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Prospective life cycle approach to buildings' adaptation for future climate and decarbonization scenarios

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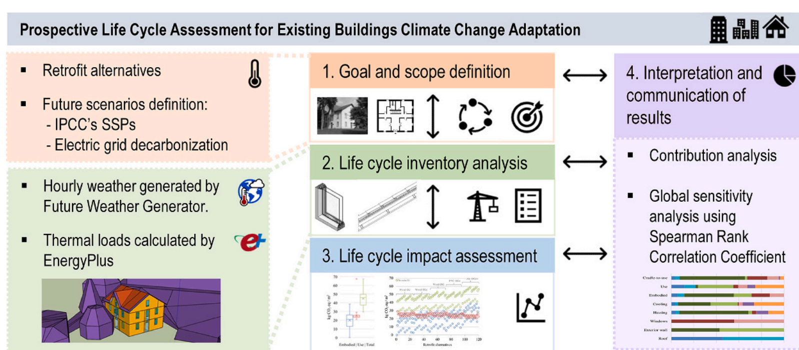
HIGHLIGHTS

- Existing buildings adaptation with low environmental impact under future climate.
- The wall U-value is the most influential parameter regardless of climate scenario.
- Roof and window parameters become less influential in future climate scenarios.
- Embodied impacts exceed operational impacts in 33% of the retrofit alternatives.
- The embodied phase becomes even more impactful with the grid decarbonization.

GRAPHICAL ABSTRACT



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ABSTRACT

The existing building stock is crucial for enhancing decarbonization targets and mitigating climate change. This article delves into a methodological approach that combines prospective life cycle assessment, building thermal simulation using projected future climate data, and global sensitivity analysis to pinpoint the most influential parameters under current climate conditions and future scenarios. The methodology covers plausible decarbonization pathways for the electricity mix, considering the growing utilization of renewable sources, which are influenced by the building locations. An adaptive reuse process involves converting a historic residence into an office building to validate the proposed methodology. Several retrofit strategies are assessed, such as exterior wall insulation, roof insulation, and window replacement. The findings reveal a 12% rise in average usage impacts and a 7% increase in cradle-to-use impacts from the base scenario to future climate projections. Embodied impacts surpass use-phase impacts by 23% in future climates and 33% in certain baseline scenarios. Utilizing future climate data in the life cycle analysis to estimate energy requirements can aid in forecasting building performance under climate change, especially in adapting the existing building stock for enhanced thermal comfort with minimal environmental impact.

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1. Introduction

Given the long lifespan of buildings, designers and developers must be encouraged to identify effective and efficient strategies to reduce the overall life cycle burden of buildings and contribute to climate change mitigation. The construction and operation of buildings are responsible for almost 40% of global energy-related greenhouse gas (GHG) emissions [1]. Considering the accelerating climate and environmental emergency, policy and decision-makers worldwide are urged to step up decarbonization efforts to ensure an adequate response. The European Union is seen as a pioneer in systematic decarbonization efforts, aiming to link various policy initiatives to drive decarbonization across different sectors, including building construction and operation [2,3]. Retrofitting is one of the most powerful tools for extending the useful life of Europe's buildings and reducing their overall impact on the environment [4]. The existing building stock plays an important role in boosting decarbonization targets, as most existing buildings are not energy-efficient, mainly rely on fossil fuels for heating and cooling, and use old technologies and inefficient appliances.

Life cycle assessment (LCA) is a widely used methodology to evaluate the environmental impacts of buildings and identify hot spots and improvement opportunities. Furthermore, considering future climate uncertainty, predicting how buildings will behave under future climate scenarios is crucial. However, the literature has not explored prospective LCA combined with future dynamic climate models to calculate future energy needs, especially regarding the existing building stock.

Table 1 summarizes the main assumptions and findings of several studies that have evaluated building components' performance under future climate scenarios. For example, the role of electricity mix and production efficiency improvements on GHG emissions of building components and future refurbishment measures shows that when the modified electricity mix is almost decarbonized, the relative contribution to the total impacts can be reduced to a point where it becomes negligible [5]. The life cycle impact of a low-energy single-family house in France, which combines heating systems and photovoltaic modules on the roof, demonstrates that accounting for climate change and the evolution of the energy system has a significant influence on LCA results with differences up to 40% [6]. Dynamic modeling of future climatic and technological trends was developed to evaluate life cycle global warming impacts and occupant satisfaction in US office buildings. Results show that decarbonization of the electricity grid results in the most significant shift in building operational GHG emissions, far outweighing the increase in emissions due to higher cooling loads compared to the current electricity mix [7].

Other studies have comprehensively assessed the building stock or several building typologies. For instance, a spatiotemporal bottom-up dynamic building stock model that integrates material flow analysis, building energy modeling, and life cycle assessment simulates future building stock evolution at the component level and tracks the associated material flows, energy demand, and generation, and GHG emissions with the consideration of both endogenous factors (*e.g.*, building energy efficiency upgrade) and exogenous factors (*e.g.*, policies, occupant behavior, and climate scenarios) [8]. In another example, a scenario-based robustness analysis of retrofit strategies in six different European contexts shows that the robustness of a retrofit strategy is sensitive to context. The electricity grid GHG emission intensity has the highest impact, mainly influencing the robustness of heating system choices and the installation of photovoltaic and battery systems [20].

Some studies are starting to address the impact of potential future climate scenarios on building performance. Results from distinct worldwide locations, such as South Europe [10], Iran [11], China [12], the United States [13], Brazil [14], Western Africa [15], and Australia [16], all point to a rise in cooling demand that outpaces the decrease in heating requirements. This aggravates the existing energy imbalance and will increase GHG emissions, independently of the building type and scale. Although some of the reviewed studies have used thermal dynamic simulation to calculate the energy needs based on future climate models, none have combined it with prospective life cycle assessments to address future decarbonization scenarios for the electricity mix. There is a gap in the literature regarding assessing the environmental performance of existing buildings in the face of future climate scenarios and how these buildings need to be adapted to fulfill thermal comfort conditions with a low environmental impact. None of the reviewed studies have performed a sensitivity analysis to assess which building parameters have the highest influence on the results depending on the climate scenario and decarbonization pathway.

This article advances the state-of-the-art by proposing a prospective life cycle approach to assess the performance of retrofitting existing buildings to be adapted to future climate scenarios. It allows us to evaluate how a building retrofitted today will behave under future scenarios and sheds light on which building elements are the most influential and if it depends on the climate scenario. Additionally, it innovates by combining the Intergovernmental Panel on Climate Change's (IPCC) climate change scenarios with decarbonization targets for the electricity mix. The revised literature demonstrates the importance of understanding how buildings' performance, particularly of the existing buildings, is expected to respond to complex future trends to assist in designing adaptive buildings that take advantage of projected changes.

The goal of this article is to develop a methodological approach that couples prospective LCA, thermal dynamic simulation, and global sensitivity analysis to identify the most influential parameters and select the most efficient retrofit strategies for existing buildings under future climate and decarbonization scenarios, employing future weather data generated with a state-of-the-art weather morphing tool. For demonstration purposes, the proposed approach is applied to a historic residential building adapted to be used as an office building on a university campus. The main contribution of this article is to propose an approach that provides insights into how existing buildings need to be adapted and which retrofit strategy is the best option to keep comfort conditions under different future climate scenarios.

This article is organized into four sections, including this introduction. Section 2 presents the materials and methods, including the proposed approach and the definition of the selected application to a historic building. This is followed by Section 3, which presents the results and discusses several retrofit strategies for future climate and decarbonization scenarios. Section 4 concludes and provides recommendations to support building design and future research.

2. Materials and methods

The proposed methodological approach combines prospective LCA, thermal dynamic simulation using future climate data, and global sensitivity analysis to identify the most influential parameters and select the most efficient retrofit strategies for existing buildings under future climate and decarbonization scenarios. LCA addresses the potential environmental life cycle impacts, combined with thermal dynamic simulation to assess the environmental performance of alternative retrofit strategies, and the global sensitivity analysis identifies the most influential parameters. In Fig. 1, the proposed approach is organized into four interrelated steps, adapted from the LCA framework recommended by ISO 14040/14044 [21,22].

In step 1, we define the **goal and scope** of the study. This includes characterizing the building, selecting retrofit strategies and climate scenarios, and defining the system boundary and functional unit. The scenario analysis involves selecting future climate scenarios based on the IPCC's shared socioeconomic pathways (SSP) and decarbonization targets [23]. Decarbonization targets may vary depending on the building's location. In step 2, **life cycle inventory (LCI) analysis** is carried out by collecting environmental foreground data for the embodied inventory, collecting the background data, and adapting literature for the electricity mix impact factors based on the

Table 1
Main assumptions and findings from the reviewed articles.

Ref.	Year	Life cycle phases	Future climate scenarios (by IPCC*)	Other future scenarios	Building design alternatives	Indicator	Location	Type of building	Functional/ Reference unit	Reference service life	Findings
[5]	2021	Cradle-to-gate	–	Electricity mix for 2050	Production efficiency	GHG emissions	Slovenia	Typical residential building from 1971 to 1980	Whole typical residential building over 60 years	60 years	Parameters that are subject to a major change (such as electricity mix) during the building's reference service life need to be treated dynamically.
[6]	2016	Cradle-to-grave	RCP 4.5 and RCP 8.5[1]	Energy mix for 2050	Heating system and integration of PV	GHG emissions	France	Single-family house	Whole house per year and square meter per year	50 years	The evolution of the energy supply system has a large influence on LCA results.
[7]	2022	Cradle-to-grave	RCP 4.5 and RCP 8.5[1]	Electricity grid for 2050	Occupant comfort	GHG emissions	US (different climate zones)	Office building	Whole building over an assumed 60-year lifetime.	60 years	The electricity grid's decarbonization results in the largest shift in building operational GHG emissions, outweighing emissions increases due to higher cooling loads.
[8]	2022	Construction/ Retrofit and use phase	SSP2-base and SSP 2–2.6[2]	–	Material recycling, Wood construction, Heat transition, renewable electricity, rooftop PV, green lifestyle	GHG emissions	The Netherlands	Residential building stock of Leiden	One square meter over one year	2016–2050	Natural-gas-free heat transition and renewable electricity supply are the most effective strategies for reducing annual GHG emissions by 2050.
[9]	2022	Cradle-to-gate and use phase	RCP 4.5 and 8.5[1]	Electricity grid for 2030–2080	40 building geometries, occupant behavior	GHG emissions	Switzerland	Multi-family house	One square meter over 20 years	20 years (period to the next renovation)	Heat pump systems perform most robustly compared to the other heating and cooling systems when assuming slow decarbonization.
[10]	2018	Use phase	RCP 2.6, 4.5, 6.0, 8.5[1]	Future weather data for 2035, 2065 and 2090	–	Operational energy	15 Southern European cities	Office building	One square meter per year	2035, 2065 and 2090	Yearly heating and cooling energy needs in 2090 are expected to increase in a range of 51–120%.
[11]	2023	Use phase	SSP 5–8.5[2]	Future weather data for 2050 and 2080	12,000 building geometries	Operational energy	Iran (seven cities)	Two-story single-family house	Whole building per year	Present-day, 2050 and 2080	Future ideal U-values can be higher or lower than today's values depending on the climate zone/ region.
[12]	2023	Use phase	SRES B2 and B1[3]	Future weather data for 2050 and 2080	Energy conservation measures (envelope, HVAC system, lighting, and equipment) and rooftop PV system	Operational energy	China	22 building types	One square meter per year	Base year, 2050 and 2080	Combining four energy conservation measures and PV systems can lead to an energy-saving rate of about 47%.
[13]	2017	Use phase	RCP 2.6, 4.5, 6.0, 8.5[1]	Future weather data for 2020–2089	Room temperature setpoints, HVAC operation hours, air volume, ventilation strategies	Operational energy	US (five cities)	Office building	Whole building per year	2020–2089	The mixed-mode ventilation measure was found as the most effective to mitigate climate change.
[14]	2024	Use phase	SSP 5–8.5[2]	Future weather data for 2050 and 2080	Alternative building orientation, indoor conditions, and building shapes	Operational energy	Brazil (30 cities)	Two-story single-family house	Whole building per year	Present-day, 2050 and 2080	Buildings' ideal U-values over time are highly dependent on the region/climate zone.
[15]	2012	Use phase	SRES scenario B2[3]	Average future weather data for reference periods	Building orientation, form, and physical properties of the envelope	Operational energy	Burkina Faso	Office building	One square meter per year	2010–2029; 2030–2049 and 2060–2079	Shading devices can reduce cooling load by up to 40%, playing a key role in climate change adaptation of buildings in Burkina Faso
[16]	2021	Use phase	SRES scenario A2[3]	Future weather data for 2050 and 2080	Wall insulation, glazing type, and overhang	Operational energy	Australia (two cities)	Office building	One square meter per year	Present-day, 2050 and 2080	The impact of future climate on the energy-optimization of building configuration is highly dependent on the building's climate zone.

* IPCC - Intergovernmental Panel on Climate Change.
[1] RCP - Representative Concentration Pathways (IPCC Assessment Report 5 [17]).
[2] SSP - Socioeconomic Pathways (IPCC Assessment Report 6 [18]).
[3] SRES - Special Report on Emissions Scenarios (IPCC Assessment Report 4 [19]).

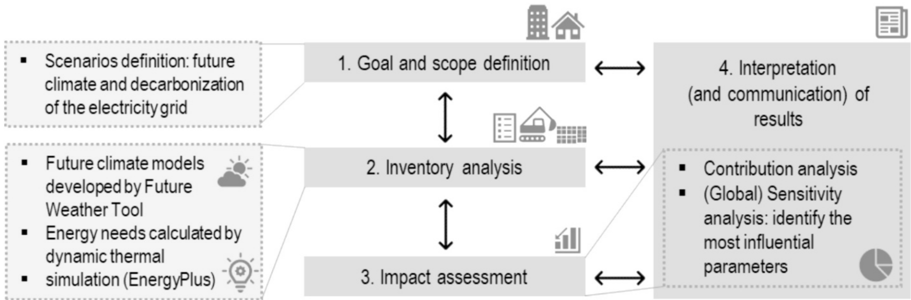

Fig. 1. Prospective life cycle methodological approach framework for building retrofits' adaptation for future climate scenarios. Adaptation from the life cycle assessment framework recommended by ISO 14040/14044 [21,22].

decarbonization targets defined in step 1. It also includes the calculation of operational energy requirements using thermal dynamic simulation. In step 3, the **life cycle impact assessment (LCIA)** evaluates the potential environmental impact by converting the LCI results (step 2) into specific results for selected impact categories. In step 4, the **interpretation and communication of results** are elaborated based on contribution and global sensitivity analyses.

The contribution analysis assesses how each life cycle phase contributes to the total life cycle impacts, and the sensitivity analysis addresses the influence of different sources of uncertainties in the inputs to the outputs' variance. Uncertainty of environmental impacts can be analyzed using a global sensitivity analysis to gain more insight into output variance. According to Groen et al. [24], several methods for global sensitivity analysis can be employed, mainly to deal with relatively small input uncertainties. The choice for one of the methods depends on the available data, the magnitude of the uncertainties of data, and the aim of the study. Squared Spearman and squared standardized regression coefficients have usually been applied to perform global sensitivity analysis [24], particularly on the LCA of buildings [25,26].

2.1. Goal and scope

An adaptive reuse process involves retrofitting a historic single-family house to be used as an office building, selected to test and validate the proposed approach. A life cycle model was implemented for a single-family detached house from the early 20th century, retrofitted to an office building on one of the University of Coimbra campuses in Coimbra, Portugal (Fig. 2). The building is organized on three floors and a finished attic. This building is already being used as an office. The ground floor includes offices, restrooms, a storage room, and a living area; the first floor comprises offices and a workshop/conference room; the second floor comprises a workshop/conference room, offices, and a storage area. The original key construction features of the building include its load-bearing stone masonry walls (average thickness of 50 cm), single-glazed wood windows, and a conventional wooden frame roof. Further details on the building are provided in Ref. [27]. The selected functional unit is one square meter of the building's useful area (438 m^2) over 20 years.

The system boundaries defined are based on a cradle-to-use model, which includes the raw material extraction, construction, implementation of retrofit strategies, and the use phase. The demolition of existing components (*e.g.*, existing roof and windows) was not included, as it is the same for all scenarios. As the scope of this model is to assess retrofit strategies, the initial construction and previous building uses are not considered. The end-of-life phase of the building after retrofit is not included because it is highly uncertain how the construction and demolition wastes will be treated in the future, mainly due to the efforts in promoting circular economy principles in the construction sector. Simapro 9.5 software was used to implement the life cycle model and calculate the life cycle impacts.

2.1.1. Retrofit strategies

The selected retrofit strategies include adding an insulation layer to the roof and the exterior walls and replacing windows. A 'do nothing'

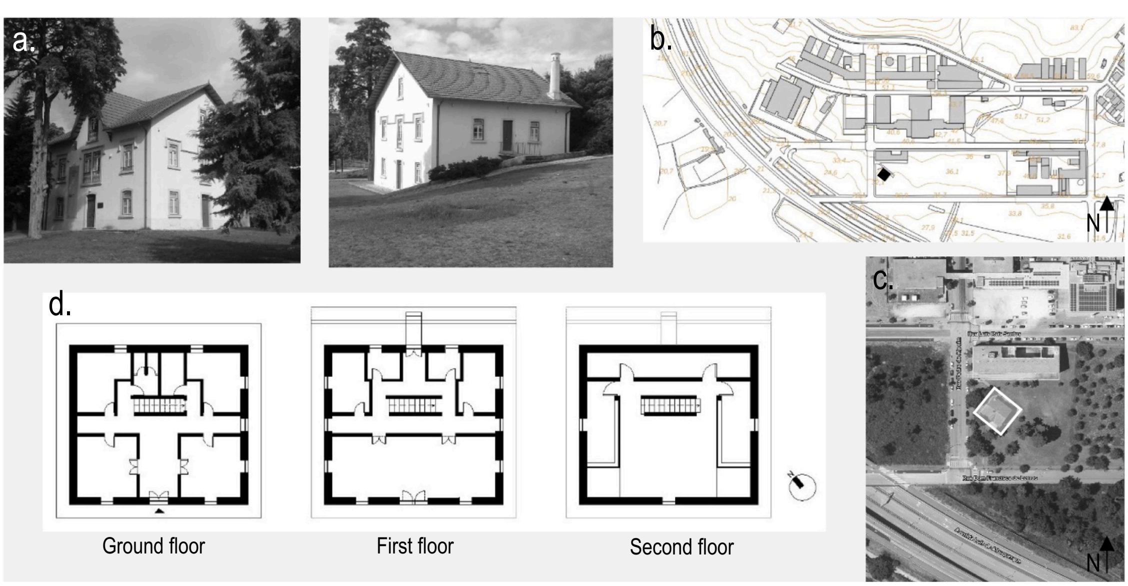

Fig. 2. (a) Southeast, southwest, and northeast façades, (b) location plan (where the building is represented in a black square), (c) terrain view, and (d) plans of the building (ground floor, first floor, and second floor).

scenario with no insulation on the roof or the exterior walls and no window replacement is also considered.

Three alternative insulation materials were considered for the roof insulation: extruded polystyrene (XPS) and mineral wool combined with three alternative insulation thicknesses (40 mm, 80 mm, and 120 mm) and one innovative insulation membrane (Skytech) with 6 mm. Skytech is a reflective insulator that ensures thermal insulation function while having an under-the-roof screen function [28]. The exterior wall retrofit incorporates an additional thermal insulation layer (40 mm) on the interior or exterior surface and new interior and exterior finishes (stucco and gypsum plasterboard). The insulation material for the exterior wall was XPS, one of the most common insulation materials used in South European construction. The window replacement strategy considered a double-glazed window with alternative frame materials (wood, aluminum, and polyvinyl chloride). The no-replacement alternative that incorporates a low-emissivity film is also considered. All scenarios assume the replacement of the existing roof frame material and interior and exterior finishes but were not considered in this study because the impacts would be the same in all retrofit alternatives in this comparative study. Additionally, all scenarios assumed the replacement of energy-efficient lighting and equipment, which were not considered due to the same comparative reason. In total, 120 combinations of alternative retrofit solutions are analyzed.

2.1.2. Climate scenarios

The present-day climate (baseline) was obtained from meteorological records between 2004 and 2018. Two future climate scenarios were selected. SSP2–4.5 (2.7 °C) represents the "roughly consistent" scenario with nations' 2030 climate pledges under the Paris Agreement—a future we are on track for if the world fails to adopt more aggressive emissions reduction measures. SSP5–8.5 (4.4 °C) is the 'do-nothing' scenario regarding climate change, exacerbating the situation with minimal effort to mitigate emissions. The outcome would lead to a 4.4 °C increase in global temperatures by 2100, ranging between 3.3 °C and 5.7 °C [29]. Despite being one of the less likely scenarios, it allows scientists to explore the upper limits of their models.

2.1.3. Decarbonization scenarios

A scenario analysis was included to illustrate plausible decarbonization pathways of the electricity mix in Portugal for 2050, accounting for the increase in sharing renewable sources. Three alternative prospective scenarios of GHG emissions reduction based on the long-term strategy for carbon neutrality of the Portuguese economy by 2050 were assessed: (i) conservative (a reduction of 30%), (ii) expected (a reduction of 60% depicting the planned Portuguese strategy for carbon neutrality until 2050), and (iii) optimistic (a reduction of 90%). For calculation purposes, a linear reduction over the 20 years of the building's lifespan was considered, as the Portuguese government has not yet provided any pathway for the decline in emissions. These results were compared with the reference scenario with a constant electricity mix over 20 years.

2.2. Inventory analysis

LCI was implemented based on primary (foreground) data collected from the scientific literature [30,31]. Producers and contractors were gathered to calculate the materials required for each retrofit strategy. Secondary (background) data was obtained using the ecoinvent 3.9 database [32]. Additional background data was collected and adapted from LCA databases and reports [30,31], Environmental Product Declarations (EPD) for insulation materials [28,33,34], EPD for window frames [35–37], and EPD for glazing systems [38–41]. LCIA data was collected from the EPD, ensuring the same system boundaries (cradle-to-site – *i.e.*, A1-A5, according to the standards [42] for insulation materials – and cradle-to-gate – *i.e.*, A1-A3 for window frames and glazing systems). The Portuguese electricity mix was based on Refs. [43, 44] and updated to the year 2022.

2.2.1. Embodied inventory

The construction phase includes the production and transportation of materials and on-site processes (assembly of the insulation layer in the roof and exterior wall and replacement of the windows). An additional 5% of materials were considered lost on-site due to cutting and fitting processes. Transportation by truck (> 32 t) was assumed to have European fleet average characteristics [45]. An average transportation distance of 300 km from the manufacturing plant to the building site was considered. Transportation from production to the building site was modeled based on the average market availability. Table 2a presents the bill of materials for the roof and exterior wall retrofit strategies. Window type (represented by the U-value) and window solar protection (represented by the solar heat gain coefficient) per total useful area are presented in Table 2b. Each retrofit alternative is defined and characterized in Tables S1-S4 in the Supplementary Material.

2.2.2. Operational inventory

A thermal dynamic simulation model (Fig. 3) was implemented in EnergyPlus to calculate the energy needs of the entire building. EnergyPlus is a well-established and validated software that uses dynamic simulation to assess buildings' thermal and energy performance [46].

The building's internal gains comprise occupation, lighting, and electric equipment, which, together with the environmental conditions, impact the thermal balance of each zone. The office spaces are occupied from 9:00 to 12:00 and 13:30 to 18:00, with 0.2 person/m^2. In the same periods, the lighting density is 10 W/person. The electric equipment operates continuously from 9:00 to 18:00, with a density of 220 W/person. The meeting rooms are used from 14:00 to 16:00, considering an occupation of 0.3 person/m^2, a lighting density of 10 W/person, and 30 W/person for electric equipment. The kitchen comprises three occupation periods—9:00 to 9:10, 12:10 to 13:20, and 16:00 to 16:20—during which four people use the space, and the lighting and equipment usage are 4 W/m^2 and 300 W, respectively. These schedules are valid during weekdays, all year long, except in August, when the building is not in use. Full shading with exterior wooden shutters is considered for all windows during the building's unoccupied periods.

A constant infiltration rate of 0.8 air changes per hour is defined for all building zones. Heating, Ventilation, and Air Conditioning (HVAC) are considered only in the offices, from 9:00 to 18:00, with a heating setpoint of 18 °C and a cooling setpoint of 25 °C. The HVAC template zone ideal loads air system model is used since it allows us to assess each zone's thermal needs directly. These are then converted to electric needs by applying the Coefficient of Performance (COP) of the systems. According to the reports from the International Energy Agency [47] and the research works of Knobloch et al. [48] and Levesque et al. [49], the COP of electric heating and cooling systems will improve, on average, to 5.0 for SSP2 and to 3.875 for SSP5 by 2100. Thus, considering the current seasonal COP values of 2.1 for heating and 3.4 for cooling, a simple interpolation results in the future efficiency values depicted in Table 3.

The present-day weather data for the building's location was downloaded from the Climate.OneBuilding.Org website [50]. It follows the TMY/ISO 15927-4:2005 methodology and is derived from meteorological records between 2004 and 2018. The future weather data results from morphing the current weather to match a predicted climate change scenario in 2055. The morphing method transforms current weather to match the projected variables of a given climate change scenario. The changes derive from numerical models representing the physical processes in the atmosphere, cryosphere, ocean, and land. It is a delta method procedure that statistically shifts and stretches the data [51], thus not requiring bias correction. The morphing procedure uses the 'Future Weather Generator PT Ed.' Tool [52], utilizing regional climate data from the Weather Research and Forecasting model with a 6 km grid covering continental Portugal. The tool implements SSP2–4.5,

Table 2
Bill of materials for the roof and exterior wall retrofit strategies (a) and windows: frame material and glazing type (b), per total useful area.

a)

Building component	Area	Material	Density	Thermal conductivity (λ)	Thickness	Weight per useful area
	m^2		kg/m^3	W/(m·K)	mm	kg
Roof	177	Expanded polystyrene (XPS)	32	0.034	40	238
					80	476
					120	714
		Mineral wool	96	0.034	40	714
					80	1208
					120	1450
		Skytech	453	0.029	6	471
Exterior wall with external insulation (ETICS[1])	412	XPS	32	0.034	40	554
		Adhesive mortar	–	–	20	1936
		Glass fibre	–	–	0.5	69
		Base plaster	–	–	10	8652
Exterior wall with internal insulation	338	XPS	32	0.034	40	454
		Gypsum plasterboard	–	–	25	8518

b)

Building component	Area	Material	U-value	SHGC[2]	Weight per useful area
	m^2		$W/(m^2 \cdot K)$		kg
Windows	36	Aluminum frame	1.1		997
		Polyvinylchloride frame (PVC)	3.56		1088
		Wood frame	3.56 (DG); 5.1(SG)		954
		Double glazing (DG)	–	0.7	720
		DGe (low emissivity)	–	0.5	900
		DGe + (high performance; low emissivity)	–	0.33	1080
		Single glazing (SG)	–	0.88	360
		SGe (low emissivity)	–	0.5	360

[1] ETICS - External Thermal Insulation Composite System
[2] SHGC - Solar Heat Gain Coefficient.

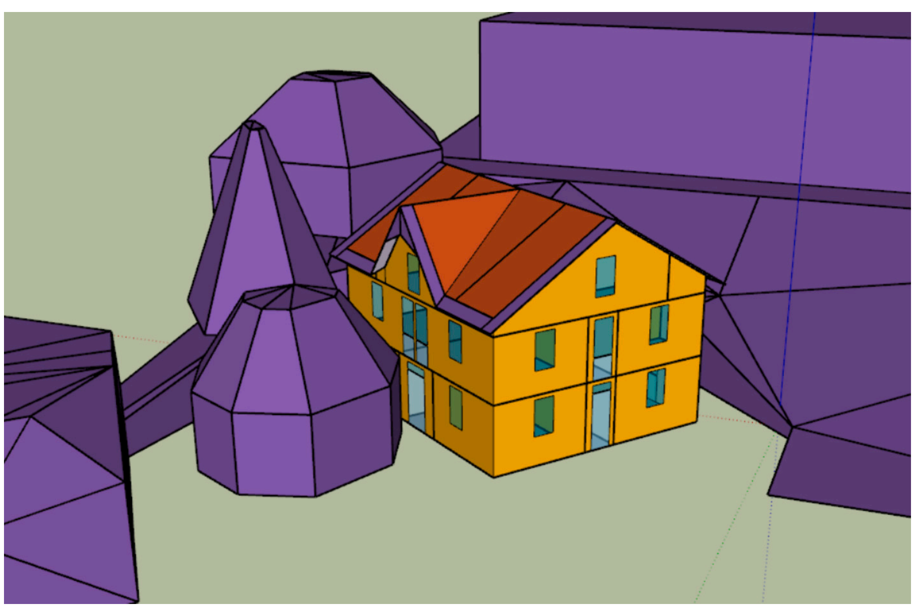

Fig. 3. Simulation model of the building. Color scheme: maroon – roof; yellow – external walls; transparent – windows; purple – shadowing elements. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

SSP3–7.0, and SSP5–8.5 scenarios. Monthly changes are computed from each median month from the period 1995–2014 to the future period 2046–2065 for each scenario. The changes for the variables are spatially downscaled by applying a bilinear interpolation method of the four nearest points of the grid to the location of the weather data. The formulation is described on the tool's website [53].

The yearly energy requirements (in MWh) are calculated based on the hourly energy multiplied by the number of operation hours of lighting, equipment, and heating and cooling systems. The heating and cooling energy needs are divided by the COP to calculate the final energy. The total final energy per year is divided by the total useful area of the building and multiplied by the lifespan of the building (20 years) for the baseline and future scenarios.

Table 3
HVAC (Heating, Ventilation, and Air Conditioning) equipment efficiencies.

	Baseline	2055	
		SSP2–4.5	SSP5–8.5
Seasonal COP heating	2.1	3.31	2.84
Seasonal COP cooling	3.4	4.04	3.57

3. Results and discussion

3.1. Life cycle impact assessment

The LCIA results for climate change are presented for a time horizon of 100 years and were calculated using the Environmental Footprint (EF) 3.1 method [54], which was adopted on the IPCC 2021 method [55]. Fig. 4 and Fig. 5 present life cycle impacts and the embodied and operational impacts to understand the contribution of the embodied (cradle-to-use) and use phases. Detailed LCIA results, including the definition of each retrofit alternative, are presented in the

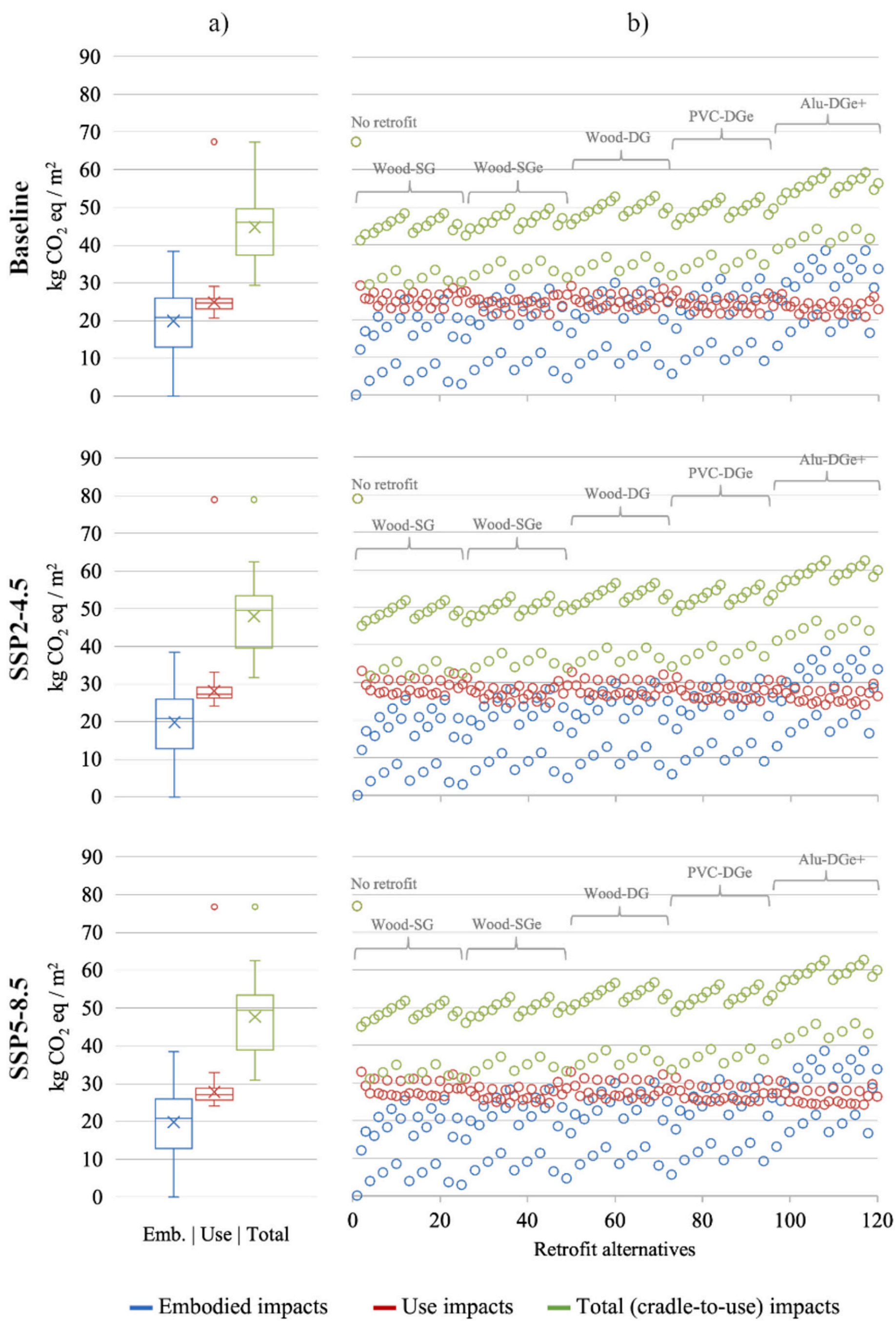

Fig. 4. Life cycle impact assessment results for the assessed scenarios: baseline (considering past meteorological records between 2004 and 2018), SSP2–4.5, and SSP5–8.5 (forecast for 2055), considering a constant electricity mix based on data from 2022. a) The box plots represent the 25th (lower line), the 50th (median), and the 75th (upper line) percentiles. The whiskers represent the lower (minimum) and upper (maximum) bounds. b) Embodied, use and total (cradle-to-use) impacts for the 120 combinations for retrofit solutions. Window set of combinations: Wood, PVC, Aluminum (Alu) frames with single-glazing (SG), SG with low-emissivity (SGe), double-glazing (DG), DG with low emissivity (DGe), and DG with high performance and low emissivity (DGe+).

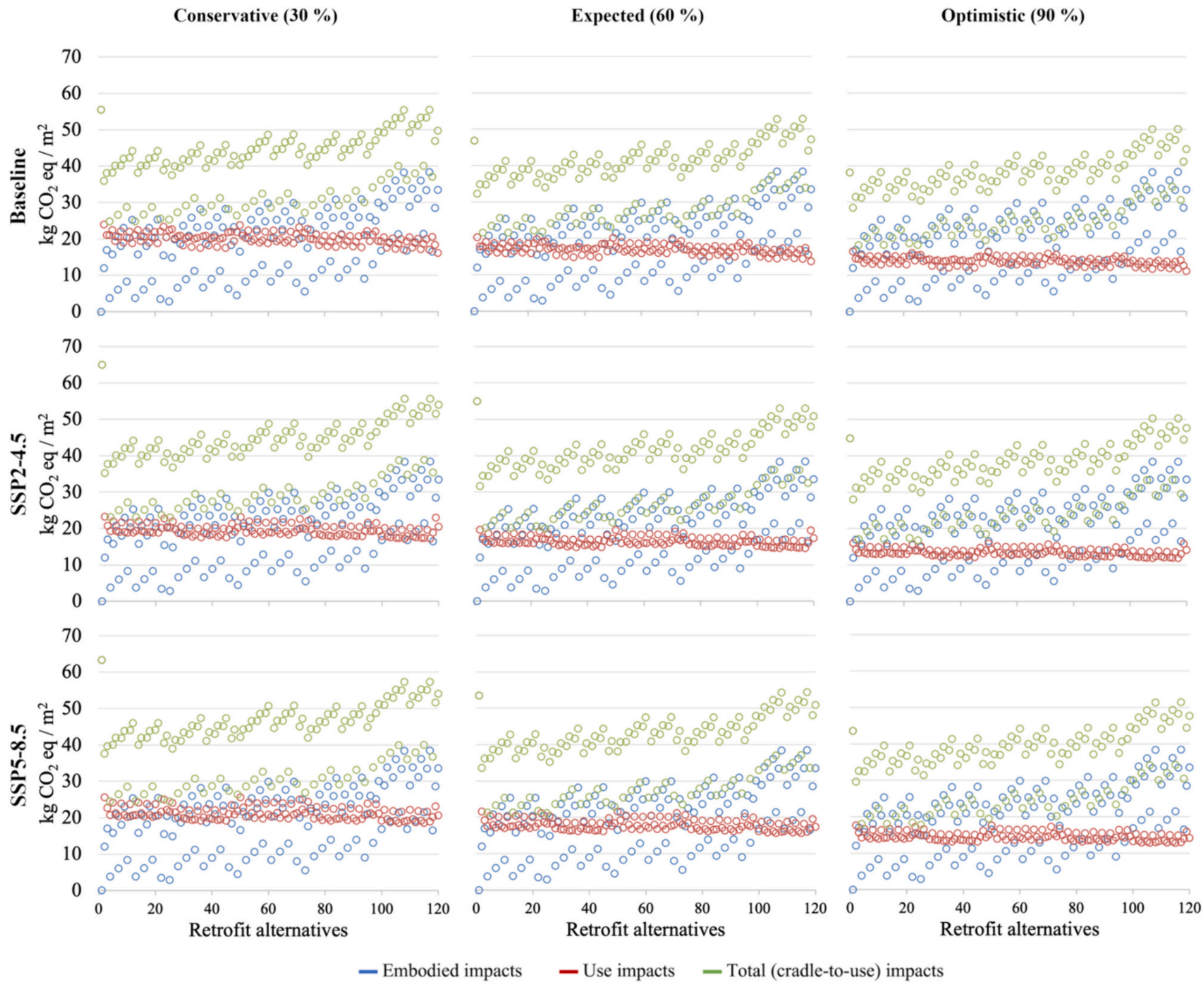

Fig. 5. Climate change results (in kg CO_2 eq/m^2) for the assessed scenarios: baseline (considering past weather data from 2004 to 2018), SSP2–4.5 (forecast for 2055), and SSP5–8.5 (forecast for 2055) combined with decarbonization scenarios for three alternative paths: 30%, 60% and 90% reduction of emissions.

Supplementary Material (Tables S1-S4). Fig. 4 illustrates the trade-offs between the embodied and use phases. Embodied impacts are higher (*i.e.*, present more emissions) than use phase impacts in 23% (future climates) and 33% (baseline) of the combinations. Fig. 4 also presents the statistical distribution of impacts for the embodied phase, use phase, and cradle-to-use. There is an increase in the average use impacts by about 12% and in the cradle-to-use impacts by about 7% from baseline to future climate scenarios. The increase of use phase impacts in the future result from the higher ambient temperatures that reduce the thermal performance for all solutions. Thus, given the identical embodied impacts in all scenarios, the increment of cradle-to-use impacts results uniquely from the use phase impacts.

Combinations without exterior wall insulation present the lowest cradle-to-use climate change impacts, given the lower cost of production, transportation, and on-site processes (embodied impacts), even if their use impacts are slightly higher due to lower thermal performance. Concerning windows, combining wooden frames and simple glazing represents the highest use impacts due to their lower thermal performance. However, the embodied impacts are low, making the cradle-to-use impacts also low. Conversely, combining an aluminum frame and high-performance glazing increases embodied impacts, which account for 13% of the alternative retrofit solutions. At the same time, it reduces the use impacts, giving it higher thermal performance.

Comparing the results with the 'do nothing' alternative for the baseline climate scenario shows a 12% to 56% decrease in cradle-to-use impacts, primarily due to a 57% to 69% reduction in the use phase impacts. The alternative future climate scenarios present a slightly higher decrease of about 20% to 60% in the cradle-to-use impacts. The retrofit solutions that show the highest reductions are the ones that implement roof insulation with 80 mm of mineral wool or 40 mm of XPS and no exterior wall insulation.

Fig. 5 displays the trend of embodied and use-phase impacts as the decarbonization scenarios become more optimistic (from a 30% to a 90% reduction of emissions). Embodied impacts exceed use phase impacts in 45% to 55% of the combinations in the conservative scenario (30%), 63% to 58% in the expected scenario (60%), and 69% to 72% in the optimistic scenario (90%) due to the progressive decrease in use phase impacts. The relative contribution of the embodied phase is less significant in scenario SSP5–8.5. The factors driving the contribution of the embodied phase include the aluminum window frame combined with high-performance glazing and external wall insulation, which increase the impacts related to production, transportation, and on-site processes. For the optimistic scenario, the roof insulation thickness adds to the increased relative importance of the embodied impacts. The statistical distribution shows a negligible decrease in impacts from the baseline to SSP2–4.5 and an increase of about 5% in use phase impacts from the baseline to SSP5–8.5 given the highest impacts due to global warming on the building performance.

The benefits of implementing a retrofit solution decrease as the decarbonization of the electricity grid increases, especially in today's climate. In this case, cradle-to-use impacts can increase by up to 30% in the optimistic scenario. This increase is due to the higher benefits during the use phase, where lower GHG emissions occur per kWh of electricity use. These reductions do not offset the high embodied impacts from the materials required for the retrofit, especially in solutions that use an aluminum window frame combined with double-glazing and 120 mm thick roof insulation. Nevertheless, retrofit solutions still result in a 50% to 60% decrease in cradle-to-use impacts compared to the 'do nothing' alternative, particularly in solutions with 40 mm roof insulation and no exterior wall insulation.

For the alternative future climate scenarios, the trend of higher impacts than the 'do nothing' case also occurs, but only for the optimistic scenario. The solutions with lower cradle-to-use impacts in the decarbonization scenarios implement roof insulation with 40 mm regardless of the material and no exterior wall insulation. On the other hand, solutions with no insulation (either roof or exterior wall) and window replacement show better climate change performance in future scenarios, along with the Skytech insulation membrane. It can be concluded that roof insulation with a thickness of 120 mm is not a good alternative. Ideally, the insulation thickness, in terms of environmental performance, should fall between 40 mm and 80 mm.

3.2. Sensitivity analysis

A global sensitivity analysis is performed to identify the parameters that have the most influence on the results using Spearman's rank correlation coefficient derived from all the combinations. The correlation coefficients are normalized and represented as a percentage, characterizing the relative contribution to the variance of total life cycle impacts for the different user retrofit input parameters: roof insulation material and thickness, exterior walls with or without insulation, exterior walls with internal or external insulation, window type, and window solar protection. Additionally, the influence of future climate is also assessed, represented by the cooling and heating degree days, showing

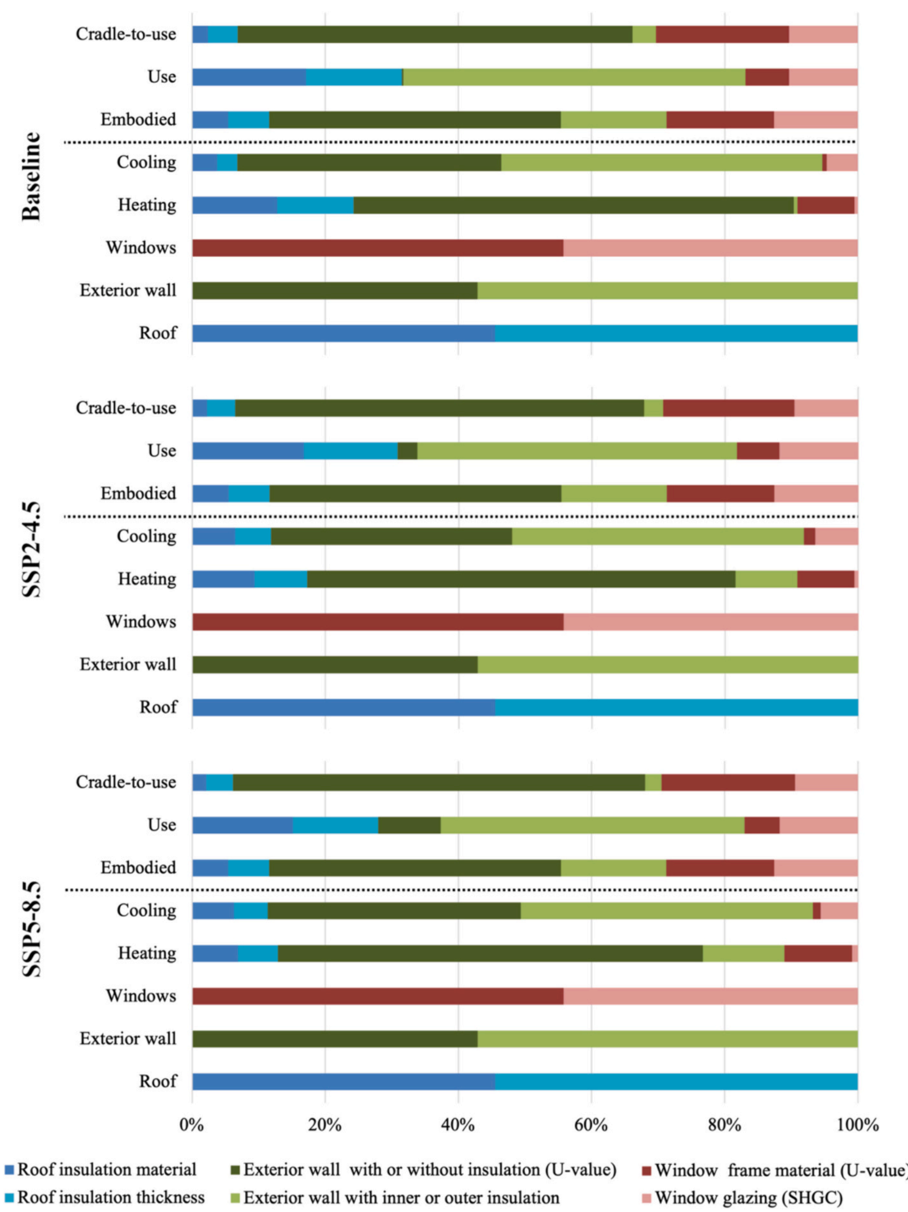

Fig. 6. Sensitivity analysis results for each climate scenario (a. baseline, b. SSP2–4.5, and c. SSP5–8.5), showing the contribution of input parameters to the variance of cradle-to-use, embodied and use phase, cooling, heating, windows, wall, and roof climate change impacts, assuming a constant electricity mix based on data from 2022 (calculated using the normalized Spearman's rank correlation coefficient). SHGC – solar heat gain coefficient; U-value – heat transfer coefficient.

that cooling degree days have a higher influence in the use phase results (78%) than heating degree days due to their higher influence both in the cooling (73%) and heating impacts (57%).

Fig. 6 presents the results by climate scenario to assess which retrofit input parameters influence the most on each scenario. For the baseline scenario, the most influential parameters on the cradle-to-use impacts are the exterior wall insulation (50%), followed by the window frame material (25%) and glazing (15%). The use phase's most influential parameters are the location of the insulation in the exterior wall (48%), followed by the roof material (20%) and thickness (15%), due to their highest impact on the building's performance. For the embodied impacts, the incorporation of insulation in the exterior wall is the most influential parameter (44%), followed by the location of the insulation (16%) and the window type (16%). Thermal insulation and window type are thus the parameters with the highest impacts on production, transportation, and on-site processes.

When considering future climate scenarios, the location of the insulation material becomes more important in terms of the heating impacts, while the roof insulation parameters become less important. Window parameters will slightly increase cooling impacts in the future. There are no significant differences within future climate scenarios. In the SSP5–8.5 scenario, the exterior wall U-value becomes slightly more influential for the cooling impacts and the location of the insulation for the heating impacts. Results for the decarbonization scenarios illustrate that the most influential attributes remain the same regardless of the scenario. Changes in the climate become less important as a higher reduction in the electricity grid GHG emissions is achieved (Fig. S1 in the Supplementary Material).

Sensitivity analysis results show that the exterior wall U-value (with or without insulation) is the most influential parameter in the cradle-to-use impacts, and it greatly influences the embodied, cooling, and heating impacts. This result is aligned with the contribution analysis results, which showed that the combinations without exterior wall insulation present the lowest climate change impacts. As expected, the importance of exterior wall insulation is emphasized due to its significant area on the building, greatly influencing its performance. Regarding the roof, its insulation thickness is slightly more influential than the material type. In general, the window type has more influence on the results than the window solar protection, which is reflected in the embodied and cradle-to-use phases. However, for the cooling and use phase, the solar heat gain coefficient is more impactful due to the importance of correctly managing the heat transfer from the solar source, especially in the warmer future.

3.3. Limitations and implications

This research presents some methodological and application-related limitations. Some assumptions considered in the application could lead to different conclusions. Regarding the scope of the study, maintenance activities, which would include the technological development of processes and materials, were not considered. The end-of-life was also not assessed; this could lead to varied results. For instance, some materials have more potential to be reused or recycled, which could result in benefits to be accounted for in a cradle-to-grave model.

Regarding the inventory analysis, several simplifications were considered. The embodied impacts of the equipment were not accounted for, along with domestic hot water energy use and equipment, which would change the absolute results but not the relative analysis between combinations and would not change the conclusions. Due to the lack of specific information, some LCI background data is based on generic/average processes. Nonetheless, the availability of raw materials depends on market demand and can originate from different manufacturers or countries covered by the average dataset. Other impact assessment methods could be used depending on the region where the LCA study is performed, leading to different results and conclusions. Finally, the approach was only applied to one building, limiting the analysis's scope and validating the proposed methodological approach.

Assessing the adaptive reuse of buildings from a future-oriented perspective provides new insights into the literature by suggesting which retrofit solutions present lower environmental impacts. The trade-off analysis between embodied and use phases reveals a range of insulation thicknesses that result in lower impacts. This means that an additional embodied impact from increasing the insulation thickness does not significantly reduce the use-phase energy requirements, ultimately increasing the life cycle impacts. Another important insight is that this thickness range varies when considering future climate scenarios, which is highly relevant for today's decisions for buildings with long lifespans.

Additionally, buildings that change their function must adapt their features to respond to new demands in uncertain future climates. Energy demands in offices differ from those in dwellings, especially regarding energy use schedules, so the impact of climate change would also vary. Historic buildings often exhibit high thermal inertia due to their thick and massive stone, brick, or earth walls. The response of these buildings in future climates would differ, potentially offering better solutions when facing an increase in cooling energy needs as projected in future climate scenarios. These findings represent significant contributions to the literature, pinpointing key areas for further exploration in upcoming studies on the adaptive reuse of buildings.

4. Conclusions

This article explores a climate change-oriented approach to assessing the future environmental performance of existing buildings from a life cycle perspective. The proposed methodological approach combines prospective LCA, thermal dynamic simulation using present-day and future climate data, and global sensitivity analysis to identify the most influential parameters and select the most efficient retrofit strategies for existing buildings under future climate and decarbonization scenarios. The proposed approach was applied to a historic dwelling adapted for use as an office building in Portugal. The main conclusions are as follows:

- **Climate Change Projections:** Future climate scenarios predict increased global temperatures, which will reduce heating energy demand but increase cooling energy needs, heightening the risk of overheating.
- **Cooling Demand and Emissions:** Increased cooling demand, which typically relies on electricity, can lead to higher greenhouse gas emissions depending on the electricity grid mix.
- **Decarbonization in Portugal:** The effect of grid decarbonization is minimal compared to the baseline, a country where the electricity grid already has a high share of renewable energy.
- **Embodied Phase Significance:** With significant decarbonization of the grid, the embodied phase becomes more crucial. Embodied impacts exceed use phase impacts in about half of the conservative scenario combinations and in over two-thirds of the optimistic scenario combinations.
- **Retrofit Solutions:** The effectiveness of retrofit solutions in terms of climate change performance varies depending on the specific climate scenario.
- **Key Influential Parameters:** Exterior wall parameters are identified as having the highest influence on results in the selected application. In contrast, roof and window parameters become less significant in future climate scenarios.
- **Climate Zone Dependency:** An exterior wall without insulation presents the lowest climate change impacts, with results heavily influenced by the building's climate zone and construction techniques.

Future developments of the approach must overcome current limitations on inventory characterization, life cycle impact assessment, and results interpretation. Advances in material technologies, such as adaptability to extreme climate conditions and maintenance activities, can be considered. It is also important to include the end-of-life building needs and assess alternative circular economy strategies for construction and demolition wastes. Although this article focuses on climate change impacts, other impact categories can also be evaluated to provide a more comprehensive assessment. Economic and social indicators need to be assessed for a holistic sustainability perspective, notably to support decision-making or the development of future policies. Furthermore, this approach could be applied to a building stock in various climate zones and assess existing buildings from different construction periods to search for correlations between architectural typologies and construction techniques, among others.

The proposed prospective life cycle approach can shed light on the future performance of buildings in the face of climate change, particularly how the existing building stock must be adapted to ensure thermal comfort conditions with minimal environmental impact. Additionally, a global sensitivity analysis can provide more insight into the robustness of the results, prioritize data collection, or simplify LCA modeling. This approach can be used, for example, to assess a diverse building stock instead of focusing on a single building.

CRediT authorship contribution statement

Carla Rodrigues: Writing – original draft, Visualization, Methodology, Investigation, Conceptualization, Data curation, Formal analysis. **Eugénio Rodrigues:** Writing – review & editing, Visualization, Methodology, Investigation, Conceptualization, Data curation, Formal analysis, Funding acquisition, Project administration, Software. **Marco S. Fernandes:** Writing – review & editing, Investigation, Conceptualization, Formal analysis. **Sérgio Tadeu:** Writing – review & editing, Data curation, Conceptualization.

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.

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Appendix A. Supplementary data

The Supplementary Material includes the definition of all the retrofit solutions (120 combinations), energy needs for heating, cooling, lighting, and equipment, detailed life cycle impact assessment results per type of retrofit solution (roof, exterior wall, and windows), as well as embodied, use, and cradle-to-use impacts (Tables S1-S4). Table S1 presents the results for all climate scenarios for the constant electricity mix, Table S2 for the 30 % decarbonization scenario, Table S3 for the 60 % decarbonization scenario, and Table S4 for the 90 % decarbonization scenario. Additional results for the sensitivity analysis are also included (for the grid decarbonization scenarios) in Fig. S1. Supplementary data to this article can be found online at [https://doi.org/10.1016/j.apenergy.2024.123867].

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