Application of the cost-optimal methodology to urban renewal projects at the territorial scale based on statistical data. A case study in Spain.

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0. Abstract

As tomorrow's cities are already largely built, many strategies stress the importance of urban renewal processes to address current energy issues. This paper focuses on the Spanish residential building stock built until 2001, which has a low level of energy performance.

Considering the current economic crisis, the future lies in renovating the built environment, which holds a significant energy-saving potential. This potential is here quantified by applying the cost-optimal methodology, initially proposed by the Energy Performance of Buildings Directive, and which calculates cost-optimal levels of minimum energy performance requirements at the building and component scale.

The originality of our study lies in the application of this methodology at the territorial scale, comparing different retrofitting scenarios by scaling-up building-scale results through an archetypal approach. We also describe an Excel-based tool allowing two types of studies: (i) at the building scale, for one archetype in a particular climatic zone; (ii) at the territorial scale, to have an overview of all building archetypes and climatic zones simultaneously. Results include economic aspects, energy consumption and savings and associated emissions.

The outcome can help construction-sector firms adapt their business plan, while also providing stakeholders with decision-support to promote a sustainable renewal of the building stock.

Keywords: *cost-optimal methodology; cost-effective strategies; urban renewal; sustainable retrofit; environmental assessment; decision-making tool; residential building; sustainable architecture.*

1. Introduction

1.1. European and Spanish building stock

One of the top priorities regarding the built environment in European countries is to reduce energy consumption and greenhouse gas (GHG) emissions and increase the use of renewable energy [1–5] . Due to the low replacement rate of existing buildings – about 1-3% per year in EU countries [6] – the majority of buildings that will exist in 2050 is already built, with many of them having a low level of energy performance [7]. In this context, the retrofit of existing buildings offers significant opportunities for reducing energy consumption and GHG emissions [8]. In fact, the International Energy Agency (IEA) estimates that the potential energy savings for 2050 are of about 1,509 million tonnes of oil equivalent [9], with a 50-75% saving when considering only the improvement of the building envelope [10]. It therefore seems clear that the residential building stock in EU-27 offers high potential for energy efficiency gains [11,12]. This large potential energy saving is particularly relevant to the Spanish context [7], where most residential buildings were constructed before 2001, when thermal regulations were modest [13–18].

According to the Energy Performance Certification (EPC) in Spain, which rates buildings from A (best) to G (worst), 96% of the certified 1.4 million existing buildings are below the current legal requirements set at an EPC level C [19]. The EPC rate depends on the type of building and the climatic zone where it is located. In general, the different levels follow a linear dependency: a building with the lowest qualification consumes ten times more than a building with the highest level of performance [20,21].

The residential building stock as a whole emits about 35 $kgCO_2/m^2$ per year in terms of primary energy (PE) consumption [22], a value that is far from the ambitious objectives of the EU horizon 2050 for new and existing buildings of around 3 $kgCO_2/m^2$ [23].

However, by considering only envelope retrofitting, it would be possible to reduce the energy used by residential buildings up to 25% by 2020 [24]. For the 2050 horizon, the total savings could reach 71% in terms of energy and 73% in terms of GHG emission [22]. These values highlight that it is theoretically possible to achieve the EU's 20% energy-saving target for 2020, as well as the long term 80-95% GHG emissions reduction target for 2050.

1.2. European and Spanish regulations and cost-optimal methodology

In response to the strong demand for housing, the construction of residential buildings in Spain underwent unprecedented growth, especially between 1960 and 2001 [13,14]. Unfortunately, these buildings were designed either without ensuring a minimum level of construction quality, in terms of comfort and energy efficiency, or relying on insufficiently restrictive regulations.

The first regulation seeking to improve the energy performance of buildings resulted from the energy crisis of 1973: the NBE-CT-79 - *Thermal Conditions in Buildings*, published on July 6, 1979 [25]. However, this first regulation did not specify a target for reducing energy consumption. It simply established a set of acceptable constructive solutions, without defining a protocol for controlling the quality of the building envelope.

The most important change appeared with the European Directive 2002/91/EU concerning the energy efficiency of buildings. The transposition of this Directive in Spain is reflected by Royal decree (RD) 314/2006 – *Technical Building* Code (CTE) [26], RD 1027/2007 – *Thermal facilities in Buildings* (RITE) [27] and RD 47/2007 – *Energy Performance Certification* (EPC) *protocol for new buildings* [28]. The mission of these new standards was to regulate all construction parameters and to define energy limits and steps to follow for the energy certification of new constructions [18,27,28]. This situation put the existing building stock in the spotlight, due to its enormous energy consumption and GHG emissions [7].

With the focus placed on the continuous increase in the demand for new residential buildings up until 2001, only recently has there been specific Spanish legislation in terms of building rehabilitation. The three most recent regulations appeared in 2013 [18]:

- RD 235/2013 – New protocol for the EPC to include existing buildings [20].
- CTE 2013 – Updated CTE for regulating the energy requirements of new and existing buildings [18].
- RD 8/2013 – Law to promote urban renewal projects [29].

These changes in the regulatory framework try to respond to the requirements of the European Directive 2010/31/EU, which establishes that all public and privately owned buildings must be nearly Zero Energy Building (nZEB) from December 31 2018 and 2020 respectively. In this directive, the cost-optimal methodology was mentioned for the first time [17]. Initially, this methodology was proposed by the EU to study different building retrofitting scenarios. It consists in a multi-criteria assessment that allows comparing different levels of intervention under various macro-economic scenarios, in terms of cost-effective strategies and energy and environmental savings [8,12,17,22,30–33].

In parallel, the evolution of EU directives continued. In 2012, the 2012/27/EU Directive was presented [34]. It defines the PE and GHG emissions savings to be achieved, and requires all EU member states (MS) to define specific strategies to achieve those objectives. As a result, in the Spanish context, the current legislation does not yet meet the requirements of the latest EU directives.

Therefore, new regulatory changes are necessary in the short term in order to reach the required level, because all EU countries should have submitted plans and regulations for the promotion of nearly nZEB, as well as measures to promote building energy rehabilitation projects following the cost-optimal methodology to ensure the viability of the improvement strategies [17,22,35].

1.3. Overview of study

Attempting to address these issues, this research proposes an application of the cost-optimal methodology at the territorial scale to estimate the energy-saving potential of the residential buildings built before 2001 in Spain. The originality of this study lies in the application of this methodology at a large scale, using statistical and population census data and taking into account the 12 climatic zones of the Spanish territory. The paper moreover describes an Excel-based calculation tool, developed to enable professionals to make strategic decisions by helping them select the best strategy for achieving the European requirements for 2020 according to the nZEB. This research is based on the work conducted during the Master thesis of the first author [36], which represents the main source for the content of this manuscript.

The structure of the paper is articulated in seven sections: (1) introduction, (2) literature review, (3) definition of the main objectives, (4) proposed methodology to carry out the development of a decision-making tool, (5) presentation of the main results through a case study in Spain, testing different renovation scenarios and different temporal horizons, (6) discussion of results, and (7) conclusions and recommendations to promote energy renovation of the building stock.

2. Literature review

The EPBD recast [17] proposes that all MS establish a comparative framework to calculate cost-optimal levels of minimum energy performance requirements for buildings and building components, using the cost-optimal methodology. Table 1 summarizes how this methodology has been employed in various studies conducted in a specific climatic context for investigating renovation strategies over existing buildings.

In terms of scale, we observe that a majority of applications of the methodology have been at the building or component scale, especially to compare different constructive solutions and construction materials or to optimize the insulation thicknesses of the building envelope [8,12,32,33,37–42]. When at the building scale, studies typically consider only one specific typology for a given period of time or year (e.g. multi-family house of 1960-1990 [8]).

To analyse the existing building(s), and according to the purpose of the study, different approaches are used. The majority of the publications make a classification of the building stock in different categories using the concept of '*reference building*' based on real building examples in a specific context [40,43,44]. This concept is applied for example in the Typology Approach for Building Stock Energy Assessment (TABULA) project [45] with the aim to have a harmonized database of existing buildings at the European level. Unfortunately, this database presents a lack of information for specific countries (e.g. Spain) and does not contain enough information to depict the whole building stock according to climatic zones.

Another approach consists in using statistical data to extract statistically relevant parameters [32,46,47]. This information can be used, as done by Schwehr et al. [48], to define *'building typologies'* within the building stock, where each typology corresponds to a building with the same set of parameters, including period of construction, context, construction characteristics, and other features related to the assessment objectives. Making an aggregation by groups using, for example, the construction period as the main parameter can then allow obtaining results for a larger scale [49].

Another statistics-based concept is that of *'archetype'*, defined as a theoretical model that represents each of the different building typologies [50]. This method is used to classify the building stock according to different parameters such as climatic conditions, construction period and context. Each archetype definition represents a major type of dwelling that can be used as input data for energy simulation [51]. Then, the estimation of energy consumption and GHG emissions of each archetype can be scaled-up to be representative of the regional or national housing stock. This is done by multiplying the results by the number of dwellings (given by the statistical data) which fit the description of each archetype [52]. This scaling-up method can also be understood as a bottom-up approach for representing the building stock.

The general purpose of application of the cost-optimal methodology is to enable the comparison of scenarios integrating different energy-efficient measures (EEM), or to identify the most cost-optimal combination of EEM. In most cases, the EEM consist of passive strategies, while a few studies have considered a mix of passive and active strategies as well as renewable energy technologies (RET) [42,43,53].

The multi-criteria analyses include outputs such as the Net Present Value (NPV), global cost, GHG emissions and energy savings, sometimes resulting from a full Life Cycle Assessment (LCA) [23,32]. However, all assessments are based on a fixed horizon period and show a unique value for each output as opposed to a temporal profile.

Looking at the whole workflow adopted in the different publications, we have identified two main different methods: simplified and complex.

The simplified methods [40,54] propose a simple way to calculate the energy demand and an expert system to assist the decision-making, assuming a certain level of error or uncertainty in the results. These methods are commonly applied at larger scales, for instance to study a regional building stock taking into account different climatic conditions using the Degree Days simplified methodology.

The complex methods [32,53,55] propose advanced simulation-based multi-objective optimisation, using a combination of tools (EnergyPlus, TRNSYS, MatLab) and genetic algorithms. They are commonly applied at a more detailed scale, e.g. to define the optimal choice of materials at the building scale, and try to be as accurate as possible [52,56,57].

Table 1: Literature review: implementation of the cost-optimal methodology in renovation projects considering scale, building typology, context and climate conditions, along with main objective of the application. See list of abbreviations at the end of the manuscript.

Ref.	Building typology and database	Context	Considered measures	Main objectives
[43]	Single-family (SF) and multi-family (MF) houses classified in three construction periods (pre-1980, 1981-2000 and after 2000). TABULA database.	Greece, three climatic zones defined by HDD.	Passive (add thermal insulation and replace windows), active (new boiler) and RET (ST panels for domestic hot water (DHW)) according to two scenarios (standard and ambitious).	Overview of total consumption and CO_2 emissions of building stock and estimation of saving potentials. Use of payback period (PBP).
[55]	Semi-detached SF house, built in 1945.	Portugal, no specified climatic zones.	Three groups of measures, including passive (type of insulation) and RET (ST panels for DHW).	Comparison between different construction materials. Based on multi-objective evaluation using GenOpt and Tchebycheff optimization technique.
[50]	Nine residential buildings built before 1960, 1960-1990 and after 1990. Concept of Archetype. CYPE Engineers database.	Portugal, Lisbon climate data conditions.	Passive strategies (insulation thickness and windows), six options of HVAC systems with solar thermal panels.	Use of cost optimal methodology to define range of optimal U-values for walls, roofs and windows.
[58]	Results of 26,000 renovated dwellings.	Spain (Madrid).	Passive (add thermal insulation and replace windows).	Application of four public plans to help owners replace windows by more efficient ones; show that incomes due to value-added tax (VAT) (related to renovation work) is superior to total amount of public aids to dwelling owners.
[40]	MF buildings, from 1946 to 1960, using TABULA database.	Italy, climates with 2100 and 3000 HDD.	Single EEM taking into account passive, active, RET and HVAC systems strategies.	Optimal value of design parameters (single strategies), comparing energy performance and global cost.
[46]	A SF house, statistical census data 2001.	Italy (Cesena), 2256 HDD, according to Italian standards.	Four EEM (insulation, windows, new boiler and solar thermal panels for DHW).	Comparison of energy savings between four construction periods for same reference building (1950, 1970, 1980 and 1995).
[59]	Construction level.	Greece (Athens), Italy (Rome) and Spain (Madrid), based on HDD and CDD.	Thickness of insulation as optimisation parameter.	Find optimum balance between cost, energy savings and thickness of insulation.
[42]	Five reference office public buildings.	Italy, Portugal, Romania, Spain and Greece.	Passive (insulation, windows, shading systems), active (electricity-based systems, lighting) and RET (solar thermal and photovoltaic panels).	Find optimal global cost for renovation projects in different countries (300 - 550€/m^2).

Table 1 (cont.): Literature review: implementation of the cost-optimal methodology in renovation projects considering scale, building typology, context and climate conditions, along with main objective of the application. See list of abbreviations at the end of the manuscript.

Ref.	Building typology and database	Context	Considered measures	Main objectives
[53]	Reinforced concrete MF building.	Italy, no specified climatic zones.	Eight design variables (coating and insulation of roof, insulation on walls, mechanical ventilation system, temperature set points, double glazing, and HVAC systems).	PE consumption versus comfort criterion optimization.
[8]	MF building (reference building period 1960-1990).	Portugal, Lisbon climate conditions.	Passive strategies: improving windows, adding insulation (roof, floor and walls).	Comparison between global cost and PE consumption of different scenarios.
[41]	MF building, built in 1970.	Spain (Tudela).	Three scenarios (minimum requirements of current regulations, deep retrofit, and a combination with RET strategies).	LCC comparison (global cost versus CO_2 emissions and PE consumption).
[39]	MF building (specific case study) built in 1931.	Vienna, no specified climatic conditions.	Evaluation of different types of insulation.	LCC though multi-criteria assessment taking into account economy, ecology and cultural history.
[47]	Six MF buildings, built 1966-1982. Statistics database.	Estonia, cold climate.	Passive (insulation, windows) and active (ventilation and heating system). Three governmental subsidies level (15, 25 and 35%).	Comparison between investment using NPV and energy savings for 2030 horizon.
[60]	SF house, non-detailed case study.	Belgium context (without taking into account different climatic zones).	Passive and active strategies without specific details.	General approach, implementation of decision-making tool (www.renofase.be).
[12]	Eight primary school buildings, with different ages and construction types.	Austria, no specified climatic conditions.	Various optimization variables (passive and active strategies).	Optimization using LCC assessment comparing heating energy demand versus NPV.
[61]	MF building (three case studies with same geometry but different envelope properties)	Turkey (Istanbul, Antalya and Erzurum). Represent three of five main climates in country.	Mainly passive strategies (envelope building improvements).	Comparison between global cost and PE consumption of different scenarios.
[32]	Representative MF buildings, period 1950-1980, population and housing census.	Spain (Madrid).	Three scenarios according to current practice, current regulation and passive house label.	Optimization method using Pareto front, analysing LCC and LCA.

The novel application of the cost-optimal methodology that we propose takes into account these two levels of complexity by defining a pre-simulated energy demand database of seven archetypes in 12 climatic zones, obtained using the official software (CE3x) [62] for generating EPC in Spain. Using this software allows us to compare our results to the EPC database of real buildings [7], in order to test the accuracy of the results at the territorial level, which is our target scale. Therefore, as Spain's EPC registry becomes more complete [19], our database may be updated without conflicts.

The pre-simulated database is generated by building upon the work conducted by the Rehabilitation Working Group (GTR) [63]. The GTR, who's objective is to facilitate the transformation of Spain's building sector, has published three main reports that detail the Spanish legislation, examine the existing housing stock, and propose a general operational framework for the building renovation sector in Spain [64–66]. In our work, the building typologies along with their parametric details identified by the GTR from the statistical census data of 2001 [13] are used to define our archetypes. This approach allows us to obtain a more detailed, precise and context-specific database, compared for instance to TABULA [45].

Pre-simulated energy demand data are obtained for the current status of each archetype, as well as following two retrofitting strategies (minor and deep) in which passive strategies are considered. Active systems and solar-based RET are then included to define complete packages of mixed strategies.

In addition to the standard cost-optimal methodology static outputs, results from a Life-Cycle Analysis (LCA) and Cost (LCC) analysis are presented to provide a temporal representation of the different retrofitting scenarios, considering the moment of application of each EEM. The final contribution of this work is the implementation of the whole workflow into an Excel tool, for use by professionals such as planners and policy-makers.

3. Objectives

This work focuses on the residential building stock, which represents 75% of the built surfaces in Europe [22]. While our study includes archetypes built before 1960, we are specifically concerned with buildings constructed over a period of 40 years from 1961-2001, when the rhythm of dwelling construction was very high. As shown in Figure 1, over 16 million dwellings were built on the Spanish territory during this period; 9.2 million between 1961 and 1980 and 6.8 million between 1981 and 2001 [13,14].

This large building stock should have already been renewed, but Spain is suffering (since 2008) from a deep economic crisis [64] that has particularly affected the building sector [67]. This is why all buildings with more than 40 years have not had the opportunity to be refurbished, as reflected by the energy performance certificate database from the Catalan Institute of Energy (ICAEN) [7]. As detailed in sections 4.1-4.3, obtaining from the census database [13,14] the type of building, its construction period and climate conditions provides enough information to know the main construction characteristics [51,52,68] and make a reliable estimation of the energy efficiency of the entire stock of housing constructed during that period (1960-2001).

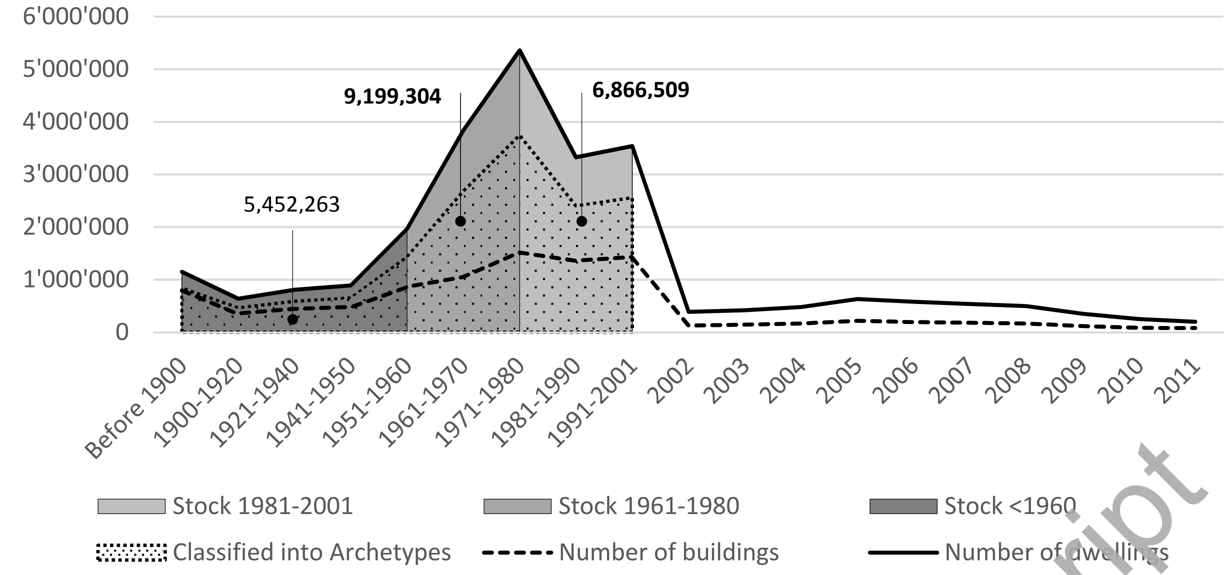

Figure 1: Total construction in Spain until 2011 (in number of residential buildings and dwellings) [13,14].

The ultimate objective of this work is to support stakeholders in the field of urban planning in making strategic medium/long-term decisions towards a sustainable urban renewal process of the building stock. To do so, we propose a decision-making tool implemented in Excel and that integrates a new systematic approach for carrying out studies at different scales: (i) at the building scale, for comparing different sets of EEM strategies for one type of housing in a particular climatic zone; (ii) at the territorial scale, scaling-up from the individual archetype analysis, for comparing different sets of EEM strategies applied to all types of buildings in all climatic zones simultaneously. The results include economic and financial aspects, consumption and energy savings, associated GHG emissions, embodied energy, and compliance with the nZEB targets of each renovation scenario [31,40,69].

According to the spatial scale of the study, different types of analyses can be conducted:

- Identify which strategy is most suitable for each type of building, climatic zone and macroeconomic scenario;
- Evaluate the number of households likely to be refurbished through a minor/deep retrofit;
- Evaluate the cost of subsidy required and the potential energy savings;
- Obtain an overview indicating the cost-effective strategies, to help define the business plan of companies in the construction sector;
- Identify the amount of surface that could be rehabilitated by architects specialized in energy efficiency and rehabilitation.

Ultimately, this information shall support the achievement of the European requirements for 2050 horizon [17,34] in the Spanish context.

4. Methodology

Our approach (Figure 2) starts from the categorization of the existing housing stock based on the climatic zone and the period of construction as detailed in sections 4.1-4.3. Scenarios of retrofitting interventions are then defined, from EEM (passive and active including solar-based RET) strategies described in 4.4, with the aim of achieving nearly Zero Energy Buildings (nZEB) according to the adopted definition presented in section 4.5. Section 4.6 lists the outputs of our multi-criteria evaluation, which is conducted for each scenario through the developed decision-making tool described in section 4.7.

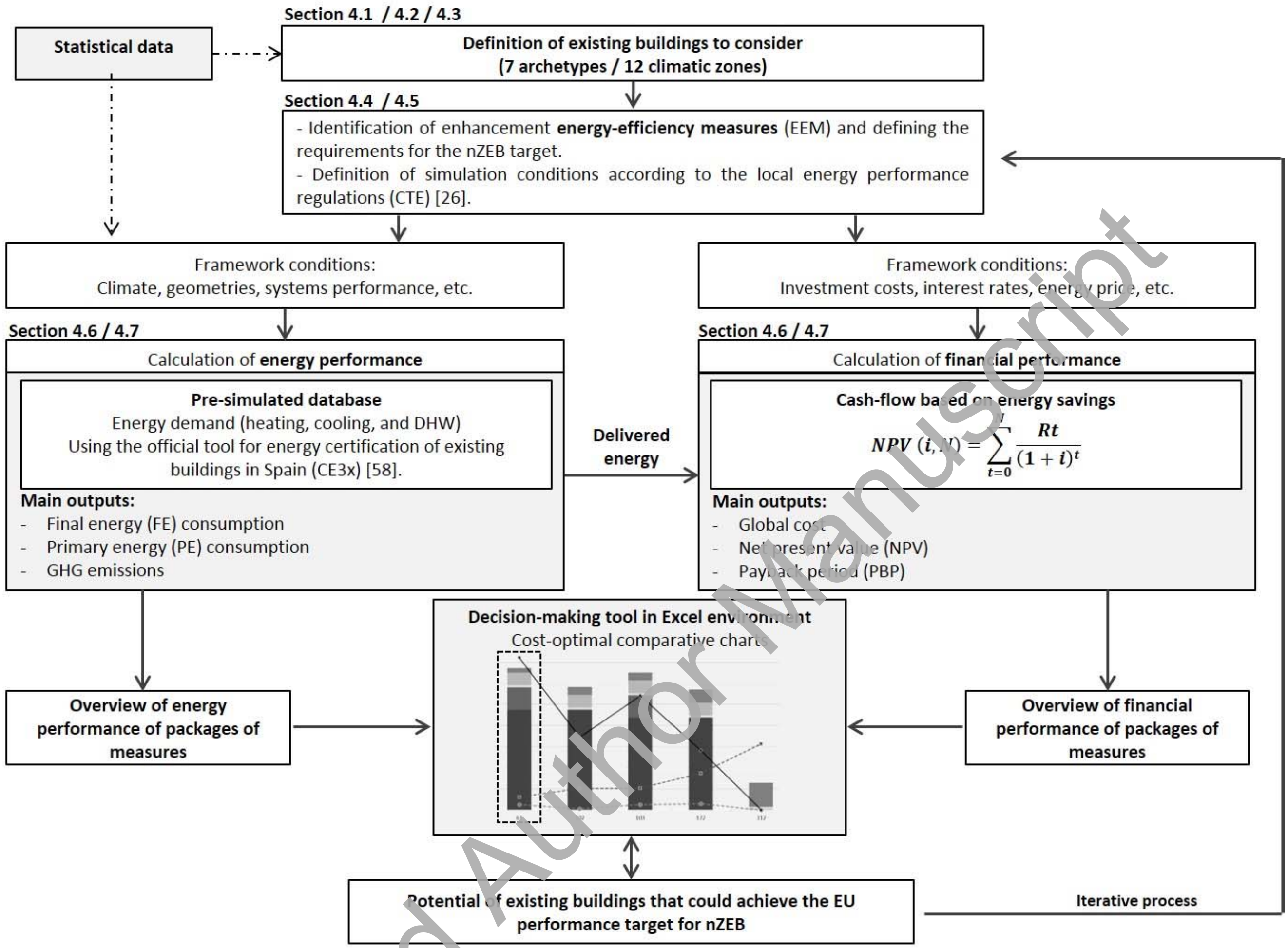

Figure 2: Flowchart of the research methodology with corresponding section. Adapted from the cost-optimal methodology chart [69] *and using official software for EPC in Spain (CE3x)* [62].

4.1. Housing stock (Archetypes)

As seen in section 2, the analysis of the building stock can be realised through different approaches, namely *reference buildings* (corresponding to real building examples) [44], *building typologies* (corresponding to common buildings) [48], and *archetypes* (defined as a theoretical model representing different building typologies) [50]. We propose to use the archetypes approach that allows us to scale-up the results from the building to the territorial scale.

We have defined our archetypes specifically for energy simulations using, as Parekh [51] recommends, a geometry and envelope parametrization, defining building typology, construction period and climate conditions as the main classification parameters, since these three values provide enough guidelines to define the archetypes [51,52,68].

The categorisation of the residential building stock up to 2001 in Spain has been carried out based on reports from the GTR [64,65] and determining each typology through statistical data [13,14], using the frequency of a building type and identifying the most relevant ones, as recommended by Schwehr et al. [48]. Finally, we managed to classify more than 15 million existing dwellings (Figure 1) in seven archetypes (Table 2).

Table 2: Building archetype definition and number of existing dwellings classified, respecting the original codification made by the GTR and exposed in their reports [65,68].

Archetype	Definition	Construction features	Numbers of classified dwellings
A <1960	SF housing in rural areas built before 1960.	Built with traditional solid and thick walls, pitched roof with a ventilated chamber and ground floor directly in contact with the ground.	2,226,973
B <1960	MF buildings over four floors and located in dense urban environments and built before 1960.	Built with solid walls, flat roof, suspended slab ground floor, and usually a commercial activity developed on the ground floor.	1,744,016
C 1961-1980	Rural houses built in the period between 1961 and 1980.	Built with cavity walls, pitched roof without air chamber, and outdoor ventilated crawl space under ground floor.	1,864,213
D,E,F 1961-1980	MF dwellings in detached buildings either in rural or urban areas, built between 1961 and 1980.	Built with cavity walls, flat roof and outdoor ventilated crawl space under ground floor.	4,566,242
G 1981-2001	SF homes in rural areas built from 1981 to 2001, after the introduction of Spain's first mandatory thermal regulations.	Built with cavity walls with integrated thermal insulation, pitched roof without air chamber, outdoor ventilated crawl space under ground floor.	1,175,785
H 1981-2001	MF housing located in rural towns and built between 1981 and 2001.	Built with cavity walls with thermal insulation, flat roofs and outdoor ventilated crawl space under ground floor.	1,381,041
I,J 1981-2001	MF housing buildings in urban areas built between 1981 and 2001.	Built with solid walls with insulation, flat roofs and outdoor ventilated crawl space under ground floor.	2,400,337
		Total main dwellings built up to 2001:	**15,358,608**

4.2. Climatic zones

Some existing applications of the cost-optimal methodology in renovation projects, as for example the *INSPIRE-Tool* developed by econcept AG for the Swiss context [70], do not take into account the different climatic zones, making their application restricted to a specific region in the country. However, we aim to apply our approach to the whole Spanish territory, so it is imperative to take into account the different climatic zones of Spain, mainly differentiated according to the winter (WCS) and summer (SCS) climate severity defined in the current regulation CTE [7,18]. Our proposal is to consider all 12 climatic zones present in the Iberian Peninsula, represented through the ombrothermic graphs in Figure 3 according to the location of the provincial capital [18].

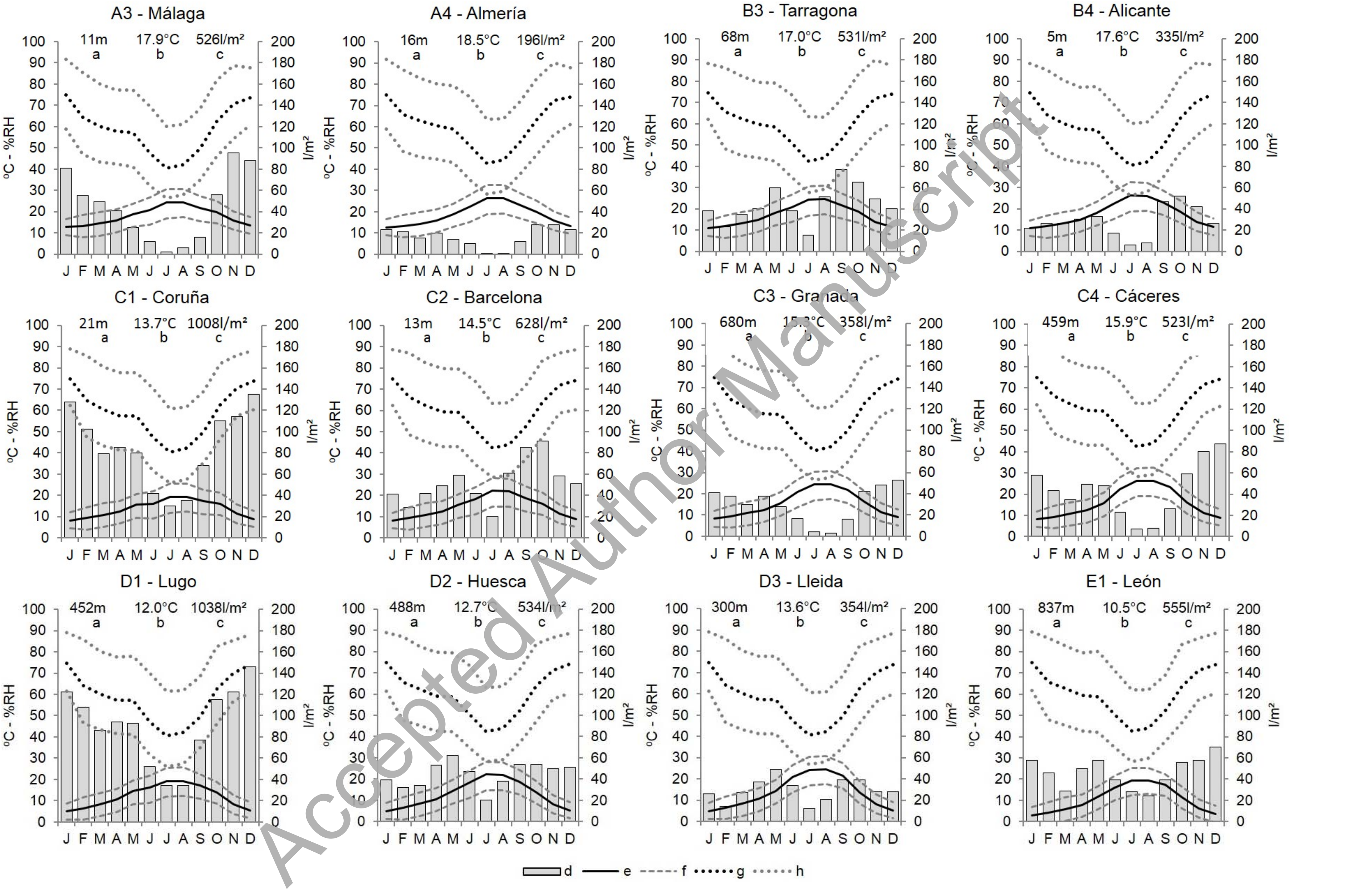

Figure 3: *Ombrothermic graphs of the 12 climatic zones in Spain (Peninsula). a. Elevation of the main city above sea [m], b. Annual average of Dry Bulb temperature [°C], c. Annual average of rain [l/m²], d. Monthly average of rain [l/m²], e. Dry Bulb temperature average curve [°C], f. Dry Bulb temperature min/max curves [°C], g. Relative humidity average curve [%], h. Relative humidity min/max curves [%]* [18].

4.3. Existing building envelope characteristics of each archetype

To simulate the energy demand of each archetype, defined as a theoretical model for each typology, and scale-up the results at the territorial scale, we utilize the shape coefficients listed in Table 3. These values, taken from a study from the GTR [68] and the master thesis of the first author [36], correspond to the ratio between the surface of each constructive component – facade, windows, roof and ground floor – and the floor area (e.g. m^2 of opaque facade / m^2 floor area).

Table 3: Shape coefficients by archetype [68].

Archetype	Shape coefficients by archetype [m^2 of component / m^2 floor area]				Floor area [m^2]	Storey height [m]
	Opaque facade	Windows	Roof	Ground floor		
A	0.87		0.69	0.69	109	
B	0.46		0.18	0.18	85	
C	0.87		0.69	0.69	109	
DEF	0.46	0.14	0.18	0.18	85	2.60
G	0.87		0.69	0.69	109	
H	0.62		0.50	0.50	93	
IJ	0.46		0.18	0.18	85	

We have obtained the envelope characteristics (U-value) for each archetype from the study of the Spanish residential building stock carried out by the GTR [68], updating and validating the values using the database of the official software (CE3x) for EPC in Spain [62]. An example for archetype DEF can be found in Table 4.

4.4. Packages of energy-efficiency measures

When considering interventions performed at different moments in the life of the building, it becomes crucial to simultaneously consider mixed solutions (active/passive). This is because the lifetime of the components is different, e.g. 15 years for a boiler versus 50 years for thermal insulating elements. Likewise, the order of priority in the implementation of different renewal strategies (passive or active) is important to achieve a high value of long-term savings in terms of energy, GHG emissions, and cost [10–12,24,41]. First, it is necessary to act on the building envelope to reduce the energy demand, and then install active systems adapted to the new demand. In this sense, the evaluation of investments takes into account not only economic aspects but also environmental impacts associated with the life of the building. Before applying the cost-optimal methodology, we must be sure that each strategy is technically feasible, according to the characteristics of the building. This is done by consulting the literature [49,71–73] and defining our different rehabilitation strategies using the GTR report [65], introduced in section 3, as a basis.

4.4.1. Packages of passive improvement strategies

For our purpose of generating a pre-simulated database, we have chosen two packages of passive strategies, representing two levels of intervention (REF01 and REF02), in addition to the current status (ORIG), in order to limit the number of combinations to simulate. These represent the options that can then be selected using our Excel-based decision-making tool, as further detailed in section 4.6. An example of the defined packages for archetype DEF, including building envelope features (simulation input data), cost, and environmental impact, is presented in Table 4.

Table 4: Definition of improvement packages with the resulting envelope characteristics, cost of each strategy and their environmental impact, for a lifetime of 15 years (for LCA). The values corresponds to archetype DEF (see Table 2) [62,68,74].

Package of strategies	Mean U-value after rehabilitation [W/m².K] for archetype DEF			
ORIG (Current status)	Facade	Windows	Roof	Ground slab floor
Without improving building performance	1.30	5.70	1.60	2.50
REF01 (Minor retrofit)	Facade	Windows	Roof	Ground slab floor
Exterior insulation and ventilated facade	0.22	-	-	-
Double-glazed window	-	2.7	-	-
REF02 (Deep retrofit)	Facade	Windows	Roof	Ground slab floor
Exterior insulation and ventilated facade	0.22	-	-	-
Double-glazed window	-	2.7	-	-
Roof insulation	-	-	0.25	
Insulation of the ground floor	-	-	-	0.25
	Cost of strategies [€ per m² of element]			
Improvement strategy	Facade	Windows	Roof	Ground slab floor
Exterior insulation	151 €/m²	-	-	-
Double-glazed window	-	335 €/m²	-	-
Roof insulation	-	-	46 €/m²	-
Insulation of the ground floor	-	-	-	10 €/m²
Environmental impacts	Embodied energy [kWh/dwelling]		GHG emissions [kgCO₂/dwelling]	
REF01 (Minor retrofit)	14'449		2'046	
REF02 (Deep retrofit)	20'439		2'443	

4.4.2. Active improvement strategies (HVAC system)

For providing the user with different active systems to be implemented in the scenarios, we have considered the performance level of the most common HVAC systems used in renovation projects in Spain given by the CYPE database [74] (Table 5). These values are applied to the pre-simulated energy demand to obtain the final consumption result (see 4.6.).

Table 5: Definition of active improvement strategies through the performance of HVAC system and the type of energy consumed (gas, biomass and electricity-based), cost of each system and their environmental impact, for a lifetime of 15 years (for LCA) [74].

HVAC system improvement strategy	Average performance of active systems			
	Heating mode		Cooling mode	
	Nominal efficacy	SCOP*	Nominal efficacy	SEER*
ORIG: Current system, maintaining the existing gas boiler	70%	57%	-	-
CALCOND: Changing the existing boiler with a condensing boiler	105%	95%	-	-
CALBIOM: Changing the existing boiler with a biomass boiler	95%	86%	-	-
BDC_VRV: Implementing a high efficiency electric heat pump	380%	315%	250%	225%

HVAC system	Cost [€/dwelling]	Environmental impacts	
		Embodied energy [kWh/dwelling]	GHG emissions [kgCO₂/dwelling]
CALCOND	1,793	63.39	6.31
CALBIOM	11,093	88.11	8.15
BDC_VRV	4,000	71.72	4.60

** The performance takes into account heat losses in the installation. SCOP: Seasonal Coefficient of performance* [75] *, SEER: Seasonal Energy Efficiency Ratio* [76].

4.4.3. Additional strategies

To take into account the potential contribution of RET on buildings to achieve the nZEB standard [77], two complementary strategies have been defined. (1) RCALOR: mechanical ventilation system with heat recovery, taking into account the percentage of the energy demand reduced by implementing this system assuming 1 ach in winter and 5 ach in summer (Table 6). (2) SOLARACS: solar panels to cover 50% of annual DHW demand. Table 7 presents the values considered in terms of cost and environmental impact for these two additional strategies.

Table 6: Percentage reduction in the energy demand when implementing RCALOR strategy (mechanical ventilation system with heat recovery with 1 ach in winter and 5 ach in summer). Values calculated from own simulations using technical system data from Soler&Palau manufacturer [79].

Climatic zone	A3	A4	B3	B4	C1	C2	C3	C4	D1	D2	D3	E1
Heating	18%	14%	21%	20%	29%	27%	23%	21%	31%	30%	28%	33%
Cooling	9%	6%	20%	13%	0%	8%	4%	12%	0%	13%	16%	0%

Table 7: Cost and environmental impacts (for LCA, considering a lifetime of 15 years) of additional strategies [75].

Additional strategy	Cost [€/dwelling]	Environmental impacts	
		Embodied energy [kWh/dwelling]	GHG emissions [kgCO_2/dwelling]
RCALOR	1,793	63.39	6.31
SOLARACS	11,093	88.11	8.15

4.5. Definition of nearly Zero Energy Buildings (nZEB) requirements

The EPBD recast [17] proposes using the cost-optimal methodology to support nZEB design [8,33]. To verify whether or not the proposed renovation scenarios may allow achieving the EU targets for the 2020 and 2050 horizons using the nZEB concept as a measure, we must first define its meaning.

All EU Member States (MS) should set the nZEB targets [17] – reflecting their national, regional or local conditions – through a numerical indicator of maximum PE consumption expressed in kWh/m^2 per year, but the literature review about this subject shows that there is no consensus to define the energy efficiency targets of a nZEB [16].

As for the moment the Spanish regulation presents a lower level of exigency, in terms of energy efficiency in building renovation [18], than the last European directive [17] and also compared to the limits of PE and GHG emissions imposed by the standards of neighbouring EU countries like Germany or France [16].

Some recent publications about the definition of nZEB across EU countries [16,78] show that only nine EU countries have formally established nZEB requirements for existing residential buildings ranging between 20-200 kWh/m^{2}per year (of PE consumption) and only six of them use the same requirements for both new and existing buildings (20-100 kWh/m^{2}per year of PE consumption). Spanish regulations are still under development.

Given this information and following the recommendations of some publications [10,50], the use of the German Passivhaus label [79] as a reference to define nZEB requirement is here considered as a reasonable approach [80]. The target values taken into account are presented in Table 8.

Table 8: Energy efficiency requirements for nZEB standard, according to the German Passivhaus label [79].

Requirement	Heating	Cooling
Maximum **energy demand** [kWh/m^2 per year]	15	15
Maximum **PE consumption** (Including heating, cooling and DHW) [kWh/m^2 per year]	120	
Minimum **Energy Performance Certification rate** (according to Spanish EPC protocol [20])	B	

Trying to go a little further, a reference publication about principles for nZEB by the Building Performance Institute Europe (BPIE) highlights a lack of implementation of the LCA approach for nZEB within the cost-optimal methodology [23]. Hernandez et al. [81] propose a new-term: life-cycle zero-energy buildings (LC-ZEB), integrating the embodied energy related to the life cycle of buildings.

In response to this, we propose to implement the Life-Cycle Assessment (LCA) and Life-Cycle Cost (LCC) into the assessment and our Excel-based tool, to have an overview and identify the possible improvements regarding the renovation strategies proposed, allowing us to check if it is possible to achieve the ambitious EU horizon 2050 objectives of 3 $kgCO_2/m^2$ per year (over the whole life cycle).

4.6. Estimation of energy performance improvements

4.6.1. Calculation horizon

For the economic and energy consumption calculation throughout the life of the building, the following horizons have been defined: 2020, 2030 and 2050 (short, medium and long term). A comparison between a reference case (no improvement actions) and four scenarios with the application of different improvement strategies are presented.

4.6.2. Outputs

The main outputs from our multi-criteria evaluation are:

- Global cost, taking into account initial investment, maintenance cost, substitution cost of the current HVAC systems, and energy consumption cost;
- Net Present Value (NPV) and Payback Period (PBP), using savings as a cash-flow to recover the investment;
- Primary energy (PE) consumption and related GHG emissions;
- Cumulative cost of energy consumption and saving depending on the horizon of calculation (for LCC);
- Embodied energy and related emissions taking into account materials and energy use (for LCA).

4.7. Decision-making tool in the Excel environment

In this section we briefly describe the workflow (Figure 5) implemented into an Excel-based decision-making tool. The main objective of this tool is to enable the comparison of different renovation scenarios in terms of the above-mentioned outputs, through graphical representations of the results. The two main screens of the tool are presented in Figures 6 and 7.

As shown in Figure 4, the tool first needs (1) the **definition of scenarios** by the user (in terms of passive, active and RET strategies) and the type of study desired (scale; for only one versus all archetype(s) and climatic zone(s)). Users can then, through the (2) **user-friendly interface** (Figures 6 and 7), define the *macroeconomic parameters* (energy price evolution, interest rate and percentage of subsidies) and the *calculation horizon* (2020, 2030 or 2050). Based on this information, the corresponding data is extracted from (3) the **tool-integrated database**, including the energy demand of each archetype from the **pre-simulated data** (see Figure 6). The data is then passed on to (4) a **calculation algorithm** based on the cost-optimal methodology (Figure 2). We obtain the results according to the chosen scenario (combination of passive, active and RET strategies – including the moment of implementation) (5a) for a specific archetype and climatic zone if the user has chosen the static calculation option. If (5b) the user has chosen the territorial scale overview, an automatic iterative process scales-up the individual results to the territorial scale using the statistical data integrated in the Excel tool. At each iteration, for a given retrofitting scenario, the archetype and climatic zone are varied. Finally, this process ends up storing all results in a double entrance table (archetype vs climatic zone, see examples in section 5.3).

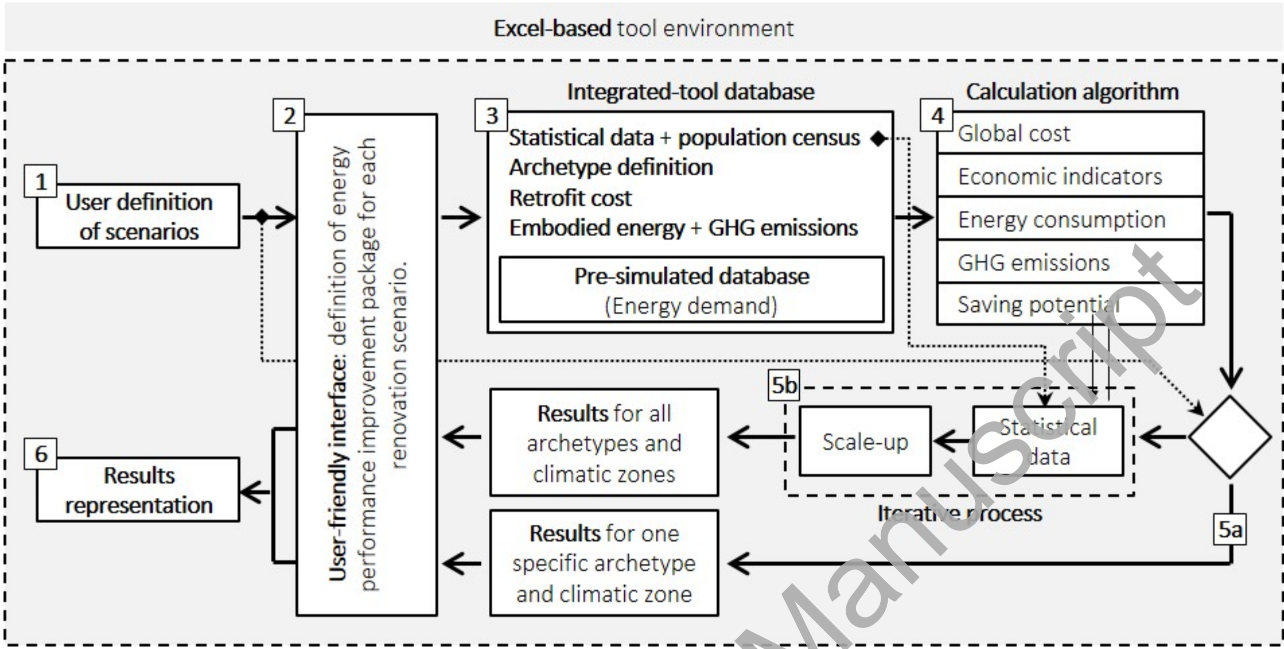

Figure 4: Excel-based decision-making workflow.

The tool-integrated database which feeds the calculation algorithm is composed of:

Census of population and statistical building construction data: mean surface of each typology and number of homes of each type for each climatic zone [13,14].

Archetype parametrization: based on surface ratios as explained in section 4.3.

Cost of each retrofit measure: investment cost [74], maintenance, substitution, and rate of efficiency loss of HVAC systems over the years [56,82].

Embodied energy and GHG emissions associated to the materials used in each scenario [74].

Pre-simulated energy demand database: as shown in Figure 6, the generation of the pre-simulated database starts with (1) the archetype parametrization (section 4.3) and (2) the assignment of three scenarios for each archetype (section 4.4). This information is introduced (3) into the simulation tool environment, currently the CE3x software since we are working at a macro scale. However, for more accurate simulations, EnergyPlus could be used, as done in section 5.1 to test the accuracy of our results. (4) Finally, we obtain the results in .xml files (from CE3x) and .csv (from EnergyPlus). (5) These form the database of energy demand for heating, cooling, and DHW integrated into our Excel tool.

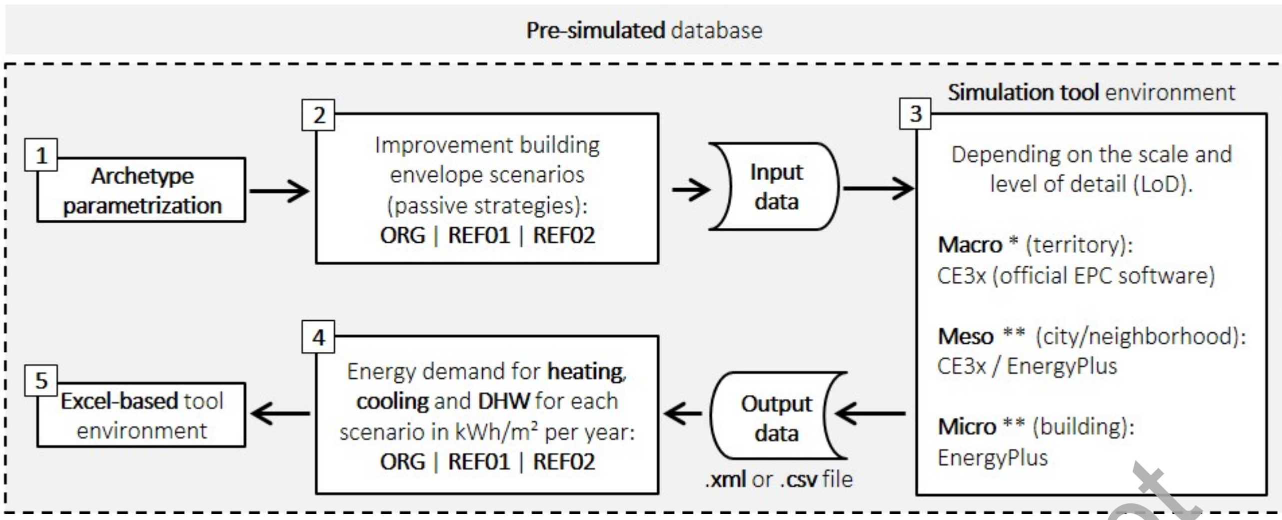

Figure 5: Workflow to obtain the pre-simulated database of energy demand.

Obtaining this pre-simulated database involves some simplifications and hypotheses that will determine the level of accuracy of the final results, and which are related to the level of detail (LoD) of the energy model. In this case, we have modelled our seven theoretical archetypes (Table 2) based on shape coefficients defined by the surface ratio of each constructive component (Table 5), taking into account two exposed facades with opposite orientation, and simulating each model in four orientations to obtain a mean value of the energy demand.

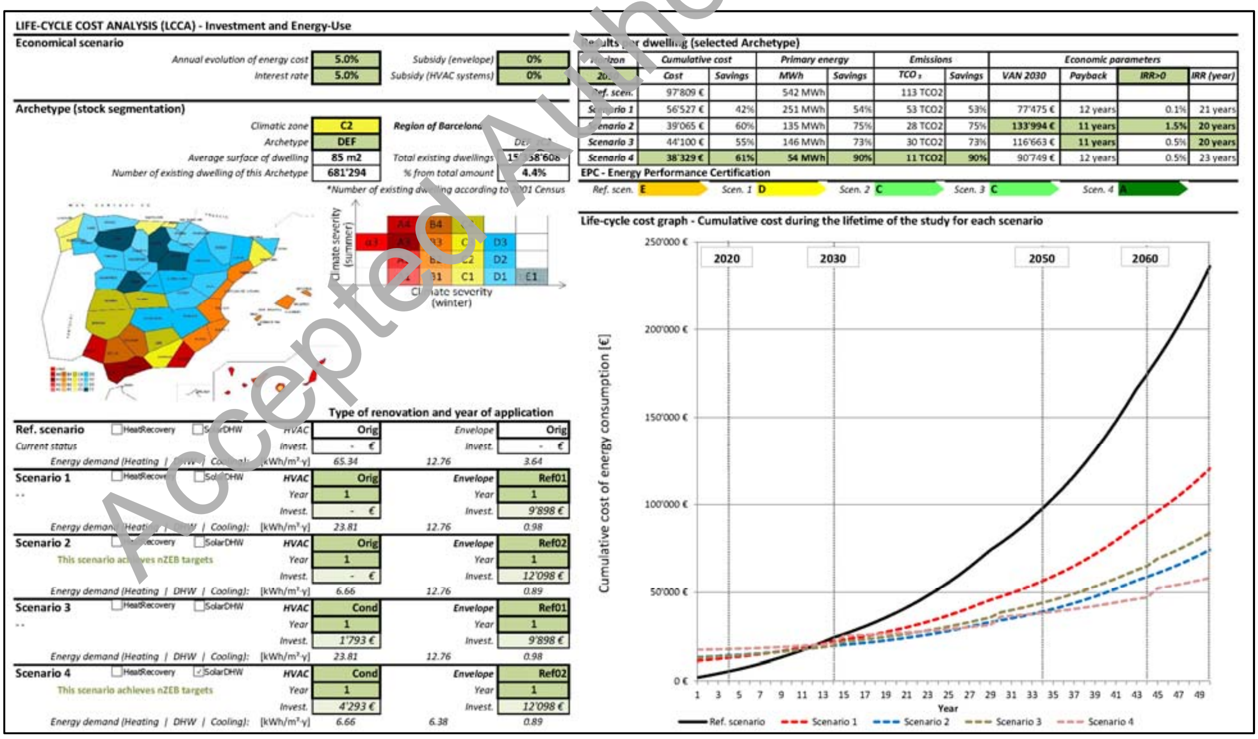

Figure 6: Decision-making tool - Main window of the LCC – Investment and energy-use for different calculation horizons.

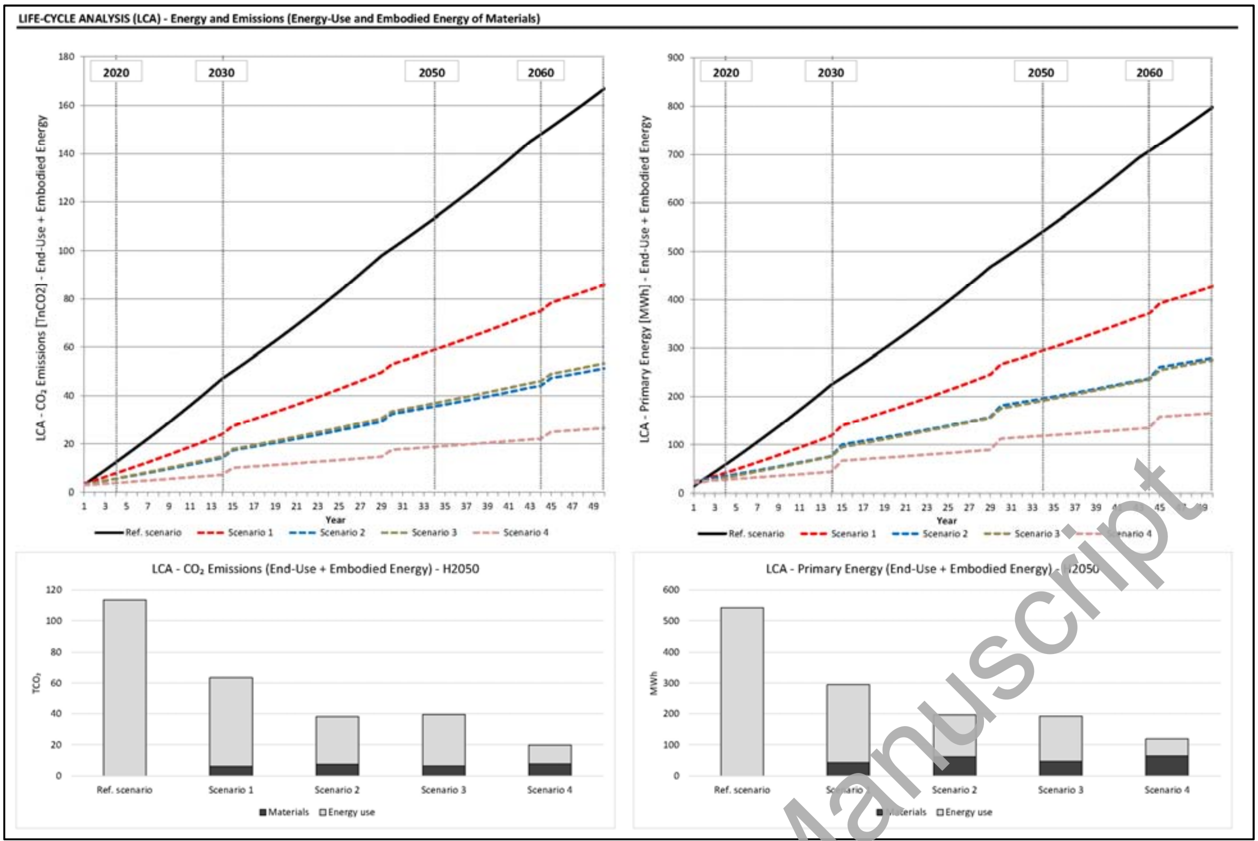

Figure 7: Decision-making tool - Main window of the LCA – Energy and emissions, including end-use and embodied energy for different calculation horizons.

5. Results

In this section, we first present the results from an accuracy test to quantify the error associated to the archetype-based approach (using the CE3x tool) compared to dynamically simulating with EnergyPlus a real building corresponding to the same archetype. The subsequent sections 5.2 and 5.3 respectively illustrate the types of studies that can be conducted at the building and territorial scales, including the examples listed in section 3.

5.1. Accuracy test

At a territorial scale, it is not possible to know exactly how is the surrounding environment, particularly to take into account solar obstructions when calculating the level of solar irradiation on each building surface. Consequently, energy simulations have been run in different orientations and the average of the results is used. To estimate the error caused by assuming this hypothesis, a detailed case study was performed of over 400 dwellings of archetype **DEF** (4-storey MF buildings) in the urban development of La Roureda – a representative neighbourhood from the 70's located in Sabadell (Barcelona) (Figure 8). This archetype was selected as it is the most widespread according to the statistical data analysed [7,13,14,65] (Table 2).

Aerial view of whole neighbourhood (Google)	Home plan type	Facade

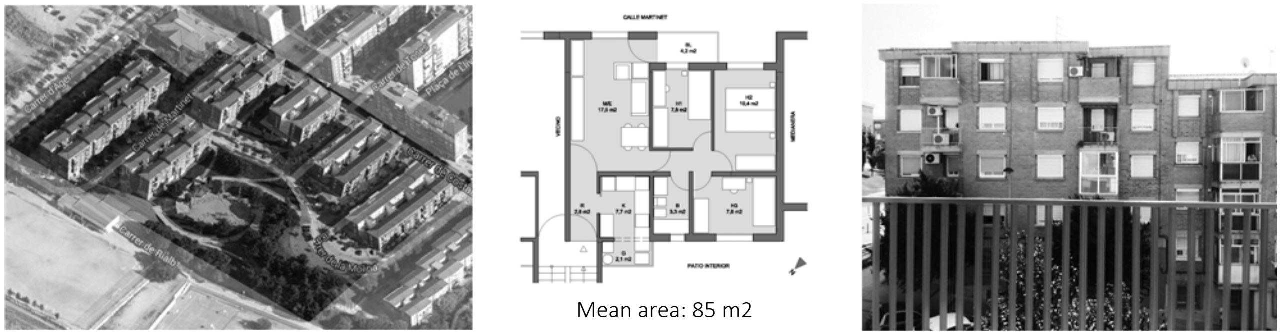

Figure 8: Definition of La Roureda Neighbourhood - Sabadell (Barcelona).

The main idea is to increase the LoD thanks to the higher precision of input parameters (from the construction and built environment point of view) to make a more accurate energy simulation using the *DesignBuilder* software based on the *EnergyPlus* calculation engine. This process allows verifying the reliability of the results, presented in Table 9, before applying the methodology at a large scale. The mean error of 25% is considered as acceptable for the purpose of application (estimation of potential savings) and given the error authorized in other studies [70].

Table 9: Comparison of CE3x and EnergyPlus simulation results.

Indicator	*CE3x*	*EnergyPlus*	Estimation error
Heating demand	65.34 kWh/m^2·year	55.25 kWh/m^2·year	+15%
Cooling demand	3.64 kWh/m^2·year	10.41 kWh/m^2·year	-35%
		Mean estimation error:	25%

5.2. Results at the building scale

Using the same archetype as in section 5.1, four renovation scenarios (S1, S2, S3 and S4) described in Table 10 were tested. This section shows an example of the results at the building scale (Figure 9, 10a, 10b).

From the cost-optimal chart of Figure 9, the four scenarios can be compared in terms of global cost, primary energy consumption, and cost-effectiveness of each strategy. For the considered horizon of 2050, S2 – with a positive NPV – is the cost-optimal solution, despite the fact that it is not the scenario with the lowest consumption. Comparing between S1 and S2, we observe that although they have similar global costs, S1 has a PE almost double that of S2, and a low NPV.

Figure 10a, illustrating the LCC though the accumulated energy consumption costs, allows comparing the same scenarios in terms of savings according to the different calculation horizons. In this case, we observe that the S1-S4 curves fall below the initial scenario (S0) after 11-13 years, therefore corresponding to the simple payback time (SBPB). This means that S1-S4 are all cost-effective in a long-term horizon (2050).

Table 10: Description of considered scenarios according to the energy-efficiency measures presented in section 4.4.

Scenario	Passive strategies	Active strategies
S0	ORIG	ORIG
S1	REF01	ORIG
S2	REF02	ORIG
S3	REF01	CALCOND + RCALOR + SOLARACS
S4	REF02	CALCOND + RCALOR + SOLARACS

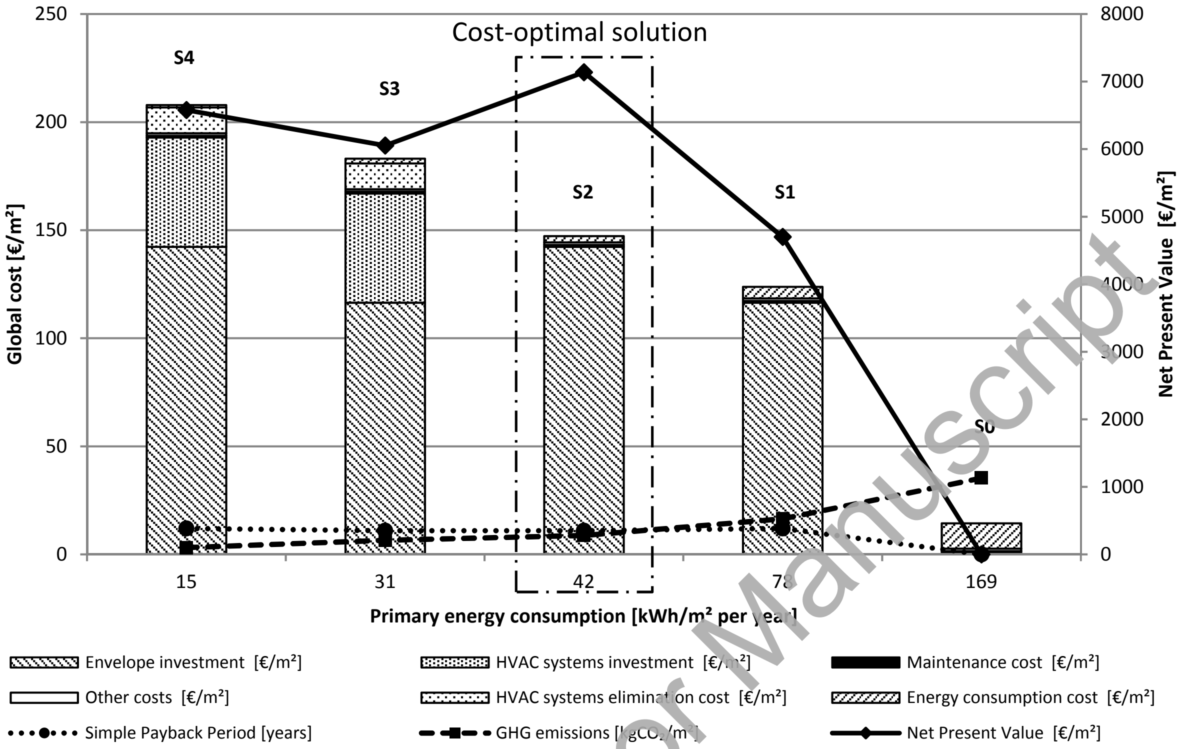

Figure 9: Cost-optimal chart for DEF archetype in the climatic zone C2-Barcelona, for a 2030 horizon.

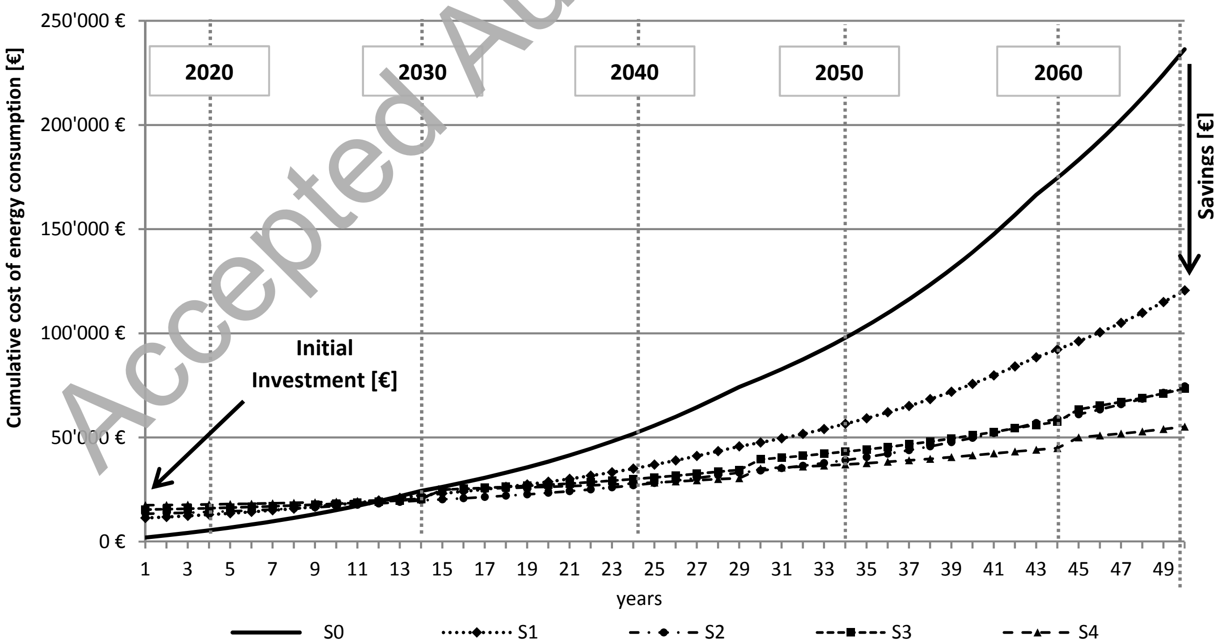

Figure 10a: Life-Cycle Cost (LCC) per dwelling. See Table 10 for description of scenarios.

Figure 10b shows the results of the LCA of each scenario in terms of embodied energy and GHG emissions.

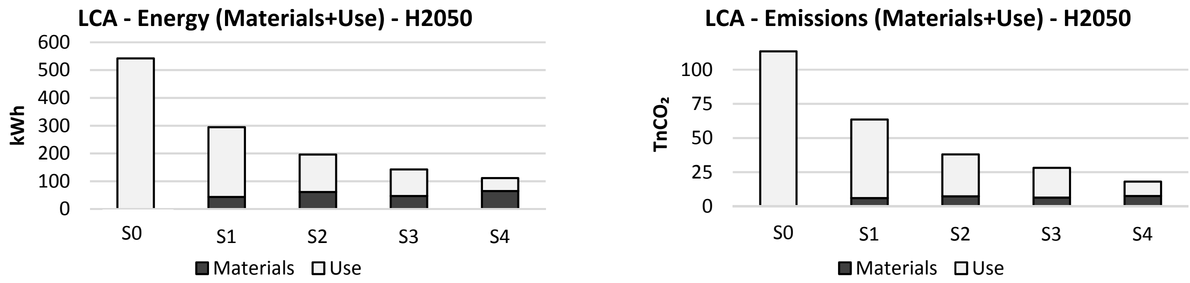

Figure 10b: Life-Cycle Analysis (LCA) per dwelling. See Table 10 for description of scenarios.

5.3. Scaling-up of results at the territorial scale

In this section, five examples of results at the territorial scale are presented. Through the bottom-up approach described in section 4.7 to obtain the results for the whole building stock, a simultaneous overview of the seven building archetypes and 12 climatic zones is provided.

5.3.1. Cost-effectiveness between active and passive strategies

In this section, the implementation of an active strategy (acting on HVAC systems) versus a passive strategy (acting on building envelope) is compared for a short- and long-term calculation (Table 11b, 11c), using a 0.5% interest rate, 5% annual rate of increased energy costs and four scenarios defined in Table 11a.

Table 11a: Legend and description of considered scenarios according to the energy-efficiency measures presented in section 4.4.

Scenario	Passive strategies	Active strategies
SC1	ORIG	CALCOND
SC2	ORIG	CALBIOM
SC3	ORIG	BDC_VRV
SC4	REF02	RCALOR + SOLARACS

*Table 11b: The most cost-effective strategy recommended (for a **short-term** horizon of calculation). Cells marked with (-) represent cases that are not cost-effective before the calculation horizon.*

Horizon 2020		Climatic Zone											
		A4	A3	B4	B3	C4	C3	C2	C1	D3	D2	D1	E1
Archetype (see Table 2)	A	SC1	SC1	SC3	SC1	SC3	SC3	SC1	SC1	SC3	SC3	SC3	SC3
	B	-	-	-	-	SC3	SC1	SC1	SC1	SC3	SC3	SC3	SC3
	C	SC1	SC1	SC1	SC1	SC3	SC1	SC1	SC1	SC1	SC3	SC3	SC3
	DEF	-	-	-	-	SC3	SC1	-	SC1	SC1	SC3	SC1	SC3
	G	SC1	-	SC1	SC1	SC3	SC1	SC1	SC1	SC1	SC3	SC3	SC3
	H	-	-	-	SC1	SC3	SC3	SC1	SC1	SC3	SC3	SC3	SC3
	IJ	-	-	-	-	SC3	-	-	SC1	SC1	SC1	SC1	SC3

*Table 11c: The most cost-effective strategy recommended (for a **long-term** horizon of calculation).*

Horizon 2050		Climatic Zone											
		A4	A3	B4	B3	C4	C3	C2	C1	D3	D2	D1	E1
Archetype (see Table 2)	A	SC3	SC3	SC3	SC3	SC4	SC4	SC4	SC4	SC4	SC4	SC4	SC4
	B	SC3	SC3	SC3	SC3	SC4	SC4	SC4	SC4	SC4	SC4	SC4	SC4
	C	SC3	SC3	SC3	SC3	SC4	SC4	SC3	SC4	SC4	SC4	SC4	SC4
	DEF	SC3	SC3	SC3	SC3	SC3	SC4	SC3	SC3	SC4	SC4	SC4	SC4
	G	SC3	SC3	SC3	SC3	SC3	SC3	SC3	SC3	SC4	SC4	SC4	SC4
	H	SC3	SC3	SC3	SC3	SC3	SC3	SC3	SC3	SC4	SC4	SC4	SC4
	IJ	SC3	SC3	SC3	SC3	SC3	SC3	SC3	SC3	SC3	SC3	SC3	SC4

Results strongly depend on the horizon of calculation. When the calculation is carried out in the short term (Table 11b), the recommended strategy is the replacement of old heating systems (active). However, when the calculation is carried out in the long-term (Table 11c) the recommended strategy is a deep retrofit (passive), acting mainly on the building envelope. Therefore, the results show that the cost-optimal methodology is a tool that prioritizes deep retrofitting strategies in less efficient buildings (archetypes A and B), located in the coldest regions such as D3, D2, D1 and E1 (see Figure 3).

5.3.2. Relevance of active measures within passive strategies

This section presents the comparison between implementing different passive strategies (REF01-minor or REF02-deep retrofit) with or without improving HVAC systems, for a mid-term horizon (2030), using a 0.5% interest, 5% annual rate of increased energy costs and five renovation scenarios, defined in Table 12a.

Table 12a: Legend and description of considered scenarios according to the energy-efficiency measures presented in section 4.4.

Scenario	Passive strategies	Active strategies
SC1	REF01	ORIG
SC2	REF02	ORIG
SC3	REF01	CALCOND
SC4	REF02	CALCOND

Table 12b. The most cost-effective strategy recommended (for a ***mid-term*** *horizon of calculation). Cells marked with (-) represent cases that are not cost-effective before the calculation horizon.*

Horizon 2030		Climatic Zone											
		A4	A3	B4	B3	C4	C3	C2	C1	D3	D2	D1	E1
Archetype (see Table 2)	A	-	-	-	-	SC3	SC3	SC2	SC2	SC4	SC4	SC4	SC4
	B	-	-	-	-	SC4	SC2	SC3	SC4	SC4	SC4	SC2	SC4
	C	-	-	-	-	SC3	-	SC2	SC2	SC4	SC4	SC3	SC4
	DEF	-	-	-	-	SC4	-	SC2	SC2	SC4	SC4	SC2	SC4
	G	-	-	-	-	-	-	-	SC4	SC4	SC4	SC4	SC4
	H	-	-	-	-	SC3	-	SC2	SC2	SC4	SC4	SC4	SC4
	IJ	-	-	-	-	-	-	SC2	SC2	SC4	SC4	SC2	SC4

The main conclusion that we can draw by extrapolating from this mid-term analysis, is that when the calculation is carried out in the short-term, no passive strategy is economically viable. So, the recommended strategy is therefore the replacement of old heating systems (active). However, when calculated mid- or long-term (as indicated by the European directives), the recommended strategy is a deep retrofit (passive strategies), acting mainly on architectural components, as shown in Table 12b, with the exception of archetypes built in warm zones (A4, A3, B4, B3). In those cases, savings achieved implementing a deep retrofit do not justify the initial investment.

If the fixed horizon is mid- or long-term (2030-2050), the building envelope retrofit strategy (REF02) is cost-effective in 52% of the building stock, in the most climatic zones, starting with the most inefficient archetypes and coldest zones (Table 12b).

5.3.3. Potential in achieving the nZEB target

This section aims at verifying which archetype(s) of existing buildings could become nZEB, by applying a deep retrofit (REF02) and taking into account the different climatic zones (Table 13a).

Table 13a: Buildings that could reach the level of performance for nZEB, through a deep retrofit REF02 strategy. Cells marked with (-) represent cases that do not achieve the nZEB targets defined in section 4.5.

Archetype (see Table 2)	Climatic Zone: A4	A3	B4	B3	C4	C3	C2	C1	D3	D2	D1	E1
A	nZEB	nZEB	nZEB	nZEB	-	-	-	-	-	-	-	-
B	nZEB	nZEB	nZEB	nZEB	-	nZEB	nZEB	nZEB	-	-	-	-
C	nZEB	nZEB	nZEB	nZEB	-	-	-	-	-	-	-	-
DEF	nZEB	nZEB	nZEB	nZEB	-	nZEB	nZEB	nZEB	-	-	-	-
G	nZEB	nZEB	nZEB	nZEB	-	-	-	-	-	-	-	-
H	nZEB	nZEB	nZEB	nZEB	-	nZEB	nZEB	nZEB	-	-	-	-
IJ	nZEB	nZEB	nZEB	nZEB	nZEB	nZEB	nZEB	nZEB	-	-	nZEB	-

Table 13b: Additional cost per dwelling to increase the facade performance (zones D2, D1, and E1) and improve the ventilation system (zones C1, D3) to achieve nZEB requirements.

Climatic zone	Performance level required for the vertical walls	Additional cost per dwelling
A4, A3, B4, B3, C4, C3, C2	12 cm of insulation (REF02). U-value: **0.25** W/m^2·K	-
C1, D3	Heat recovery exchanger for ventilation is recommended	4,049 €
D2, D1, E1	18 cm of insulation. U-value: **0.18** W/m^2·K	6,126 €

As shown in Table 13a, dwellings located in the most extreme climatic zones (D1, D2, D3 and E1) do not achieve the level of energy performance required for nZEB. In these zones, it is necessary to increase the level of insulation, the initial investment or public aids, as shown in Table 13b listing the additional retrofit and cost needed to achieve nZEB requirements.

5.3.4. Level of public aid required to implement a deep retrofit strategy

The purpose of this section is to define the total amount of public aid necessary to make the deep-retrofit strategy (REF02) cost-effective (Table 14a). This information could help companies in the construction sector produce business plans focused on energy-driven building renovation, while also encouraging the government to assign public aid more efficiently [49], by seeing if the revenue of taxes derived from the generated work could cover these public subsidies [58]. The calculation is done in an iterative process, increasing the level of subsidies from 0% to 100%, and checking at each step if the payback time is over 20 years (for each archetype and climatic zone, taking into account the current status and the deep retrofit scenario – REF02).

Table 14a: Level of public aid [%] required to implement a deep retrofit strategy (REF02) with a payback over 20 years with an interest rate of 0.5%. Cells marked with (-) correspond to homes that do not need subsidies to recover investment.

Horizon 2030 – Archetype (see Table 2)	Climatic zone: A4	A3	B4	B3	C4	C3	C2	C1	D3	D2	D1	E1
A	49%	41%	23%	21%	-	9%	-	-	-	-	-	-
B	38%	33%	2%	13%	-	-	-	-	-	-	-	-
C	58%	53%	35%	36%	8%	24%	2%	-	-	-	-	-
DEF	47%	42%	18%	23%	-	3%	-	-	-	-	-	-
G	61%	57%	40%	41%	13%	29%	9%	4%	-	-	2%	-
H	60%	55%	35%	39%	1%	20%	-	-	-	-	-	-
IJ	52%	48%	28%	33%	12%	17%	-	-	-	-	-	-

Table 14b: Building element surfaces that could be rehabilitated without public aid by 2030 horizon [thousands of m^2]. Cells marked with (-) are where public subsidies are required to achieve cost-effectiveness.

Horizon 2030 – Building element	Climatic zone: A4	A3	B4	B3	C4	C3	C2	C1	D3	D2	D1	E1
Facade	-	-	-	-	**65,053**	10,913	13,080	**45,578**	32,959	**48,158**	**144,764**	**26,910**
Windows	-	-	-	-	15,133	3,321	3,280	10,427	7,155	10,509	**33,419**	5,852
Roofs	-	-	-	-	**38,527**	4,270	7,482	**28,614**	21,487	**31,300**	**89,519**	17,531
Ground floor	-	-	-	-	**38,527**	4,270	7,482	**28,614**	21,487	**31,300**	**89,519**	17,531

As shown in Table 14a, only for the residential buildings built in the coldest climatic zones could a deep retrofit strategy (REF02) be applied without subsidies. We can see that the buildings in warm zones (A4, A3, B4 and B3) need to obtain subsidies to ensure cost-effectiveness. Table 14b shows the total surface of building elements that could be renovated if all buildings that do not need public aids implemented the deep retrofit scenario (REF02).

5.3.5. Payback time estimation for deep retrofit strategy

This section aims to identify which archetype(s) could be deeply retrofitted (REF02) with a payback over 7 years (short-term horizon) and with or without 25% of public aid.

Table 15: Payback [years], implementing a deep retrofit REF02 with and without 25% of public aid. Values in bold correspond to homes with a payback period equal to or less than 7 years. Values with a star (*) correspond to homes that could have a payback less than 7 years when obtaining 25% of aid. Remaining archetypes always present a payback of more than 7 years.

Horizon 2030		Climatic zone											
		A4	A3	B4	B3	C4	C3	C2	C1	D3	D2	D1	E1
Archetype (see Table 2)	A	17	16	13	13	10	11	9*	9*	8*	8*	9*	**7**
	B	15	14	11	12	8*	9*	8*	8*	**6**	**6**	**7**	**5**
	C	20	18	15	15	11	13	11	10	9*	9*	10	8*
	DEF	17	16	12	13	10	11	9*	9*	8*	8*	9*	**7**
	G	21	19	15	16	12	13	11	11	9*	10	11	8*
	H	20	19	14	15	11	12	11	10	8*	9*	10	**7**
	IJ	18	17	13	14	12	12	10	10	9*	9*	10	8*

As shown in Table 15, only dwellings in the coldest climatic zones (D3, D2, D1 and E1) – in bold – present a payback period (PBP) equal to or less than 7 years. Dwellings in temperate climatic zones (C4, C3, C2 and C1), corresponding to starred numbers in the table, need 25% of public aids to reduce their payback to 7 years. The remaining dwellings, in the hottest climatic zones (A4, A3, B4 and B3), need more than 25% of public aids to reduce their payback to 7 years.

6. Discussion

If the horizon of calculation is in the mid- to long-term, the cost-optimal methodology prioritizes passive strategies on the building envelope, allowing an important reduction in energy demand (Tables 11a, 11b and 11c). Therefore, work on the envelope of the buildings is a priority to achieve the objectives established by the EU to reduce energy consumption of the built environment.

The cost-optimal methodology is designed for mid- and long-term investment scenarios, which is why, in the short-term studies, the most cost-effective strategies are always related to improving the efficiency of HVAC systems (Table 12a, 12b). However, by using only active strategies, a maximum of about 40% energy savings can be expected, while up to 80% can be achieved by combining passive and active strategies.

During the period of 2004-2013, the average annual increase in the price of energy in Spain has been between 6.5% and 10.9% (without considering associated taxes) [82]. The methodology is very sensitive to this parameter. In fact, if the annual energy cost increase exceeds 10%, a deep-retrofit strategy becomes the preferred option, also in the short-term.

If the interest rate is very high, the most disadvantaged strategy is deep-retrofit due to the higher initial investment. Offering credits with a lower interest rate of 5% could therefore potentially encourage this type of strategy. This is the case in most EU countries today. Since 2008, probably due to the economic crisis, the interest rate of EURIBOR [83] has remained around 0.5%. Therefore, the context is ideal for promoting energy rehabilitation projects of existing buildings [84].

As a result of the studies realised with the help of the decision-making tool, if the target is to rehabilitate about 100% of existing homes (built between 1960 and 2001) from 2016 until 2030 and following a deep-retrofit strategy, the Spanish government would have to invest about 29,286 M€ (1,464 M€/year).

The potential housing stock that would achieve the level of requirements of nZEB by implementing a deep-retrofit could reach 54.6% (around 9 million homes; Table 13a), but an additional investment cost (Table 13b) of about 5,000 € per home would be necessary for buildings located in the coldest zones (C1, D1, D2, D3 and E1).

Table 16: Number of homes it would be advisable to refurbish from 2016 until 2030 on the Spanish territory.

Number of homes to be refurbished (25% of public aid to the investment cost)	9,366,395 homes	61%
Primary energy saving [GWh], from 2016 until 2030	5,906,915	-79.6%
GHG emissions savings [kgCO_2-eq], from 2016 until 2030	1,198,387,749	

According to the results in Table 16, companies in the construction sector should concentrate, firstly, on homes situated in the coldest zones, such as E1-Leon, D1-Lugo, C4-Cáceres, C3-Granada and D2-Huesca. Indeed, in these regions, it is cost-effective to propose a deep-retrofit strategy without considering public aid.

7. Conclusions and recommendations

The literature review suggests that the cost-optimal methodology can perfectly be used to compare different renovation scenarios to make strategic decisions assuming an error up to 30%, due to uncertainties in input data, working at the urban scale and without taking into account different climatic zones [70].

Therefore, the purpose of this study was to investigate if the cost-optimal methodology could successfully be applied at the territorial scale – based on the extrapolation of results from building and neighbourhood scales using more accurate input data than typically used – to obtain an overview of the status of existing buildings and their potential energy and GHG emissions savings.

This is accomplished by implementing a new systematic strategy, starting from the categorization of the existing housing stock based on the climatic zone and the period of construction, using statistical data and linking this information at different scales – city and building – through energy simulations based on different levels of detail and their extrapolation to the territorial scale.

This research provides empirical evidence that the most effective levers to manage the renewal processes of the built environment to achieve the targets of the EU energy directives are passive strategies acting on buildings' envelopes. Such strategies could give significant benefits including higher levels of energy savings (about 40%), while increasing interior comfort, quality and value of buildings. It is essential to highlight that to achieve about 80% savings, it is necessary to consider improvement packages where passive and active strategies are contemplated at the same time, paying special attention to the order of priority in which they are implemented.

The results of this study also indicate that the definition of the horizon of calculation, the macroeconomic parameters, the urban environment and the climatic zone conditions are critical to achieve an accurate level of results and may significantly contribute to progress toward increasing the level of sustainability of the residential building stock of tomorrow.

Taking into account the actual macroeconomic situation in Spain, using a reasonable scenario with 25% of public aid to the investment cost of the renovation and an interest rate of 0.5%, the potential housing stock that would achieve the level of requirements of nZEB by implementing a deep-retrofit could reach 61% (around 9 million dwellings) with 79.6% of PE (5,906,915 GWh) and CO_2 emissions (1,198,388 tCO_2) savings.

Our proposed approach, implemented into an Excel-based decision-making tool relying on (and extending) the cost-optimal methodology, can support urban planners make strategic decisions towards more sustainable urban renewal processes of the building stock. It can moreover help the construction sector adapt their business goals to promote energy renewal projects.

Derived from the main results of this study, a list of recommendations to encourage owners to undertake a renovation of their building is proposed:

- Public aid to subsidize the initial investment;
- More attractive credits to implement passive strategies;
- Increase in value-added tax (VAT) on less efficient HVAC systems;
- Reduction in VAT, to promote the use of more ecological certified products;
- Campaign to promote the rehabilitation of buildings, lowering the Property Tax (IBI) during the years in which investment is being recovered;
- Promote energy rehabilitation of entire buildings, offering communities city-funded advice and management. The owners would only have to pay a fee to the city council, equivalent to the monthly savings of the overall energy bill. The preliminary study would be to calculate the monthly fee that a community could pay, based on energy savings achieved after rehabilitation. Therefore, they would know whether they can pay the investment through a soft loan; if not, the administration should finance the rest.

Future development of this research will look into incorporating more case studies at the neighbourhood and building scales, using accurate energy simulation and involving more building-typology diversity, with the aim to better calibrate the decision-making tool for territorial-scale applications. Implementing the calculation algorithm into a geographic information system (GIS) platform could be envisioned mainly for enhanced visualization.

To further refine our building stock database, satellite-derived data could be used. Along the same line of thought, optimization methods could be employed to better identify cost-optimal strategies [32].

The inclusion of Building-Integrated Photovoltaic (BIPV) into the renewable energy strategies is also planned, in order to achieve Low-Carbon horizon targets in EU countries [85].

Finally, in terms of economic outputs, it would be advisable to calculate the government incomes due to the VAT (e.g. through increased retrofit-related work), which could be superior to the total amount of public aids to the dwelling owners, as demonstrated in [58].

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9. Abbreviations

CDD	cooling degree days
CE3x	official software for energy performance certification
CTE	technical building code
DHW	domestic hot water
EEM	energy-efficient measures
EPBD	energy performance of buildings directive
EPC	energy performance certification
EU	European Union
GIS	geographic information system
GHG	greenhouse gas
GTR	rehabilitation working group
HDD	heating degree days
HVAC	heating ventilation and air conditioning
LCA	life-cycle assessment
LCC	life-cycle cost
LoD	level of detail
MF	multi-family
MS	member states
NPV	net present value
nZEB	nearly zero energy buildings
ORIG	current status scenario
PE	primary energy
RD	royal decree
REF01	minor retrofit scenario
REF02	deep retrofit scenario
RET	renewable energy technologies
SF	single-family
PBP	payback period
TABULA	typology approach for building stock energy assessment
VAT	value-added tax

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