Energy & Buildings 312 (2024) 114182

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enb

Parametric simulation tool for the enviro-economic evaluation of energy renovation strategies in residential buildings with life cycle thinking: PARARENOVATE-LCT

Markel Arbulu [a,*], Xabat Oregi [a], Lauren Etxepare [b]

[a] *CAVIAR Research Group, Department of Architecture, University of the Basque Country UPV/EHU, Plaza Oñati, 2, 20018 Donostia - San Sebastián, Spain*
[b] *Department of Architecture, University of the Basque Country UPV/EHU, Plaza Oñati, 2, 20018 Donostia - San Sebastián, Spain*

ARTICLE INFO

Keywords:
Building performance simulation
Economic scenario
Energy transition
Life cycle assessment
Life cycle cost
Renovation strategies
Residential building stock
Occupant behaviour

ABSTRACT

The EU regulations require long-term renovation strategies (LTRS) for the energy transition of the existing building stock, emphasising the importance of the whole-life carbon evaluation and the cost-effectiveness of the processes. The building performance simulation (BPS) tools combined with the integration of the life cycle thinking (LCT) are considered a promising approach for evaluating the renovation of buildings. Besides, the performance gap due to occupant behaviour (OB) and the uncertainty of the economic scenario is an essential barrier to the accurate assessment of renovation strategies in residential buildings. The objective of this study is to develop a simulation tool to evaluate the environmental and economic sustainability of energy renovations in residential buildings based on LCT, considering the OB diversity and economic uncertainty. For this, the study develops the PARARENOVATE-LCT tool. This script-based tool combines the dynamic BPS and the integration of the environmental life cycle assessment (LCA) and the economic life cycle cost (LCC), evaluating different renovation strategies in multiple scenarios based on the combination of multiple variables of archetype, climatic zone, OB patterns, economic scenario and orientation. The methodological tool is applied in a case study of the most common archetypes of single-family and multi-family residential buildings of the Basque Country, in northern Spain. The results show how the tool can prioritise strategies, analyse the significance of baseline scenario parameters, and measure the influence of the LCT application. This way, the study provides a methodological tool as a new approach towards developing policies and plans to answer the EU requirements.

1. Introduction

1.1. Context

The energy transition of the residential building stock is one of the biggest challenges towards the goal of carbon neutrality [1], as residential buildings are responsible for over 25 % of the total energy consumption in the European Union (EU) [2] and 75 % of the buildings are inefficient [1]. For this challenge, the legislation of the EU claims an adequate evaluation of the decarbonisation of the building stock by the latest version of the Energy Performance of Buildings Directive (EPBD) (Directive 2018/844 [3]) and the recommendation document relative to the updates of the EPBD, the “Commission Recommendation (EU) 2019/786 of May 8, 2019, on building renovation” [4]. The Directive and the Commission Recommendation include the key points that the long-term renovation strategies (LTRS) should apply to evaluate the renovation of the building stock in the member states. The key points for the evaluation claim the need to quantify the energetic performance of the buildings evaluating the whole-life carbon and the economic cost-effectiveness of the renovation processes towards an efficient reduction of whole-life carbon [3,4]. A previous study underlined the existing barriers to quantifying the indicators related to the reduction of whole-life carbon and calculating the cost-effectiveness of the renovation processes [5]. As the answer to this challenge, the building performance simulation (BPS) enables the precise calculation of the energetic performance of the buildings, which can be a good resource for evaluating potential renovation strategies. Additionally, the integration of life cycle thinking (LCT) can answer the need to assess the impact of the whole life carbon as well as the economic cost-effectiveness of the potential interventions, known as the environmental life cycle assessment (LCA)

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* Corresponding author.
E-mail address: markel.arbulu@ehu.eus (M. Arbulu).

https://doi.org/10.1016/j.enbuild.2024.114182
Received 4 January 2024; Received in revised form 10 April 2024; Accepted 15 April 2024

and the economic life cycle cost (LCC) methods [6].

The BPS has become one of the most significant resources in the energetic analysis of building renovations [7] that can provide the energetic performance data of the building, which is necessary for sustainability evaluation. The advanced complete dynamic simulation tools and calculation engines, like the ones based on Energy-Plus [8] or TRNSYS [9], are the most utilized ones. Many interfaces have been developed with Energy-Plus [8], such as Design-Builder [10] or Open-Studio [11] as an application programming interface. Furthermore, many other tools have been developed based on Energy-Plus, such as jEPlus [12], Eppy [13], Geomeppy [14], Besos [15] or Predyce [16] with extended applications.

Nevertheless, the energetic calculation is insufficient to evaluate the environmental and economic assessment of the renovation of residential buildings. The application of the environmental LCT, the LCA, can evaluate the environmental sustainability of building renovations, being the prioritising method [17,18]. The LCA is a normalised methodology for assessing the environmental impact in buildings regulated by the standard EN-15978 [19]. This methodology has been applied in many frameworks, including Level(s) [20] and many studies and research projects focused on the renovation of existing buildings [6,17]. Other studies also provided methodologies for applying the LCT, like Yeung et al. [21], who applied the LCA and the BPS by the building information modelling (BIM) framework, analysing a case study of two non-residential buildings. In addition, the LCT can also be an optimal resource for evaluating the economic sustainability of buildings by the LCC, regulated by the standard EN-16627 [22]. The LCC has been applied in many studies to calculate the economic cost, taking into account the life cycle of the building [6]. Ekström et al. [23] studied the cost-effectiveness of renovation of single-family houses in Sweden from the 1960s using LCC with the BPS; Milić et al. [24] developed a methodological tool named OPERA-MILP for the economic evaluation of renovation strategies in historic buildings using LCC. Furthermore, Apostolopoulos et al. [25] could create the tool VERIFY, combining the BPS and the evaluation of the LCA and LCC in a dynamic online tool.

Despite the advances made in the last years in the evaluation of the renovation of buildings by the BPS and the application of the LCT, there is still a gap between the theoretical results and the real data [26,27], the so-called performance gap. Many studies have developed accurate calibration techniques [28–32], but the evaluation of residential buildings with a considerable diversity of behavioural usage still has difficulties, according to a previous study [33]. This can be an essential barrier in evaluating the decarbonisation process of residential sector, which is the primary energy consumer of the building stock [2]. The performance gap can be caused by the uncertainty and diversity of the occupant behaviour (OB) patterns data in the calculation of the energetic performance [34,35]. Many studies identified the OB-related input data as the most influential in the energetic calculation of residential buildings [36]. Furthermore, previous studies have also proved that the economic scenario can affect the economic performance of renovation strategies investment [37]. Therefore, the uncertainty can be understood as the diversity of possible scenarios that can cause the performance gap between the predicted and real data regarding economic sustainability. This phenomenon can be increased due to the ups and downs of the economic growth of the last years caused by several events in society, for instance, the decrease of economic growth caused by the pandemic of COVID-19 [38] or the abrupt increase of the inflation rate caused by the conflicts in Ukraine and Gaza [39,40]. As a response to the OB diversity and economic uncertainty, a potential opportunity is the analysis of multiple scenarios, ergo, the parametric study that considers all the possible scenarios covering the uncertainty and closing the performance gap by a range of possible results instead of a single values.

1.2. Objective

The study's main objective is to develop a simulation tool to evaluate the environmental and economic sustainability of energy renovations in residential buildings, analysing multiple scenarios considering the OB diversity and economic uncertainty. For an effective evaluation method, the environmental and economic sustainability evaluations need to include the LCT, taking into account all the significant non-operative impacts and costs during the life cycle of the building. Moreover, to minimise the performance gap of conventional simulation and evaluation methods, it is necessary to consider multiple scenarios of the building typology, climate conditions, OB patterns and economic situations to cover a wide range of possible scenarios. Furthermore, many possible combinations require an automated method to build and assess all the combinations. For that, the study develops a script-based tool, "PARARENOVATE-LCT", a parametric simulation tool for the enviro-economic evaluation of energy renovation strategies in residential buildings under LCT, which evaluates the environmental and economic sustainability of renovation strategies in different scenarios according to the OB diversity, climatic factors and economic situation. Therefore, PARARENOVATE-LCT answers the challenge of the efficient evaluation of the renovation of the residential stock, assessing the whole life carbon and the economic cost-effectiveness, and considering the diversity of scenarios related to the OB and economic uncertainty.

The paper is articulated in five sections: Section 2 explains the methodological approach and functionality of the tool; Section 3 presents the results of the application of the tool in a case study of one collective residential building typology and another single-family residential building typology of northern Spain; Section 4 discusses the results of the previous section; and Section 5 concludes with the highlights of the study.

2. Methodology

The study develops the script-based automatized tool "PARARENOVATE-LCT" written in Python 3, which evaluates parametrically residential building renovation strategies departing from different baseline scenarios. The tool evaluates different scenarios according to five groups of factors: the building typology factors defined as "archetype", the climatic factors defined as "climatic zone", the OB pattern factors defined as "OB cluster", the economic factors defined as "economic scenario" and the orientation of the building. The tool is based on calculating the environmental and economic sustainability of multiple renovation strategies on several baseline residential scenarios developed by combining the five factors. As a result, the tool provides the output key performance indicators (KPI) of each scenario, assessing the fields of energy, environmental sustainability and economic sustainability. The tool is exclusively focused on analysing energetic performance related to heating, cooling and DHW. The tool's functionality is completely automatized with the processing by a single calculation cycle: one input step, the processing and one output data item. Furthermore, the BPS performed is a "complete level" calculation scheme using Energy-Plus [8] as a dynamic energy simulation calculation engine. Moreover, for the LCT integration, the study incorporates the LCA and LCC in the midpoint level following the standards EN-15978 [19] for the environmental evaluation – the LCA – and the EN-16627 [22] for the economic evaluation – the LCC. The methodological tool is based on one script written in Python 3 (*.py* format), and one input data Excel file (*.xlsx* format) with the requirement of the base energy models (*.idf* format compatible with Energy-Plus) and the weather files (.epw format). The algorithm of the methodological tool is explained in three stages: (1) the input data, (2) the processing of data and (3) the output (see Fig. 1).

For the life cycle environmental and economic assessment – the application of the LCA and LCC–, the method defines the parameters of the life cycle evaluation scope in common (see Table 1): the functional unit (FU), the reference study period (RSP), the system boundary conditions, the impact indicators and the assessment KPIs.

The FU is the "quantified performance of a product system for use as a reference unit" according to the definition ISO-14040:2006 [41], and

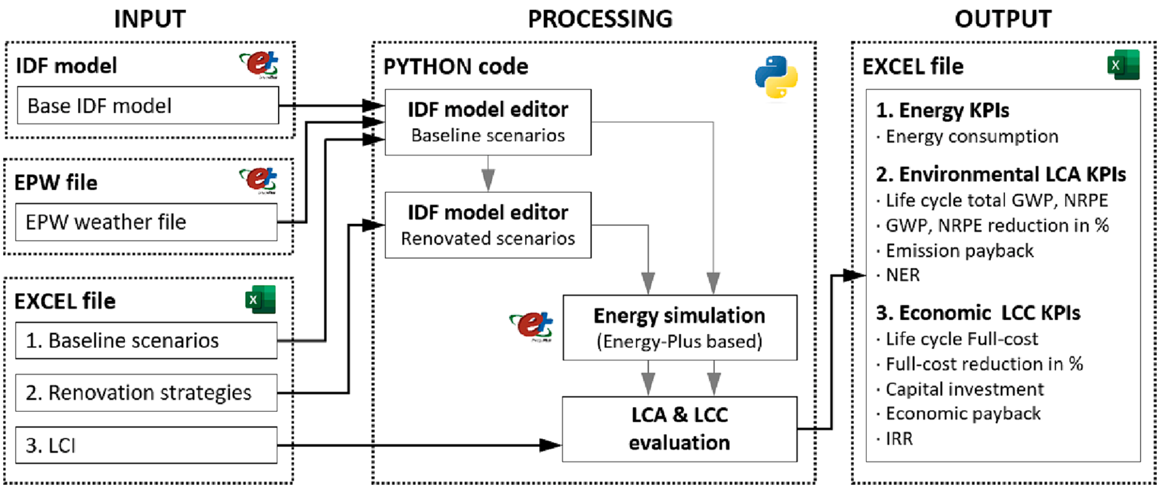


Fig. 1. Algorithm of the parametric simulation tool PARARENOVATE-LCT for the enviro-economic evaluation of energy renovation strategies in residential buildings integrating the LCT.

Table 1
LCA and LCC scope parameters definition.

Scope parameters		
Functional unit (FU)		
m^2·yr		
Reference study period (RSP)		
50 years		
Boundary conditions		
Life cycle stage	*LCA*	*LCC*
A1-3 (Product)	✓	✓
A5 (Construction)		✓
B2 (Maintenance)		✓
B4 – A1-3 (Product of replacement)	✓	✓
B4 – A5 (Construction of replacement)		✓
B6 (Use of energy)	✓	✓
Impact indicators	*Unit*	
GWP	kg CO_2eq. / m^2·yr	
NRPE	MJ / m^2·yr	
FC	€ / m^2·yr	
Assessment KPIs	*Unit*	
Energy consumption	kWh / m^2·yr	
Life cycle total GWP	kg CO_2eq. / m^2·yr	
Life cycle total NRPE	MJ / m^2·yr	
GWP life cycle reduction	%	
NRPE life cycle reduction	%	
Emission life cycle payback	years	
NER	–	
Life cycle FC	€ / m^2·yr	
FC reduction	%	
Capital investment	€	
Economic life cycle payback	years	
IRR	%	

it provides a common reference to analyse the input and output, allowing the comparison between different case studies and analysed scenarios. This study applies the FU of m2·year of the habitable conditioned net area of the residential units.

The RSP of the methodology is the period where the analysis is carried out according to the characteristics of the subject under evaluation [19]. The LCA and LCC standards do not define any specific value, so the present methodology applies the estimated service of the building renovation following the EN-15978:2012 [19], as the reference service life of the building (RSL_B). The RSP applied in this study is 50 years.

The boundary conditions specify the life stages to be assessed, which are defined in the EN-15978:2012 [19]. This methodology considers the most influential life stages, applying the cut-off rule in the life stages with less than 1 % of influence in the final impact indicators (the same impact indicators used in this methodology) based on the previous study by Oregi et al. [42]. Following this, the present methodology evaluates the life stages shown in Table 1 for the LCA and the LCC.

The impact indicators measure the environmental impact and economic cost of the renovation strategies during the life cycle of the building within the RSP. The methodology applies the “Global warming potential” (GWP) and the “Total use of non-renewable primary energy resources” (NRPE) for the LCA, in the units of kg·CO2eq and MJ respectively, defined by the EN-15978:2012 [19]; for the LCC the methodology uses the Full-cost (FC) impact indicator, in the unit of € as the currency of the EU (see Table 1).

For the final evaluation, the methodology develops 11 KPIs for each scenario as the output results assessing three fields: energy (one KPI), environmental sustainability (six KPIs), and economic sustainability (four KPIs). The energetic KPI measures the operational energy consumption of the building (see Table 1). For the environmental evaluation, two KPIs indicate the life cycle total impact of the building as the impact indicators GWP and NRPE (including the embodied and operation impacts); the next two measure the percentage of reduction of the total life cycle impacts for both the GWP and NRPE, in comparison with the baseline scenario; the KPI “Net energy ratio” (NER) measures the ratio between the embodied energy of the renovation strategy and the energy saving caused by the renovation [43]; the last environmental KPI “Emission payback” quantifies the number of years when the embodied energy of the renovation strategy is compensated by the energy saving provided by the renovation. For the economic assessment, the first KPI measures the life cycle FC of the building (including the embodied and operation costs); as in the environmental evaluation, the reduction of the life cycle FC is also measured in percentage in the “FC reduction” KPI; the following KPI “Capital investment” indicates the total initial capital investment needed to carry on the renovation strategy; the last two economic KPIs evaluate the profitability of an investment by the “Economic life cycle payback” and the “Internal rate of return” (IRR).

2.1. Input

The first stage of the tool is the data input, which is divided into three items: (1) the base energy model, (2) the weather file and (3) the Excel file. Firstly, (1) the base energy model defines the initial baseline model for each building typology to be analysed, (2) the weather file determines the outdoor climatic factors, and (3) the Excel file defines the input parameters of the baseline scenarios, the input parameters of the energy renovation strategies and the life cycle inventory (LCI).

2.1.1. Base IDF model

The tool enables the analysis of different renovation strategies in several scenarios of residential buildings, including the analysis of several buildings, defined as "archetypes", making it possible to evaluate different scale case studies from one single building to a national or regional residential stock. For each "archetype" to assess, the tool requires a base energy model in a baseline situation in IDF format modelled by an Energy-Plus [8] compatible software; this research suggests the software Design-Builder [10]. The accuracy of the base model will define part of the accuracy of the outputs in terms of building construction, geometrical design, and energy calculation parameters that will not be defined in the Excel file.

2.1.2. EPW weather file

The tool also enables the analysis of several climatic conditions, and for each "climatic zone", one weather file is required in EPW format, which can be provided by databases such as the International Weather for Energy Calculation (IWEC) [44] or it can be developed with monitored climatic data.

2.1.3. Excel file

As the third input file, the Excel file defines the input parameters divided into seven data categories grouped into three input data groups: the "baseline residential scenarios" (five data categories), the "renovation strategies" (one data category) and the "life cycle inventory" (LCI) (one data category), organised in different sheets of the excel file, one for each data category (see Annex 1).

In the first group, the data category "baseline scenarios" (data sheet 1.1_scenarios) defines the departing baseline scenarios according to the five groups of factors of "archetype", "climatic zone", "OB cluster", "economic scenario" and orientation. The "archetype" (data sheet 1.2_archetype) assigns the base IDF model and defines the RSL_B (rslb) and the main energetic processes parameters related to heating, cooling and DHW, such as the energy efficiencies (ee_h, ee_c, ee_dhw) and the energy sources (es_h, es_c, es_dhw) at the baseline scenario. The "climatic zone" (data sheet 1.3_clima) assigns the Energy-Plus weather file (.epw) and defines the annual global horizontal irradiation (rad) to calculate the solar energy based renovation strategy. The data category of "OB cluster" (data sheet 1.4_ob) defines the diverse OB patterns that can be evaluated by defining the energetic behaviour parameters of use of heating and cooling (heat_onoff, cool_onoff), setpoint and setback temperatures (setpoint_h, setback_h, setpoint_c, setback_c), ventilation rate (vent_rate) and consumption of DHW (dhw_rate). Finally, the "economic scenario" (data sheet 1.5_ec) data category defines the different economic scenarios in terms of the level of economic growth, specifying the discount rate (dr), economic inflation rate (inf) and the energy price increase (EPI) for different energy sources (epi_g, epi_e). The parameters of discount rate and EPI should use nominal values, including the economic inflation.

The second input data group defines the renovation strategies to be analysed in each baseline scenario by the "renovation strategy" data category (data sheet 2_renovation). The input parameters describe different renovation strategies with passive, active and renewable energy source (RES) based interventions and the combination of them. Six types of interventions can be defined, and all the possible combinations: exterior façade insulation, internal façade insulation, roof insulation (for both sloping roofs and flat roofs), window replacement, heat pump (HP) installation, and photovoltaic (PV) modules installation. For each strategy intervention, specific input parameters must be defined as specified in Annex 1.

In the third input data group, for the quantification of the environmental impact and economic cost, the "LCI" data category (data sheet 3_LCI) sets the required environmental and economic parameters for each energetic process and product (see Annex 1). For the operational energetic processes, the input parameters for the "use of energy" life stage (B6) – also denominated as "conversion factor" [42] – define the environmental impact and cost of each unit of use of energy as the impact indicators (GWP, NRPE and FC). In terms of the products used by the renovation interventions, the LCI sets the input parameters that quantify their environmental impact and economic cost for the non-operational life stages within the boundary conditions – including the "use of product stage" (A1-3), the "construction stage" (A5) and the maintenance stage (B2) – as the impact indicators (GWP, NRPE and FC). Moreover, the LCI requires the reference service life of the material (RSL_M) to calculate the replacement impact and costs during the life cycle; the quantification of the B4 stages is carried out by the automatized tool departing from the already set parameters.

2.2. Processing

The second stage processes the input data using the script written in Python 3, which is based on energetic, environmental and economic data calculations, as a "white-box" tool. The processing is divided into three modules: (1) the IDF model editor module, (2) the energy simulation module and (3) the LCA & LCC evaluation module. All the processing modules are applied by looping through all the baseline scenarios, applying the renovation strategies to be analysed, and calculating the output KPIs for each renovation scenario.

2.2.1. IDF model editor module

The first module is in charge of preparing the scenarios for the evaluation, and it is divided into two parts: the IDF model editor for the "baseline scenarios" and the IDF model editor for the "renovation scenarios".

For the "baseline scenario" model definition, the "baseline scenarios" IDF model editor module identifies the base IDF file assigned in the "archetype" input data and the EPW weather file assigned in the "climatic zone" input data. Then, the input parameters set in the data categories of the "baseline scenarios" – "archetype", "climatic zone", "OB cluster" – are applied to the baseline model, creating the IDF model of the "baseline scenario", ready to carry on the dynamic BPS. The treatment of the IDF models is carried on by the Eppy [13] scripting language for Energy-Plus. This module only applies the modifications defined in the parameters of the mentioned scenarios without modifying the rest of the parameters of the IDF model.

Afterwards, the IDF model editor for the "renovation scenarios" develops the models departing from the "baseline scenario" model and applying the renovation interventions set in the "renovation strategy" input data, getting the "renovation scenarios" models ready for the BPS.

2.2.2. Energy simulation module

The energy simulation module carries on the BPS with the calculation engine Energy-Plus [8] using the Eppy [13] scripting language. The BPS is run for each baseline scenario and renovated scenario by the assigned IDF model and EPW weather file. The simulations are run annually with the calculation rules set in the base IDF model. Once the BPS is completed, the module saves all the results and IDF models. Once the simulation is carried out, firstly, the tool reads the results regarding the energetic performance and the geometric specifications, including the annual energy demands, the peak of demanded power and the areas of the façade, roof, window glazing and window framing of for the energetic analysis and the sizing of the renovation interventions. All these data is compiled for each baseline and renovated scenario ready for the LCA & LCC evaluation module.

2.2.3. LCA & LCC evaluation module

The third processing module performs the enviro-economic evaluation of the life cycle of each renovation scenario according to the LCA and LCC scope parameters (defined in Table 1). The final product of this module are the output KPIs for the evaluation of the renovation scenarios as well as other secondary indicators reported in the output file. The basis of the calculation follows the same structure as the previous study that developed an environmental and economic optimisation and prioritisation toolkit [45].

The calculation departs from the energetic parameters of each scenario and the environmental and economic parameters defined in the LCI of the input data. The evaluation begins with calculating the impact of the operational energy use (stage B6) – environmental and economic – of heating, cooling and DHW production in all the scenarios. The impacts are calculated as the impact indicators and defined, GWP and NRPE as the environmental and FC as the economic impact. In this stage, the yearly environmental impact remains constant during the life cycle; the economic impact grows yearly due to the EPI.

To continue, the impact of non-operational life stages – the embodied impacts – is calculated following the boundary conditions. The first category of the product stage (A1-3) considers the “cradle to gate” impact of the products applied by the renovation scenarios for both LCA and LCC. The following construction process stage (A5) calculates the economic impact of the construction costs for the LCC. The maintenance stage (B2) is only assessed by the LCC and includes the economic cost of the maintenance works required by the renovation strategy. For the calculation of the B2, the costs are calculated according to the yearly economic inflation, which plays a big role in the renovation strategies with a significant maintenance cost. The replacement of certain products during the life cycle of the building is evaluated in the replacement stage (B4), divided into two sub-stages: the product stage (B4 A1-3) for the LCA and LCC evaluation and the construction stage (B4 A5) evaluated only by the LCC. The economic cost for the LCC of this stage considers the year when the replacement is needed based on the RSL_M and the economic inflation rate.

Finally, the evaluation module calculates the KPIs for the energetic, environmental and economic evaluation. For the environmental evaluation, the LCA calculation departs from the two impact indicators – GWP and NRPE – calculating the total impact, the impact reduction, the emission life cycle payback and the NER. For the economic evaluation, the LCC calculation is based on the economic impact indicator FC calculating the total cost during the life cycle, the cost reduction, the economic life cycle payback, the IRR and the initial capital cost required to execute the renovation strategy.

2.3. *Output*

The final product of the parametric simulation tool is an Excel file exported by the script. The Excel file contains all the input data sheets, adding two sheets: (1) the “all data” sheet containing all the parameters, including intermediate calculation parameters and extra result indicators (data sheet 4_all_data) and (2) the “KPI” data sheet containing the defined KPIs (data sheet 5_KPI).

3. Results

The presented methodological tool is applied in the case study of two of the most common residential typologies prior to the energetic regulations of the Basque Country, in northern Spain. The study considers multiple residential scenarios with multiple climatic factors, OB factors, economic factors and different orientations. Moreover, different renovation strategies are evaluated in the residential scenarios created from all the possible combinations of the five-factor groups with two “archetypes”, three “climatic factors”, 13 “OB clusters”, five “economic scenarios” and four orientations (see Table 2).

Table 2
Characterization of the variables of the case study.

Archetype (2)	Climatic zone (3)	OB cluster (13)	Economic scenario (5)	Orientation (4)
SF – Single-family	C1	OB0 – Average behaviour	EC0 – Average growth	North
MF – Multi-family	D1	OB1.1 – Low heating use 1	EC1 – Low growth 1	West
	E1	OB1.2 – Low heating use 2	EC2 – Low growth 2	East
		OB1.3 – High heating + cooling use 1	EC3 – High growth 1	South
		OB1.4 – High heating + cooling use 2	EC4 – High growth 2	
		OB2.1 – Low ventilation rate 1		
		OB2.2 – Low ventilation rate 2		
		OB2.3 – High ventilation rate 1		
		OB2.4 – High ventilation rate 2		
		OB3.1 – Low DHW consumption 1		
		OB3.2 – Low DHW consumption 2		
		OB3.3 – High DHW consumption 1		
		OB3.4 – High DHW consumption 2		

The “archetypes” of the case study are composed of two typologies from the period between 1961 and 1980, where the most significant number of residential buildings were built [46,47], selecting the most common multi-family (MF) and single-family (SF) typologies. They were identified by a previous work based on the characterisation of the residential stock of the Basque Country as part of the project “Long-term intervention strategy for the Basque Country’s building stock” [46,47]. The characterisation was based on a clustering tree of four levels according to four characterisation indicators. The first level is the “Construction date” with six possible values (before 1900, 1901–1940, 1941–1960, 1961–1980, 1981–2007, after 2008), the second level is the “Residential typology” with two possible values (collective, individual), the third levels is the “Number of storeys” with three possible values (ground + <3, ground + 3–8, ground + >8) and the last level is the “Constructive typology” for the last segregation level according different constructive solutions; the study developed 33 archetypes. The selected archetypes are clustered with the following characterisation indicators departing from the same “Construction date” clustering level of “1961-1980″. The MF (see Fig. 2a) belongs to the branch ”collective“ of the ”Residential typology“, to the branch of ”ground + 3-8″ for the “Number of storeys” and with a “Constructive typology” distinctive in the isolated buildings; the SF (see Fig. 2b) takes the “individual” branch for the “Residential typology” level, “ground + <3″ for the ”Number of storeys“ and no segregation is made in this branch according to the ”Constructive typology“.

For the climatic factors, the case study analyses the three “climatic zones” of the area of the Basque Country defined by the national technical building code (TBC) [48], the zones “C1″, ”D1″, and “E1″. Moreover, for the OB factors, the analysis develops 13 ”OB clusters“ to reflect different behavioural models in terms of energetic use of the residence. The clusters are obtained departing from the TBC, setting one average OB cluster according to the regulations (OB0) and another 12 clusters with differing parameters: four clusters with differing use of heating – two clusters with low heating use (OB1.1, OB1.2) and two clusters with high heating use (OB1.3, OB1.4) –, four with differing ventilation rates – two with lower (OB2.1, OB2.2) and two with higher ventilation rate (OB2.3, OB2.4) –, and another four with differing DHW consumptions – two with a higher consumption (OB3.1, OB3.2) and two with lower (OB3.3, OB3.4). The quantification and average limits of the OB input parameters were obtained based on a recent study about the OB

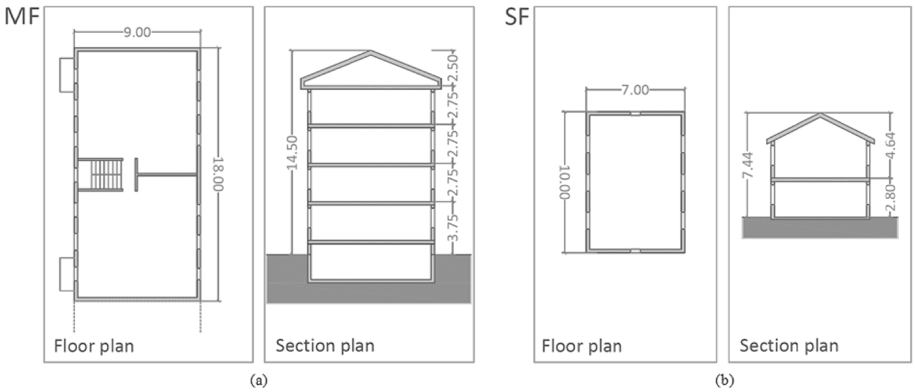


Fig. 2. The studied two archetypes, the MF (a) and SF (b) residential building typologies of the case study.

diversity in the Basque Country [49], and none of the OB clusters uses cooling due to the current trends of the territory and needs. For the ”economic scenarios“, one average economic scenario is set aligned to the economic growth targets of the EU (EC0) [50], two scenarios with lower economic growth (EC1, EC2) and another two scenarios with higher economic growth (EC3, EC4). Finally, the four orientations are also considered. Considering the five groups of factors, the study covers a wide range of possible residential scenarios beyond the average values set by the technical regulations and standard data.

The renovation strategies to be evaluated consist of the most common renovation interventions carried out in the residential stock in Spain [51,52], including passive, active and RES integration interventions. The passive interventions include the façade exterior insulation by exterior thermal insulation system (ETICS) and ventilated façade, the insulation of the roof and windows replacement; the active interventions include the replacement of the boiler with an aerothermal heat pump and the integration of RES the photovoltaic (PV) energy for the energy supply of the HP. The renovation strategies are composed of one single intervention or combining more than one intervention, combining passive, active and RES-based interventions.

3.1. Input

For the application of the case study, the input data is organised into the three input items: (1) two base energetic models representing the two archetypes, (2) three weather files belonging to the three climatic zones, and (3) one excel file with the input data of the “baseline scenarios” – two “archetypes”, three “climatic zones”, 13 “OB clusters”, five “economic scenarios” and four orientations – together with the “renovation strategies” input parameters and the “LCI”.

3.1.1. Base IDF model

The analysis of the selected “archetypes” begins with the design of the generic model to represent the residential topology with the features shown in Table 3, from which the results could be extrapolated to all the buildings belonging to reference residential topology. The energetic models are built in the software Design-Builder [10] as the two base models for the two “archetypes”– MF and SM – (see Fig. 3) and they are exported as IDF models as input items.

3.1.2. EPW weather file

The case study’s climatic conditions are compounded by the three “climatic zones” selected following the TBC [48]. For the data entry, one EPW file is selected for each “climatic zone” provided by the database of the IWEC [44]: the EPW from Bilbao for the C1 zone, the EPW from Vitoria-Gasteiz for the D1 zone and the EPW from Burgos for the E1 zone.

Table 3
Characteristics of the generic models of the representing archetypes.

Characteristic	MF	SF
Number of dwellings	8	1
Residential storeys	ground + 3	ground + 1
Heated surface	570.44 m^2	127.04 m^2
Façade transmittance	1.48 $W/m^2{\cdot}K$	1.30 $W/m^2{\cdot}K$
Roof transmittance	2.68 $W/m^2{\cdot}K$	2.16 $W/m^2{\cdot}K$
Window-frame transmittance	5.89 $W/m^2{\cdot}K$	5.89 $W/m^2{\cdot}K$
Window-glass transmittance	3.63 $W/m^2{\cdot}K$	3.63 $W/m^2{\cdot}K$
Heating system	Gas boiler	Gas boiler
Energy efficiency of heating	0,70	0,70
DHW production system	Gas boiler	Gas boiler
Energy efficiency of DHW	0,70	0,70
Ventilation system	Natural	Natural
Air tightness (n50)	10 ach/h	10 ach/h

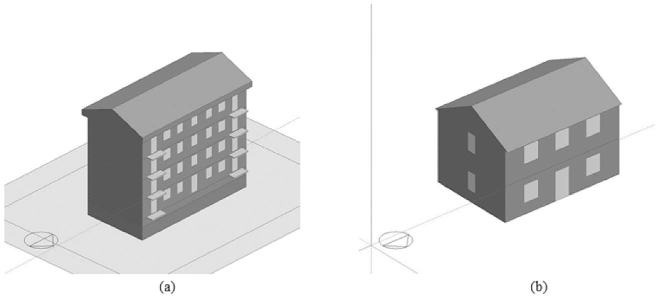


Fig. 3. Visual representation of the building models by Design-Builder. Figure (a) represents the MF archetype; figure (b) represents the SF archetype.

3.1.3. Excel file

The input Excel file collects the data on the residential scenarios, the renovation strategies and the LCI. For the residential scenarios, the first data category of “baseline scenarios” sets 1,560 residential scenarios by combining the five factors (see Table 2). The following data category of “archetype” defines the two archetypes developed as IDF base models assigning the URL path of the file and the calculation parameters according to Table 3. The “climatic factors” assigns the URL path of the three weather files and the annual global horizontal irradiation (rad) provided by the photovoltaic geographical information system of the EU [53] for each “climatic zone”. For the data category “OB clusters”, the 13 OB clusters are defined following Table 4. Finally, for the “economic scenarios”, Table 5 sets the input parameters for the five economic scenarios.

Table 4
OB cluster definition for the data category “OB clusters” (sheet 1.4_ob).

OB cluster	Heating (on/off)	Cooling (on/off)	Heating setpoint [°C]	Heating setback [C°]	Cooling setpoint [C°]	Cooling setback [C°]	Ventilation rate [ach/h]	DHW rate [l/m^2·day]
OB0	1	0	20	17	25	27	0.63	0.84
OB1.1	1	0	**18**	**15**	25	27	0.63	0.84
OB1.2	1	0	**19**	**16**	25	27	0.63	0.84
OB1.3	1	0	**21**	**18**	25	27	0.63	0.84
OB1.4	1	0	**22**	**19**	25	27	0.63	0.84
OB2.1	1	0	20	17	25	27	**0.50**	0.84
OB2.2	1	0	20	17	25	27	**0.57**	0.84
OB2.3	1	0	20	17	25	27	**0.69**	0.84
OB2.4	1	0	20	17	25	27	**0.76**	0.84
OB3.1	1	0	20	17	25	27	0.63	**0.67**
OB3.2	1	0	20	17	25	27	0.63	**0.76**
OB3.3	1	0	20	17	25	27	0.63	**0.92**
OB3.4	1	0	20	17	25	27	0.63	**1.01**

Table 5
Economic scenarios definition for the data category “economic factors” (sheet 1.5_ec).

Economic scenario	Discount rate	Inflation rate	EPI – Gas [%]	EPI – Elect. [%]
EC0	0.030	0.020	0.060	0.060
EC1	0.020	0.010	0.015	0.015
EC2	0.025	0.015	0.030	0.030
EC3	0.035	0.025	0.090	0.090
EC4	0.040	0.030	0.120	0.120

3.2. *Processing*

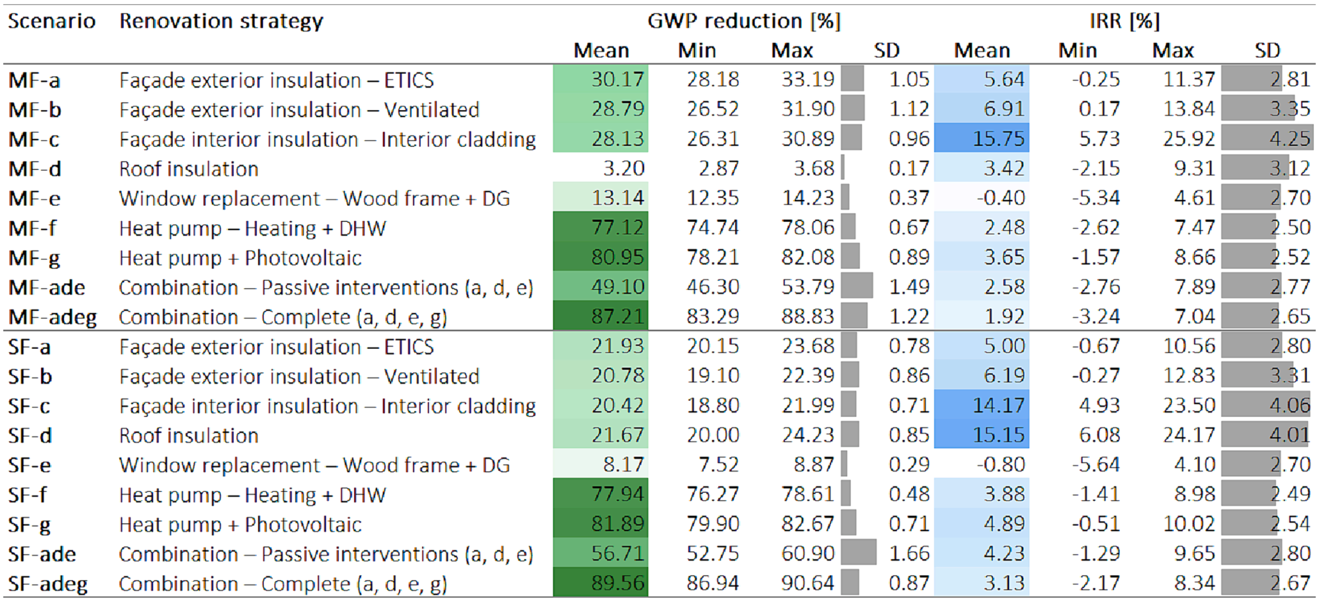
For the processing, the defined input items are read by running the script written in Python 3. The tool evaluates the 1,560 baseline scenarios, creating nine renovation scenarios for each baseline-departing scenario. In total, the tool evaluates 15,600 scenarios, 1,560 baseline in the baseline level and 14,040 renovated scenarios.

3.3. *Output*

As the simulation tool results, the script exports the final Excel file with the KPIs and additional parameters of each of the 15,600 scenarios. The interpretation of the results can be very diverse; nevertheless, for this case study, as the demonstration of the methodological “white-box” evaluation tool, three interpretations are made: (1) the analysis of the impact of the renovation strategies, (2) the influence of the baseline scenarios input parameters in the results of the sustainability KPIs of the renovation strategies, and (3) the influence of the life cycle perspective for the evaluation of renovation strategies.

3.3.1. *Analysis of the impact of renovation strategies*

For the analysis of the renovation strategies, the decisive KPIs can differ according to different situations and case studies. This study has selected the environmental KPI “GWP reduction in percentage” and the economic KPI “IRR” to assess different renovation strategies in the case study. For the correct interpretation, the results of the KPIs have been processed, calculating the statistical summary of each renovation strategy for each analysed archetype as it is shown in Fig. 4, indicating the mean, the minimum value, the maximum value and the standard deviation (SD) of each renovation strategy for each of the two archetypes. This way, it is possible to calculate the range of possible values of each KPI for each renovation strategy, covering a wide range of possible situations. The mean value can be a reference value, but it is also essential to take into account the minimum and the maximum values; moreover, the SD, which measures the accuracy of the mean value, indicates how much can the mean value change in different scenarios depending on the “climatic zone”, “OB cluster”, “economic scenario”



Scenario	Renovation strategy	GWP reduction [%]				IRR [%]			
		Mean	Min	Max	SD	Mean	Min	Max	SD
MF-a	Façade exterior insulation – ETICS	30.17	28.18	33.19	1.05	5.64	-0.25	11.37	2.81
MF-b	Façade exterior insulation – Ventilated	28.79	26.52	31.90	1.12	6.91	0.17	13.84	3.35
MF-c	Façade interior insulation – Interior cladding	28.13	26.31	30.89	0.96	15.75	5.73	25.92	4.25
MF-d	Roof insulation	3.20	2.87	3.68	0.17	3.42	-2.15	9.31	3.12
MF-e	Window replacement – Wood frame + DG	13.14	12.35	14.23	0.37	-0.40	-5.34	4.61	2.70
MF-f	Heat pump – Heating + DHW	77.12	74.74	78.06	0.67	2.48	-2.62	7.47	2.50
MF-g	Heat pump + Photovoltaic	80.95	78.21	82.08	0.89	3.65	-1.57	8.66	2.52
MF-ade	Combination – Passive interventions (a, d, e)	49.10	46.30	53.79	1.49	2.58	-2.76	7.89	2.77
MF-adeg	Combination – Complete (a, d, e, g)	87.21	83.29	88.83	1.22	1.92	-3.24	7.04	2.65
SF-a	Façade exterior insulation – ETICS	21.93	20.15	23.68	0.78	5.00	-0.67	10.56	2.80
SF-b	Façade exterior insulation – Ventilated	20.78	19.10	22.39	0.86	6.19	-0.27	12.83	3.31
SF-c	Façade interior insulation – Interior cladding	20.42	18.80	21.99	0.71	14.17	4.93	23.50	4.06
SF-d	Roof insulation	21.67	20.00	24.23	0.85	15.15	6.08	24.17	4.01
SF-e	Window replacement – Wood frame + DG	8.17	7.52	8.87	0.29	-0.80	-5.64	4.10	2.70
SF-f	Heat pump – Heating + DHW	77.94	76.27	78.61	0.48	3.88	-1.41	8.98	2.49
SF-g	Heat pump + Photovoltaic	81.89	79.90	82.67	0.71	4.89	-0.51	10.02	2.54
SF-ade	Combination – Passive interventions (a, d, e)	56.71	52.75	60.90	1.66	4.23	-1.29	9.65	2.80
SF-adeg	Combination – Complete (a, d, e, g)	89.56	86.94	90.64	0.87	3.13	-2.17	8.34	2.67

Fig. 4. Statistical summary of the KPIs “GWP reduction” and “IRR” of the case study by archetypes (MF and SF).

and orientation. When evaluating the environmental impact reduction of the renovation strategies, both archetypes have a similar “GWP reduction”; the strategies based on active interventions (*g, h* and *adfh*) have a higher performance. Nevertheless, almost all the strategies show an improvement, with façade insulation having the highest “GWP reduction” among the passive strategies. However, according to the economic KPI “IRR”, the passive interventions have the best economic performance. Within passive strategies, façade insulation offers a high GWP reduction, where the exterior insulation based strategies offer better thermal advantages in comparison to the interior insulation, reducing thermal bridges, an aspect which has been included in the analysis but does not affect significantly in the final results; the study considers that the exterior insulation only provides the elimination of the thermal bridge in the joint of the façade with the slab but not the thermal bridge of the windows and other joints. Besides, the interior insulation reduces interior floor area by adding the cladding system, even if it is not significant, which in this study has been neglected. However, the interior cladding achieves a good economic performance due to the lower economic cost.

Additionally, it is also essential to check the minimum values because, in some cases, they can be negative, indicating that the economic investment is not going to be returned in the defined RSL_B of 50 years. Levene’s test has been performed to analyse the equality of both archetypes, which indicates inequality of variances of both KPIs, “GWP reduction” and “IRR”, with a p-value bellow 0.0001 ($p < 0.05$).

Furthermore, even if the “IRR” of both archetypes can differ significantly, the results of both archetypes can also be represented together to evaluate the performance of different renovation strategies applied in the case study. Therefore, Fig. 5 represents the performance of the renovation strategies by a box plot indicating the “GWP reduction” (a) and the “IRR” (b). The difference in the SD between the KPIs, where the “GWP reduction” has a lower deviation, can be appreciated. At the same time, the “IRR” values can vary significantly, adding to the inequality of variances of the two archetypes.

3.3.2. Influence of baseline scenarios parameters

The previous sections demonstrate that the results of the KPIs can differ in different degrees. However, it is also essential to check the influence of the input parameters in the final KPIs. For this, the significance of five parameters are analysed in the KPIs of “GWP reduction” and “IRR”: the climatic zone to analyse the influence of the climatic factor, the heating setpoint temperature, the ventilation rate and the DWH rate for the OB influence analysis, and the economic inflation rate to measure the influence of the economic scenarios.

The influence of the climatic zones is analysed carrying on, on the one hand, the Kruskal–Wallis one-way analysis to compare the means of the results of different climatic zones for both “GWP reduction” and “IRR” KPIs, and on the other hand, the Levene test of variances to compare the variances. The Kruskal–Wallis analysis indicates that the means of both “GWP reduction” and “IRR” of different climatic zones do not match with a p-value below 0.0001 ($p < 0.05$) for both KPIs. However, the Levene test shows that “GWP reduction” presents equal variances for the different climatic zones with a p-value of 0.6699; in contrast, the variances in the results of the “IRR” are not equal with a p-value below 0.0001 ($p < 0.05$). This shows that the climatic zone does influence both KPIs, with the “IRR” more sensitive to the change in the climatic zone.

In order to measure the influence of the input parameters that define the OB clusters and economic scenarios as continuous variables, an influence coefficient (IC) is applied and calculated by Eq. (1) [60]. The IC is a dimensionless indicator that measures the variation of the KPI output result caused by the input parameter variation. For both factors of OB clusters and economic scenarios, the influence of the variation of the input parameters is calculated departing from the baseline scenarios of OB cluster (OB0) – analysing the input parameters of heating setpoint, ventilation rate and DHW consumption – and the baseline scenarios of the economic scenario (EC0) – analysing the input parameter of inflation rate, as the primary indicator of economic growth – in each renovation scenario, applied to the “GWP reduction” and “IRR” as the perturbed KPIs.

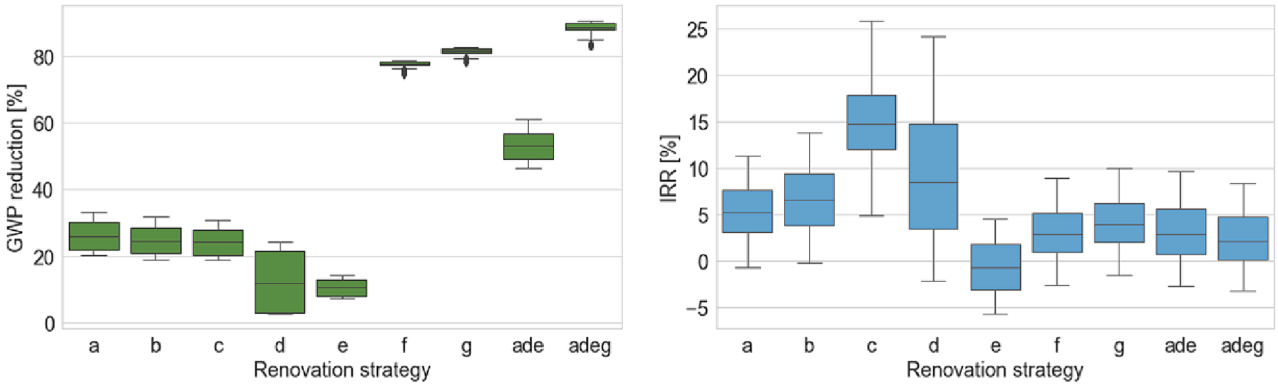
$$IC = \left|\frac{(\Delta KPI/KPI_{base})}{(\Delta IP/IP_{base})}\right| \tag{1}$$

Where:

- KPI_{base}: KPI in the baseline scenario.
- IP_{base}: input parameter of the baseline scenario.
- ΔKPI: variation of the KPI ($KPI_{scenario} - KPI_{base}$).
- ΔIP: variation of the input parameter ($IP_{scenario} - IP_{base}$).

When analysing its influence in the final KPIs of this assessment, three ICs of three input parameters are calculated to measure the influence in the KPIs of “GWP reduction” and “IRR”. The IC of the first OB related parameter of heating setpoint in the variation of the “GWP reduction” KPI has a median value of 0.21 and SD of 0.22; the heating setpoint is the parameter with the most significant influence in the “GWP reduction” (see Fig. 6). For the rest of the OB input parameters, ventilation rate and DHW consumption, have a lower influence with a median IC of 0.16 and SD of 0.08 for the ventilation rate and a median IC of 0.07 and SD of 0.05 for the DHW consumption. Fig. 6 shows the low significance of these two input parameters, however, the influence of the ventilation rate is slightly higher, considering the IC values (see Fig. 6).

In terms of the influence in the KPI “IRR”, the heating setpoint variation has the highest effect as in the “GWP reduction”, with a median IC of 2.06 and SD of 3.37 (see Fig. 7). The variation of the economic KPI “IRR” caused by the perturbation of the ventilation rate and DHW



(a) (b)

Fig. 5. Representation of the KPIs “GWP reduction” (a) and “IRR” (b) of the case study.

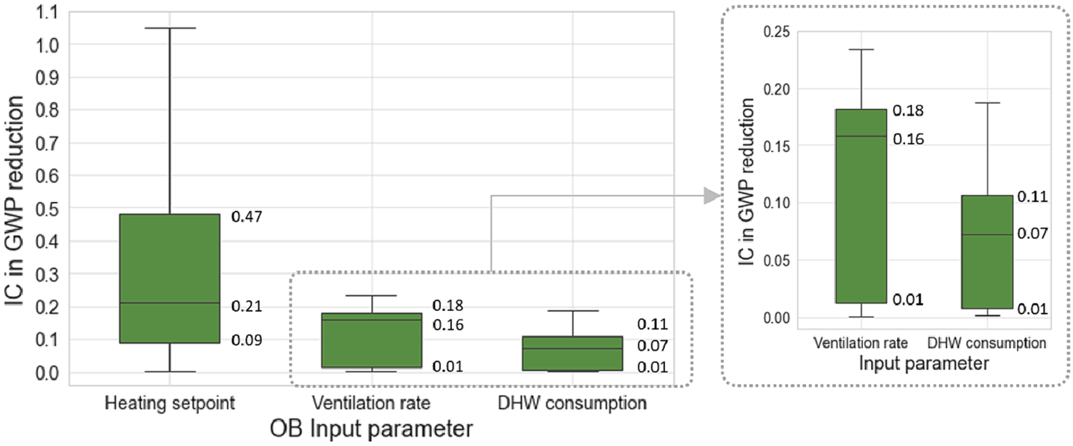


Fig. 6. Influence of the OB input parameters on the GWP reduction measured as IC.

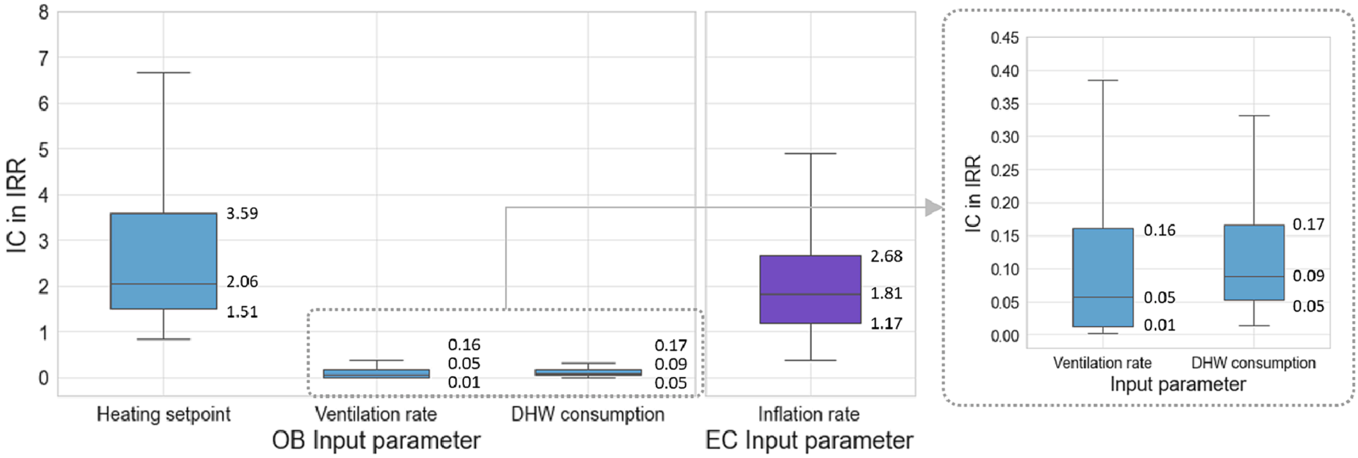


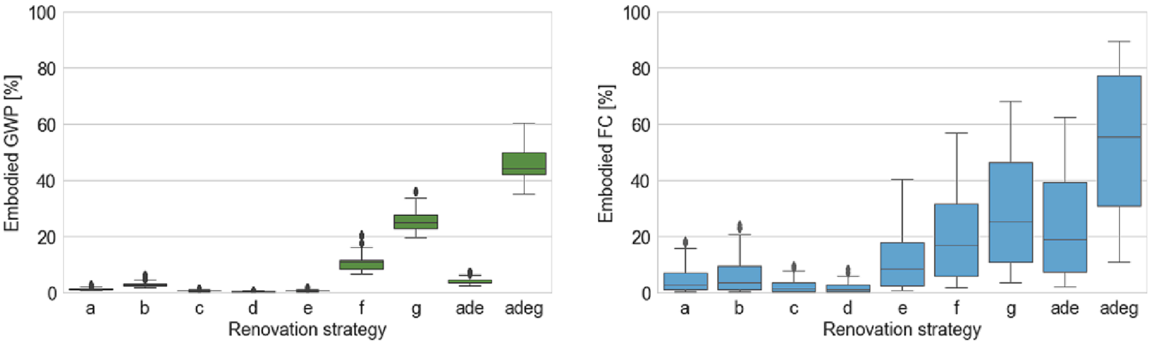
Fig. 7. Influence of the OB and economic growth input parameters on the IRR measured as IC.

consumption presents a lower significance. The ventilation rate has a median IC of 0.06 and SD of 0.21. The IC of the DHW consumption has a median value of 0.09 and SD of 1.67, being slightly higher than the ventilation rate. To measure the influence of the economic scenarios, the IC of the economic inflation rate, which reflects the degree of growth of the economy, is analysed (see Fig. 7). The inflation rate presents a significant influence with a median IC value of 1.81 and SD of 1.67. Analysing the results in deep, scenarios with a higher economic growth reflected with higher inflation rates derive to higher EPI and discount rate values, where the big influence of the EPI in the energy saving economic quantification generates a better rate of return of investment, ergo, a higher IRR. Moreover, in comparison to the rest of the input parameters analysed, in terms of the IC values, the inflation rate, as the main economic growth numeric indicator, has a much higher influence than the ventilation rate and DHW consumption, but not as high as the heating setpoint. This analysis shows that the tool enables the deep analysis of the influence of the baseline scenarios, showing that the economic outcomes usually have a higher variation than the environmental ones, as it happens with the SD of the results shown in the Fig. 5.

3.3.3. *Influence of the life cycle thinking application*

The influence of the life cycle perspective for the evaluation of renovation strategies determines how important it can be to assess the life cycle of the renovation strategies instead of assessing only the operational stage of the use of energy (B6). To analyse this, the study calculates, on the one hand, the share of the non-operational environmental impact – embodied impact – of the life cycle total impact, and on the other hand, the share of the non-operational economic cost – embodied cost – of the life cycle total cost for each renovation strategy. Fig. 8 shows the share of the embodied impact and cost for one environmental impact indicator, the "life cycle GWP", and the economic impact indicator, the "life cycle FC". In the case of the environmental impact, the embodied impact does not reach 5 % in most cases, where the strategies with active renovation interventions (*f, g, adeg*) have the highest share. This means that in the cases of active renovation strategies, where the impact caused in the early life stages, like the product stage (A1-3) and the replacement stage (B5), have a significant impact, it is essential to consider the life cycle, including the non-operational stages. However, for the passive renovation strategies, the impact of the non-operation stages is below the 5 % of the life cycle impact. In the case of the economic cost, the share of the non-operational stages is more significant, being higher in the renovation strategies that include active interventions and the combination of passive interventions (*f, g, ade, adeg*). The study demonstrates the importance of considering the life cycle for the economic assessment of renovation strategies, where the share of the embodied cost in active and combined strategies can exceed half of the total cost.

For the second input data of "renovation strategies", nine renovation strategies are introduced for the evaluation, including five strategies based on single passive intervention strategies (*a, b, c, d, e*), one strategy with one active intervention (*f*), one strategy with active intervention with the integration of RES (*g*), one passive integral strategy combining three passive interventions (*ade*), and another integral renovation combining passive, active and RES interventions as a complete



(a)

(b)

Fig. 8. Share of the embodied environmental impact and economic cost the totals life cycle by renovation strategies measured as the percentage of the non-operational GWP of the life cycle total impact (a) and the percentage of the non-operational FC of the total life cycle cost (b).

renovation strategy (*adeg*). Table 6 details the interventions applied by each renovation strategy.

Finally, the data for the last input data group of "LCI" defines the environmental and economic impact of processes and products obtained from different data sources. On the one hand, the environmental impact data of the life cycle stage "use of energy" (B6) of energetic processes are obtained from the database Ecoinvent [54], where the impact of the energy source of the gas is obtained directly from the database; the impact related to the electric energy has been modelled in the software OpenLCA [55] according to the electric mix of Spain of the previous year (2022) [56]. For the environmental impact of the production stage (A1-3), the environmental product declarations (EPD) have provided all the data. On the other hand, the data about the economic cost of the stage "use of energy" (B6) comes from Eurostat [57,58]; the economic costs of the production (A1-3) and maintenance stages (B2) are obtained from the construction database of Spain developed by Cype [59]. As the result of the "LCI", Table 7 shows the environmental impact and economic cost as the impact indicators defined in the LCA and LCC scope (GWP, NRPE and FC), expressed for one reference unit of each process and product.

4. Discussion

The development of the methodological tool PARARENOVATE-LCT presents a new approach of holistic simulation tool unifying the advanced dynamic BPS with the enviro-economic life cycle thinking, considering the diversity of OB patterns and the constantly changing economic scenarios. Many energy simulation tools have been developed departing from the main calculation engines like Energy-Plus [8] or TRNSYS [9]. These tools provide a complete framework in the field of energetic calculation, based on the so-called white box [31] or physics-based models [61], deeply analysed by many recent reviews [61–63]. The last review by Pan et al. [63] stated the integration of OB modelling as the recommendation for future research lines that the parametrical modelling of the diversity of the OB can cover. In this line, PARARENOVATE-LCT allows the introduction of OB clusters that can be explicitly modelled for the case study to analyse, as it has been done by Perez-Bezos et al. [49] investigating the occupants' behavioural diversity and modelling the OB clusters of a social house by a statistical study departing from monitoring and survey data.

Table 6
Renovation strategies to be analysed for the data category "renovation scenario" (sheet 2_renovation).

Code	Type	Renovation strategy	Intervention details
a	Passive	Façade exterior insulation – ETICS	EPS insulation (100 mm) + ETICS with acrylic mortar
b	Passive	Façade exterior insulation – Ventilated façade	Rockwool insulation (100 mm) + ceramic finish
c	Passive	Façade interior insulation – Interior cladding	Rockwool insulation (100 mm) + gypsum cladding
d	Passive	Roof insulation	XPS insulation (100 mm) + ceramic tiles
e	Passive	Window replacement – Wood frame, double glass	Wood frame + double low-E glass
f	Active	Heat pump for Heating and DHW	Aerothermal individual HP
g	Active + RES	Heat pump for Heating and DHW with PV energy	Aerothermal individual HP + PV modules
ade	Comb. Passive	Combination – Passive interventions (*a, d, e*)	(ETICS + Roof insulation + Windows)
adeg	Comb. Complete	Combination – Complete (*a, d, e, g*)	(ETICS + Roof insulation + Windows + HP + PV)

Furthermore, the challenge of the energy transition of the residential stock requires a next-level approach focusing on the sustainability of the decarbonisation process. PARARENOVATE-LCT provides an evaluation framework in alignment with the current requirements of the EU policy [3,4], firstly, regarding the evaluation of the whole life carbon towards effective decarbonisation by the LCA, and secondly, assessing the economic cost and cost-effectiveness by the LCC. The application of the LCA and LCC follows the same evaluation methodology, calculation equations, and evaluation scope as the previous publication [45], justifying the efficient integration of LCT. Furthermore, the results of the study demonstrate the importance of the LCT integration due to the share of the non-operational stages in the final impacts, being significant for active intervention-based renovation strategies in the evaluation of the environmental sustainability and being very significant in all the studied renovated scenarios (see Fig. 8).

Concerning the existing performance gap, the parametric assessment evaluates many possible scenarios covering a range of results, as suggested in previous research [33]. Even if many studies have developed advanced calibration techniques for non-residential buildings [29–31], the previously mentioned studies identified many barriers to the accurate calibration of residential buildings [33] in terms of OB calibration. The present tool combined with calibration techniques, as the previous research mentioned [33], can be an approach as a response to the performance gap caused by the OB patterns uncertainty [34,35]. Moreover, as the study suggested [33], this tool enables the lecture of the results in ranges instead of using one single value to cover a diversity of scenarios, not only in terms of OB but also in the constantly changing economic scenario.

The limitation of this research is the data entry, where the accuracy of the input data determines the accuracy of the results. Firstly, the current case study uses "typical year" weather files with data from 2007 to 2021 a static scenario, but weather conditions will change during the RSP set in 50 years, making it important to consider future climate scenarios. As a future research line, dynamic climatic factors can be implemented following different climate change scenarios such as the Representative Concentration Pathway (RCP) scenarios. Secondly, the energy mix will also suffer changes with the rise of RESs, with a decrease in the GWP of electricity [64]. The methodology also considers static

Table 7
LCI of the processes and products for the data category “LCI” (sheet 3_LCI).

Process / Product	RSL_M [yr]	A1-3 GWP [$kgCO_2$]	A1-3 NRPE [MJ]	A1-3 FC [€]	A5 FC [€]	B2 FC [€]	B6 GWP [$kgCO_2$]	B6 NRPE [MJ]	B6 FC [€]	Ref. unit
Energy – Gas	–	–	–	–	–	–	0.252	3.960	0.1574	kWh
Energy – Electricity	–	–	–	–	–	–	0.180	5.450	0.3350	kWh
Insulation EPS	50	4.29	138.16	9.33	0.00	0.00	–	–	–	m^2
Insulation XPS	50	9.14	276.00	26.12	0.00	0.00	–	–	–	m^2
Ins. – Rockwool	50	3.54	48.38	36.22	0.00	0.00	–	–	–	m^2
ETICS system	50	7.19	111.11	21.11	32.00	0.00	–	–	–	m^2
Ventilated structure	50	17.80	247.00	31.25	31.33	0.00	–	–	–	m^2
Ventilated panels	50	22.80	436.50	70	0.00	0.00	–	–	–	m^2
Cladding frame	50	7.05	122.40	15.94	18.25	0.00	–	–	–	m^2
Gypsum board	50	2.60	52.00	0.00	0.00	0.00	–	–	–	m^2
Window frame	30	200.78	9338.56	4337.76	525.29	124.01	–	–	–	m^2
Window glass	30	36.80	486.00	70.86	15.10	0.00	–	–	–	m^2
Roof tiles	50	8.28	143.10	47.71	49.31	0.00	–	–	–	m^2
Tiles disassembly	50	0.00	0.00	0.00	18.35	0.00	–	–	–	m^2
Heat pump	15	1270.00	17500.00	6833.00	138.66	451.45	–	–	–	unit
PV module	25	539.94	1828.01	262.80	24.92	13.89	–	–	–	unit
PV installation	50	0.00	0.00	6773.45	347.74	373.39	–	–	–	unit

this parameter, therefore, in the future development of the tool, dynamic values of the impact regarding the energy mix for electricity production should be considered. Thirdly, the input data of the LCI is also an important barrier, where data related to the environmental impact and economic cost of the construction products and processes in their different life stages have a direct impact on the final KPIs and can differ significantly the results of the analysis. This limitation is more challenging in economic quantification, where the prices of the products can change drastically in terms of location, time, desired material quality and other factors, and needs to be precisely defined according to the type, aim and scope of the analysis to be performed. Besides, in terms of the modelling of the archetypes, the base models need to be built in an external tool compatible with Energy-Plus. However, an answer for this limitation, and as a future research line, is to link the BIM modelling with PARARENOVATE-LCT. Additionally, the modelling of a large number of archetypes and the data collection for this can be carried out using a procedure for data collection and urban modelling using GIS, as suggested in the review by [61]. Moreover, this tool can feed machine-learning algorithms to create a black-box simulation tool.

5. Conclusion

The study carries out the development of the automatized tool PARARENOVATE-LCT, which can answer the need to evaluate the enviro-economic sustainability of the decarbonisation process and energy transition of the residential stock taking into account a diversity of socioeconomic scenarios and applying the LCT. Firstly, for the enviro-economic evaluation, the LCA and LCC are optimised by considering the most relevant life stages and factors in alignment with the latest trends in the evaluation scope. This evaluation enables the answer to the EU requirements regarding the environmental and economic evaluation of the building renovation process. It can aid the development of LTRS and policy-making in this field. Secondly, the parametric study covers a wider range of possible scenarios, combining several scenarios in terms of OB, economy, orientation and climate, and evaluating multiple archetypes beyond the evaluations carried out under average scenarios set by the technical regulations and standard data. This way, it is possible to reflect diversity, and it is a new approach to closing the performance gap of residential buildings in combination with calibration techniques. Furthermore, the data analysis of the research also can enable the identification of data inputs with high significance. In the same way, the tool can also measure the importance of the application of theLCT, identifying the application of the LCC as very significant in all the cases and the relevant importance of the application of the LCA in renovation strategies with active interventions or with a high degree of passive intervention.

In conclusion, the study presents a new approach in the parametric enviro-economic evaluation of energy renovation strategies in residential buildings with LCT by the simulation tool PARARENOVATE-LCT, which can aid the development of building renovation policies and plans answering to the EU requirements and covering the performance gap, taking into account the OB diversity and the constant changing economic scenario.

CRediT authorship contribution statement

Markel Arbulu: Writing – original draft, Visualization, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Xabat Oregi:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization. **Lauren Etxepare:** Writing – review & editing, Validation, Project administration, Investigation.

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.

Data availability

Data will be made available on request.

Acknowledgments

This research work is part of the first author’s Doctoral Thesis, which aims to investigate the holistic assessment of renovation strategies in residential buildings in the Basque Country funded by the Predoctoral Training Programme for Non-Doctor Research Personnel of the Department of Education of the Basque Government (PRE_2022_2_0121). The University of the Basque Country provides Open Access funding.

Appendix

Annex 1. Parameters of the input excel file

Table A1. Parameters of the input excel file indicating the definition of the input, the acronym used in the tool syntax and the unit, divided in the seven data categories and sheets of the excel file

Data category	Input	Acronym	Unit
1.1. Baseline scenarios (1.1_scenarios)	Baseline scenario	scenario	–
	Archetype cluster	arch	–
	Climatic cluster	clima	–
	Occupant behaviour (OB) cluster	ob	–
	Economic factors	ec	–
	Orientation of the entrance of the building	ori	–
1.2. Archetypes (1.2_archetype)	Archetype cluster name	archetype	–
	Baseline computer model URL in IDF format	idf	–
	Reference Service Life of the Building (RSL_B)	rslb	yr
	Energy efficiency of the system – Heating	ee_h	–
	Energy efficiency of the system – Cooling	ee_c	–
	Energy efficiency of the system – DHW	ee_dhw	–
	Energy source code of the system – Heating	es_h	–
	Energy source code of the system – Cooling	es_c	–
	Energy source code of the system – DHW	es_dhw	–
1.3. Climatic factors (1.3_clima)	Climatic cluster name	clima	–
	Weather data file in.epw format	epw	–
	Annual global horizontal irradiation	rad	kWh/m2·year
1.4. OB clusters (1.4_ob)	Occupant behaviour cluster name	ob_cluster	–
	Heating availability on/off (1/0)	heat_onoff	(1/0)
	Cooling availability on/off (1/0)	cool_onoff	(1/0)
	Heating setpoint temperature (for all days for 7–22 h)	setpoint_h	°C
	Heating setback temperature (for all days for 0–6 h and 23 h)	setback_h	°C
	Cooling setpoint temperature (for all days for 15–22 h)	setpoint_c	°C
	Cooling setback temperature (for all days for 0–14 h and 23 h)	setback_c	°C
	Ventilation rate as uniform flow	vent_rate	ach
	DHW consumption per day area	dhw_rate	l/m2·day
1.5. Economic factors (1.5_ec)	Discount rate	dr	%
	Economic inflation rate	inf	%
	Energy price increase for Gas	epi_g	%
	Energy price increase for Electricity	epi_e	%
2. Renovation strategies (2_renovation)	Renovation strategy name	strategy	–
	Façade exterior insulation – Thickness of the insulation	FE_t	m
	Façade exterior insulation – Conductivity of the insulation	FE_c	W/m·K
	Façade exterior insulation – Insulation product code	FE_mi	–
	Façade exterior insulation – Other product 1 code	FE_m1	–
	Façade exterior insulation – Other product 2 code	FE_m2	–
	Façade interior insulation – Thickness of the insulation	FI_t	m
	Façade interior insulation – Conductivity of the insulation	FI_c	W/m·K
	Façade interior insulation – Insulation product code	FI_mi	–
	Façade interior insulation – Other product 1 code	FI_m1	–
	Façade interior insulation – Other product 2 code	FI_m2	–
	Roof (slope) insulation – Thickness of the insulation	RS_t	m
	Roof (slope) insulation – Conductivity of the insulation	RS_c	W/m·K
	Roof (slope) insulation – Insulation product code	RS_mi	–
	Roof (slope) insulation – Other product code 1	RS_m1	–
	Roof (slope) insulation – Other product code 2	RS_m2	–
	Roof (flat) insulation – Thickness of the insulation	RF_t	m
	Roof (flat) insulation – Conductivity of the insulation	RF_c	W/m·K
	Roof (flat) insulation – Insulation product	RF_mi	–
	Roof (flat) insulation – Other product code 1	RF_m1	–
	Roof (flat) insulation – Other product code 2	RF_m2	–
	Window replacement – Glass – Thickness of the glass	WG_t	m
	Window replacement – Glass – Overall conductivity of the glass	WG_c	W/m·K
	Window replacement – Glass – Emissivity ratio of the inner face	WG_ei	–
	Window replacement – Glass – Emissivity ratio of the outer face	WG_eo	–
	Window replacement – Glass – Glass product code	WG_m	–
	Window replacement – Frame – Width of the frame	WF_w	m
	Window replacement – Frame Transmittance of the frame	WF_u	W/m2·K
	Window replacement – Frame – Absorptance of the frame	WF_ab	–
	Window replacement – Frame – Frame product code	WF_m	–
	Heat pump – Energy efficiency for Heating (COP)	HP_ee_h	–
	Heat pump – Energy efficiency for Cooling (COP)	HP_ee_c	–
	Heat pump – Energy efficiency for DHW (COP)	HP_ee_w	–
	Heat pump – Energy source code for Heating	HP_es_h	–
	Heat pump – Energy source code for Cooling	HP_es_c	–
	Heat pump – Energy source code for DHW	HP_es_w	–
	Heat pump – System type: individual or collective (i/c)	HP_i-c	–
	Heat pump – Installation maximum power	HP_p	kWh
	Heat pump – Product code	HP_m	–

(*continued on next page*)

Table A1. Parameters of the input excel file indicating the definition of the input, the acronym used in the tool syntax and the unit, divided in the seven data categories and sheets of the excel file (*continued*)

Data category	Input	Acronym	Unit
	Photovoltaic panels – Percentage to cover by PV in Heating	PV_p_h	kWh/yr
	Photovoltaic panels – Percentage to cover by PV in Cooling	PV_p_c	kWh/yr
	Photovoltaic panels – Percentage to cover by PV in DHW	PV_p_w	kWh/yr
	Photovoltaic panels – Area of the reference PV module	PV_pa	–
	Photovoltaic panels – Performance of the panel	PV_np	–
	Photovoltaic panels – Performance of the system	PV_ns	–
	Photovoltaic panels – Orientation and inclination factor	PV_factor	–
	Photovoltaic panels – Panels product code	PV_mp	–
	Photovoltaic panels – Product 1 code	PV_m1	–
	Photovoltaic panels – Product 1 quantity	PV_m1_q	(RU)
3. LCI	Name of the product / system / process	code	–
(3_lci)	Reference service life of the Material (RSL$_m$)	rslm	yr
	Environmental impact of the process as GWP in stage B6	gwp_b6	kg CO_2eq/MJ
	Environmental impact of the process as NRPE in stage B6	nrpe_b6	MJeq/MJ
	Economic cost of the process as FU in stage B6	fc_b6	€/MJ
	Environmental impact of the product as GWP in stage A1-3	gwp_a113	kg CO_2eq/(RU)
	Environmental impact of the product as NRPE in stage A1-3	nrpe_a13	MJeq/(RU)
	Economic cost of the product as FU in stage A1-3	fc_a13	€/(RU)
	Economic cost of the product as FU in stage A5	fc_a5	€/(RU)
	Economic cost of the product as FU in stage B2	fc_b2	€/(RU)

References

[1] European Commission, "Energy efficiency in buildings," 2020. [Online]. Available: https://ec.europa.eu/info/sites/default/files/energy_climate_change_environment/events/documents/in_focus_energy_efficiency_in_buildings_en.pdf.

[2] Eurostat, "Energy consumption in households," 2023. Accessed: Nov. 01, 2023. [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_consumption_in_households#Energy_products_used_in_the_residential_sector.

[3] European Commission, "Directive (EU) 2018/844 of the European Parliament and of the Council of 30 may 2018 amending directive 2010/31/EU on the energy performance of buildings and directive 2012/27/EU on energy efficiency.," 2018. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L0844&from=EN.

[4] European Commission, "Commission Recommendation (EU) 2019/786 of 8 May 2019 on building renovation," 2019. [Online]. Available: https://data.europa.eu/eli/reco/2019/786/oj.

[5] M. Arbulu, X. Oregi, L. Etxepare, R.J. Hernández-Minguillón, Barriers and challenges of the assessment framework of the Commission Recommendation (EU) 2019/786 on building renovation by European RTD projects, Energy Build. 269 (Aug. 2022) 112267, https://doi.org/10.1016/j.enbuild.2022.112267.

[6] H. Amini Toosi, M. Lavagna, F. Leonforte, C. Del Pero, and N. Aste, "Life Cycle Sustainability Assessment in Building Energy Retrofitting; A Review," Sustain. Cities Soc., vol. 60, p. 102248, Sep. 2020, doi: 10.1016/j.scs.2020.102248.

[7] P. A. Jensen, E. ; Maslesa, N. ; Gohardani, F. ; Björk, S. ; Kanarachos, and P. A. Fokaides, "Sustainability Evaluation of Retrofitting and Renovation of Buildings in Early Stages," 2017.

[8] U.S. Department of Energy's (DOE), Building Technologies Office (BTO) [Online]. Available: "energy plus Energy Simulation Tool". (2001) https://energyplus.net/.

[9] "TRNSYS". (2019) [Online]. Available: https://www.trnsys.com/.

[10] Design Builder, "Design Builder simulation tool." 2022. [Online]. Available: https://designbuilder.co.uk/.

[11] NREL, ANL, LBNL, ORNL, and PNNL, "OpenSudio." 2008. [Online]. Available: https://openstudio.net/.

[12] Y. Zhang, "JEPlus." 2007. [Online]. Available: https://www.jeplus.org/wiki/doku.php.

[13] U.S. Department of Energy's (DOE) Building Technologies Office (BTO), "Eppy 0.5.63." 2022. [Online]. Available: https://pypi.org/project/eppy/.

[14] J. Bull, "Geomeppy." 2016. [Online]. Available: https://github.com/jamiebull1/geomeppy.

[15] G. Faure, T. Christiaanse, R. Evins, and G. M. Baasch, "BESOS: A collaborative building and energy simulation platform," *BuildSys 2019 - Proc. 6th ACM Int. Conf. Syst. Energy-Efficient Build. Cities, Transp.*, pp. 350–351, 2019, doi: 10.1145/3360322.3360995.

[16] G. Chiesa, F. Fasano, P. Grasso, A New Tool for Building Energy Optimization: First Round of Successful Dynamic Model Simulations, Energies 14 (19) (Oct. 2021) 6429, https://doi.org/10.3390/en14196429.

[17] A. Vilches, A. Garcia-Martinez, B. Sanchez-Montañes, Life cycle assessment (LCA) of building refurbishment: A literature review, Energy Build. 135 (2017) 286–301, https://doi.org/10.1016/j.enbuild.2016.11.042.

[18] C. Thibodeau, A. Bataille, M. Sié, Building rehabilitation life cycle assessment methodology–state of the art, Renew. Sustain. Energy Rev. 103 (January) (2019) 408–422, https://doi.org/10.1016/j.rser.2018.12.037.

[19] European Committee for Standardization, "EN 15978:2012. Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method." 2012.

[20] European Commission, "Level(s) European framework for sustainable buildings," 2022. https://ec.europa.eu/environment/topics/circular-economy/levels_en (accessed May 18, 2022).

[21] J. Yeung, A. J Hahn Menacho, A. Marvuglia, T. Navarrete Gutiérrez, T. Beach, and Y. Rezgui, "An open building information modelling based co-simulation architecture to model building energy and environmental life cycle assessment: A case study on two buildings in the United Kingdom and Luxembourg," *Renew. Sustain. Energy Rev.*, vol. 183, p. 113419, Sep. 2023, doi: 10.1016/j.rser.2023.113419.

[22] European Committee for Standardization, "EN 16627:2016. Sustainability of construction works - Assessment of economic performance of buildings - Calculation methods." 2016.

[23] T. Ekström, R. Bernardo, Å. Blomsterberg, Cost-effective passive house renovation packages for Swedish single-family houses from the 1960s and 1970s, Energy Build. 161 (Feb. 2018) 89–102, https://doi.org/10.1016/j.enbuild.2017.12.018.

[24] V. Milić, K. Ekelöw, M. Andersson, B. Moshfegh, Evaluation of energy renovation strategies for 12 historic building types using LCC optimization, Energy Build. 197 (Aug. 2019) 156–170, https://doi.org/10.1016/j.enbuild.2019.05.017.

[25] V. Apostolopoulos, et al., An integrated life cycle assessment and life cycle costing approach towards sustainable building renovation via a dynamic online tool, Appl. Energy 334 (Mar. 2023) 120710, https://doi.org/10.1016/j.apenergy.2023.120710.

[26] S. Coleman, M.F. Touchie, J.B. Robinson, T. Peters, Rethinking performance gaps: A regenerative sustainability approach to built environment performance assessment, Sustain. 10 (12) (Dec. 2018) 4829, https://doi.org/10.3390/su10124829.

[27] M. Sunikka-Blank, R. Galvin, Introducing the prebound effect: The gap between performance and actual energy consumption, Build. Res. Inf. 40 (3) (2012) 260–273, https://doi.org/10.1080/09613218.2012.690952.

[28] G. Li, J. Xiong, S. Sun, J. Chen, Validation of virtual sensor-assisted Bayesian inference-based in-situ sensor calibration strategy for building HVAC systems, Build. Simul. 16 (2) (Feb. 2023) 185–203, https://doi.org/10.1007/s12273-022-0935-7.

[29] Z. Zhang, A. Chong, Y. Pan, C. Zhang, K.P. Lam, Whole building energy model for HVAC optimal control: A practical framework based on deep reinforcement learning, Energy Build. 199 (Sep. 2019) 472–490, https://doi.org/10.1016/j.enbuild.2019.07.029.

[30] D. Palaić, I. Štajduhar, S. Ljubic, I. Wolf, Development, Calibration, and Validation of a Simulation Model for Indoor Temperature Prediction and HVAC System Fault Detection, Buildings 13 (6) (May 2023) 1388, https://doi.org/10.3390/buildings13061388.

[31] D. Coakley, P. Raftery, M. Keane, A review of methods to match building energy simulation models to measured data, Renew. Sustain. Energy Rev. 37 (2014) 123–141, https://doi.org/10.1016/j.rser.2014.05.007.

[32] E. Cuerda, O. Guerra-Santin, J.J. Sendra, F.J. Neila, Understanding the performance gap in energy retrofitting: Measured input data for adjusting building simulation models, Energy Build. 209 (Feb. 2020) 109688, https://doi.org/10.1016/j.enbuild.2019.109688.

[33] M. Arbulu, S. Perez-Bezos, A. Figueroa-Lopez, and X. Oregi, "Opportunities and barriers of calibrating residential building performance simulation models using monitored and survey based occupant behavioural data. A case study in northern Spain" 2024.

[34] S. Chen, G. Zhang, X. Xia, Y. Chen, S. Setunge, L. Shi, The impacts of occupant behavior on building energy consumption: A review, Sustain. Energy Technol. Assessments 45 (Jun. 2021) 101212, https://doi.org/10.1016/J.SETA.2021.101212.

[35] D. Charlier, Explaining the energy performance gap in buildings with a latent profile analysis, Energy Policy 156 (Sep. 2021) 112480, https://doi.org/10.1016/J.ENPOL.2021.112480.

[36] P. van den Brom, A. Meijer, H. Visscher, Performance gaps in energy consumption: household groups and building characteristics, Build. Res. Inf. 46 (1) (Jan. 2018) 54–70, https://doi.org/10.1080/09613218.2017.1312897.

[37] E. Baldoni, S. Coderoni, M. D'Orazio, E. Di Giuseppe, R. Esposti, From cost-optimal to nearly Zero Energy Buildings' renovation: Life Cycle Cost comparisons under alternative macroeconomic scenarios, J. Clean. Prod. 288 (Mar. 2021) 125606, https://doi.org/10.1016/j.jclepro.2020.125606.

[38] E. H. Dyvik, "Impact of the coronavirus pandemic on the global economy - Statistics & Facts," 2023. [Online]. Available: https://www.statista.com/topics/6139/covid-19-impact-on-the-global-economy/#topicOverview.

[39] C. Wyplosz, "And now, the Ukraine shock," *Publications Office of the European Union*, 2022. [Online]. Available: https://op.europa.eu/en/publication-detail/-/publication/f7488467-070c-11ed-acce-01aa75ed71a1/language-en.

[40] A. Barnes, "IMF: Middle East conflict could drive up inflation in Europe," *Euronews*, 2023. [Online]. Available: https://www.euronews.com/business/2023/11/08/imf-middle-east-conflict-could-drive-up-inflation-in-europe.

[41] International Organization for Standardization, "ISO 14040:2006, Environmental Management – Life Cycle Assessment – Principles and Framework." p. 20, 2006.

[42] X. Oregi, P. Hernandez, R. Hernandez, Analysis of life-cycle boundaries for environmental and economic assessment of building energy refurbishment projects, Energy Build. 136 (2017) 12–25, https://doi.org/10.1016/j.enbuild.2016.11.057.

[43] P. Hernandez, P. Kenny, From net energy to zero energy buildings: Defining life cycle zero energy buildings (LC-ZEB), Energy Build. 42 (6) (Jun. 2010) 815–821, https://doi.org/10.1016/j.enbuild.2009.12.001.

[44] ASHRAE, "International Weather Files for Energy Calculations 2.0 (IWEC2)." 2012. [Online]. Available: https://www.ashrae.org/technical-resources/bookstore/ashrae-international-weather-files-for-energy-calculations-2-0-iwec2.

[45] M. Arbulu, X. Oregi, L. Etxepare, Environmental and economic optimization and prioritization tool-kit for residential building renovation strategies with life cycle approach, Build. Environ. 228 (Jan. 2023) 109813, https://doi.org/10.1016/j.buildenv.2022.109813.

[46] CAVIAR research group, "Estudio previo para la elavoración de la estrategia de intervención a largo plazo en el parque de edificios de Euskadi," 2019.

[47] UPC, Cíclica [space · community · ecology], and CAVIAR research group (EHU/UPV), "Estrategia de intervención a largo plazo en el parque de edificios de Euskadi," 2019. [Online]. Available: https://www.euskadi.eus/informacion/regeneracion-urbana/web01-a2lurral/es/.

[48] Ministerio de Transportes Movilidad y Agenda Urbana. Gobierno de España, "CTE - Código Técnico de la Edificación." 2019. [Online]. Available: https://www.codigotecnico.org/.

[49] S. Perez-Bezos, O. Guerra-Santin, O. Grijalba, and R. J. Hernandez-Minguillon, "Occupants' behavioural diversity regarding the indoor environment in social housing. Case study in northern Spain," J. Build. Eng., p. 107290, Jul. 2023, doi: 10.1016/j.jobe.2023.107290.

[50] Eurostat, "Inflation rate in the euro area." Accessed: Sep. 01, 2022. [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Inflation_in_the_euro_area#Euro_area_annual_inflation_rate_and_its_main_components.

[51] J. Pérez-Navarro, M.C. Bueso, G. Vázquez, Drivers of and Barriers to Energy Renovation in Residential Buildings in Spain—The Challenge of Next Generation EU Funds for Existing Buildings, Buildings 13 (7) (Jul. 2023) 1817, https://doi.org/10.3390/buildings13071817.

[52] N. S. Ibañez Iralde, J. Pascual, and J. Salom, "Energy retrofit of residential building clusters. A literature review of crossover recommended measures, policies instruments and allocated funds in Spain," *Energy Build.*, vol. 252, p. 111409, Dec. 2021, doi: 10.1016/j.enbuild.2021.111409.

[53] European Union, "Photovoltaic geographical information system," 2023. https://re.jrc.ec.europa.eu/pvg_tools/ (accessed Oct. 01, 2023).

[54] Ecoinvent centre. Swiss Centre for the Life Cycle Inventories, "Ecoinvent." 2014. [Online]. Available: https://ecoinvent.org/.

[55] GreenDelta, "OpenLCA." 2022. [Online]. Available: https://www.openlca.org/.

[56] Red Eléctrica, "Spanish electric net webpage," 2023. https://www.ree.es/es (accessed Oct. 01, 2023).

[57] Eurostat, "Energy price in euro area - electricity," 2022. https://ec.europa.eu/eurostat/databrowser/view/NRG_PC_204/default/table?lang=en&category=nrg.nrg_price.nrg_pc (accessed Sep. 01, 2022).

[58] Eurostat, "Gas prices for household consumers," 2022. https://ec.europa.eu/eurostat/databrowser/view/NRG_PC_202/default/table?lang=en&category=nrg.nrg_price.nrg_pc (accessed Sep. 01, 2022).

[59] Cype Ingenieros S.A., "Generador de precios de la construcción." 2023. [Online]. Available: http://www.generadordeprecios.info/.

[60] X. Oregi, N. Hermoso, E. Arrizabalaga, L. Mabe, I. Munoz, Sensitivity assessment of a district energy assessment characterisation model based on cadastral data, Energy Procedia 147 (2018) 181–188, https://doi.org/10.1016/j.egypro.2018.07.053.

[61] M. Ferrando, F. Causone, T. Hong, Y. Chen, Urban building energy modeling (UBEM) tools: A state-of-the-art review of bottom-up physics-based approaches, Sustain. Cities Soc. 62 (Nov. 2020) 102408, https://doi.org/10.1016/j.scs.2020.102408.

[62] V.S.K.V. Harish, A. Kumar, A review on modeling and simulation of building energy systems, Renew. Sustain. Energy Rev. 56 (Apr. 2016) 1272–1292, https://doi.org/10.1016/j.rser.2015.12.040.

[63] Y. Pan, et al., Building energy simulation and its application for building performance optimization: A review of methods, tools, and case studies, Adv. Appl. Energy 10 (Jun. 2023) 100135, https://doi.org/10.1016/j.adapen.2023.100135.

[64] A. Marashli, A. M. Gasaymeh, and M. Shalby, "Comparing the Global Warming Impact from Wind, Solar Energy and Other Electricity Generating Systems through Life Cycle Assessment Methods (A Survey)," *Int. J. Renew. Energy Res.*, vol. 12, no. v12i2, pp. 899–920, Jun. 2022, doi: 10.20508/ijrer.v12i2.13010.g8474.