such as HVAC and DHW, which are disregarded in the renovation actions. The electricity contribution made by photovoltaics provide a 32% savings in energy consumption in the sector.

The statistical consumption per household has been assimilated with the resulting consumption per dwelling in the UBEM model. Lastly, an adjustment or calibration coefficient of 0.5220 is obtained (see Figure 9) as the quotient between the electricity consumption per household recorded in the area and the results of consumption per dwelling in the UMI simulation. Therefore, the operational consumption values of the lifetime phase can be considered to be aligned with the reference values since they have been weighted in a top-down process with official energy consumption values at district level.

The difference between consumption under standard conditions and the real situation is widely documented in social neighbourhoods in the same region [49]. The adjustment has been made as if all consumption were electric, and hence the consumption of other types of fuels, such as LPG or natural gas for DHW or heating, which are in the minority in the area, are not considered. This simplification underestimates the overall energy consumption in the area, although, since electricity also presents a higher emission factor than do fossil fuels, the final emission balance of the model is compensated.

The results obtained for the weighted H0 hypothesis for the base scenario falls within the expected range for the reference region, by considering that it is a vulnerable neighbourhood. As expected, the H0 results, represented in Figure 10, are below the regional and national average.

4.2.2. EEC standard lifetime carbon footprint

Regarding the EEC standard emissions in Table 3 of Annex B, it can be found that option H4 of overlapping solar panels, (without including their energy contribution), presents an insignificant impact of -0.09% on overall standard energy consumption. It is much lower than expected, given the theoretical effect of the reduction in demand for cooling from a sun protection element over the sector roofs. H3, roof renovation, achieves -4.65%. Although the overall effect on energy demand is slight, both actions must be considered as positive due to the local effect on upper floor dwellings.

The H1 intervention on the façades alone exerts the greatest impact on the reduction of energy demand, at 17.88%, which is approximately 3 and 4 times that of the intervention on windows and roofs. Moreover, the combined scenario H123 represents a reduction in standard consumption of 27.53%, remarkably close to the minimum of 30% required for access to Next Generation EU funding. This reduction is comparable with emission-saving values in studies with similar characteristics for this type of intervention [50]. Nevertheless, the incorporation of PV into the base scenario (H4), would exceed this threshold (31.52%), although it would not exert an impact on the improvement of the building envelope or on the comfort of the users. It follows that compliance with the requirements alone provides no guarantee of an improvement in the habitability of dwellings. However, passive measures on the building envelope must be complemented with actions on the installations (HVAC & DHW) and renewable energies for their technical/economic feasibility.

Overall, the observed effect of the PV contribution is truly relevant. In the case of the envelope refurbishment, H1234, the savings reach 72.66%, which is almost ¾ of the baseline scenario. The PV included in the new-building intervention, H5, almost reach 100%, thus achieving a zero-energy building (ZEB) standard for the whole sector.

4.3. Analysis of PH03.3: Carbon footprint scenarios

The joint representation (seen in Figures 12 and 13) of the carbon footprint of the intervention and use phases facilitates the unequivocal contrast of the temporal evolution of each intervention scenario and their comparison.

4.3.1 Gross carbon footprint scenarios

The initial emissions of H5, the new-building case, are equivalent to the emissions of H0, base scenario until 2050, when the new building would be 30.1% more than the ‘no intervention’ case. By the year 2100, the new-building scenario would result in lower CO_2 emissions than all retrofit scenarios except for the comprehensive retrofit + PV (H1234).

In 2050, the new-building scenario (H5) emissions are 30.09% higher than the baseline scenario (H0), while the most ambitious scenario (H1234) would reduce current emissions by 46.97% compared to the baseline scenario. In this respect in 2050, the lowest expected carbon footprint per housing area (H1234) is 220.28 kg CO_2/m^2, with a base scenario H0 of 415.41 kg CO_2/m^2 and a maximum of 540.42 kg CO_2/m^2 for the new building (H5). This scenario presents the least inclined slope of the whole complex, in accordance with the greater efficiency of its buildings, not only for their thermal envelope, but also for the installations (air-conditioning, solar DHW, etc.). For future studies, it would be advisable not to disregard the potential of installation renovations in the intervention strategies.

Even if the life cycle is exceeded, if the results are extrapolated to the 22nd century, then the H5 new-building scenario fails to offset the H1234 comprehensive retrofit + PV scenario emissions 140 years from now.

4.3.2. Renewable energy extensive contribution

It can be noticed that the incorporation of PV almost immediately offsets the emissions (0.98 years), and by 2050 (the end of the foreseeable lifetime) would reduce the carbon footprint of the baseline scenario by 30%, and hence there is a clear benefit of extensive PV installation for self-consumption in existing buildings.

4.3.3. Renovation vs. new-building scenarios

The new building outperforms any real intervention in terms of emissions, while its standard emissions are equivalent to the comprehensive retrofit H123=H5, thereby improving on the current state and partial interventions. The emissions of the new plant would be equal to those of the full retrofit with PV, H5=H1234, in 2100.

5. Conclusions

This research has applied an innovative methodology that integrates UBEM and LCA models in the same case study. This approach has enabled an assessment of the environmental impact at the 2050 horizon considering greenhouse gas emissions, both due to the functioning of buildings (operational emissions) and construction processes (embedded emissions). The application to the case study of an obsolete neighbourhood was intended to evaluate the results of several environmentally low-impact retrofitting scenarios, which has been achieved, as the results show. Furthermore, it has been possible to compare the results of the extensive retrofit strategies with an alternative scenario of constructing equivalent new buildings in accordance with current quality standards. For this comparison, a time projection with various intervention scenarios has been considered.

It has been demonstrated that this GIS-UBEM-LCA methodology has been particularly suitable for the assessment of obsolete residential areas of low-income, using open data. The typological repetition that characterises this type of dwelling has facilitated the collection of data using a reduced number of archetype templates for their characterisation. The use of the UBEM-LCA tool (UMI v3.0) has allowed an assessment at district scale, by developing simulation models that incorporate the environmental complexity of the urban layout (shade from buildings and various solar orientations), as well as the material and constructive characterisation of a set of 357 buildings in a single scenario. The energy simulation of the model, once having been calibrated with reference methods, provides not only results on aggregate energy consumption and on embodied energy, but also specific results for every building for each intervention scenario analysed.

The findings show that total emissions (embedded and operational) are lower for retrofitting existing buildings compared to new construction at horizon 2050. The results are still in favour of retrofitting even at horizon 2100. The study shows that to reach the targets of net-zero greenhouse gas emissions by 2050, it is a priority to upgrade the existing residential stock, especially obsolete residential neighbourhoods built between 1951 and 1980.

The feasibility of the methodology has been demonstrated in the case study of the district of San Pablo in Seville, where it has been possible to develop a physical bottom-up model for the estimation of energy consumption and its carbon footprint from open data at the scale of individual buildings for an entire residential sector. Our method has enabled the life cycle of the neighbourhood to be analysed with an extended time scenario (2050-2100) based on LCA and UBEM models and validated with reference methods. Moreover, it evaluates various scenarios of extensive intervention, by integrally computing energy consumption and gross or standard CO_2 emissions, in accordance with the objectives of the study.

Modelling using UBEM methodology and open data is cost-effective and comparable to other much more resource and time-intensive BEM models. This model can rigorously analyse the impact of massive intervention strategies at neighbourhood scale and can determine the foreseeable effects over their lifecycle with an acceptable range of confidence. Based on the results and their analysis, the research findings have provided evidence that:

- In the analysis of operational emissions, it is necessary to use a double metric adapted to two different phenomena: actual gross consumption and emissions, towards an environmental approach and a reduction target scope; and EEC standard emissions, for technical and administrative verification of technical solutions and compliance with standards for renovation incentives.
- During the construction phase, energy and associated emissions are in the order of 100 times lower in the retrofit cases compared to the equivalent new construction. Initial energy over a 70-year lifetime horizon constitutes up to 3% of operational energy in the retrofit cases, and 116% for new buildings.
- In our study, Net-Zero EEC standard emissions in building stock by 2050 are only observed in the scenario of new buildings. None of the renovation hypotheses analysed reaches that neutrality level, and hence additional measures should be considered towards achieving this level in extensive renovations.
- The alternative of building new districts at the present time would lead to future higher greenhouse emissions, caused by the impact of the construction process of new energy-efficient buildings. To clarify this consequence, emission targets should consider the cumulative emissions of the period from now up to the year 2050, and not only the emission rate in 2050.
- The minimum real carbon footprint expected by 2050, in the best-case scenario (H1234), is of 220.28 kg CO_2/m^2, which improves on the base scenario H0 by 46.97%, which is 415.41 kg CO_2/m^2. The new-building hypothesis (even excluding demolition energy) presents the highest impact among all the options, at 540.42 kg CO_2/m^2. That worsens the base scenario by 30.09%, and therefore it can be concluded that this is the worst option for the 2050 horizon, and is still a worse option than the full envelope renovation with PV by 2100.
- The incorporation of on-grid PV for self-consumption at neighbourhood scale offers major benefits even from a very early stage, and hence its massive incorporation into urban regeneration actions seems clearly indicated to help meet the 2050 decarbonisation targets.

Limits for the present research consist of certain simplifications in the formulation of time scenarios, whereby the energy consumption is considered constant, while in fact it might be affected by changes in climate, user behaviour, and active systems such as HVCA and DHW. No energy spent on building conservation during the lifetime has been taken into account. Changes in future weather conditions influencing the evolution of the operational energy use has not been considered. Conversion factors from final energy to the equivalent primary and carbon emissions could change in the future according to the energy distribution framework. Lastly, the future lines of research that this investigation has entailed are set out below.

- The results obtained at neighbourhood level, broken down per building, will enable the prioritisation of interventions according to their degree of effectiveness and potential for improvement over the baseline scenario.
- Actual consumption forecasting models can be improved by characterising the usage profile and the installation systems present in buildings, by employing reference consumption and socio-economic open datasets available at district scale.
- Extensive interventions including hypotheses regarding the renovation of active systems (HVAC & DHW) deserve to be explored in future case studies, as do smart metering and control systems.
- The developed methodology can be replicated for the assessment of other cases of obsolete residential neighbourhoods and can serve as a tool for environmental impact assessment of rehabilitation strategies at district level.

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CRediT authorship contribution statement

All authors have conceived, designed, and performed the experiments; analysed the data; have written, reviewed and approved the final manuscript.

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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ANNEX A. Case Study Characteristics

Table A1. Construction, structure, and installation features of the current state (Hypothesis H0)

Hypothesis H0	BUILDING TYPE				U value	Thick.
CONSTRUCTION SYSTEM	CAT A	CAT B	CAT C	CAT SOCIAL	W/m²·K	cm
Façade	Cladding + 12 cm brick + 5 cm air chamber + 7 cm hollow brick				1.56	27
Ground floor	Artificial stone paving + Cavity floor slab				0.75	17
Partition floors	Artificial stone paving + Floor slab				2.23	20
Party wall	12 cm brick masonry + MW insulation blanket				1.83	16
Roof	Floor slab + membrane + slag insulation + ceramic tile flooring				1.60	28
Windows	Steel carpentry + 1single-pane glazing				5.70	5
Vertical partitions	Gypsum-rendered hollow brick partition.				2.48	8
Window/Wall Ratio, WWR	24.67%	17.71%	13.44%	15.41%		
Structure	One-way reinforced concrete slabs & concrete columns					
Domestic Hot Water, DHW	Electric heater					
Ventilation	Natural					
Heating	Heat pump DX A/A Split COP 2.5					
Cooling	Heat pump DX A/A Split EER 1.8					

Table A2. Construction, structure, and installation characteristics of H5, new-building hypothesis

H5	BUILDING TYPE				U value	Thick.
CONSTRUCTION SYSTEM	CAT A	CAT B	CAT C	CAT SOCIAL	W/m²·K	cm
Façade	Cladding + 12 cm brick masonry + 3 cm PUR + 5 cm air chamber + Lightweight gypsum plasterboard cladding with 5 cm MW insulation.				0.31	27.0
Ground floor	Artificial stone pavement + Cavity floor slab				0.75	28.0
Partition floors	Artificial stone pavement + Floor slab				2.23	28.0
Party wall	12 cm brick masonry 12 cm + MW insulation blanket				1.83	16.0
Roof	Floor slab + membrane + 8 cm XPS insul. + ceramic tile flooring				0.42	28.5
Windows	Al. carpentry with thermal break + Low-emissivity double-pane glazing				2.56	7.0
Vertical partitions	Lightweight gypsum plasterboard partition system with MW				0.68	8.0
Window/Wall Ratio, WWR	24.67%	15.41%	17.71%	13.44%		
Structure	One-way reinforced concrete slabs & concrete columns					
Domestic Hot Water, DHW	Gas boiler + solar thermal 70% contribution					
Ventilation	Mechanical					
Heating	Heat pump DX A/A Split COP 2.7					
Cooling	Heat pump DX A/A Split EER 2.5					

Table A3. Physical characteristics of intervention hypotheses H1, H2, H3, and H4

Systems	Description	U value	Density	Thick.
		W/m²·K	kg/m³	cm
H1: Façade	12 cm brick masonry + 5 cm cavity insulation + 7 cm brick masonry	0.53	50	27
H2: Openings	PVC window frame thermal break + triple glazing and low-e glazing	2.26	873	7
H3: Roof	Ash waterproofing and insulating sheet + Floor screed with 5 cm insul.	0.42	1.007	38
H4: Roof	Photovoltaic panels on auxiliary structure	-	-	-

ANNEX B. Case Study Results of Energy and Carbon Emissions

Table B1. Intervention scenarios: LCA Embodied energy and GWP CO_2 eq in sector

Case	Description	Embodied energy		GWP emissions	
		kWh	kWh/m²	$kgCO_2$ eq	$kgCO_2$ eq/m²
H0	Base	-	-	-	-
H1	Cavity injection	24,158,461	88.01	1,273,864	4.64
H2	Window renovation	935,391	3.41	90,799	0.33
H3	Roof improvement	2,826,814	10.30	228,362	0.83
H123	Envelope retrofit	27,920,666	101.72	1,593,024	5.80
H4	Base + PV.	8,886,807	32.38	2,596,506	9.46
H1234	Envelope retrofit + PV	36,807,472	134.10	4,189,531	15.26
H5	New building with PV	314,816,063	1,146.95	112,389,334	409.46

Table B2. UBEM-modelled intervention scenarios: annual operational final energy use and carbon emissions

Case	Description	Annual Consumption		Annual Emissions		Reduction
		kWh	kWh/m²	$kgCO_2$	$kgCO_2/m^2$	%
H0	Base	23,533,681	85.7	8,401,524	30.61	-
H1	Cavity injection	20,600,301	75.1	7,354,307	26.79	12.46%
H2	Window renovation	22,517,655	82.0	8,038,803	29.29	4.32%
H3	Roof improvement	22,770,969	83.0	8,129,236	29.62	3.24%
H123	Envelope retrofit	19,016,999	69.3	6,789,069	24.73	19.19%
H4	Base + PV	16,116,628	58.7	5,753,636	20.96	31.52%
H1234	Envelope retrofit + PV	11,614,392	42.3	4,146,338	15.11	50.65%
H5	New building with PV	7,419,028	27.0	2,648,593	9.65	68.47%

Table B4. UBEM-modelled intervention scenarios: annual EEC standard operational final energy use and carbon emissions (HVAC and DWH services)

Case	Description	Annual Consumption		Annual Emissions		Reduction
		kWh	kWh/m²	$kgCO_2$	$kgCO_2/m^2$	%
H0	Base	16,403,981	59.76	5,856,221	21.34	-
H1	Cavity injection	13,470,601	49.08	4,809,005	17.52	17.88%
H2	Window renovation	15,387,955	56.06	5,493,500	20.01	6.19%
H3	Roof improvement	15,641,269	56.98	5,583,933	20.34	4.65%
H123	Envelope retrofit	11,887,299	43.31	4,243,766	15.46	27.53%
H4	Base + PV	8,986,928	32.74	3,208,333	11.69	45.21%
H1234	Envelope retrofit + PV	4,484,692	16.34	1,601,035	5.83	72.66%
H5	New building with PV	289,328	1.05	103,290	0.38	98.24%

Table B4. Intervention scenarios: annual lifetime operational standard and weighted carbon emissions

Case	Description	Standard emissions	Weighted* emissions.	
		$kgCO_2$	$kgCO_2$	$kgCO_2/m^2$
H0	Base	8,401,524	4,385,480	15.98
H1	Cavity injection	7,354,307	3,838,847	13.99
H2	Window renovation	8,038,803	4,196,144	15.29
H3	Roof improvement	8,129,236	4,243,349	15.46
H123	Envelope retrofit	6,789,069	3,543,800	12.91
H4	Base + PV	5,753,636	3,003,319	10.94
H1234	Envelope retrofit + PV	4,146,338	2,164,331	7.89
H5	New building with PV	2,648,593	1,382,529	5.04

(*) Weighting Coefficient= 0.5220

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Declaration of interests

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