The impact of energy refurbishment interventions on annual energy demand, indoor thermal behaviour and temperature-related health risk.

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Highlights

- Integrated evaluation of the impact of energy refurbishment interventions
- Relationship between energy demand and thermal comfort level variation
- Influence of diverse indoor thermal comfort requirements on energy demand
- Influence of energy refurbishment strategies on indoor thermal health risk
- Questionable suitability of current energy refurbishment regulations towards health

Abstract

The reduction of energy consumption in the built environment by energy renovation strategies is an important target to deal with buildings sector's negative impact on our planet. Regardless of the potential for energy and emissions savings, building renovation has other relevant effects on users' quality of life and health that has not been so well assessed. The present study aims to contribute to current building energy efficiency targets, particularly to Spanish residential building sector, from a still non-existing integrated vision. To this end, an evaluation method was developed to discuss the impact of energy renovation interventions on annual energy demand, indoor thermal comfort and indoor thermal health risk variation. The approach was applied to an open linear residential block located in the Basque Country (northern Spain), and twelve scenarios based on three variables were analysed using DesignBuilder tool. The results obtained show a clear contrast in the impacts caused by energy refurbishment interventions. In particular, the generalized decrease in the number of hours in which indoor temperatures are within comfortable ranges is significant in contrast to the noteworthy reduction

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in annual energy demand. In conclusion, the results suggest new factors to be considered when updating energy renovation policies.

Keywords: energy refurbishment; energy demand; indoor thermal behaviour; indoor thermal comfort; temperature-related health risks.

1. Introduction

The objective of European public policies and recommendations for building renovation has varied over recent decades. While initially focused on building conservation and maintenance [1], [2] emphasis is now placed on achieving 21st Century energy efficiency goals [3], due to that fact that the building sector accounts for a high percentage of final energy consumption, 32% in 2017 [4]. Energy renovation policies, therefore, promote reductions on buildings' carbon and greenhouse gas emissions, and produce energy-cost savings [5-11].

As a consequence of buildings sector's negative impact on our planet and climate change mitigation, the European Union (EU) has set itself targets for reducing its greenhouse gas emissions progressively up to 2050 to achieve the transformation towards a low-carbon region by long-term strategies [12]. Current climate and energy framework sets key targets for 2030, which includes at least 40% cuts in greenhouse gas emissions (compared to 1990 levels), 32% share for renewable energy and 32.5% improvement in energy efficiency. Accordingly, each EU member country must stablish its own Long-Term Renovation Strategy (LTRS) to achieve global targets. In response to it, Spain submitted its first LTRS in 2014 [13], a second one in 2017 [14] and the latest update in June 2020 [15], which provides evidence-based scientific assessment and an updated overview of the impact of building renovation strategies under the latest Energy Efficiency Directives [6-8] with measurable progress indicators.

Regardless of the potential for energy and emissions savings, building renovation has other relevant effects on users' quality of life and health that has not been so well assessed, nor equally valid considered when prioritizing renovation strategies. Nevertheless, based on the Spanish LTRS 2020, it could be observed that users' well-being is receiving an increasing amount of attention.

Within this framework, this paper aims to contribute to current building energy efficiency targets, particularly to Spanish residential building sector, from a still non-existing integrated vision. To this end, an integrated evaluation method is developed to assess, correlate and discuss the impact of energy renovation interventions on annual energy demand, indoor thermal comfort and indoor thermal health risk variation. Considering thermal comfort and health risk of users linked to building thermal performance, the evaluation prioritizes passive measures rather than active ones, which encourages energy-efficiency measures towards the improvement of the thermal efficiency of the building envelope (upgrading the U-value through additional roof insulation, additional façade insulation, additional flooring insulation, window replacement and new sealing to reduce air leakage).

The results obtained in this approach may be useful for researchers, policy-makers, stakeholders, and even users and residents' associations when decision making processes.

2. Literature review

The assessment for building energy renovation strategies to reduce energy demand, and so promote energy-cost savings, normally considers local building regulations' requirements and standards, which, in our particular case (Spanish Technical Building Code-CTE) [16], are in accordance with EU targets and policies. With respect to the definition of indoor thermal well-being and temperature ranges, however, there is no common framework. In accordance with the literature, we could consider from national building codes [16, 17] to divergent international recommendations [18] and standards [19-21], as well as scientific research [22-27]. Moreover, indoor thermal conditions are related not only to comfort, but also to human health [28-30]. In this regard, several studies have demonstrated that exposure to inadequate wintertime indoor temperatures results in a significant increase in seasonal mortality [31-33] and morbidity rates [34], which mainly affects vulnerable populations, especially the elderly and those confronting fuel poverty [35-37].

Within this framework, many studies with different scopes and approaches have been carried out for the assessment of energy efficiency interventions in buildings due to their potential for environmental improvements. Some proposals are focused on defining the best renovation strategies to achieve the highest possible energy savings in residential buildings [38-43], and others are based on the assessment of energy demand and consumption reduction after refurbishment processes are concluded (these have demonstrated significant reductions in energy consumption of between 55% [44] to 90% [45] over unrefurbished buildings). In addition, various studies expand their scope and consider the sustainable approach [46, 47], which rely mostly on life-cycle methodology assessment, offering the optimal perspective from which to evaluate the environmental impact of a refurbished building [48], or evaluating different renovation strategies to define optimal approaches to obtain the lowest possible environmental impact [49].

As a consequence of so much research, it could be said that improving the energy efficiency of a building through the addition of insulating layers on the thermal envelope, positively influences indoor temperature levels and stability [50, 51], which alleviates the abovementioned temperature-related health risk situations [28] and also engenders economic benefits for society [52]. Hence, the analysis of the impact of energy efficiency renovations on the quality of life and health of inhabitants is receiving an increasing amount of attention in the literature [53-56]. Nevertheless, there is no general agreement about the impact of these interventions on overheating. While some authors claim that the addition of insulation to façades and roofs prevents solar gains [57-59], others state that increased indoor temperatures during summertime represent a health risk [60, 61], in addition to vulnerability towards summer energy poverty situations [62].

In view of temperatures are expected to rise due to climate change, the impact of current energy renovation strategies needs to be studied over the entire annual period, where the challenge is to take action in the built environment focusing the strategies on the impact on health and well-being/comfort of users as co-benefits or co-disadvantages of building energy renovation.

3. Methodology

To achieve the objective of this study, a work methodology attempting to assess the influence of energy renovation strategies is proposed. To this end, the calculation method is classified or divided into two general sections (see Figure 1): the indicators, which may determine the results, and the variables considered when evaluating the indicators. Based on machine learning models and hourly bases, different energy simulation scenarios are developed and evaluated under the EnergyPlus simulation tool and DesignBuilder interface according to three variables of analysis to demonstrate the relationship among the three indicators.

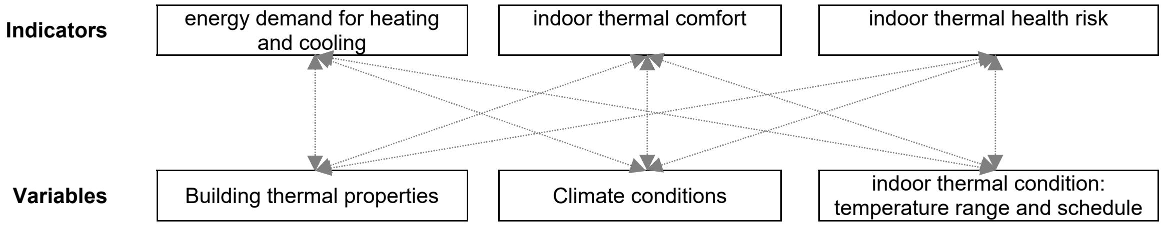

Figure 1. Calculation methodology scheme.

3.1 Indicators

Through the calculation and comparative study of the three indicators, the influence of energy refurbishment in buildings is determined. The procedure and ranges considered for each indicator are described below.

3.1.1 Heating and cooling annual energy demand

Transient building energy modelling and prediction are the basis for knowledge of building operations, especially for energy demand issues. The literature on building energy modelling and forecasting focuses on three categories: long-term load forecasts for system planning, medium-term forecasts for system maintenance, and short-term modelling for daily operations, scheduling and load-shifting plans.

Existing building energy models for short-term modelling can be categorized as purely physics-based models (white box), purely empirical models (black box), and those in between (grey box models) [63, 64]. Building energy modelling (BEM) [64-70] or building energy performance simulation (BEPS) tools [63, 71-73] are within the category of white boxes, which use detailed physics based equations to model building components, subsystems and systems to predict whole buildings and their subsystems behaviours, such as their energy demand and indoor comfort. Due to the detailed dynamic equations in white box models, they have the potential to capture building dynamics more accurately, yet they are time-consuming to develop and solve.

Many mature white box software tools, such as EnergyPlus Simulation Engine [74], DOE-2 [75], ESP-r [76], TRNSYS [77], DesignBuilder [78], eQuest [79], Green Building Studio [80], International Building Physics Toolbox (IBPT) [81], Integrated Environmental Solutions (IES) Virtual Environment (VE) [82], Modelica Buildings Library [83] and Sefaira [84], have been widely used to analyse the energy demands of the buildings. Each of these tools is categorised by its characteristics, mainly focused on input formats, outputs, weather condition predictions, calculation engines, duration of time calculation, or precision of the geometric description [63-65, 85, 86]. The choice of one tool or another and the hypotheses considered during the modelling process may directly influence the uncertainty of the building simulation result [87-94].

After analysing the benefits and potential of each of the BEMs previously mentioned and being aware of the degree of uncertainty associated with particular elements of the BEM model or underlying mathematical formulation, this study considers DesignBuilder to proceed with calculating the heating and cooling energy demands of the building.

DesignBuilder is an interface for EnergyPlus, which is one of the most widely-known energy simulation tools. It is important to note that EnergyPlus does not have a visual interface that allows users to see and conceptualize the building. The use of DesignBuilder, therefore, greatly facilitates aspects such as building model development, the design of the thermal properties of envelope elements or the definition of schedules, such as occupations and HVAC systems.

Considering the different outputs provided by DesignBuilder, this methodology proposes to show the results of the annual energy demand for heating and cooling for each useful square metre ($kWh/m^2 \cdot year$). To this end, heating and cooling energy generation systems are activated to reach the predetermined indoor temperatures during the selected schedule.

3.1.2 *Indoor thermal comfort*

The American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) defines thermal comfort as the condition of mind that expresses satisfaction with the thermal environment [19]. When discussing thermal comfort, two main models can be used: the static model and the adaptive model. The static model was developed by P.O. Fanger using heat-balance equations and empirical studies on skin temperature to define comfort [95]. Standard thermal comfort surveys ask subjects about their thermal sensation on a seven-point scale from cold (-3) to hot (+3). Fanger's equations are used to calculate the predicted mean vote (PMV) of a group of subjects for a particular combination of air temperature, mean radiant temperature, relative humidity, airspeed, metabolic rate, and clothing insulation. Fanger developed another equation to relate the PMV to the predicted percentage of dissatisfied (PPD). This relation was based on studies that surveyed subjects in a chamber where the indoor conditions could be precisely controlled. The PPD ranges from 5% to 100%, depending on the calculated PMV. The second model is the adaptive comfort model, which is based on the idea that outdoor climate influences indoor comfort because humans can adapt to different temperatures during different times of the year [96]. This new variable was incorporated in different standards, such as the ASHRAE 55-2013 [19], the European EN 15251 [21] and ISO 7730 standards [20].

In this study, instead of using the PMV or PPD indicators, the indoor thermal comfort is calculated based on the annual hours (hours per year) that each dwelling stays within the advisable range of air temperature defined by regulations, standards or international recommendations (see Figure 2). The selection of one standard or another [17-21, 97, 98] may directly influence the calculation process and the interpretation of the results.

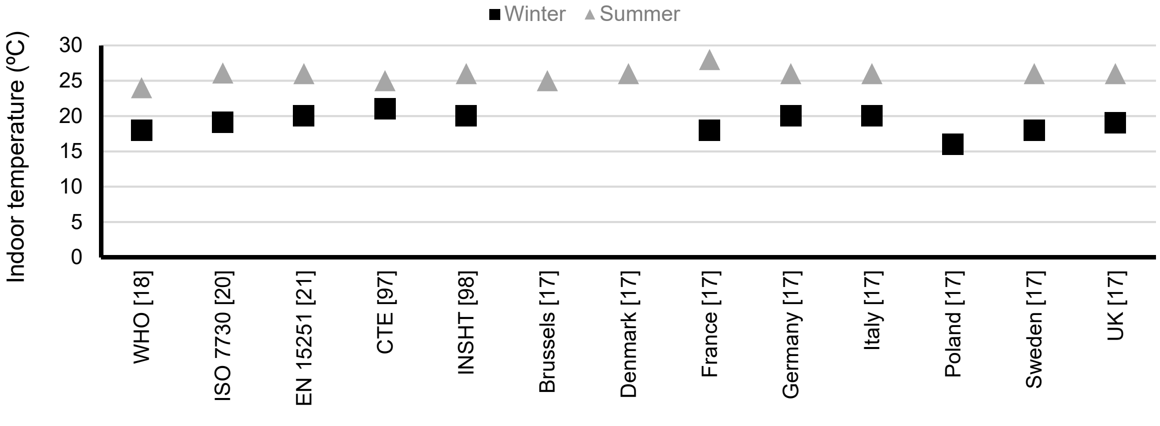

Figure 2. International divergent comfort temperature ranges.

In the case of adaptive models, upper and lower operative temperatures (t_o) are dynamic since they are directly linked to mean outdoor air temperature ($t_{pma(out)}$). For example, ASHRAE 55-2013 defines equations (1) and (2) to determine the upper and lower limits considering the 80% acceptability limits.

$$\text{Upper 80\% acceptability limit, } t_o \text{ (°C)} = 0.31\ \overline{t_{pma(out)}} + 21.3 \quad (1)$$

$$\text{Lower 80\% acceptability limit, } t_o \text{ (°C)} = 0.31\ \overline{t_{pma(out)}} + 14.3 \quad (2)$$

Based on the values of the mean monthly outdoor air temperatures, this study used different ranges of comfortable indoor operative temperatures for each month.

To carry out the calculation of indoor thermal comfort, as mentioned above, this methodology is based on the DesignBuilder tool, which allows calculating the temperature of each room or dwelling in hourly periods throughout the year. It is important to clarify that for the analysis of indoor thermal comfort, no energy generation systems are used, since this decision may allow assessing the variation in the thermal performance of the building before and after being renovated.

3.1.3 Thermal health risk

Indoor thermal conditions are related not only to comfort but also to human health [28-30]. In this regard, apart from the temperature ranges to determine the heating and cooling energy demand or indoor thermal well-being, this method also considers indoor temperature limits associated with negative impacts on health.

Low temperatures increase the risk of cardiovascular events [99-102], respiratory diseases, and minor problems such as the cold and flu [31]. According to previous studies [103], temperatures below 18°C are linked with an increased risk of respiratory infections (T^a< 16°C) increased in blood pressure and viscosity increase, which may cause heart attacks and strokes (T^a< 12°C), and decreases in core temperature (T^a< 9°C).

Higher temperatures, on the other hand, are less harmful, with dangers more related to the time needed for acclimatisation. However, the frequency and duration of heatwaves, which produce sharp increases in outside temperatures, are growing. Cardiovascular diseases [104, 105], clinical syndromes of heatstroke, heat exhaustion, heat syncope and heat cramps [58, 106]; permanent damage to organ systems; and risk of early mortality can be caused or aggravated by high temperatures. Several studies demonstrate that the recommended upper temperature should not exceed 22°C to prevent sick-building syndrome [107], although the WHO establishes 24°C as the upper limit [18]. Other studies [108, 109], however, argue that upper-temperature limits should be set relative to the outdoor climate. Recent studies published in Spain [110] divide the whole Spanish territory into local climate areas and recommend local upper limits for each region.

To quantify the thermal health risk, this methodology regards to hourly temperatures calculated during the indoor thermal comfort evaluation process.

3.2 Variables

The uncertainty or precision of the three indicators previously described is directly related to several variables. In this regard, this methodology is focused on the assessment of three variables: thermal properties of the building, climatic conditions and indoor thermal conditions. The settings considered for each variable are described as follows.

3.2.1 Building thermal properties

The adequacy of defining the thermal properties of the building envelope (roof, façade, openings, floor) is relevant during the building energy performance simulation process [111]. This calculation methodology defines the value of the thermal performance of the envelope using the U-value or the thermal transmittance parameter. The value of this parameter varies remarkably according to the architectural and construction characteristics [112] and improves considerably as a result of energy renovation interventions. Therefore, it is important to revise the information source and accuracy of the data used to define the thermal behaviour of each element in DesignBuilder.

3.2.2 Climate conditions

Climate data used in the development of BEM processes directly influence the final results. Therefore, the quality and accuracy of the database are relevant to this type of study. Regarding the ambivalence of the information source, the influence of the heat island on the temperature of certain areas of a city [113-115] or the climate change itself [116], the uncertainty of this parameter is an aspect to consider. To capture the uncertainty of weather prediction, several predictive optimal control models have been developed and applied during the last two decades [117-123].

DesignBuilder software is based on EnergyPlus hourly weather data (“epw”), which is supplied by automatic download from the EnergyPlus website [124], or on manually created files from data of other sources or other applications.

3.2.3 Indoor thermal conditions

As shown in Section 2.1, different regulations, standards or recommendations regulate the temperature range of indoor thermal conditions with different values. Furthermore, depending on the type of regulation or type of building use, the programming or hourly scheduling of these temperature ranges may also vary. Therefore, the definition of the temperature range and the schedule may influence the results of the three indicators considered in this study.

4. Modelling approach: The Basque Country as a case study

The abovementioned methodology was applied to a case study in the Autonomous Community of the Basque Country, a region situated in Northern Spain. According to most recently published database of the Spanish Statistical Office [125], 65% of residential buildings[2] in the Autonomous Community of the Basque Country were built before 1980, which means they were constructed before Spanish building regulations first imposed standards with respect to thermal envelopes [126]. Recent data published by the Basque government differs slightly [127], giving the average age of residential buildings as 42.8 years, suggesting that half (46%) were built prior to the implementation of the abovementioned regulations. In addition, the renewal values of the residential stock in Spain compared to other EU countries are low [128]: in 2014 in Spain approximately 0.8% of residential buildings were thoroughly renovated, compared to 1.82% in Austria, 1.75% in France or 1.49% in Germany.

With regard to Article 4 of the abovementioned Directive 2012/27/EU [7], the "Long-term Strategy for Energy Rehabilitation in the Building Sector in Spain" was approved in 2014. As a result, current building renovation statistics are somewhat better, yet the objectives have still not been achieved. The strategy is currently being revised based on Directive (EU) 2018/844 [8], which establishes the objective of renovating more than 1,200,000 homes by 2030, approximately five million square metres per year.

In this context, the Autonomous Community of the Basque Country is a pioneering region in Spain in terms of refurbishment policies. It is developing its own strategy for building energy renovation [129]. The diagnosis developed for this purpose was based on a disaggregated building-scale geographical information system (GIS) application, which provides more accurate information than the method based on archetype data. The classification of the current residential building stock according to architectural design, construction characteristics and energy performance, therefore, provides useful information for the selection and characterisation of the predominant typologies and constitutes a solid basis for the case study selection.

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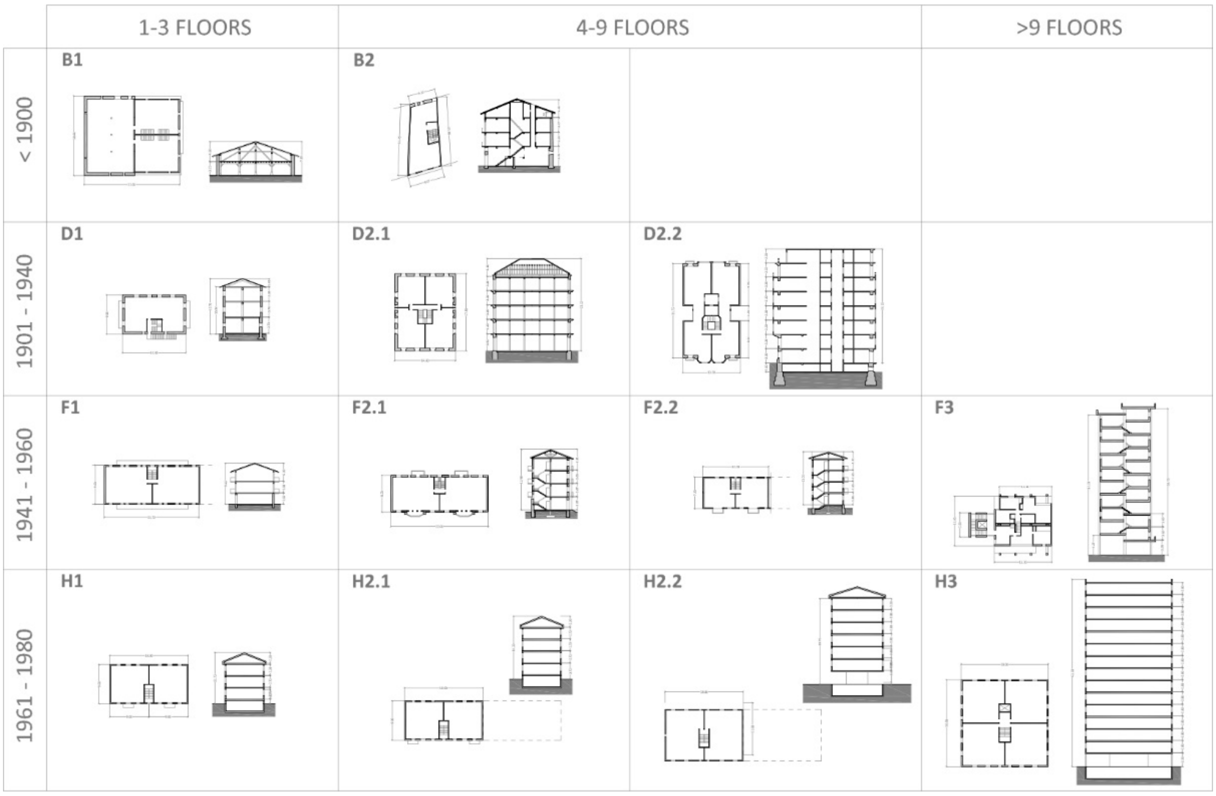
[2] According to the most recently published database from the Spanish Statistical Office, the number of residential buildings nationally reached 9,730,999 in 2011, of which 163,642 are in the Autonomous Community of the Basque Country.

Furthermore, the evolution of the construction of multifamily residential buildings in the Basque region has been similar to the rest in Spain; hence, the typologies are largely representative of the whole of the Spanish housing stock. In addition, the climate characteristics determined by the CTE [130] for the Autonomous Community of Basque Country, the region divided into climates C and D, cover the highest percentages of housing locations in Spain, 27.59% and 33.74%, respectively. This means that the conclusions obtained from this case study may suggest problems that may arise in the rest of the regions with similar climates.

4.1 Building type selection

The study was performed on the most representative building type with the greatest energy renovation potential. Within the previously mentioned diagnosis, a research project called the "*First step study for the elaboration of a long-term Action Plan dealing with the residential building stock of Euskadi*"[3] was carried out. It characterised all the residential buildings in the Autonomous Community of the Basque Country and identified the predominant types. It was concluded that 91.9% of the residential buildings were multifamily, of which the open block type of between four and nine floors was predominant (F2 or H2) (see Figure 3).



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[3] Original title: *Estudio previo para la elaboración de un Plan de Acción a largo plazo en el parque de edificios de Euskadi*. The research was carried out by the research group CAVIAR (UPV/EHU) in collaboration with researchers from the UPC and the Department of Environment, Territorial Planning and Housing of the Basque Government.

Figure 3. Classification of multifamily residential buildings in the Autonomous Community of the Basque Country built before 1980 **and** the most representative typology for each. The percentages regarding multifamily residential buildings constructed before 1980 are the following: B1=4.76%; B2=4.76%; D1=3.17%; D2=6.35%; F1=3.17%; F2=14.29%; F3=1.59%; H1=3.17%; H2=46.03% and H3=12.70%.

This building type was created in 1940 with the greatest development taking place in the period 1960-1980, precisely when residential building construction was a necessity. According to the classification drew in the "Long-term strategy for energy renovation in the building sector in Spain", the highest percentage of housing (24.8%) belongs to the multifamily housing cluster, with more than four floors and built between 1969 and 1980. Of these, the open linear block type represented in Figure 3 as H2.2 is the most common. Therefore, it was the type selected for this study.

4.2 Analysis variables

4.2.1 Building thermal properties: description of building model pre- and post-energy refurbishment

With a total building area of 3290.70 m^2 and a net conditioned surface of 2487.73 m^2, the building consists of an unoccupied ground floor and seven residential floors (with four apartments of a depth of 12 m on each floor). All apartments are naturally ventilated and lack mechanical ventilation or cooling, and no renewable energy systems are installed. The building models were developed through the DesignBuilder v.5.5.2.003 simulation interface (see Figure 4).

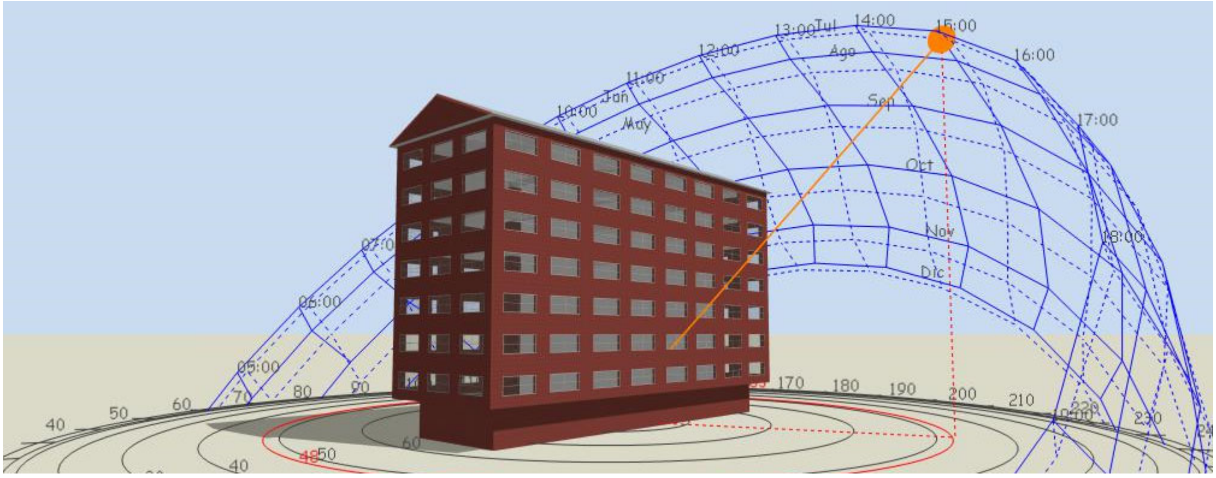

Figure 4. Case study model design obtained from the simulation software DesignBuilder.

4.2.1.1 Existing or unrefurbished state (baseline)

The construction and thermal characteristics of the building envelope were defined during the initial stage of the study. The U-values (W/m^{2}K) of the existing building envelope, the baseline building, include a cavity wall façade (1.25 W/m^{2}K); a reinforced concrete deck with ceramic finish (3.46 W/m^{2}K); a reinforced concrete first-floor slab (2.51 W/m^{2}K); monolithic glazing (5.77 W/m^{2}K); and an aluminium frame (4.2 W/m^{2}K) (see Table 1). As mentioned above, this building type was built before the Spanish building regulations addressed the issue of the thermal envelope's energy efficiency; hence, the U-values do not meet the minimum requirements established by the current CTE.

4.2.1.2 Energy refurbished state

Considering the thermal comfort and health risk of users associated with building thermal performance, the evaluation prioritizes passive measures rather than active ones, which encourages energy-efficiency measures towards the improvement of the thermal efficiency of the building envelope (e.g., upgrading the U-value through additional roof insulation, additional façade insulation, additional flooring insulation, window replacement and new sealing to reduce air leakage). Assessing only passive measures makes it possible to know to what extent these measures have an impact and how much the household situations would improve in the most extreme cases where heating or air-conditioning systems cannot be paid for.

Of three possible intervention strategies for increasing the thermal resistance of the façade (the installation of insulation from the inside, from the outside, or air gap insulation), the external installation was selected based on technical and energy efficiency criteria. The addition of insulating layers can be carried out with two different techniques: an external thermal insulation technique or a ventilated façade technique. Based on a previous study [48], which evaluated the energy, environmental and economic performance of several refurbishment strategies[4], a ventilated façade technique was finally chosen for renovation, which includes a 10 cm XPS insulation, an air gap and a ceramic cladding panel. As a result, a continuous insulation layer is provided over the total area of the vertical thermal envelope, which also protects internal layers and slab edges.

Alongside the solid façade intervention, the replacement of the existing windows, both the frame and glazing area, was also considered. New windows include double glazing area (2.1 W/(m2k) and Polyvinyl Chloride (PVC) frames (2.0 W/(m2k); the material was selected for its thermal capacity, profitability and low need for maintenance.

In addition to the improvement of the vertical envelope, the energy refurbishment strategy also considered the horizontal envelope, that is, the concrete floors that were in contact with unheated spaces (first floor and upper floor). As a result, a 6 cm thermal insulation layer with its flooring finish layer was added to the existing concrete slabs.

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[4] Note that the climatic zone, type of building and construction characteristics of the reference case study are similar to the ones evaluated by Oregi et al. [48]. Consequently, it was considered that the conclusions obtained could be applied in this research.

This set of passive intervention measures improves the thermal properties of the total area of the thermal envelope (see Table 1).

ENVELOPE	THICKNESS (mm)	DENSITY (kg/m^3)	CONDUCTIVITY (W/(m·k))	U-value (W/(m^2·K))
EXTERNAL FAÇADE				
Baseline existing composition				
Double hollow brick partition	80	930	0.375	
Air gap	80	-	-	
Double hollow brick partition	80	930	0.375	
Refurbishment layers				
Insulation – XPS	100	37.5	0.032	
Air gap	50	-	-	
Ceramic panel	15	2000	1	
Current façade				1.25
Refurbished façade				0.248
ROOF				
Ceramic tile	25	2300	1.3	
Concrete floor	200	1740	1.923	
Current roof				3.46
CONCRETE FLOOR IN CONTACT WITH HEATED SPACES				
Concrete floor	180	2100	1.4	
Current concrete floor in contact with unheated space				2.51
CONCRETE FLOOR IN CONTACT WITH UNHEATED SPACES (first and last floors)				
Baseline existing composition				
Concrete floor	180	2100	1.4	
Refurbishment layers				
Insulation – XPS	60	37.5	0.032	
Current concrete floor in contact with unheated space				2.51
Refurbished concrete floor in contact with unheated space				0.47
WINDOWS (78% glazing and 22% frame)				
Baseline existing composition				
Single glazing	6			* 5.7
Aluminium frame with no thermal bridge break	-			* 4.2
Refurbished composition				
Double glazing	6+12+6			* 2.0
PVC frame	-			* 2.1
Existing window				5.37
Refurbished window				2.1

Table 1. Building envelope layers and U values (W/m^2·K) for the unrefurbished and refurbished models.

4.2.2 *Climate condition: local climate data*

Regarding outdoor environmental conditions and the ubiquitousness of this building type throughout the territory of the Autonomous Community of the Basque Country, this study used climate data for two cities, Bilbao and Vitoria-Gasteiz, which represent the most divergent climates in the region.

The Köppen-Geiger worldwide climate classification [131, 132] classifies the whole Basque Country [133] as "warm temperate-Cfc" (C: warm temperate; f: fully humid; c: cool summer). However, analysed in the context of the Iberian Peninsula, the climate can more accurately be described as "Cfb" (temperate with a dry season and temperate summer). As mentioned above, the current Spanish Technical Building Code provides specific climate reference data for the provincial capitals of Spain [130]. In the case of Bilbao, the reference climate zone is C1, where the minimum and annual average outdoor dry bulb temperatures are -0.2°C and 14.7°C, respectively. Vitoria-Gasteiz falls within a different category, D1, with minimum and annual averages of -4.0°C and 12.1°C, respectively [134].

Based on these classifications and machine learning models, energy use calculations were obtained based on the International Weather for Energy Calculation climatic files [135] for both cities.

4.2.3 Indoor thermal conditions: temperature ranges and schedules

In addition to the outdoor climate temperature data, three different definitions of thermal comfort were modelled and evaluated based on different assessment criteria: the CTE regulation-based definition, the ASHRAE 55-2013 adaptive definition and the WHO health standards definition (see Table 2). These different standards were added as thermal requisites in the modelling process.

- CTE requisites (“C”): Spanish Technical Building Code regulation-based indoor thermal range and schedule.
- ASHRAE 55-2013 requisites (“A”): adaptive comfort thermal range over 24 h. The monthly comfortable indoor operative temperatures (t_o) were determined according to equations (1) and (2) defined in Section 2.1.2 for both local climates regarding the prevailing mean monthly outdoor air temperatures ($\overline{t_{pma(out)}}$).

  However, the fourth criterion established for applying the adaptive comfort method, that is, the one that sets the prevailing mean outdoor temperature range (10-33.5°C), was not met during winter months. Consequently, the acceptable minimum temperature value (10°C) was adopted to calculate the 80% acceptability limits for such months according to each reference climate.
- WHO requisites (“H”): healthy thermal range over 24 h.

INDOOR THERMAL COMFORT REQUISITE		PERIOD	INDOOR Tª RANGE	SCHEDULE
CTE		Annual	20-25°C	Heating: 30th Sep. - 31st May From 07:00 h to 23:00 h
				Cooling: 31st May - 30th Sep. From 15:00 h to 23:00 h
ASHRAE 55-2013	BILBAO_C1	January, February, December	17.4-24.4°C	Heating: 30th Sep. - 31st May 24 h
		March	17.5-24.5°C	
		April	17.9-24.9°C	
		May	18.9-25.9°C	
		June	19.6-26.6°C	
		July	20.4-27.4°C	Cooling: 31st May - 30th Sep. 24 h
		August	20.5-27.5°C	

		September	20.1-27.1°C	
		October	19.3-26.3°C	
		November	18.0-25.0°C	
	GASTEIZ_D1	January, February, March, April, November, December	17.4-24.4°C	Heating: 30th Sep. - 31st May 24 h
		May	18.2-25.2°C	
		June	19.1-26.1°C	
		July	20.0-27.0°C	Cooling: 31st May - 30th Sep. 24 h
		August	20.1-27.1°C	
		September	19.4-26.4°C	
		October	18.3-25.3°C	
WHO		Annual	18-24°C	Heating: 30th Sep. - 31st May 24 h
				Cooling: 31st May - 30th Sep. 24 h

Table 2. Indoor thermal range and schedule parameters considered for the simulation process.

4.3 Thermal limits and health risk

Apart from the temperature ranges described above that determine the energy demand for comfortable conditions, the following thermal limits were considered to evaluate the impact on health:

- Low temperatures:
  - Risk 1: Tª< 16°C
  - Risk 2: Tª< 12°C
  - Risk 3: Tª< 9°C
- High temperatures:
  - Risk 4: Tª< 30°C for Bilbo_C1 climate, and Tª< 34°C for Gasteiz_D1 climate

4.4 Machine learning models: energy simulation scenarios

Finally, the combination of the options described for each variable, results in a matrix of 12 scenarios (see Table 3). The comparative analysis of the results obtained in these scenarios for each indicator may assess the main objective of the calculation method.

BUILDING THERMAL PROPERTY	CLIMATE CONDITION	INDOOR THERMAL CONDITION	ID
BASELINE (B)	BILBAO_C1 (B)	CTE (C)	B_B_C
		ASHRAE 55-2013 (A)	B_B_A
		WHO (H)	B_B_H
	GASTEIZ_D1 (G)	CTE (C)	B_G_C
		ASHRAE 55-2013 (A)	B_G_A
		WHO (H)	B_G_H
REFURBISHED (R)	BILBAO_C1 (B)	CTE (C)	R_B_C
		ASHRAE 55-2013 (A)	R_B_A
		WHO (H)	R_B_H
	GASTEIZ_D1 (G)	CTE (C)	R_G_C
		ASHRAE 55-2013 (A)	R_G_A
		WHO (H)	R_G_H

Table 3. Energy simulation scenarios by case study parameters.

5. Results

To provide a comprehensive overview of the results, this section is divided into three sections according to the study's variables of analysis, that is, energy demand for heating and cooling, indoor thermal comfort and temperature-related health risk. From the above-described matrix, six different scenarios are analysed in parallel for each construction state (baseline vs refurbished), which facilitates the assessment of the influence of the renovation strategies considered and generates a discussion of the relationship between the three indicators.

5.1 Energy demand for heating and cooling

Due to the prevailing climatic conditions and residential use of buildings, which is the object of the study, the demand for heating was much higher than the demand for cooling for all six baseline or unrefurbished scenarios. If two of the extreme cases that are considered, it can be observed that heating makes up 98.8% of the total demand in the B_G_A scenario, while for the B_B_H scenario, it does not exceed 87.5%

This relationship between the demand for heating and cooling, however, changes completely once energy efficiency renovations are taken into account. It is worth mentioning that the measures addressed in this study were aimed at improving the thermal resistance of the building envelope, which in turn directly affects the demand for heating. Accordingly, annual energy demand across all six scenarios was considerably reduced, by an average of 60%, (see Figure 5, Table 4) once the energy refurbishment measures were applied to the machine-learning models. Although this is an important gain, it corresponded primarily to a decrease in the demand for heating (an average of 81.89% for R_B and 77.89% for R_G). One clear example is the R_B_A scenario, in which demand is reduced by 84%.

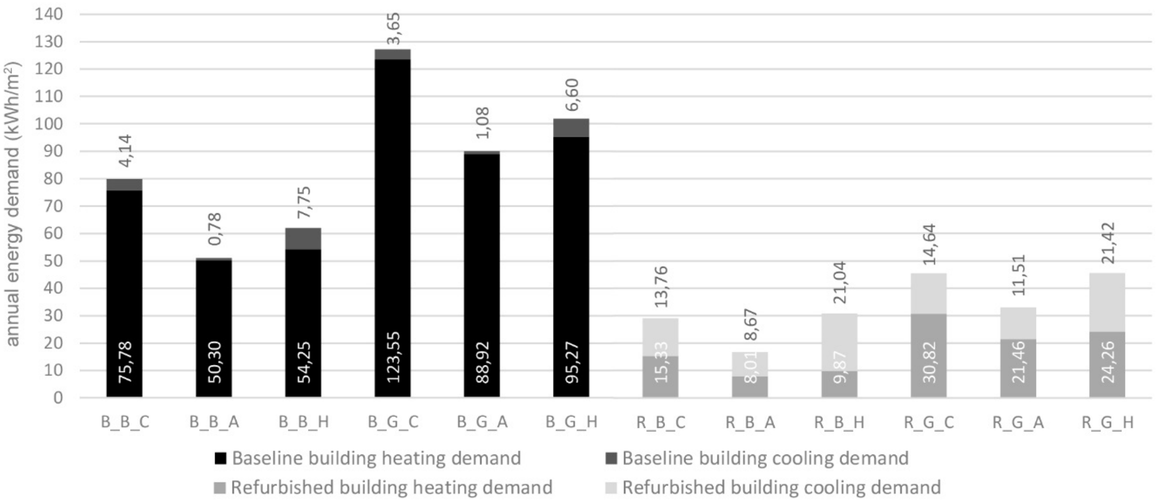

Figure 5. Annual energy demand (kWh/m^2) for all energy simulation scenarios.

Increasing the thermal resistance of the thermal envelope, however, produced the opposite result with respect to cooling demand, given that this increased in all postintervention scenarios. The average increase was 470.02% for R_B and 495.48% for R_G, while in the most extreme case (R_B_A), the increase in demand for cooling was over 1000% (see Table 4). However, it must also be taken into account that the cooling demand in the baseline scenario (B_B_A) was 0.78 kWh/m,^{2} but 8.67 kWh/m^2 for the refurbished building, that is, an increase of 7.88 kWh/m^2. For the other five postintervention scenarios, the highest increase in the demand for cooling reaches 14.8 kWh/m^2 in the case of the R_G_H scenario.

As a consequence of the decrease in heating demand and the increase in cooling demand, in postintervention scenarios, the annual energy demand obtained was nearly equal for both heating and cooling, except for R_B_H, in which the cooling demand exceeded the heating demand (9.87 kWh/m^2 for heating in comparison to 21.04 kWh/m^2 for cooling).

With regard to the outdoor climate variable, “B” for Bilbao and “G” for Gasteiz, it should be pointed out that its influence is relevant in reading the results. The energy demand for the baseline scenarios located in Gasteiz is higher than that for parallel scenarios located in Bilbao. In the most extreme case, this difference reaches 76%, where the energy demand for a building located in Gasteiz is 90 kWH/m^2 (B_G_A), compared to 51.1 kWH/m^2 for the same building in Bilbao (B_B_A). The climate variable also notably influenced the postintervention scenarios. In the most extreme case, the difference reaches 98%, as the energy demand for a building located in Gasteiz is 32.9 kWH/m^2 (R_G_A), compared with 16.7 kWH/m^2 for the same building located in Bilbao (R_B_A).

The final variable is the indoor thermal requirement, which prescribes the temperature range inside a building and the periods in which active systems must be deployed to maintain temperatures within a comfortable range. Energy demand is higher when following CTE standards compared with those of ASHRAE and the WHO. For example, in the baseline scenario in Bilbao, the energy demand imposed by CTE requisites (B_B_C) is 25% higher than the imposed by the same building following WHO standards (B_B_H) and 34% higher than that imposed by a building conforming to ASHRAE standards. The same results were found with the building located in Gasteiz, where the difference is somewhat smaller. There is a variation of 25% between the CTE (B_G_C) and ASHRAE (B_G_A) scenarios. This is due to heating demand, as the indoor comfortable temperature range defined by the CTE is more restrictive, thus more heating is needed. For ASHRAE conditions, based on adaptive comfort, the defined temperature range is wider, so there is less demand for the use of active systems to remain within this bracket. However, if internal thermal conditions are analysed with respect to cooling, it can be observed that the scenarios that have greater demand are those of the WHO, as the maximum indoor temperature is established at 24ºC. However, it is worth noting that the demand for cooling in the base scenarios (B_B_H and B_G_H) is minimal.

These differences are similar to those in post-refurbishment scenarios (see Figure 5). Those scenarios that meet CTE guidelines are those with the highest demand for heating (up to 47% more than those following ASHRAE guidelines in Bilbao), while those scenarios that confirm to WHO standards are linked to a higher demand for cooling (up to 59% more than the ASHRAE scenario in Bilbao). Similarly, as in the baseline scenarios, the results for the scenarios run under ASHRAE requisites give lower values with respect to the demand for both heating and cooling.

ID	**ANNUAL ENERGY DEMAND REDUCTION**					
	kWh/m^2			**%**		
	HEATING	**COOLING**	**TOTAL**	**HEATING**	**COOLING**	**TOTAL**
R_B_C	60.46	-9.62	**50.83**	79.77	-232.48	**63.60**
R_B_A	42.30	-7.88	**34.41**	84.08	-1006.22	**67.36**
R_B_H	44.39	-13.29	**31.10**	81.81	-171.36	**50.15**
R_G_C	92.73	-10.98	**81.74**	75.05	-300.55	**64.26**
R_G_A	67.46	-10.42	**57.04**	84.08	-961.46	**63.37**
R_G_H	71.01	-14.82	**56.19**	74.54	-224.42	**55.16**

Table 4. Annual energy demand reduction (kWh/m^2 and %) for refurbished scenarios in comparison with their corresponding baseline scenario.

5.2 Indoor thermal comfort

The second set of results shows the level of indoor thermal comfort for the baseline and refurbished states for each of the six scenarios evaluated. The abovementioned results were obtained based on the assumption that no active systems were activated. In this way, the simulations permitted an analysis of the effect of the suggested passive intervention strategies on indoor thermal comfort.

The results over an annual period for both the baseline and the refurbished building (see Figure 6) reflect a general reduction in the hours of thermal comfort for both climate zones and all three thermal requisite conditions. Considering that an annual cycle contains 8760 hours, the number of annual comfortable hours for CTE requisites was the lowest in both climates and construction states (30.8% of annual hours in B_B and 19.9% in R_B; 24% in B_G and 19.6% in R_G). ASHRAE 55-2013 requisites, in contrast, were most often achieved (43.5% in B_B and 42.6% in R_B; 35.6% in B_G and 33% in R_G). The scenarios under the WHO requirements, therefore, illustrate intermediate results. In addition, the highest annual reduction in comfortable hours in the baseline and energy-refurbished scenarios was demonstrated in those scenarios based on CTE requisites.

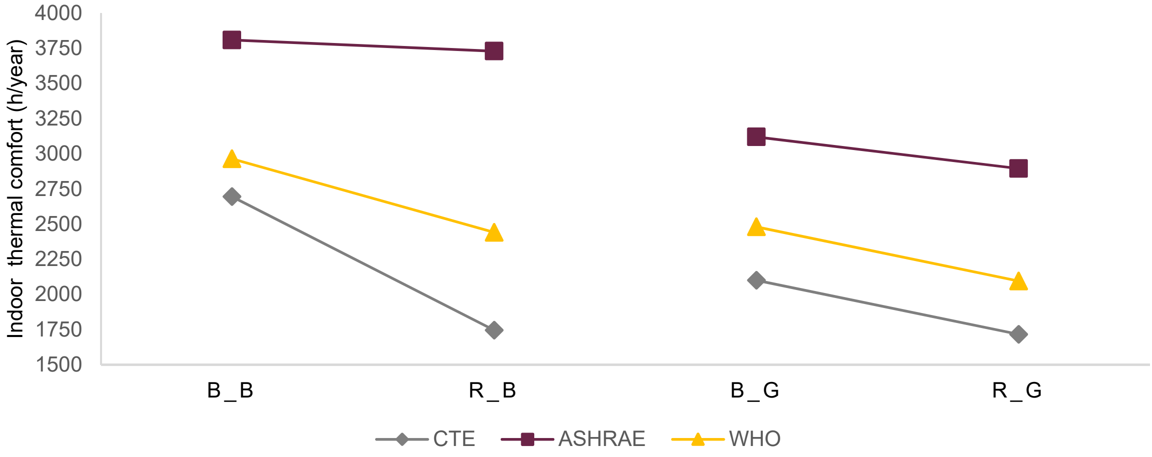

Figure 6. Annual indoor thermal comfort hours for baseline and refurbished scenarios in both climates.

These results, however, must be classified and analysed over annual periods, given that the interpretation varies significantly (see Figure 7). The classification of different periods coincides with three different sets of seasonal conditions: winter (December to March), summer (July to September) and the transitional seasons of autumn and spring (June to September and October to November).

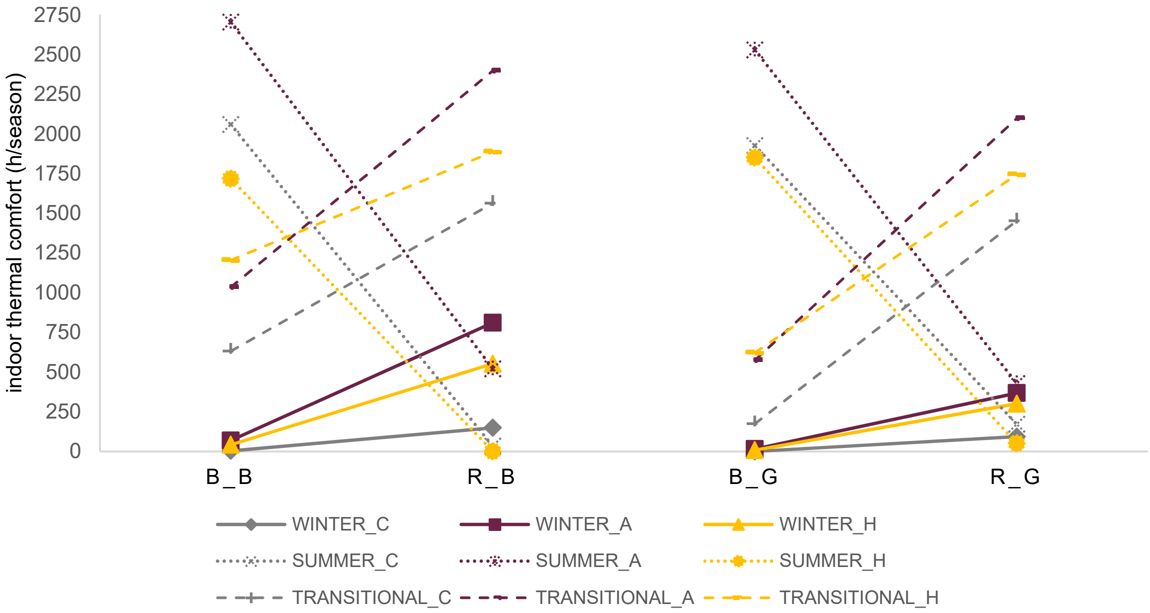

Figure 7. Indoor thermal comfort hours per season for baseline and refurbished scenarios in both climates.

The results obtained (see Figures 7-9) confirm that the level of indoor comfort, or the number of comfortable hours after refurbishment, improves notably in winter and in the transitional seasons. One example is that of the refurbished building in Bilbao (R_B), where the number of comfortable hours in winter increases by 145 hours under CTE requisites, 511 under WHO requisites and 742 under ASHRAE requisites. The results are similar in Gasteiz, where refurbishment interventions achieved an increase in the number of wintertime comfortable hours by 93 under CTE requisites and 293 under WHO and ASHRAE requisites. If we take into account that the winter period defined by this study has a duration of four months (2904 hours), the results demonstrate that in Bilbao, a maximum of 2.3% (B_B_A) of hours are classified as wintertime comfortable hours over this period. By comparison, the proportion for the same building after an energy refurbishment can reach 27.2% (R_B_A scenario). A similar outcome can be observed in Gasteiz, where the severity of the winter climate is greater than in Bilbao. The most positive result demonstrated by an unrefurbished building is 0.5% (B_G_A) of wintertime comfortable hours, as opposed to 12.4% after refurbishment (R_G_A). It is again worth highlighting that the different standards for thermal comfort influence the results. In the case of scenarios evaluated under the CTE criteria, these values are significantly reduced and only 5% of wintertime hours are comfortable for a refurbished building in Bilbao (R_B_C) and 3.1% for a refurbished building in Gasteiz (R_G_C). Scenarios evaluated under WHO requisites display intermediate results.

With respect to transitional season periods, those in which external temperatures are most moderate, the values obtained demonstrate that there are more hours within a comfortable range than in winter. For example, for the unrefurbished building located in Bilbao and evaluated according to WHO standards (B_B_H), up to 40.5% of the total 2928 seasonal hours are considered comfortable. Applying the same requisites to a building located in Gasteiz (B_G_H), the result is 20.9%. The postintervention results demonstrate an increase in the number of comfortable hours according to the three sets of criteria for comfort that were modelled, with the R_B_A and R_G_A scenarios in particular reaching 80.6% and 70.5% respectively. The requisites used to evaluate thermal comfort also influence the results during this period, as the number of comfortable hours is considerably reduced when buildings are assessed according to CTE requisites.

Finally, the results obtained for summer show contrasting results, that is, the hours of comfort are considerably reduced for the six postintervention scenarios, as shown in Figures 7, 8 and 9. The improvement of the thermal properties of the building envelope without any improvement in the ventilation system causes an increase in the internal temperature of the building, which exceeds the maximum value determined to be comfortable under all three sets of requisites considered in the study (CTE, ASHRAE and WHO). If the most dramatic results are considered for each climate zone, it can be seen that in the R_B_A scenario in Bilbao, the number of comfortable hours is reduced to 530, an 80.8% reduction with respect to the 2705 hours of comfort in the corresponding baseline scenario (B_B_A). Something similar occurs for the scenarios located in Gasteiz, where the reduction in comfortable hours reaches 83% (2102 h) in the R_G_A scenario compared to the baseline scenario (B_G_A; 2530 h).

It is worth highlighting that this analysis of indoor thermal comfort has only focused on determining the number of hours in which the building is within or outside the comfortable range. However, it has not taken into account how far internal air temperatures diverge from the comfortable range. If we consider that the internal air temperature was 4ºC at 08:00 h and 14ºC 16:00 h, the temperature would be outside the thermal comfort range at both points in time. Considering the minimum temperature of 20ºC, as defined by the CTE, in the first case, the gap would be 16ºC, while in the second, it would be only 6ºC. Therefore, the energy required to adapt indoor temperatures to a comfortable range for users is directly linked to the difference between the internal temperature of the building and the comfortable temperature. This is relevant to an analysis of energy usage, as a larger gap implies higher energy demand. Furthermore, this gap can also be used as a value to evaluate the level of discomfort, thus adding a complementary parameter to those used so far.

To calculate this value, equation 3 was used, where HTD is the number of hours-temperature-difference, j is the day-of-year; i is the hour-of-day, Tc is the indoor-thermal-comfort-temperature (depending on the indoor thermal comfort criteria) and Ti is the indoor-temperature of the building. This equation only considers positive values.

$$HTD_{i,j} = (T_c - T_i)_{((T_c - T_i) > 0)} \qquad (3)$$

From data obtained from hourly basis simulations, the HTD values were calculated for all six scenarios, covering baseline and refurbished buildings. From these values, it was possible to calculate the reduction in the level of discomfort for each scenario (see table 5). This has permitted an analysis of how the suggested energy efficiency renovation measures bring internal temperatures closer to ranges defined as comfortable. HTD values are conceptually similar to “degree hour” values used for energy calculations. To conclude the reading of these results, Table 5 also describes the increase in the number of comfortable hours in each refurbished scenario.

ID	INCREASE IN COMFORT HOURS (h)				REDUCTION IN THE LEVEL OF DISCOMFORT (h·C)			
	winter	summer	transitional season	total	winter	summer	transitional season	total
R_B_C	145	-2027	932	**-950**	10885	-9922	6466	**7429**
R_B_A	742	-2185	1364	**-79**	9968	-6166	2969	**6771**
R_B_H	511	-1718	683	**-524**	10347	-13812	4743	**1278**
R_G_C	93	-1756	1279	**-384**	12179	-10663	10391	**11907**
R_G_A	353	-2102	1524	**-225**	11609	-7083	7123	**11649**
R_G_H	293	-1801	1123	**-385**	11802	-14593	7019	**4228**

Table 5. Indoor thermal comfort hours and indoor thermal discomfort level for refurbished scenarios in comparison with their corresponding baseline scenario.

The general results across all six refurbished scenarios are similar. On the one hand, the results demonstrate that due to the energy efficiency renovations of the buildings, the indoor temperature of the dwellings increases substantially in summer, which promotes a reduction in the number of comfortable hours with respect to the baseline scenarios. Due to this enormous increase in uncomfortable hours in summer, the number of annual comfortable hours in refurbished buildings is reduced in the six scenarios analysed. HTD values, on the other hand, offer a different perspective. They demonstrate that even if the number of degree hours increases during summer, an analysis of annual data reveals that the HDT reduction is positive. That is, differences between indoor temperatures and comfort limits are reduced thanks to energy refurbishment interventions.

5.3 Indoor thermal health risk

The graphics below show the passive thermal behaviour and the existing thermal fluctuations for both baseline and refurbished scenarios under Bilbao (Figure 8) and Gasteiz (Figure 9) climate conditions. In addition to the comfortable temperature ranges analysed above, the thermal limits with respect to health impacts mentioned in Section 3.2.2.2 are also marked. The baseline scenarios indicate indoor temperatures that significantly exceed the risk limits in both cities, covering 4531 hours in the case of Gasteiz (B_G) and 3702 in Bilbao (B_B). If energy refurbishment scenarios are considered, however, these figures are reduced by 30%: 2994 hours per year in the case of Gasteiz (R_G) and 2042, instead, in the case of Bilbao (R_B). Furthermore, the number of hours at which temperatures are considered to represent a health risk is reduced by almost 45% in the case of Gasteiz (see Figure 10).

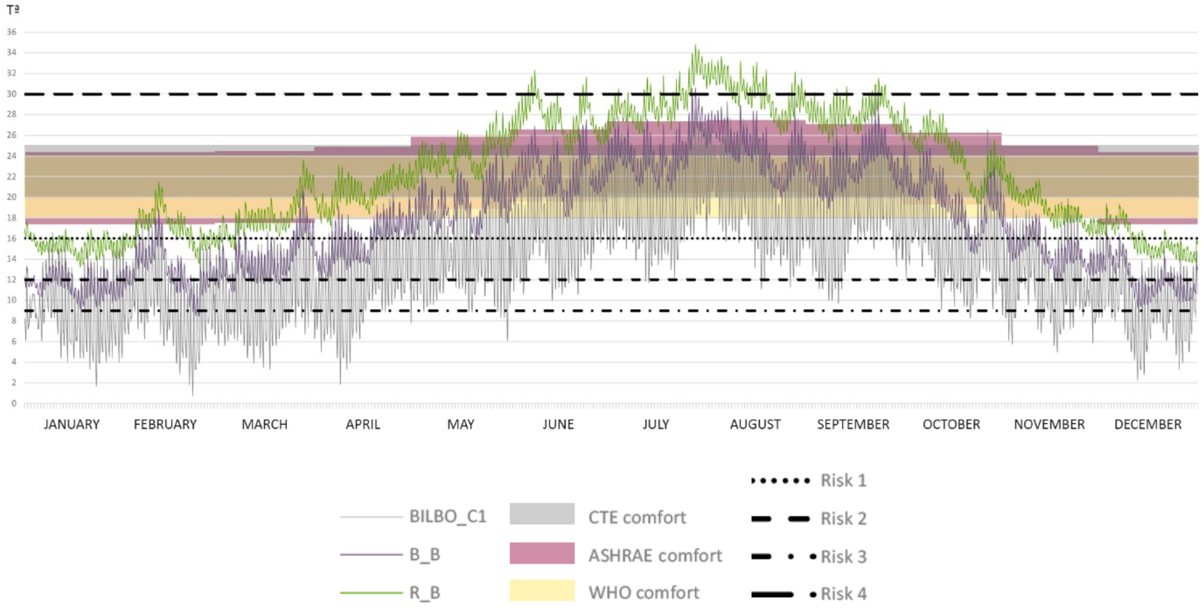

Figure 8. Annual passive thermal behaviour for baseline (purple shades) and refurbished (green shades) scenarios according to Bilbo_C1 climate.

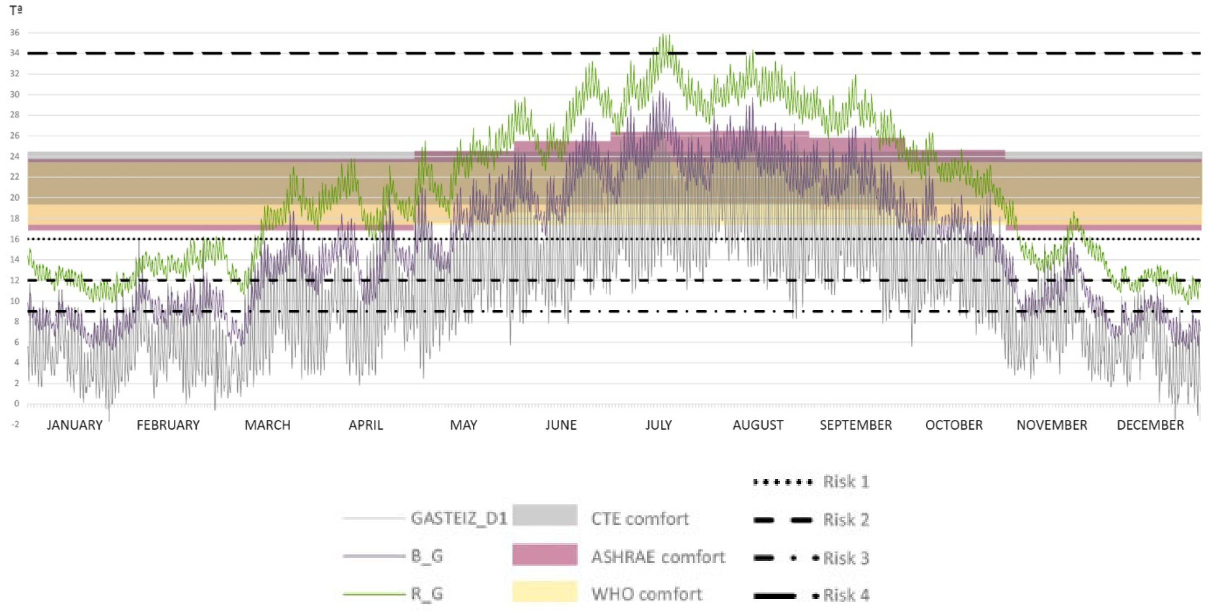

Figure 9. Annual passive thermal behaviour for baseline (purple shades) and refurbished (green shades) scenarios according to Gasteiz_D1 climate.

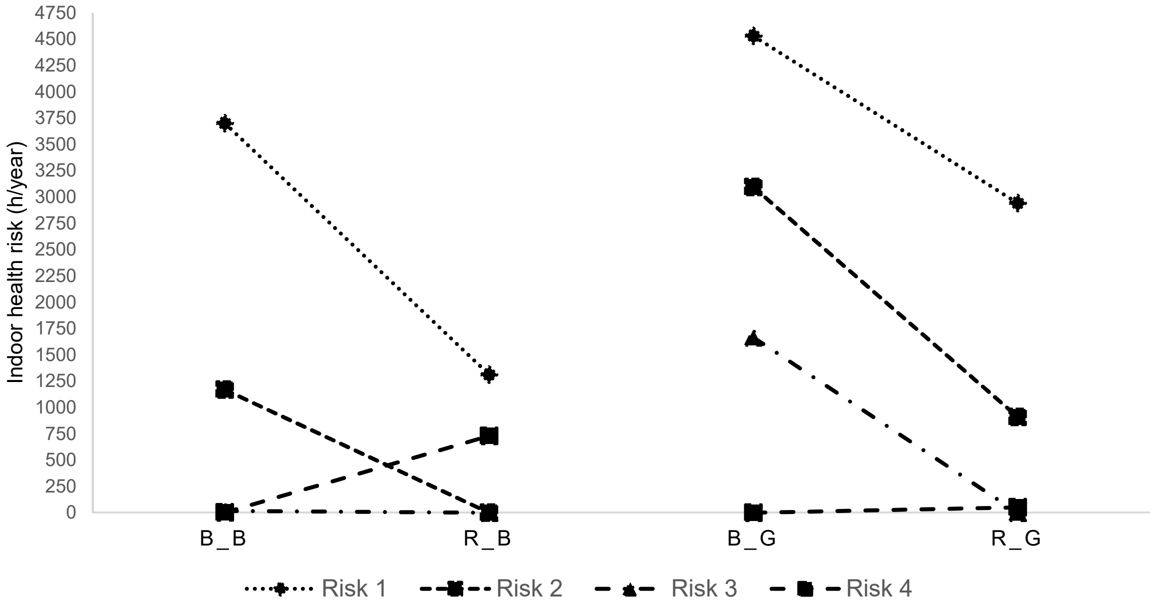

Figure 10. Indoor thermal health risk hours per year for baseline and refurbished scenarios in both climates.

Although the general annual results are positive, it is also necessary to analyse the results obtained separately (see Figure 11). With respect to the temperature limits established, two types of dynamics can be observed. First, the amount of time at which indoor temperatures are below the lowest limits is reduced (Risk 1, Risk 2, Risk 3). The results for Risk 3 (Tª<9ºC), in which the number of hours was reduced by 100% for refurbished scenarios (R_B and R_G), are especially worthy of attention. Second, the increase in hours at which temperatures are above the established upper limit (Risk 4), was almost non-existent in the baseline scenarios (B_B and B_G). This increase is the result of higher indoor summer temperatures, especially in the case of Bilbao: from 3 hours in the baseline scenario to 730 hours in the refurbished scenario, a 243% increase. In addition, seasonal results in refurbishment scenarios indicate that temperature-related health risks are reduced by almost 100% during the transitional season periods.

If the results obtained are analysed according to climate, certain differences can be observed between the two outdoor climate conditions. In the case of the baseline scenario located in Gasteiz (B_G), the most extreme climate, it is estimated that indoor temperatures would be below 16ºC (Risk 1) during 4531 hours a year, that is, practically the entire winter and a large portion of the transitional seasons. Moreover, 4531 hours, 68%, would also be below 12ºC (Risk 2) and more than 36% below 9ºC (Risk 3). The upper limit of 34ºC (Risk 4), on the contrary, would not be exceeded. The results for the post-refurbishment scenario (R_G) show that the evaluated energy refurbishment measures are effective for reducing the number of unhealthy indoor hours, especially for low-temperature risks. Temperatures under 9ºC are eliminated (100% reduction of risk hours), the number of hours at which temperatures are under 12ºC are reduced by 2185 h (a reduction of 70.6%) and those under 16ºC are reduced by 1586 h (a reduction of 35.1%). The risk of high temperatures, on the contrary, increases slightly, given that there is a change from zero hours of risk to 52 hours during July and August.

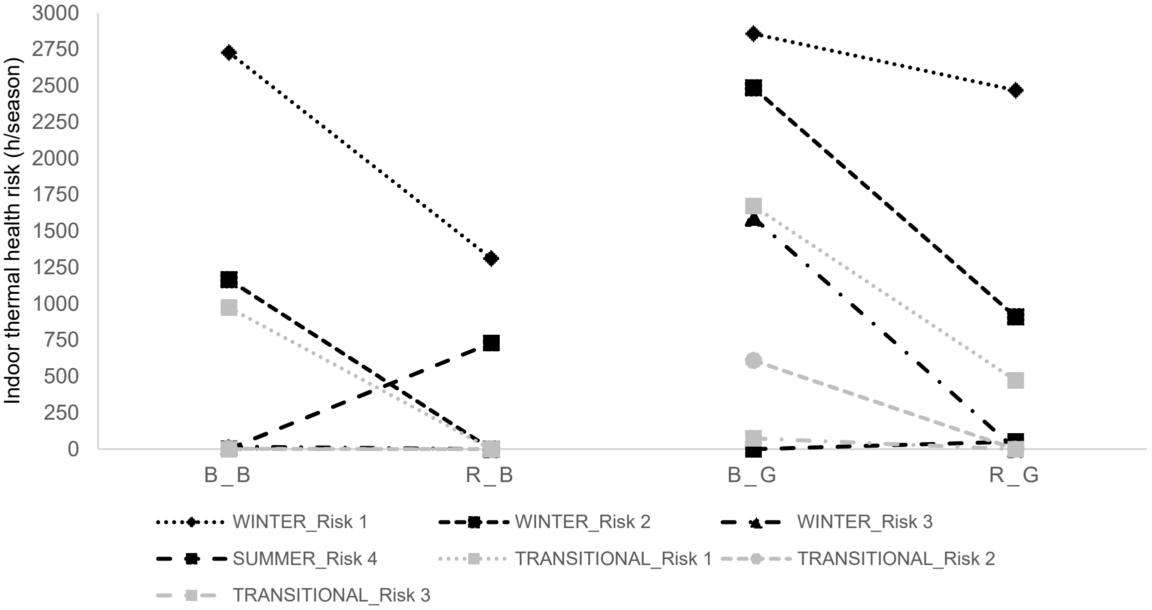

Figure 11. Indoor thermal health risk hours per season for baseline and renovated scenarios in both climates.

In the case of Bilbao, the climate is less severe, especially in winter, so the results for the baseline scenario (B_B) reflect a lower health risk. It is estimated that indoor temperatures would be below 16ºC (Risk 1) for 3702 hours per year, 18% less than the baseline scenario in Gasteiz. Of these 3702 hours, 31% would be below 12ºC (Risk 2) and only 0.35% below 9ºC (Risk 3), very positive results as compared to Gasteiz. In addition, the upper limit of 30ºC (Risk 4) would rarely be exceeded. Regarding the comparison between the baseline and the refurbished scenario, it is also worth drawing attention to the difference between the results obtained for winter and summer. With respect to low temperatures, in the R_B scenario there are no hours at which indoor temperatures are below 9ºC and 12ºC, and the number of hours below 16ºC is reduced by 2390 h/year or 64.5% in comparison with the baseline scenario. The risk of high temperatures, on the contrary, increases notably in comparison to the baseline scenario and to the refurbishment scenario in Gasteiz (R_G), leading to 730 hours of temperatures that pose a health risk during summer.

ID	**REDUCTION OF RISK HOURS (h)**							**REDUCTION OF RISK LEVEL (h·C)**						
	winter			summer	transitional			winter			summer	transitional		
	R1	R2	R3	R4	R1	R2	R3	R1	R2	R3	R4	R1	R2	R3
R_B	1416	1166	18	-727	974	3	0	8457	1163	5	-960	1565	0	0
R_G	389	1575	1592	-52	1200	610	75	11087	8082	2257	-40	4726	1026	24

Table 6. Indoor thermal health risk hours and health risk level for refurbished scenarios in comparison with their corresponding baseline scenario.

6. Discussion

The annual results obtained are meaningful because they contrast the impacts caused by energy refurbishment interventions in different fields of study (energy demand, indoor comfort and health). In particular, the generalized decline in the number of hours at which indoor temperatures are within a comfortable range contrasts with the significant annual energy demand reduction. This affirmation places in doubt the justification of energy renovation interventions solely upgrading the U-value through additional insulation and making airtight the thermal envelope: it is not reasonable to carry out an energy efficiency intervention on a multifamily residential building if this worsens indoor thermal conditions for its users, even if the environmental justification and energy targets are sound. There is evidence that improving the energy efficiency of the thermal envelope of a building through the addition of insulating layers positively influences both indoor temperature levels [50, 51] and energy demand targets. Nevertheless, several studies developed in northern [136-141], central [142, 143] and southern [144-147] Europe have demonstrated that problems can arise with poor thermal comfort related to high indoor temperatures during summer in buildings with high thermal performance, as it happens with Passivhaus standard buildings for instance [148-150].

However, a more nuanced analysis of the results shows that (a) although the number of hours at which temperatures are within a comfortable range decreases, the level of discomfort (the difference between the prevailing indoor temperature and the determined comfortable range) is reduced; (b) in the climates studied, comfortable conditions during the winter and transitional seasons improve noticeably; and (c) the worsening of indoor thermal conditions occurs only during the summer months. Considering the scenario most susceptible to overheating (B_R_C), for 62.8% of the hours at which temperatures exceed the comfortable temperature limit of 25ºC, the building could be cooled and ventilated simply by opening the windows as the exterior temperature would be below 20ºC in this climate zone. Therefore, human factor and users' behavior should be also assessed and considered for future challenges and policy-making processes for optimal use of energy renovated residential buildings, as current policies do not discriminate between different type of users, number of family members and occupancy profiles.

Aligned with the Spanish LTRS 2020, the abovementioned factors mitigate the negative impact on thermal comfort. Furthermore, the important reduction in health risk associated with low temperatures in dwellings identified in this study tips the balance definitively towards the positive impact of the suggested passive energy renovation measures and, therefore, justifies the intervention in the climatic zones analyzed, hence, it should be regarded as a co-benefit.

Nevertheless, it is necessary to add a final point. Due to the results obtained for summer, energy renovations in climates with harsher summers or in scenarios considering global warming demand more rigorous prior study that goes beyond energy demand to determine if the global impact would be positive, a co-benefit, or negative, a co-disadvantage.

7. Conclusion and Policy Implications

The work carried out has enabled an integrated evaluation of the impact, co-benefits and co-disadvantages, of building energy renovation interventions on energy demand, indoor thermal comfort and temperature-related health risk variation, a correlated vision that has not been present in existing literature. As a result, our research places in doubt current policies suitability as they are mainly focused on energy efficiency. The results obtained show that they cannot be oriented solely to reducing first, heating and cooling energy demand, and second, final energy consumption and emissions. However, they should also be aware of users' thermal well-being.

As regarded the guidelines set by the Passivhaus Institute, for example, it would be interesting that updated refurbishment policies integrate new aspects such as a limit value which may consider the hours outside a certain temperature range. This new limit would allow increasing the scope of the prioritization process among the refurbishment strategies by the integration of the energy demand, the indoor thermal comfort and the health risk within the decision-making process, as well as evaluating the passive performance of the building. As a consequence, it would demand a deep update of current mandatory Energy Performance Certification tool and the definition of indicators to measure all improvements in order to assess the achieved progress and compare it with the stablished goals.

All in all, it could be said that energy renovation policies might be more complex while flexible to guarantee their adequacy to all type of uses, building construction characteristics, users and occupancy profiles from the point of view of the comfort and quality of life. In addition, due to the situation generated by COVID-19, indoor well-being has become a basic factor for human health. Therefore, building energy renovation policy-making processes should be based on multicriteria decision analysis.

Acknowledgements

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