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Relationship Between Energy Demand, Indoor Thermal Behaviour and Temperature-Related Health Risk Concerning Passive Energy Refurbishment Interventions

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Abstract **– The main objective of this article is to demonstrate that passive energy refurbishment interventions influence comfort conditions of households for both cold and hot annual periods, while they help to avoid or promote temperature-related health risk situations. However, improving the thermal efficiency of the building envelope is encouraged in order to reduce energy demand for heating and cooling instead of considering also their impact on users' health. The calculation methodology to quantify improvements, on the other hand, is drawn from regulation-based standards, which describe the optimal achievable efficiency levels and energy cost savings. The present study, however, addresses how diverse thermal performance variables are (climate, thermal comfort range and occupancy rate), and shows that different thermal assessment standards influence the obtained results. An energy simulation approach was developed to evaluate different scenarios and compare the results. In conclusion, the results contribute to an understanding or to a discussion of the suitability of current energy renovation policies with regard to indoor thermal comfort and temperature-related health risk situations.**

Keywords **– Energy demand; energy refurbishment; indoor thermal behaviour; indoor thermal comfort; indoor thermal health risk**

1. INTRODUCTION

The objective of public European policies and recommendations towards building renovation has varied over decades; from being focused on the conservation and maintenance of buildings [1], [2] to 20th Century energy efficiency standards [3]–[5], due to building sector's high percentage of final energy consumption (32 % in 2017) [6].

Energy efficiency measures, therefore, were and are mainly promoted because of their capacity to reduce buildings' carbon and greenhouse gas emissions while saving energy costs and improving thermal performance [7]–[13].

Alongside such purposes, it is worth mentioning their capacity and positive influence in the indoor thermal behaviour and comfort quality level [14]–[16]. With respect to indoor thermal well-being, however, there are divergent international recommendations, standards and regulations, including those defined by the World Health Organisation [17], [18], the ASHRAE [19], the ISO 7730 [20]. In addition, diverse scientific research support there are

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different comfortable temperature conditions for determining indoor comfort [21]–[25], protecting human health [26]–[36] and decreasing mortality and morbidity rates [37]–[41].

On the other hand, if construction characteristics of buildings are considered, it has been demonstrated that the residential building sector is characterized by poor thermal efficiency in countries with milder climates, which promotes low and unhealthy indoor winter temperatures [42]–[44].

Improvements in the energy efficiency and the thermal behaviour of the residential building stock, therefore, need to be considered in order to achieve thermally healthier and more stable indoor hygrothermal conditions for winter or cold periods [45], [46].

Energy efficiency calculations and policies, however, are commonly based on regulation-based standards, which establish both the achievable comfort ranges and the occupancy rates [47]. These standards are useful for the simplification of the calculation methodology, but they are aimed at achieving higher efficiency levels and energy cost savings. Theoretical comfort ranges and occupancy rates, though, could be regarded as variable factors due to their high impact on the energy demand calculation and indoor thermal behaviour.

2. OBJECTIVE

The objective of this paper, therefore, was focused on demonstrating that passive energy refurbishment interventions, in addition to reducing energy demand, do influence households' comfort conditions for both cold and hot annual periods, while they help to avoid or promote temperature-related health risk situations. The evaluation of the influence regarded diverse regulation-based and thermally healthy comfort ranges, and different occupancy rates.

3. CALCULATION METHODOLOGY

To this end, a calculation methodology was defined in order to determine the relationship between heating and cooling energy demand, indoor thermal comfort conditions and temperature-related health risk situations in a multifamily residential building (Fig. 1). Based on machine learning models [48], different energy simulation scenarios were developed and evaluated according to three different analysis variables (climate data, indoor thermal range and schedule, and occupancy rate) and two construction state conditions (existing unrefurbished and energy-refurbished). Among the energy-refurbishment criteria, only passive strategies were assessed. Active, renewable and/or control systems were not considered.

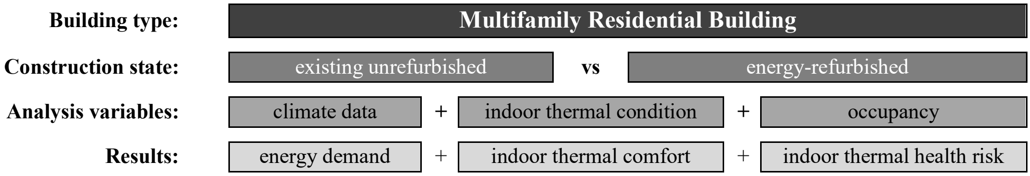

Fig. 1. Calculation methodology scheme.

The results obtained from the diverse scenarios were distinguished according to annual energy demand (heating and cooling), indoor thermal comfort level and temperature-related health risk situations. Dealing with energy demand (kWh/m^2 per year), heating/cooling systems were activated to reach the established temperature ranges, but for the quantification of the indoor thermal well-being level and thermal risk results (hours per year), no active systems were used, that is, the results displayed the passive performance of the building.

4. CASE STUDY

The above-detailed calculation methodology was applied to a multifamily residential building in the Autonomous Community of the Basque Country, region situated in northern Spain.

According to the most recent Basque statistical database [49], the average age of the residential building stock is established in 42.8 years, suggesting almost the half (46 %) was built before the approval of the first Spanish building regulations and thermal envelope requirements [50]. Within this context, the research project called *First step study for the elaboration of a long-term Action Plan dealing with the residential building stock of Euskadi*† was developed, which aimed to classify and categorize the current Basque residential building stock. It concluded that 91.9 % of the total were multifamily residential dwellings, of which 46 % described the H2 type, the one built between 1961 and 1980 (Fig. 2).

H2 type was constructed during the economic development period, period in which the urgent demand of the society promoted buildings with poor construction quality and deficient thermal properties, with no concern on the resulting health risk. Consequently, it is worth mentioning their great improvement potential for both energy demand characteristics and indoor environmental properties.

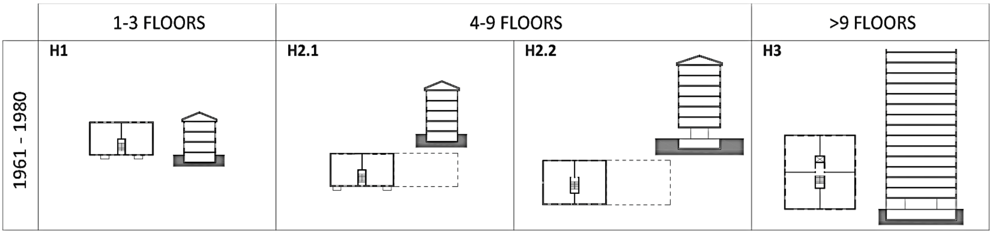

Fig. 2. Classification of multifamily residential buildings in the Autonomous Community of the Basque Country built between 1961 and 1980.

4.1. Construction State: Description of Building Model

4.1.1. Existing Unrefurbished

A multifamily residential building constructed between 1961 and 1980 was, therefore, selected for this study.

With a total building area of 3290.70 m^2 and a net conditioned surface of 2487.73 m^2, the building consists of a non-occupied ground floor and 7 residential floors (with 4 apartments

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† Original designation: «Estudio previo para la elaboración de un Plan de Acción a largo plazo en el parque de edificios de Euskadi». The research has been developed 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.

of 12 m depth on each floor). All apartments are naturally ventilated and lack mechanical ventilation. No renewable energy systems were installed.

The building envelope's construction and thermal characteristics were defined during the initial stage of the abovementioned research project. The U values (W/m^{2}K) of the existing building envelope, 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 aluminium frame, 4.2 (W/m^{2}K) (see Table 1). As mentioned, this building typology was built before the first Spanish building regulations, hence, the U values do not meet the minimum requirements established by the current Spanish Technical Building Code [51].

TABLE 1. BUILDING ENVELOPE LAYERS AND U VALUES FOR THE BASELINE AND REFURBISHED MODELS

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

4.1.2. Energy Refurbished State

The principal energy renovation strategy was focused on the improvement of users' quality of life, that is to say, increasing the indoor thermal comfort, while reducing the energy demand. For this purpose, the considered strategies were based on passive measures, such as increasing the thermal resistance of the envelope, replacing the windows and reducing the air leakage.

There were three possible intervention strategies related to the improvement of the thermal resistance of the façade: external insulation, internal insulation, and air gap insulation. Considering the best technical and energy efficient practice, however, the selected strategy was the external insulation. The addition of that new skin, though, could also be evaluated according to two different techniques, that is, external thermal insulation technique or ventilated façade technique. Based on a previous study developed by Oregi *et al.* [52], which evaluated the energy, environmental and economic performance of several refurbishment strategies, a ventilated façade technique was selected[‡], which included a 10 cm XPS insulation, an air gap and a ceramic outlayer panel (see Table 1).

Alongside with the solid façade intervention, the replacement of the existing windows, both the frame and the glazing, was also considered. The measure included a new PVC frame (2.0 $W/(m^2k)$) and double glazing (2.1 $W/(m^2k)$).

In addition to the improvement of the vertical envelope, the strategy also considered the horizontal one, that is to say, the concrete floors in contact with unheated spaces (first floor and upper floor). For that purpose, a 6 cm thermal insulation layer with its flooring finish layer was added to the existing concrete slab.

As a result, the set of passive intervention measures suggested improved the thermal properties to the total area of the thermal envelope.

4.2. Analysis Variables

4.2.1. Climate Data

Regarding the varying outdoor environmental conditions and the sheer quantity of such building typology across the whole territory of the Basque Country, this study used climate data for two cities, Bilbao and Vitoria-Gasteiz, which represent the two divergent climates in the region.

[‡] Note that the climatic zone, type of building and the construction characteristics of that reference case study were similar to the one evaluated by this study.

According to the Köppen-Geiger worldwide climate classification [53], [54] and its identification within the Iberian Peninsula [55], the Basque Country should be considered as «warm temperate-Cfc» (C: warm temperate, f: fully humid, c: cool summer), or «Cfb» (temperate with a dry season and temperate summer), respectively. However, if the current Spanish Technical Building Code is regarded, it provides different reference climate data for the provincial capitals of the whole of Spain [56]. In the case of Bilbao, the reference climate zone is C1, where the minimum and average outdoor dry bulb temperatures are –0.2 °C and 14.7 °C, respectively. Vitoria-Gasteiz, instead, falls with a different category, D1, with a minimum and an average of –4.0 °C and 12.1 °C, respectively [57].

Based on these classifications, EnergyPlus 8.6 [58] simulation tool was selected for the operational energy use calculations, where the International Weather for Energy Calculation [59] climatic files were used for both cities. Alongside, the building models were developed through the DesignBuilder v.5.5.2.003 interface [60]. It should be mentioned, that the defined construction models reproduced the selected building typology according to pre-stablished modelling criteria simplifications, which may influence in the results, including some little errors or variations in comparison to the real construction ones.

4.2.2. Indoor Thermal Condition

4.2.2.1. Thermal Comfort Range and Schedule

Two different definitions of thermal comfort were stablished and evaluated (see Table 2) to determine the energy demand.

- Condition CTE (“C”): Spanish Technical Building Code regulation-based indoor thermal range and schedule [51].
- Condition WHO (“H”): healthy thermal range [17], [18] over 24 h.

TABLE 2. INDOOR THERMAL RANGE AND SCHEDULE PARAMETERS CONSIDERED FOR THE SIMULATION PROCESS

Indoor thermal comfort condition	**Temperature range**	**Schedule**
CTE	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
WHO	18–24 °C	Heating: 30th Sep. – 31st May 24 h
		Cooling: 31st May – 30th Sep. 24 h

4.2.2.2. Thermal Limits for Health Risk

The following thermal limits describe indoor temperatures associated with negative impacts on health, so the exposure to such inadequate temperatures may result in an increase in seasonal mortality and morbidity rates.

- Cold-related temperatures may cause higher risk of cardiovascular events [26], [31], [33], [35], [36], respiratory diseases, or minor problems such as cold and flu [39]. Temperatures below 18 °C, therefore, show an increasing risk:
  - Risk 1: $T^a < 16$ °C, respiratory infections;
  - Risk 2: $T^a < 12$ °C, blood pressure and viscosity increase, which may cause heart attacks and strokes;

  - Risk 3: Tª <9 °C, deep body temperature fall.
- Heat-related temperatures are less harmful but involve cardiovascular diseases [26], [35], [61], clinical syndromes of heat stroke, heat exhaustion, heat syncope and heat cramps [62], [63], permanent damage to organ systems and risk of early mortality. Several studies demonstrate that the recommended upper temperature should not exceed from 22 °C to prevent from Sick Building Syndrome [27], while the WHO sets it in 24 °C [17], [18]. Other studies [38], [64], however, argue that upper temperature limits should be relative the outdoor climate. Within such context, recent studies developed in Spain [41], divide the whole Spanish territory in local climate areas and establish particular upper limits for each area in order to reduce mortality. Considering the two reference climates evaluated, therefore, these were the fixed limits:
  - Risk 4: Tª < 30 °C for Bilbo_C1 climate, and Tª < 34 °C for Gasteiz_D1 climate.

4.2.3. Occupancy

Together with the thermal comfort range and schedule, the occupancy rate may generally be derived from building regulations. In this study, however, even if the regulation-based "Pr2 profile" was the base scenario to set the internal energy performance (see Table 3), two more occupancy scenarios were evaluated in order to consider also other users' behaviour [65]:

- Profile 1 ("Pr1"): medium occupancy rate, heating and cooling are just switched on in the most used rooms. Only the 65 % of the total living area of the household was considered to be thermally conditioned, and the remaining 35 %, instead, unconditioned. The internal energy performance parameters for the conditioned area, though, were the regulation based ones (Table 3);
- Profile 2 ("Pr2"): medium occupancy rate. Current Spanish regulation-based occupancy rate, schedule and internal energy performance parameters;
- Profile 3 ("Pr3"): highest occupancy rate. The regulation-based occupancy was considered to be the double, that is, 0.06 people/m^2. However, the rest of the internal energy performance parameters were the ones defined in Table 3.

TABLE 3. PR2 PROFILE OCCUPANCY AND ENERGY PERFORMANCE PARAMETERS CONSIDERED FOR THE SIMULATION PROCESS

Parameter	Unit	Value
Occupancy (household)	People/m²	0.03
	Schedule	Until 07:00 (100 %), until 15:00 (25 %), until 23:00 (50 %), until 24:00 (100 %)
Occupancy (ground floor, stairs, under roof)	People/m²	0
	Schedule	Until 24:00 (100 %)
Ventilation (natural)	Renovations per hour (r/h)	0.75
Ventilation (infiltrations)	Renovations per hour (r/h)	0.135
Lighting (household)	Lighting level (lux)	200
	Power (W/m²)	5
	Schedule	Until 07:00 (10 %), until 18:00 (30 %), until 19:00 (50 %), until 23:00 (100 %), until 24:00 (50 %)
Lighting (common areas)	Lighting level (lux)	100

	Power (W/m²)	3
	Schedule	Until 24:00 (On)
Lighting (ground floor)	Schedule	Off
Equipment (household)	Power (W/m²)	4.4
	Schedule	Until 07:00 (10 %), until 18:00 (30 %), until 19:00 (50 %), until 23:00 (100 %), until 24:00 (50 %)

4.3. Machine Learning Models: Energy Simulation Scenarios Outline

Finally, from the above-described variables a total of 24 different analysis scenarios (see Table 4) were obtained.

TABLE 4. ENERGY SIMULATION SCENARIOS BY CASE STUDY PARAMETERS

Construction state	Climate data	Indoor thermal condition	Occupancy	ID
Baseline (B)	Bilbao_C1 (B)	CTE (C)	Profile 1 (Pr1)	B_B_C_Pr1
			Profile 2 (Pr2)	B_B_C_Pr2
			Profile 3 (Pr3)	B_B_C_Pr3
		WHO (H)	Profile 1 (Pr1)	B_B_H_Pr1
			Profile 2 (Pr2)	B_B_H_Pr2
			Profile 3 (Pr3)	B_B_H_Pr3
	Gasteiz_D1 (G)	CTE (C)	Profile 1 (Pr1)	B_G_C_Pr1
			Profile 2 (Pr2)	B_G_C_Pr2
			Profile 3 (Pr3)	B_G_C_Pr3
		WHO (H)	Profile 1 (Pr1)	B_G_H_Pr1
			Profile 2 (Pr2)	B_G_H_Pr2
			Profile 3 (Pr3)	B_G_H_Pr3
Refurbished (R)	Bilbao_C1 (B)	CTE (C)	Profile 1 (Pr1)	R_B_C_Pr1
			Profile 2 (Pr2)	R_B_C_Pr2
			Profile 3 (Pr3)	R_B_C_Pr3
		WHO (H)	Profile 1 (Pr1)	R_B_H_Pr1
			Profile 2 (Pr2)	R_B_H_Pr2
			Profile 3 (Pr3)	R_B_H_Pr3
	Gasteiz_D1 (G)	CTE (C)	Profile 1 (Pr1)	R_G_C_Pr1
			Profile 2 (Pr2)	R_G_C_Pr2
			Profile 3 (Pr3)	R_G_C_Pr3
		WHO (H)	Profile 1 (Pr1)	R_G_H_Pr1
			Profile 2 (Pr2)	R_G_H_Pr2
			Profile 3 (Pr3)	R_G_H_Pr3

5. RESULTS

5.1. Energy Demand Variation

Due to the prevailing climatic conditions and residential use of building, almost all the annual energy demand (Fig. 3) corresponded to heating for all 12 baseline or unrefurbished scenarios (see Table 4). As a result, the total energy demand, including the heating demand, was considerably reduced for all refurbished scenarios, even if cooling demand increased (see Table 5). Even more, there were some simulation scenarios, such as R_B_C_Pr2, R_B_C_Pr3, R_B_H_Pr1, R_B_H_Pr2, R_B_H_Pr3 for Bilbao_C1 climate, and R_G_H_Pr3 for Gasteiz_D1 climate, in which the cooling energy demand became higher than the heating energy demand.

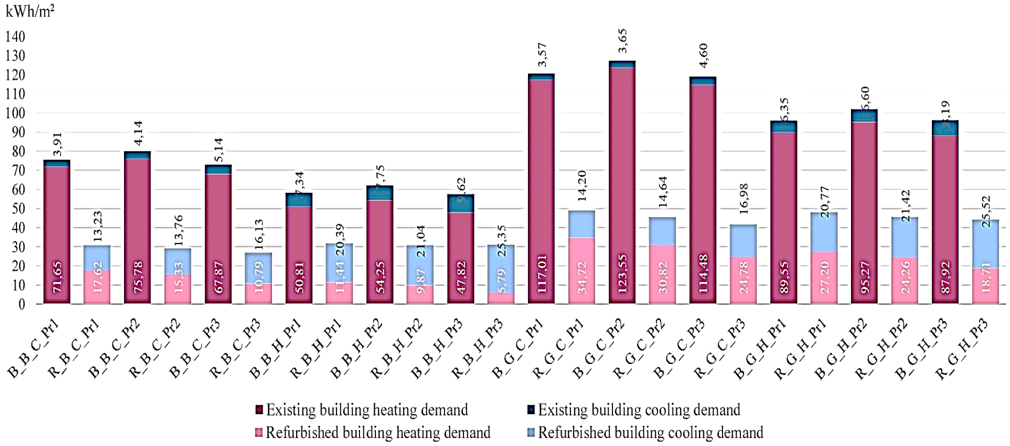

Fig. 3. Annual energy demand (kWh/m^2) for all the energy simulation scenarios.

TABLE 5. ANNUAL ENERGY DEMAND VARIATION (%) FOR REFURBISHED SCENARIOS. VARIATION: NEGATIVE VALUES MEAN A REDUCTION, POSITIVE VALUES AN INCREASE

ID	**Annual energy demand variation**					
	CTE comfort condition			**WHO comfort condition**		
	Total	Heating	Cooling	Total	Heating	Cooling
R_B_Pr1	–59.18	–75.41	238.73	–45.26	–77.48	177.78
R_B_Pr2	–63.60	–79.77	232.48	–50.15	–81.81	171.36
R_B_Pr3	–63.13	–84.10	214.13	–45.79	–87.90	163.58
R_G_Pr1	–59.43	–70.33	297.52	–49.98	–69.63	227.12
R_G_Pr2	–64.26	–75.05	300.55	–55.16	–74.54	224.42
R_G_Pr3	–64.93	–78.35	269.45	–53.99	–78.72	211.55

With regard to the three analysis variables, the major differences corresponded to the climate; the total energy demand for the extremer Gasteiz_D1 climate was always higher if models under equal analysis variables were compared. However, those differences were higher if only baseline scenario results were considered.

Likewise, the diagram shows there were variations among the results obtained if the occupancy rate and the indoor thermal comfort condition variables were taken into consideration.

According to the occupancy, the “Pr2 profile” displayed both the highest annual energy demand and the heating demand. The highest cooling demand, instead, was defined by “Pr3” as a consequence of its higher internal gains. The variation between “Pr1” and “Pr2”, on the other hand, did not describe a considerable difference due to the reduced (35 %) thermally conditioned area. Nevertheless, the results obtained were not as impressive as the ones obtained with regard to the climate variable.

If both indoor thermal comfort conditions are considered, it should be noticed that the requisites set by the Spanish building code, involved the highest total energy demand for unrefurbished scenarios, in which CTE thermal range described higher heating demand, but lower cooling demand in comparison with the results for WHO thermal range. However, the total annual energy demand once the energy-refurbishment strategies were applied was almost equal for both indoor thermal conditions, which described an important total decrease, but an increased cooling demand.

Accordingly, provided that both reference climate data, regulation-based Pr2 profile, CTE indoor thermal comfort range, and both construction state scenarios are compared, that is to say, B_B_C_Pr2 vs R_B_C_Pr2, and B_G_C_Pr2 vs R_G_C_Pr2, the results described a significant total energy demand reduction for both refurbished scenarios, a 63.6 % and a 64.3 %, respectively, which depended not only on the decrease of the heating demand, but also on the increase of the cooling demand.

5.2. Passive Indoor Temperature Variation

With regard to the annual passive thermal behaviour of the building, it is worth mentioning that indoor comfortable hours were reduced in all energy refurbished scenarios for both climates and for the three occupancy rates analysed (See Table 6).

TABLE 6. ANNUAL COMFORT/RISK HOURS’ VARIATION (%) FOR REFURBISHED SCENARIOS. VARIATION: POSITIVE VALUES MEAN A REDUCTION, NEGATIVE VALUES AN INCREASE

ID	**Annual comfort/risk hours’ variation**					
	Comfort condition		**Risk limits**			
	CTE	**WHO**	**Lower limits**			**Upper limit**
			Risk 1	Risk 2	Risk 3	Risk 4
R_B_Pr1	37.62	21.64	58.52	100.00	100.00	–11 560.00
R_B_Pr2	35.24	17.67	64.56	100.00	100.00	–24 233.33
R_B_Pr3	26.66	0.57	87.04	100.00	0	–10 533.33
R_G_Pr1	20.64	16.12	33.38	60.70	100.00	–3900.00
R_G_Pr2	18.28	15.52	35.07	70.60	100.00	–5200.00
R_G_Pr3	12.94	17.75	40.72	95.18	100.00	–7600.00

The variation shows an important reduction for the CTE thermal condition variable, especially for Bilbao_C1 climate, where the reductions reached up to 37 %, 35 % and 26 %

for Pr1, Pr2 and Pr3, respectively. The reason for such results was related to indoor summer temperatures. They were higher than the ones obtained in the existing unrefurbished building scenarios, which meant that during the hottest months they easily exceeded the established comfortable upper temperature limits (Fig. 4, Fig. 5).

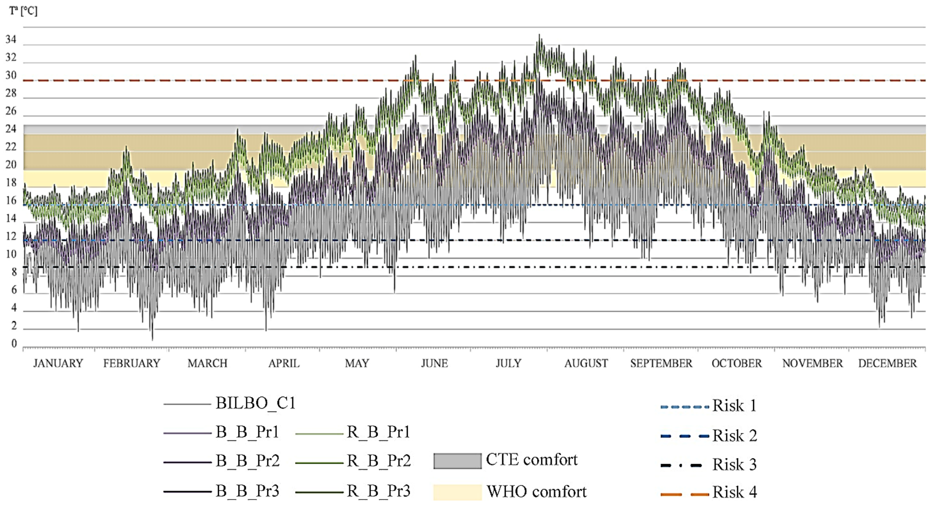

Fig. 4. Annual thermal passive behaviour for baseline (purple shades) and refurbished (green shades) scenarios according to the occupancy variable and Bilbo_C1 climate.

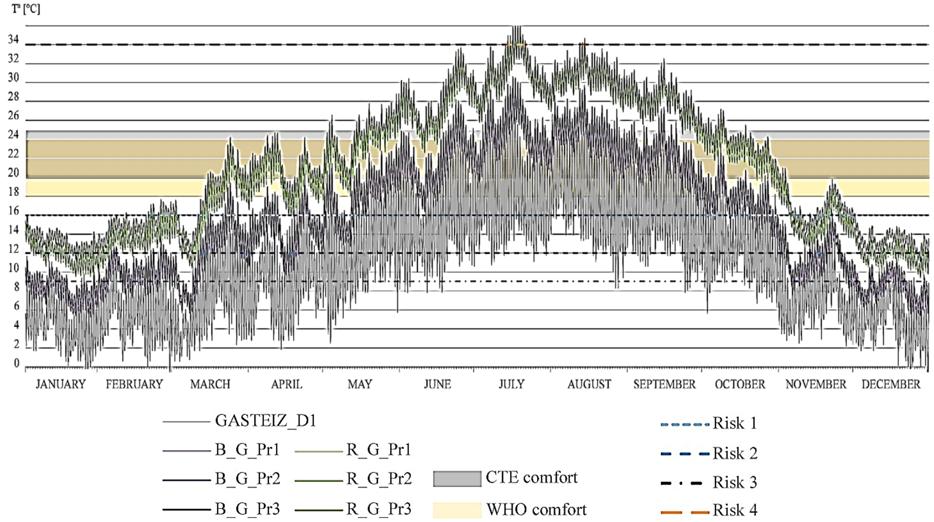

Fig. 5. Annual thermal passive behaviour for baseline (purple shades) and refurbished (green shades) scenarios according to the occupancy variable and Gasteiz_D1 climate.

With regard to cold-related temperature risk limits, none of the refurbished building scenarios (considering the three occupancy rates) showed indoor temperatures below 12 °C for Bilbao_C1 climate, and even in the worst scenario, the unhealthy hours below 16 °C were reduced in 58 %. For Gasteiz_D1 climate, instead, where winter outdoor temperatures are more severe, it could be observed that indoor temperatures were never lower than 9 °C, and in the worst scenario, the unhealthy hours below 12 °C and 16 °C were reduced in 60 % and 33 %, respectively.

Heat-related temperature risky hours' results, on the contrary, offer a totally different reading. If existing buildings were healthy for both climates and the three occupancy rates, after refurbished the situation worsened considerably, leading to completely unhealthy indoors during hot seasons for scenarios under Bilbao_C1 climate.

On the other hand, the data referring to temperature-related health risk situations, showed that the evaluated intervention strategies were quite efficient if both cold-related and heat-related temperature risk limits were all together considered (Fig. 6). However, the results described completely different situations if upper and lower limits were analysed on their own.

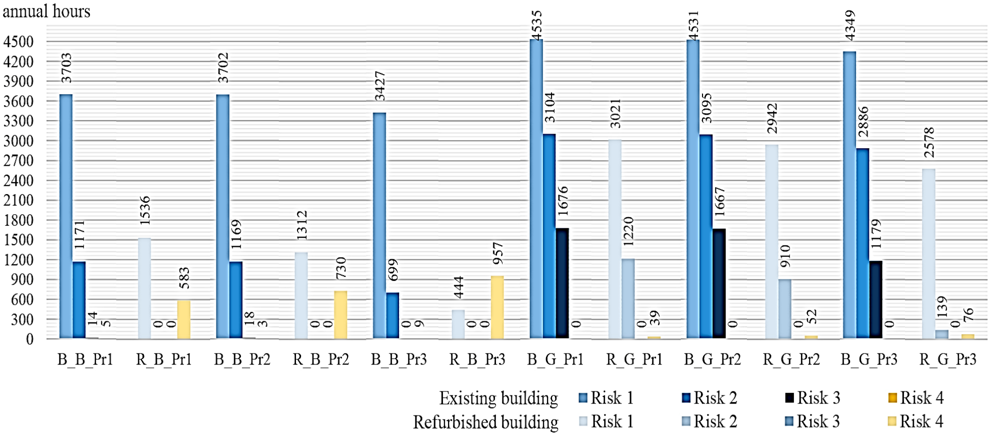

Fig. 6. Annual health risk hours for baseline and refurbished buildings according to both reference climates.

6. CONCLUSIONS AND DISCUSSION

The energy refurbishment strategies suggested in this study meet the energy demand regulations' requirements, hence, they promote energy efficient solutions and fulfil thermal envelope improvements. The efficiency and the potential of energy refurbishment measures is commonly calculated according to regulation-based standards. This research, however, was aimed at demonstrating that considering diverse thermal variables (climate, indoor thermal conditions and occupancy rates) final optimal results might be influenced. Moreover, the work carried out has enabled an integrated evaluation of the impact of energy refurbishment interventions on energy demand, indoor thermal comfort and temperature-related health risk. An integrated vision has not been present in existing literature

Thermal well-being conditions describe comfortable and healthy indoors, but in order to reach such conditions, be efficient, and reduce the energy demand, there is a need to understand their interaction with the thermal performance of the envelope. As demonstrated, the Spanish regulation-based comfortable temperature range (20–25 °C) is preservatory towards unhealthy indoors, yet is almost unattainable for unreburbished H2 type residential buildings with regard to their energy demand control.

Energy refurbishment interventions, on the other hand, do have a positive impact on the energy demand reduction, but lead to a variation of the indoor thermal environment. As supposed, the evaluated energy refurbishment strategies on the thermal envelope result in higher indoor temperatures during cold seasons, upgraded comfort levels, less thermally unhealthy hours, and reduced needs for active systems, which describes a beneficial situation for fuel poverty and low-income households, for instance. Nevertheless, the suggested interventions illustrate also an increase in indoor temperatures during hot seasons. Therefore, it could be said that they describe a conflicting scene, in which the cooling demand is raised, comfortable conditions are worsen, and health risk situations are increased. However, a more nuanced analysis of the results shows that in the climates studied, comfort conditions during winter and transitional seasons improve noticeably, and the worsening of indoor thermal conditions occurs only in summer months. The evaluated climates, however, are mild and temperate even during summer periods. As a result, the increased indoor temperatures could be mitigated thanks to the natural ventilation, which may promote also a reduction in the cooling demand.

Therefore, 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 refurbishment and, therefore, justifies the intervention in the climatic zones analysed.

Nevertheless, refurbishments 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 or negative.

In conclusion, it could be said, there is still an open research line dealing with energy refurbishment intervention strategies, indoor thermal comfort and their impact on human health.

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