Title: Holistic analysis to reduce energy poverty in social dwellings in southern Spain considering envelope, systems, operational pattern, and income levels

Authors:

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Abstract: Energy renovations carried out in energy poor households should consider a holistic view in the short-, mid- and long-term, especially in warm areas such as Andalusia, in the south of Spain. This study addresses the existing knowledge gap on technological and economic interactions in the energy poverty of family units in warm areas of Spain. To do this, the study performs a parametric analysis. In this parametric analysis, a dataset of 36,230,400 instances was developed considering envelope, HVAC systems, an operational pattern (based on static and adaptive thermal comfort models), and family units' income levels. Likewise, the energy poverty ratio was compared based on the high share of energy expenditure in income (2M). The results showed that improving envelope and establishing adaptive operational patterns did not effectively reduce energy poverty cases in low-income families in the south of Spain. However, these strategies were appropriate in family units with greater incomes to remove energy poverty cases, regardless of the low reduction in energy consumption by improving the envelope. This study is a starting point to combine social aids, energy improvements and rational energy use through adaptive operational patterns.

Keywords: Energy poverty; envelope; parametric analysis; adaptive thermal comfort; warm areas

1. Introduction

Generally the built environment has poor energy performance [1,2]. This is mainly due to both the great building development before energy efficiency standards in many countries and the standard development with no demanding criteria until a few years ago [3]. Consequently, building energy consumption is high [4,5], thus leading to energy poverty situations, an uncommon social phenomenon in developed countries until two decades ago. However, it is increasing in all countries due to the recent strong economic crisis and energy increase. Energy poverty is different in developed and developing countries [6]. Energy poverty varies by region: some struggle with energy supply access [7,8] or suitable installations [9], while others face issues meeting basic heating or cooling needs [9,10]. These phenomena depend on the type of country (e.g., inability for keeping household under comfort conditions in developed countries, and difficulty to access to energy in developing countries [11]); however, both phenomena could take place together: low-income family units cannot pay energy bills, thus cutting supply [12]. Consequently, performance policies on energy poverty should be immediately adopted to avoid more serious problems and that combine the energy quality of homes, costs, income and the energy transition [13]. For instance, children living today under poor conditions are likely to be in the same situation as they become adult [14,15]. Governments should therefore address this situation.

Recently, the Spanish government adopted the National Strategy against Energy Poverty 2019-2024, aiming to cut energy poverty cases by 50% by 2025 [16]. The four indexes of the European Union Energy Poverty Observatory (EPOV), currently named as Energy Poverty Advisory Hub (EPAH), are used to quantify energy poverty cases, thus assessing energy poverty from various perspectives, although it is mainly the combination of energy expenditure and incomes considering various analysis thresholds [17]. However, these analyses could be limited as low-income users consume minimum energy to reduce bill costs, although their health is affected. Recent studies indicate that energy poverty affects users' health [18,19] as families spend extended periods outside thermal comfort [20], even leading to the death of a household member [21,22]. Performance measures against energy poverty could therefore be useful for family units to keep their dwellings under appropriate thermal comfort conditions [9,10]. It is worth stressing that most energy bill prices are influenced by HVAC systems as the energy consumption of electrical household appliances [23] and domestic hot water [24] is often lower. Consequently, energy poverty cases could be reduced by reducing their energy consumption. In addition, building stock's decarbonisation goals would be met to reduce the impact of climate change. Several studies have reported the relationship of decarbonisation performance of the built environment and energy poverty [25,26]. However, performing in buildings to tackle climate change could be ineffective to reduce energy poverty. This could be due to rebound effects (consumption expectation increases [27,28]) and strict energy transition policies in some countries [29,30], leading to increased energy poverty when switching fuels [31] (e.g. using gas instead of carbon). For instance, Lise Desvallées discusses the challenges and contradictions faced by social housing providers in Southern Europe when addressing energy efficiency and social inclusion due to obsolete housing and energy poverty. It highlights a preference for retrofitting building envelopes over renewable energy solutions, potentially overlooking the complexity of energy poverty situations in the social housing sector [32].

Building energy renovation could reduce energy consumption, particularly in areas with high climate severity [33], and keep users under thermal comfort conditions a longer time [34], an aspect mainly analysed in the winter months [35,36], although studies on the summer months are increasing [37,38]. However, high investment payments [39] and rebound effects [28] could limit building energy renovation, regardless of the financing plans in Spain [40]. Educating users on operational patterns for HVAC systems could be another performance measure: Gianfrate et al. [41] established that adjusting setpoint temperatures in HVAC systems could reduce the severity of energy poverty cases, and Ghose et al. [42] determined that an appropriate resource use could be among the best energy efficiency performance. The possibility of applying operational patterns based on adaptive thermal comfort models have also been studied. The energy saving in HVAC systems has been analysed by adapting setpoint temperatures to adaptive model limits [43], thus reducing energy consumption [44]. The possibilities of reducing energy poverty has also been studied, obtaining appropriate results in current and future scenarios [45,46].

Various approaches could therefore be used for both energy poverty reduction and appropriate performance, particularly in regions where energy renovation performances are not very effective due to high temperatures. In the state of the art, few studies focused on action limitations in energy poverty cases in warm climate zones. There is therefore a knowledge gap on the performance possibilities of acting in the built environment in which cooling energy demand is greater. This study aims to address the existing limitations by holistically evaluating the energy poverty situation of family units in warm climatic zones, which constitutes the novelty aspect. To do this, the following questions are raised:

- Is energy renovation (envelope and HVAC systems) effective in avoiding energy poverty in all cases in southern Spain?
- Does the use of adaptive patterns serve to reduce cases of energy poverty?
- Is it necessary to adopt measures other than the energy renovation of buildings to avoid energy poverty?

In this regard, Andalusia (in the south of Spain) is characterized by warm climate conditions which could be more severe in the next years due to climate change [47]. Likewise, this region is among the most affected by energy poverty [48] due to both a deficient building stock [34] and the fact that the employment and income rate is the lowest in Spain [49]. This study therefore contributes to literature and practice by proposing a holistic analysis of the performance required to reduce energy poverty in the region. The analysis was conducted from two perspectives: building energy characteristics and users' operational pattern. In economic terms, only family units' income level was considered. To have a detailed knowledge of the effect of the variables considered on the built environment in southern Spain, a parametric analysis was carried out. In this parametric analysis, configurations of wall, roof, floor, windows, HVAC system, operational pattern and family income were combined, generating a dataset of 36,230,400 instances.

2. Methodology

The methodology carried out in this study is divided into 3 different sections: (i) in the first one, the dataset is described , which is composed of an extensive number of building energy simulation results generated in a parametric analysis, which considers multiple U-values for the envelope, multiple performance rates (COP/EER) values for the HVAC system, multiple setpoint temperatures, and finally, multiple income levels; (ii) the second one explains the calculation of the energy prices used in this study; and (iii) the third one, describes the limitations of the study.

2.1. Dataset

Numerous dwelling configurations were analyzed using a large dataset to understand energy poverty reduction limitations in southern Spain. A social housing building representing the common geometries of this type of buildings in the region was selected. The building consists of 51 social housing units across four floors, featuring 2 to 3 rooms and a total area of 60 to 90 m2 (Fig. 1). The building was modelled with EnergyPlus and validated according to the ASHRAE Guideline 14's criteria [50] reported in previous studies [45,51]. The model of the building was parametrized (Fig. 2). Dwellings on ground, middle and top floors were used. Dwellings on the second floor, and not on the first floor, were used as previous studies showed that energy consumption values in dwellings on the first and second floors were the same [45]. A total of 37 dwellings were therefore considered. Parametrization involved configuring each dwelling with varied envelope and system settings. Regarding the envelope, options were explored for façade, floor, roof, and windows. The thermal transmittance of façade, floor, and roof varied between 0.1 and 2.0 W/(m^2K), with intervals of 0.1, resulting in 20 different configurations in each element. As a result, there were envelope configurations including both building solutions with poor energy performance (high thermal transmittance values) and effective solutions (low thermal transmittance values). Changing the thermal transmittance value did not vary the useful surface area of dwellings. Likewise, 3 typologies of windows were considered. Table 1 includes their values. Window 1 is a monolithic glass and a metallic framework without thermal bridge break, and Windows 2 and 3 are more advanced solutions, with double glass and frameworks with lower thermal transmittance. On the other hand, various combinations were considered for HVAC systems. The most used system in the south of Spain is the heat pump. A total of 17 typologies of heat pump were considered by varying the coefficient of performance (COP) and the energy efficiency ratio (EER). Table 2 includes their performance values.

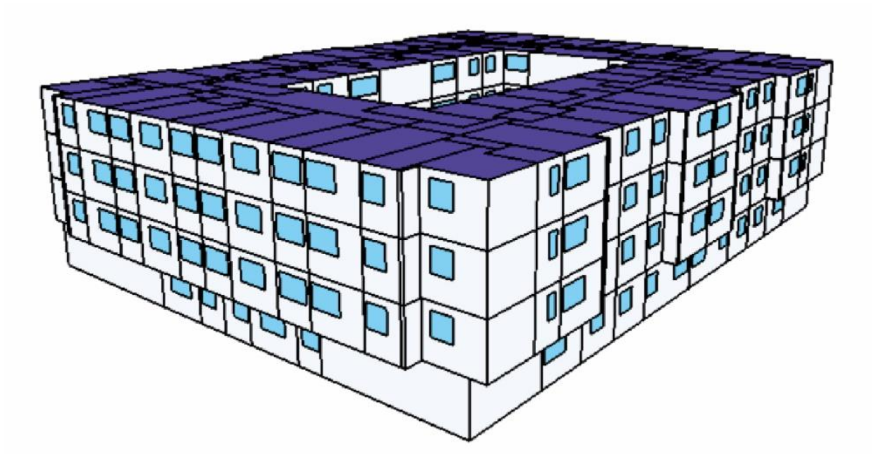

Fig. 1. Geometry of the building used in the study.

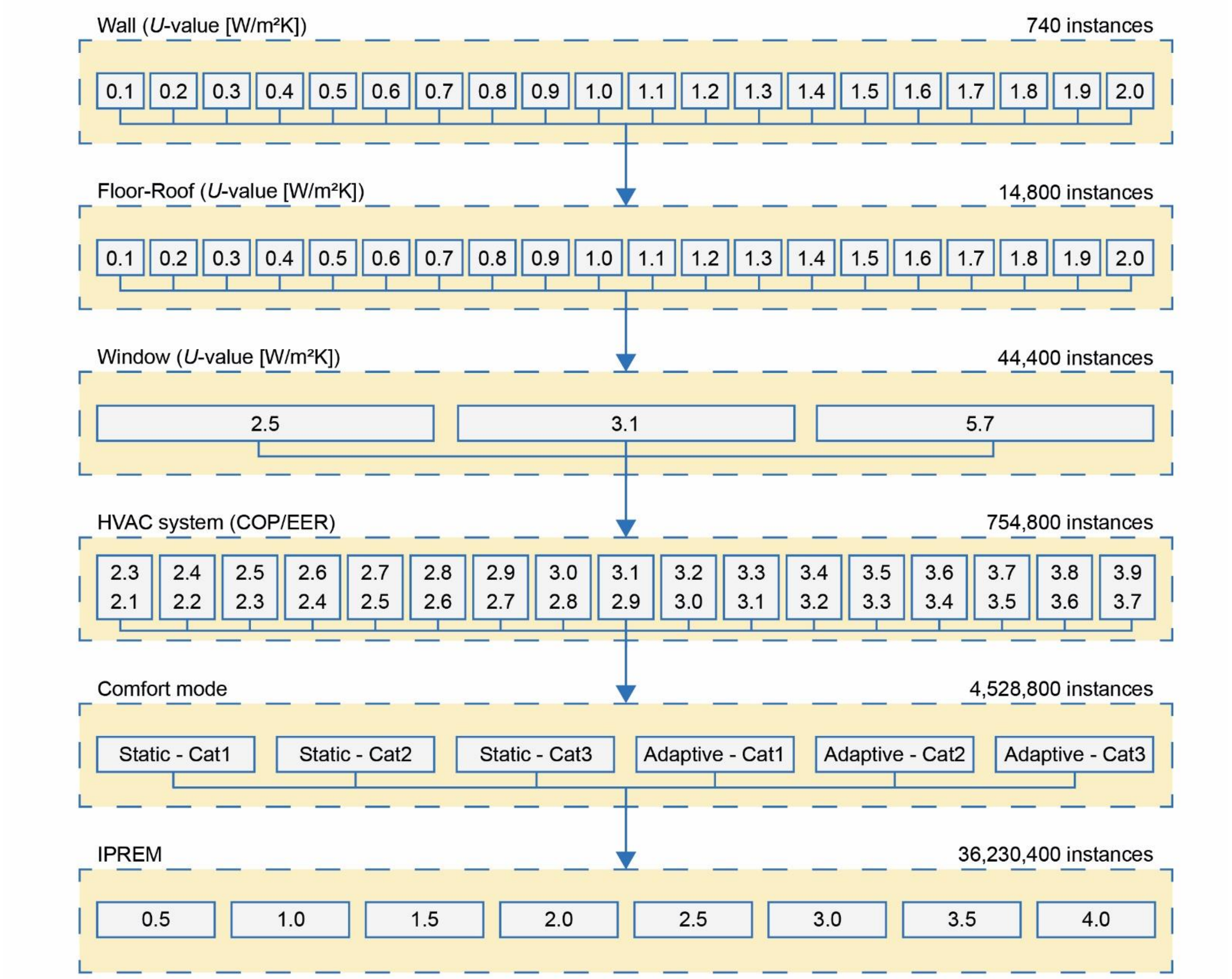

Fig. 2. Workflow of the dataset simulation process.

Table 1. Typologies of windows.

Type of window	U-value [W/(m^{2}K)]
Window 01	5.7
Window 02	3.1
Window 03	2.5

Table 2. Typologies of HVAC systems.

Type of HVAC system	EER	COP
HVAC 01	2.1	2.3
HVAC 02	2.2	2.4
HVAC 03	2.3	2.5
HVAC 04	2.4	2.6
HVAC 05	2.5	2.7
HVAC 06	2.6	2.8
HVAC 07	2.7	2.9
HVAC 08	2.8	3.0
HVAC 09	2.9	3.1
HVAC 10	3.0	3.2
HVAC 11	3.1	3.3
HVAC 12	3.2	3.4
HVAC 13	3.3	3.5
HVAC 14	3.4	3.6
HVAC 15	3.5	3.7
HVAC 16	3.6	3.8
HVAC 17	3.7	3.9

Operational patterns for HVAC systems were studied in both static (fixed setpoint temperatures) and adaptive (changing setpoint temperatures) profiles. These setpoint temperatures were based on EN 16798-1:2019 [52], which is the European adaptive thermal comfort standard. This standard is a development of a previous standard (EN 15251:2007 [53]), which was set with data from the smart controls and thermal comfort (SCATs) project [54]. The standard includes static and adaptive approaches. As for the static approaches, the values established in 3 use categories were considered: (i) Category I, with temperatures of 25.5 ºC for cooling and 21 ºC for heating; (ii) Category II, with temperatures of 26 ºC for cooling and 20 ºC for heating; and (iii) Category III, with temperatures of 27 ºC for cooling and 18 ºC for heating.

As for the adaptive model, the development of the EN 16798-1:2019 is similar to other adaptive models, such as that from ASHRAE 55-2019 [55]. Linear correlations were established for upper and lower thermal comfort limits, compared to the running mean outdoor temperature (RMOT). This is a fictitious variable that determines outdoor temperature oscillations in the previous days using weightings. RMOT is useful to know whether the adaptive model could be applied. For this purpose, RMOT should be between 10 and 30 ºC. If not, the adaptive model could not be applied. However, the target in this studio is achieving thermal comfort at all hours in the year (8760), therefore a setpoint range was needed also below 10 and above 30 °C. For this purpose, this study considered the hypothesis used in other studies in which the limit values of RMOT (10 and 30 ºC) are horizontally extended [56], in order consider a comfort range and heating and cooling setpoint temperature for any value of RMOT. As an example, if RMOT has a value of 7 ºC, the limit values of the thermal comfort model for RMOT of 10 ºC are used. It is worth highlighting that the configuration of the set temperatures in Table 3 shows all the possibilities based on the adaptive thermal comfort models. However, cooling conditions with an RMOT lower than 10 ºC were not given in the study. Table 3 summarises the configurations for operational patterns. The limit values associated with the 3 categories of the adaptive thermal comfort model of EN 16798-1 were used. This allowed comparisons to be made between the static and adaptive pattern for each category used.

Table 3. Operational patterns.

Mode	Category	Acronym	Cooling setpoint temperature (°C)			Heating setpoint temperature (°C)		
			$RMOT < 10\ ºC$	$10\ ºC \leq RMOT \leq 30\ ºC$	$RMOT > 30\ ºC$	$RMOT < 10\ ºC$	$10\ ºC \leq RMOT \leq 30\ ºC$	$RMOT > 30\ ºC$
Static mode	1	Sta-C1		25.5			21	
	2	Sta-C2		26			20	
	3	Sta-C3		27			18	
Adaptive model	1	Ada-C1	24.1	$RMOT \cdot 0.33 + 18.8 + 2$	30.7	19.1	$RMOT \cdot 0.33 + 18.8 - 3$	25.7
	2	Ada-C2	25.1	$RMOT \cdot 0.33 + 18.8 + 3$	31.7	18.1	$RMOT \cdot 0.33 + 18.8 - 4$	24.7
	3	Ada-C3	26.1	$RMOT \cdot 0.33 + 18.8 + 4$	32.7	17.1	$RMOT \cdot 0.33 + 18.8 - 5$	23.7

Likewise, the public income indicator of multiple effects (IPREM in Spanish) was used as referential value to establish various income levels. IPREM is an index used in Spain to obtain economic aids. This indicator is not the same as the minimum guaranteed interprofessional wage. IPREM has developed slower than the minimum guaranteed interprofessional wage, so family units with low economic resources could obtain economic aids. The basis of IPREM for the year 2019 was used. A total of 8 income typologies were considered by applying factors between 0.5 and 4 times the IPREM, with intervals of 0.5. Table 4 includes its values.

Table 4. Income combinations according to IPREM.

Abbreviations	Factors applied to IPREM in the hypothesis analysis of family units' incomes	Yearly net income [€]
IPREM 0.5	0.5	3,759.80
IPREM 1.0	1.0	7,519.59
IPREM 1.5	1.5	11,279.39
IPREM 2.0	2.0	15,039.18
IPREM 2.5	2.5	18,798.98
IPREM 3.0	3.0	22,558.77
IPREM 3.5	3.5	26,318.57
IPREM 4.0	4.0	30,078.36

Each combination of façade, floor, roofs, windows, HVAC systems, operational patterns, and incomes was applied to 37 dwellings. Floor and roofs were grouped together as no dwelling had roof and floor as envelope elements. A dataset made up of 36,230,400 instances was obtained by combining all these factors. Likewise, all instances were simulated in EnergyPlus by using the internal load profile included in the Spanish building technical code for residential buildings [57]. This profile is characterized by the variation of occupancy loads, equipment, and lighting according to the time and day of the week (Table 5). Moreover, the B4 climate zone was used as it corresponds to one of the areas with the greatest climate severity due to high temperatures according to the climate classification established by the Spanish building technical code.

Table 5. Percentage load distribution in the simulations performed with EnergyPlus.

Loads		Hours and load (W/m^2)					
		0:00 – 6:59	07:00 – 14:59	15:00 – 17:59	18:00 – 18:59	19:00 – 22:59	23:00 – 23:59
Occupation (sensible load)	Weekdays	2.15	0.54	1.08	1.08	1.08	2.15
	Weekend	2.15	2.15	2.15	2.15	2.15	2.15
Occupation (latent load)	Weekdays	1.36	0.34	0.68	0.68	0.68	1.36
	Weekend	1.36	1.36	1.36	1.36	1.36	1.36
Lighting	Weekdays and weekend	0.44	1.32	1.32	2.2	4.4	2.2
Equipment	Weekdays and weekend	0.44	1.32	1.32	2.2	4.4	2.2

The energy consumption distributions obtained with the average energy consumption values in the region were compared to validate the results of the simulation. To do this, the results included in the Energy and Cities report of the Spanish Energy Club [60] were used. Fig. 3 shows the energy consumption distribution obtained in the dataset and its comparison with the average consumption values in the region. The average energy consumption value in the region was within the result distribution. Lower and greater values were due to the characteristics of the parametric study, considering both high technical performance buildings and low energy performance buildings.

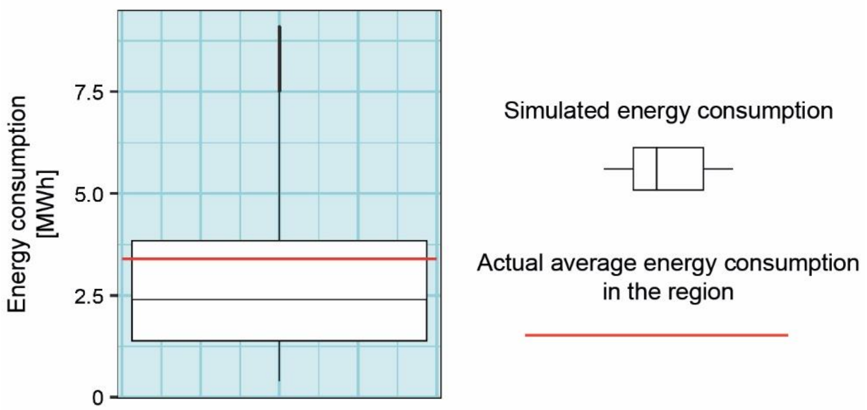

Fig. 3. Comparison of actual average energy consumption in the region and simulated energy consumption.

2.2. Energy poverty analysis

The high share of energy expenditure in income (2M) was used to analyse energy poverty as it is used by EPOV for the same purpose. The 2M indicator establishes that family units that pay over twice the average national energy expenditure in the energy bill are under energy poverty situation [58]. This indicator is widely used [59,60] because it provides a quantitative analysis to energy poverty assessment and to the possibility of adapting the energy expenditure threshold value to the characteristics of each country. In Spain, the representative threshold value has been characterized by energy expenditure. The study by Sánchez-Guevara Sánchez et al. [17] determined that the threshold value in Spain for the 2M indicator is 10%, thus coinciding with the threshold established by Boardman [61].

Thresholds of 10% were compared by determining the energy poverty ratio (EPR) in each case study. EPR is a relationship between household energy cost and income level (Eq. (1)). It is worth stressing that households tried to keep always thermal comfort conditions. Other casuistries related to energy poverty, such as hidden energy poverty, were therefore not considered.

$$\begin{aligned} &EPR = \frac{C}{I} \cdot 100 \quad [\%] \\ &Case\ in\ fuel\ poverty \quad \text{if} \quad EPR \geq 2M\ (10\%) \end{aligned} \tag{1}$$

where C is household energy consumption cost [€], and I is household income [€].

Family units' income level (values related to IPREM) has been previously described. As for the energy cost, energy consumption was obtained in each case through the parametric process. However, it was not household energy cost. The methodology existing in Spain was used to determine it. The rate was the voluntary price for the small consumer (PVPC in Spanish). PVPC was created by the Spanish government in 2014 to establish a regulatory rate that reduce family units' risk [62]. It is related to low-income family units, so studies on energy poverty in Spain have used it [63,64]. The energy cost that a family unit should pay is obtained by summing several concepts (Eq. (2)): energy term (ET), power term (PT), electricity tax (ElT), rent of measurement equipment (RME), and value added tax (VAT). ET is related to energy consumption and is obtained by multiplying energy consumption by the cost of kWh (Eq. (3)). Likewise, ET was obtained by considering hourly energy consumption as PVPC has an hourly variable rate. PT was applied to always guarantee a power within dwellings. It includes costs from both grid access and marketing margin in the contracted power (Eq. (4)). A power of 4.6 kW was considered, which was appropriate when using a heat pump and electrical household appliances simultaneously. Finally, the remaining concepts are related to taxes: (i) ElT was applied, thus increasing ET and PT by 5.1127% (Eq. (5)); and (ii) $a\ VAT$ of 21% was applied to the sum of ET, PT, ElT, and EMR (Eq. (6)). Moreover, the time series of PVPC corresponding to the year 2019 was considered.

$$EC = ET + PT + ElT + RME + VAT \tag{2}$$

$$ET = Energy\ consumption \cdot Price\ of\ electricity\ in\ kWh \tag{3}$$

$$PT = 0.115188 \cdot Contracted\ power \cdot Number\ of\ days \tag{4}$$

$$ElT = 0.051127 \cdot (ET + PT) \tag{5}$$

$$VAT = 0.21 \cdot (ET + PT + ElT + RME) \tag{6}$$

2.3. Limitations of the study

A parametric analysis has been performed to address most of the built environment; however, there are limitations. The first one was associated with family performance to assess energy poverty. In this study, family units always tried to maintain thermal comfort conditions to assess family units that did not compromise thermal comfort conditions or health. Operational patterns varied users' behaviour, but always maintained thermal comfort conditions indoors. The use of the 2M indicator was therefore logical and consistent, and other possibilities of energy poverty, such as hidden energy poverty, were not considered. The results of this study could be different in those families that reduced energy cost with less use of housing systems.

Another limitation was the analysis scale. Energy poverty was assessed on an annual scale. However, results could vary monthly, especially in the months with greater demand. Finally, implementing social aids to address energy bill costs was not considered. The socioeconomic component was the family units' income level through percentage relationships with IPREM. Results could therefore vary if social assistance is included. From the technical perspective of the building and income level, the results of this study aimed to address the variation of the energy poverty situation of families that live in warm areas.

3. Results

First, the influence of the thermal transmittance values of façade and roofs/floor on energy poverty cases was analysed. Figs. 4 and 5 show the distributions of EPR values according to the various opaque envelope configurations and using a static operational pattern (without distinguishing the configurations of static setpoint temperatures), as well as the various family units' income levels. As for the influence of the thermal transmittance values of the façade, the use of low thermal transmittance values was related to EPR distributions with lower values. The lowest thermal transmittance configuration reduced EPR quartile values between 1 and 5%. Nonetheless, these variations could be insignificant considering the number of cases that could overcome 10% of the energy poverty threshold value. Fig. 4 shows that the distributions related to low income levels (IPREM 0.5, 1, 1.5, and 2) obtained more energy poverty cases: (i) IPREM 0.5 obtained EPR values between 21 and 33% in Q1 , between 22 and 36% in Q2, and between 23 and 39% in Q3, with a maximum value of 52%; (ii) IPREM 1.0 obtained EPR values between 11 and 16% in Q1, between 11 and 18% in Q2, between 12 and 20% in Q3, and maximum values between 14 and 26%; (iii) IPREM 1.5 obtained maximum values between 11 and 17% in the three quartiles, although EPR value was lower than 10% in some cases; and (iv) some combinations with the lowest thermal transmittance obtained quartiles with an EPR value greater than 10%. Incomes equal or greater than IPREM 2.5 did not obtain energy poverty cases, so family units' income level was a significant factor to remove energy poverty risk. Likewise, the floor on which the dwelling was located influenced EPR values. This study analysed three types of floors (ground, middle and top floors), and EPR distributions depended on them. Dwellings on the ground floor presented lower energy poverty risk as their distributions obtained a lower interquartile range and a lower average value. EPR distributions on the ground floor obtained reductions between 5 and 20% with an income level corresponding to IPREM 0.5, between 3 and 10% with IPREM 1.0, between 2 and 7% with IPREM 1.5, between 1 and 5% with IPREM 2.0, between 1 and 4% with IPREM 2.5, between 1 and 3% with IPREM 3.0, and between 1 and 2% with IPREM 3.5 and 4.0. Dwellings on the ground floor influenced when family units' income level was very low. When family units' income level increased, the difference between living on the ground floor and on the other floors did not significantly vary EPR values (aspect shown in the similarity of EPR distributions). Allocating low-income family units in dwellings on the top floor would imply greater energy poverty risk as EPR value is increased (due to the increase of energy consumption in the dwelling).

The same behaviour was detected in the thermal transmittance values related to roof and floor (Fig. 5). The lowest thermal transmittance values obtained EPR values lower than the worst envelope configurations, but their impact was low (with EPR reductions between 1 and 2%). The use of various typologies of windows had a similar effect (Fig. 6). Although EPR values were reduced between 1 and 5% by improving the window, the percentage of instances with values greater than the energy poverty threshold did not significantly vary. Thus, the income level significantly influenced the possibility of reducing EPR values. In the analyses in Figs. 4 and 5, family units behaved according to a static operational pattern, i.e., users used fixed configurations for setpoint temperatures of HVAC systems. However, adopting adaptive operational patterns could be an opportunity for lower energy consumption, thus reducing energy poverty risk. To analyse this aspect, Fig. 7 shows the point clouds with EPR values by using adaptive and static patterns. The configurations of each operational pattern were included in Table 3, in the Methodology section.

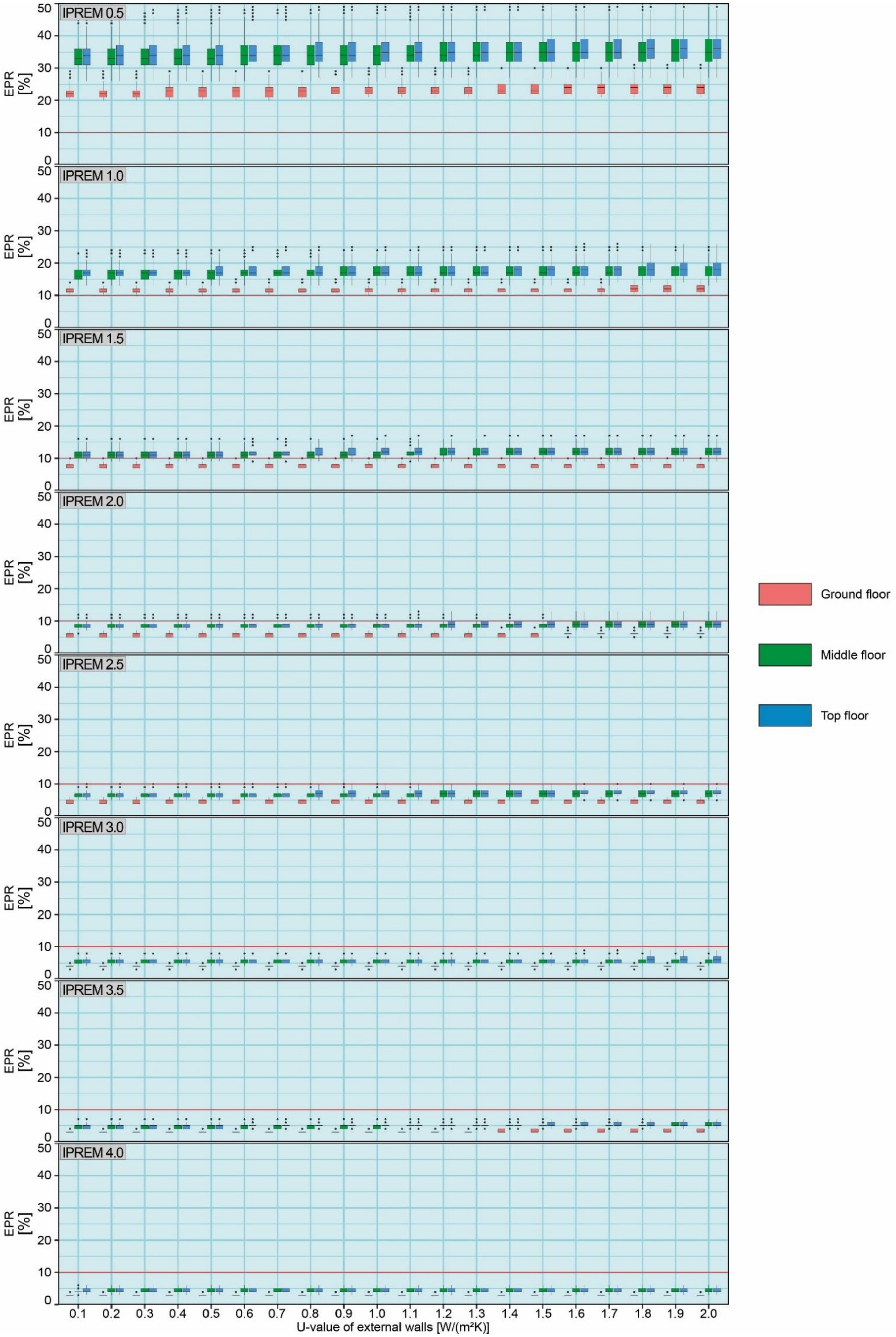

Fig. 4. Distribution of EPR values according to façades and income level by using a static operational pattern.

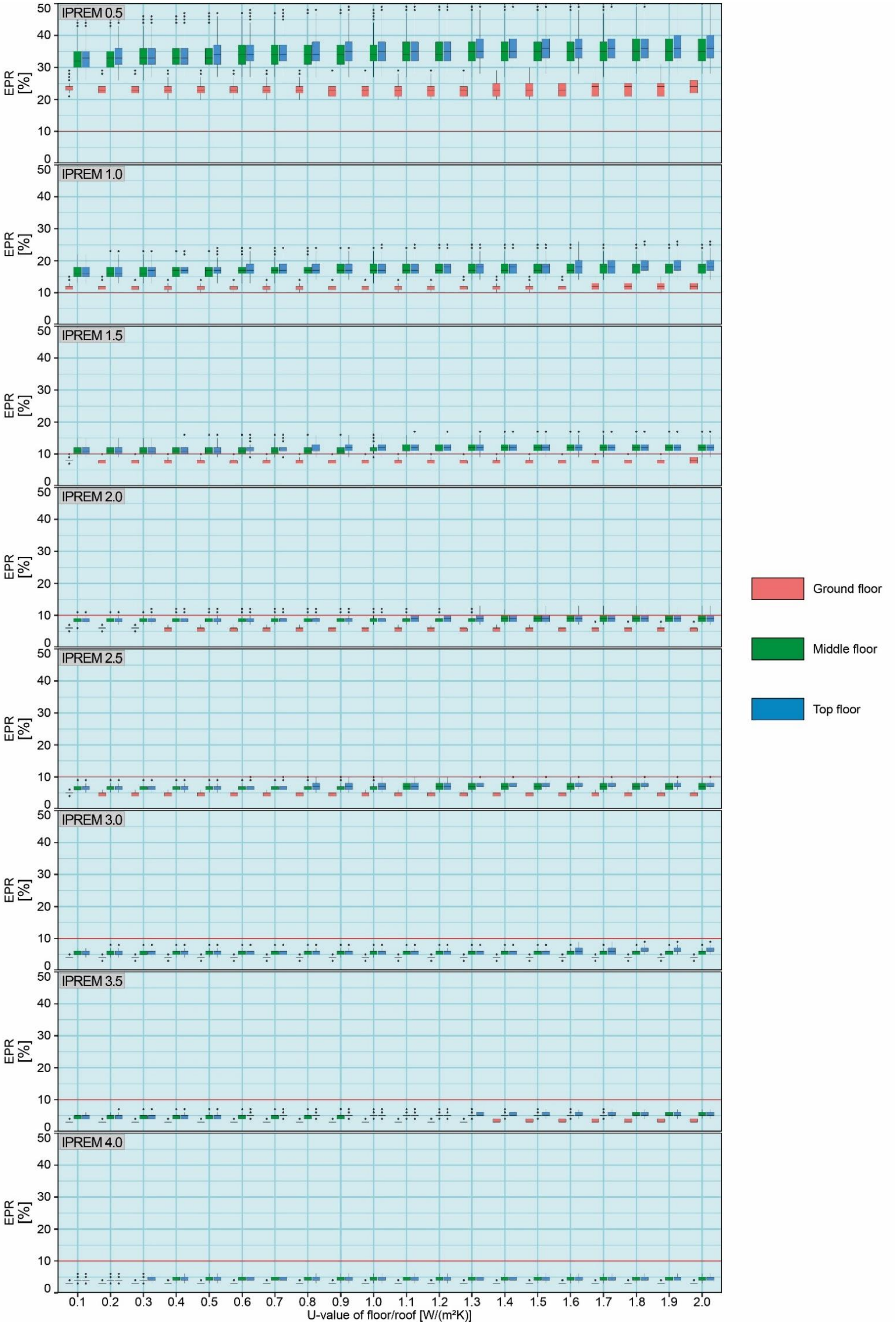

Fig. 5. Distribution of EPR values according to roofs and income level by using a static operational pattern.

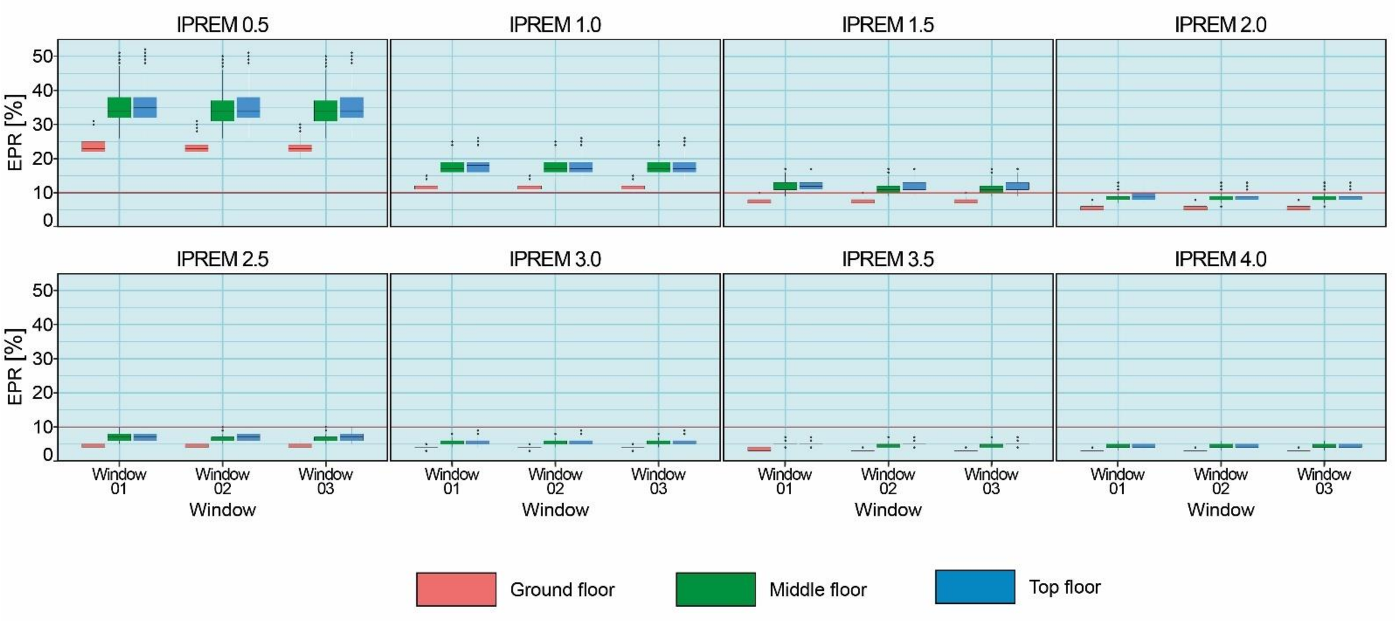

Fig. 6. Distribution of EPR values according to windows and income level by using a static operational pattern.

Adaptive operational patterns reduced EPR values in comparison with static operational patterns. This result was obtained even with highly effective configurations of static patterns (e.g., Sta-C3 with 27 ºC for cooling and 18 ºC for heating). Average reductions were significant with adaptive patterns, although both family unit's income level and the category used from EN 16798-1 should be considered. Family units with IPREM 0.5 presented the following average reductions in EPR: (i) as for the approach of static setpoints Sta-C1, reductions of 7.4% were obtained with Ada-C1, 9.8% with Ada-C2, and 11.6% with Ada-C3; (i) as for the approach of static setpoints Sta-C2, reductions of 5.0% were obtained with Ada-C1, 7.3% with Ada-C2, and 9.2% with Ada-C3; and (iii) as for the approach of static setpoints Sta-C3, reductions of 1.2% were obtained with Ada-C1,3.5% with Ada-C2, and 5.4% with Ada-C3. This average EPR reduction was lower as the family unit's income level increased. Moreover, the increase of income levels obtained reductions between 0.1 and 3.4%, compared to the variations in the previous income threshold. Nonetheless, EPR values were also reduced in the family units with greater income levels. Adopting adaptive patterns was therefore significant to reduce high energy consumption but maintaining thermal comfort conditions. This aspect could also be useful to reduce energy poverty cases. However, these measures were insufficient to avoid energy poverty cases in family units with low-income levels (IPREM 0.5 and IPREM 1.0). It is worth stressing that this aspect is independent of the HVAC system used in the dwelling. As mentioned in the Methodology section, 17 heat pump systems were considered. Fig. 8 shows EPR distributions according to the type of HVAC system and distinguishes operational patterns. To understand better Fig. 8, the distributions of static operational patterns include the 3 typologies of setpoints (Sta-C1, Sta-C2, and Sta-C3). EPR values were reduced by improving the HVAC system, although it did not imply that family units could overcome energy poverty. In the static approach, the improvement obtained between HVAC 17 and HVAC 01 reduced EPR values between 1 and 14%, although low-income values presented all cases in energy poverty situation. As for adaptive patterns, EPR values were reduced by improving the HVAC system, although reductions were not the same as with the static pattern: (i) Category I, with reductions between 1 and 7%, (ii) Category II, with reductions between 1 and 5%, and (iii) Category III, with reductions between 1 and 3%. This made sense due to the low EPR values presented as HVAC system was more sustainably used. This aspect can be seen in the differences of the distribution quartiles of the adaptive patterns, reducing EPR values up to 17.0%. Users' behaviour are therefore crucial to overcome energy poverty without affecting habitability conditions. Fig. 9 shows the heatmap of the percentage of energy poverty cases obtained with various design combinations including case studies, income levels, and operational patterns. First, adaptive patterns obtained a lower percentage of energy poverty cases. Improvements in the building reduced energy poverty cases by using the static operational pattern, but there were energy poverty cases with family units with income levels of 2.5 times the IPREM. However, with adaptive patterns, the greatest income threshold that obtained energy poverty cases was 1.5 times the IPREM. This result was only obtained with Categories I and II, and Category III did not obtain energy poverty situations with income levels of 1.5 times the IPREM. Second, improving the building was interesting in some assumptions to reduce energy poverty cases, e.g., family units with incomes of up to 2.5 times the IPREM and with a static pattern. As for adaptive patterns, these improvements would be significant only for Categories I and II. The parameters related to current or renovated buildings according to the standard on energy efficiency in Spain were grouped in the category of envelopes with thermal transmittance lower than 0.6 $W/(m^2K)$. The use of both a HVAC system with great performance (something usual in the market) and adaptive patterns would allow energy poverty situations to be avoided by family units with income levels equal or greater than 1.5 times the IPREM. If a static operational pattern is adopted, family units could be in energy poverty situation (only family units on the ground floor could avoid this situation).

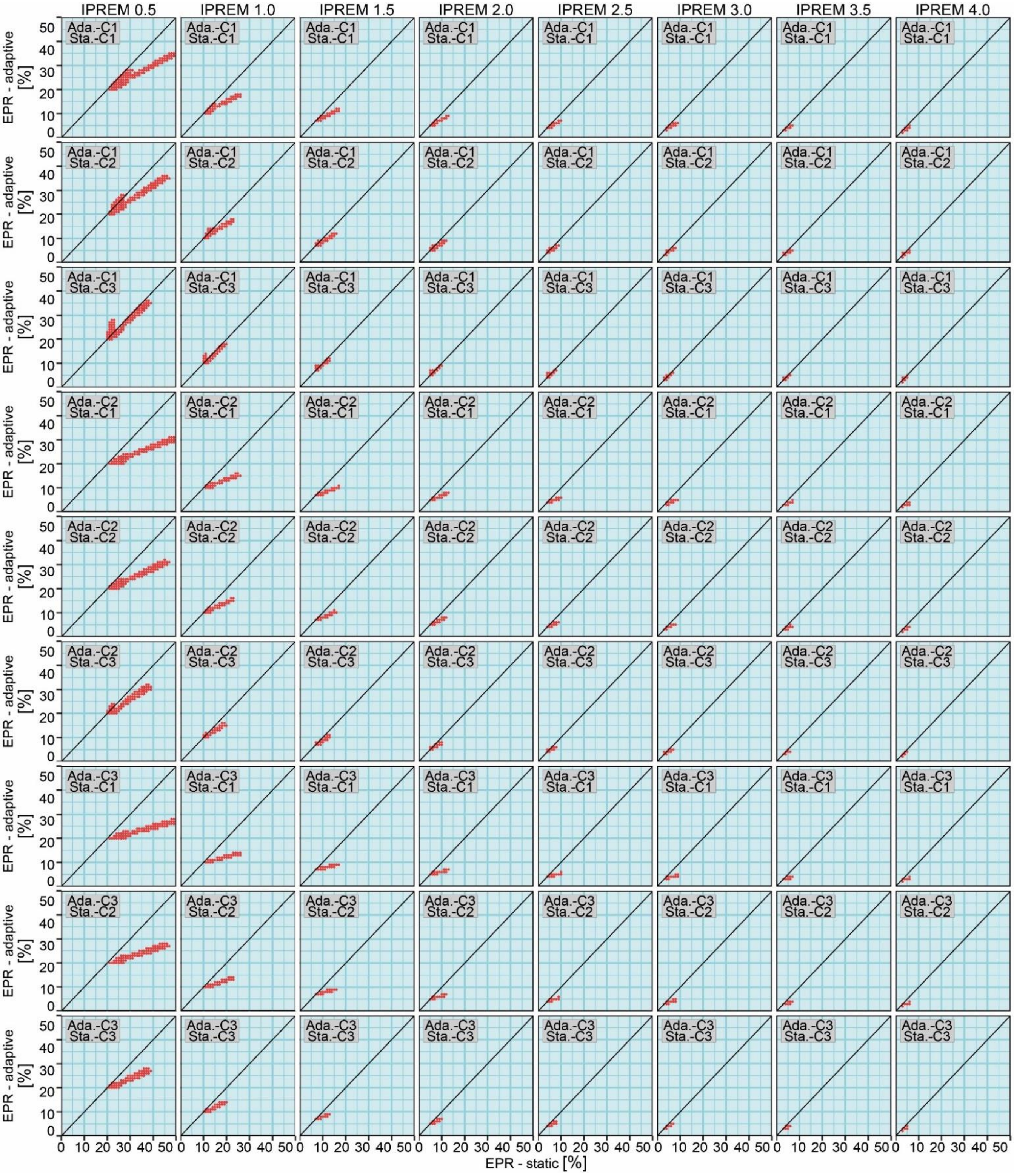

Fig. 7. Point cloud of EPR values with the adaptive operational pattern in comparison with the static pattern.

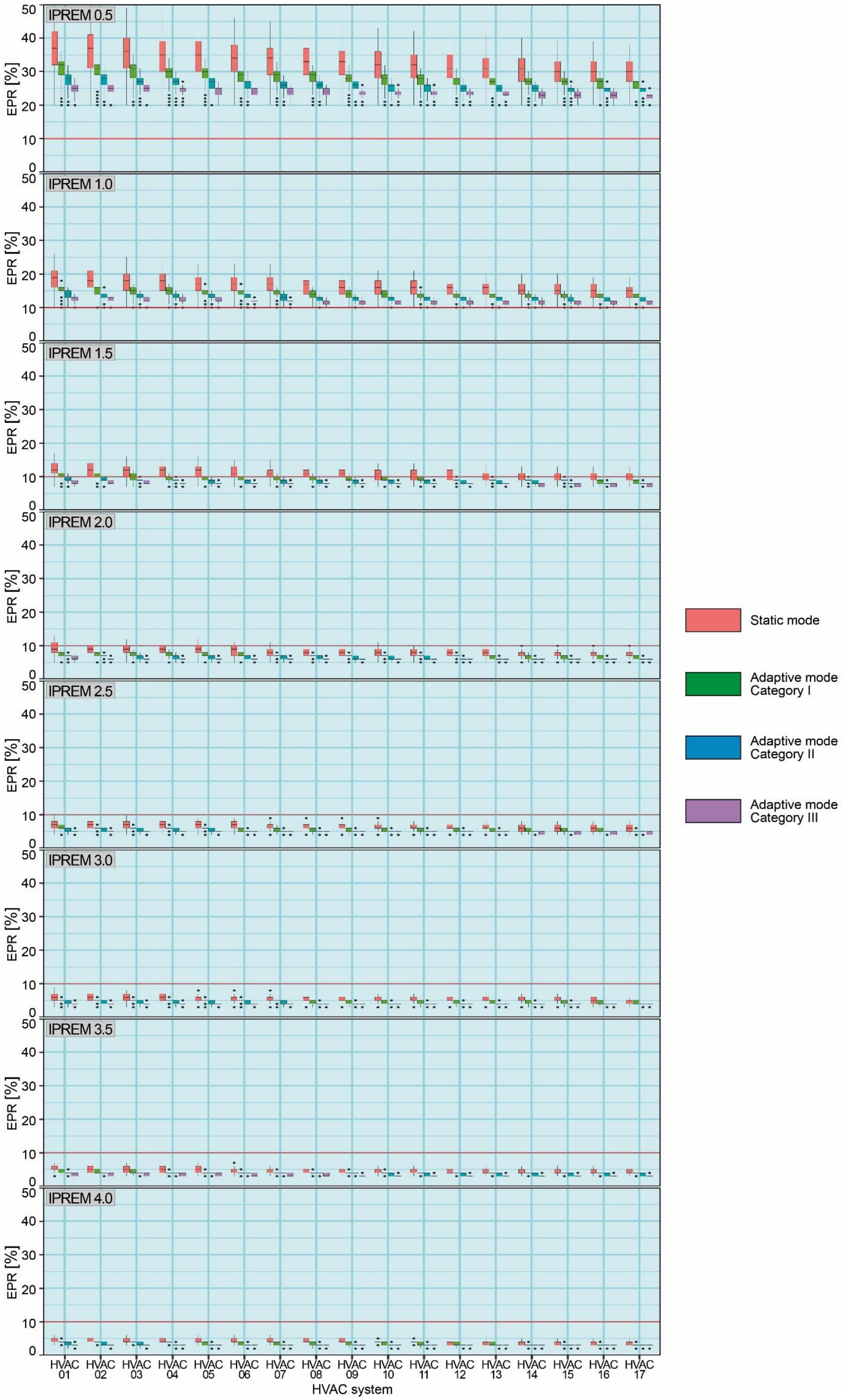

Fig. 8. Distribution of EPR values according to the other variables.

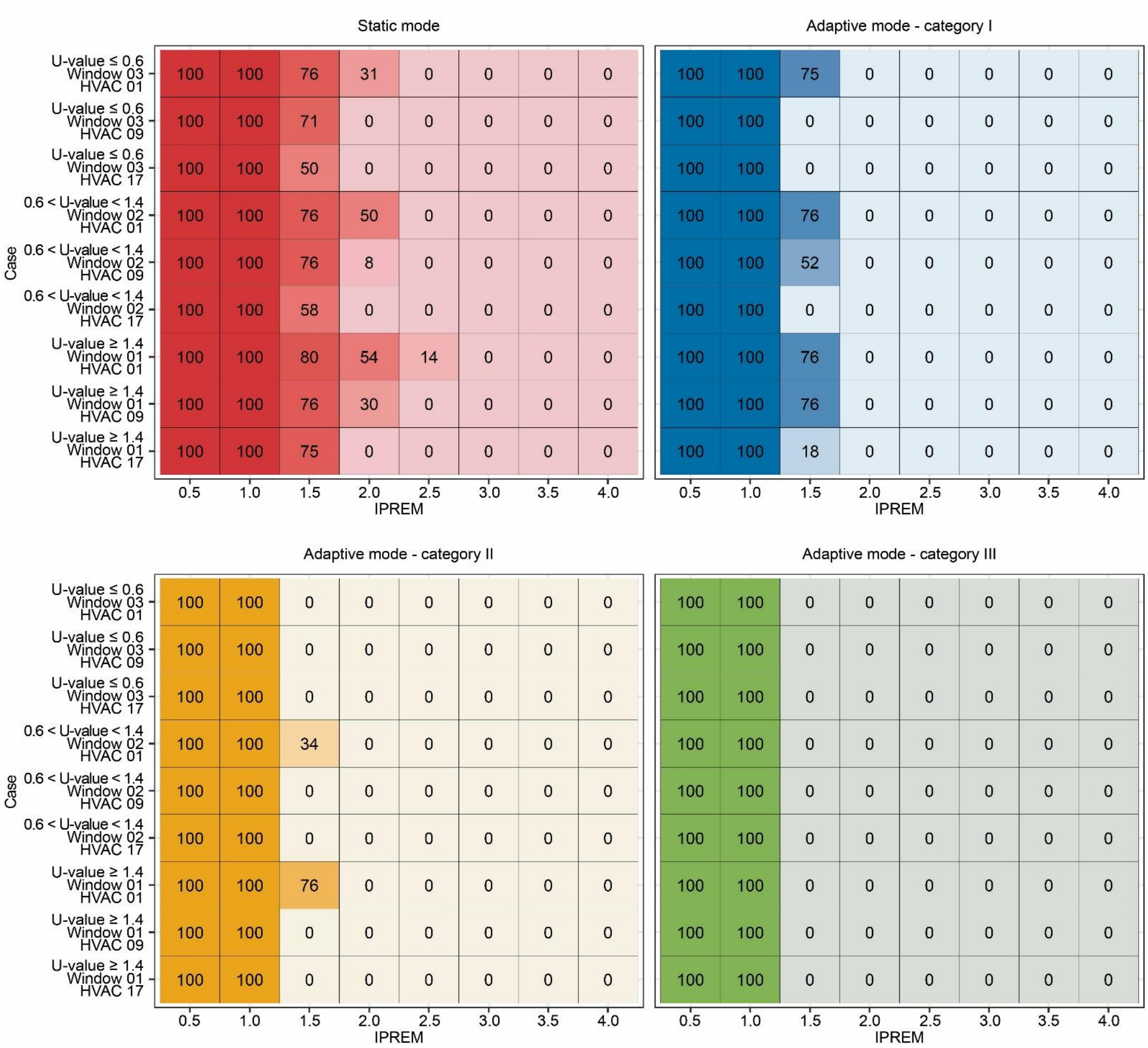

Fig. 9. Heatmap with the percentage of energy poverty cases.

4. Discussion

The results showed that family units with income levels equal or lower than IPREM would always be in energy poverty situation, regardless of the characteristics of the dwelling. If family units' income levels were greater, behaviour would vary when improving some of the characteristics of the dwelling. When envelope and HVAC systems were improved, the energy poverty ratio decreased. Nonetheless, reductions were not always effective as many family units were in energy poverty situation. This was due to a decrease in the building's energy consumption. The reduction in energy consumption of buildings in climatic zones of Spain with the improvement of envelope and systems has been widely analysed in the scientific literature [65,66]. Thus, the results of this study are aligned with those investigations. Thus, there is a direct relationship between the effectiveness of energy rehabilitation to reduce energy poverty and family income. Families with very low income did not improve their situation of energy poverty, even though the house had characteristics of buildings with almost zero energy consumption. To improve their situation of energy poverty, it is necessary to combine technical improvement with socioeconomic measures (e.g. an improvement in wages, the labour market, etc.). Many families have difficulties finding a decent job and survive with economic subsidies that end up in a situation of energy poverty. In addition, the most developed job sectors in these regions are also characterized by high job insecurity. As an example, we can highlight the great dependence of southern Spain for tourism and hospitality. This dependence favours a situation of vulnerability, since the activity of the sector is variable over the years (e.g. the low rate of tourists during the years of the Covid-19 pandemic). This aspect, together with low wages and job insecurity in the sector, means that a high percentage of families that work in the tourism sector may have difficulties paying the energy bill. In addition, it is possible to highlight the increasingly complicated situation of farmers and winners due to the drought and the increase in temperatures caused by climate change. This generates a decrease in labour demand and a greater dependence on subsidies. Therefore, the existing labour difficulties in the region are clear and favour low income in families. Improving income is a clear way to reduce the situation of energy poverty. In this sense, families with higher incomes to the IPREM decreased their energy poverty ratio with the improvement of the building. Therefore, public policies against energy poverty should not focus solely on the energy improvement of buildings since limited effectiveness is to be expected in families with limited economic resources. These results align with Castaño-Rosa et al. [67] by reflecting in his study the need to solve energy poverty not only by improving the energy efficiency of homes. In any case, this conclusion is based solely about energy poverty of families based on the 2M indicator. The improvement of buildings has benefits that are not computed in the analysis that has been carried out in the study, such as the reduction of extreme conditions of heat or cold in the interior environment, improving the thermal well-being of users [68]. This is an aspect that has not been directly considered in the study due to the use of the 2M indicator. It is also worth noting that the hypothesis that families try to maintain their thermal comfort conditions most of the time may vary in real conditions. In this sense, in 2019, 45% of Spanish households had especially low energy consumption [69]. This suggests the possible existence of many cases of hidden energy poverty. The adoption of technical improvements could provide relief for low-income families, although it is not a completely effective measure to reduce cases of energy poverty.

In relation to this last aspect, the thermal adaptability of users plays an important role in evaluating the situation of energy poverty in families. Family unit's' operational pattern is among the most determining aspects to assess the effectiveness of building improvement. Adaptive operational patterns were an effective measure to reduce energy poverty cases. Static operational patterns obtained the worst energy poverty results, whereas adaptive patterns based on the 3 categories of the EN 16798-1:2019 removed energy poverty cases in most typologies of income levels. This result was also obtained in buildings with poor characteristics. Results could therefore be useful to take immediate actions in the existing built environment to avoid energy poverty situations.

This adaptive behavior should not be understood as a self-restriction associated with a case of hidden energy poverty [70,71]. The adoption of adaptive patterns makes it possible to ensure thermal comfort conditions in indoor spaces, so the health of family members would not be compromised. In this sense, a wide variety of studies in the scientific literature have successfully evaluated the conditions adaptive thermal comfort of users in many buildings [72]. In the case of the relationships between energy poverty and adaptive thermal comfort, some previous studies are in line with the results obtained in this study. In this sense, Sánchez-Guevara Sánchez et al. [73] reflected the importance of considering adaptive patterns in the behavior of low-income families.

As for family units with static operational patterns, improving buildings was effective to avoid energy poverty cases. Thus, it is necessary to also bet on educational policies about the proper way to use the air conditioning facilities. The combination of educational programs for families that indicate efficient operational patterns, the technological improvement of buildings and socioeconomic improvements could constitute the action trident of energy poverty policies. Likewise, an optimization of the control of thermostats through home automation systems could eliminate the variability of use of HVAC systems. By educating families and using automatic thermostat setting systems, significant improvements could be achieved in the energy poverty situation of families. Independent pilot experiences, like that conducted in Barcelona with the "Energía, La Justa" programme, have reduced the energy vulnerability of family units by educating them on the sustainable use of the dwelling [74]. Although this experience was conducted in an area with characteristics different from those in the south of Spain, the results are expected to be satisfactory. Third, family units with income levels equal or lower than IPREM were always in energy poverty situation, regardless of the building design and operational pattern. In these cases, energy expenditure was greater than 10% of the family units' income levels. Having economic aids to reduce energy poverty cases should therefore be reconsidered. This aspect should not be only focused on the increase of the minimum guaranteed interprofessional wage, as the Spanish government has recently done [75]. Temporary and part-time jobs are usual in Spain, so the income levels of many family units could be lower than the minimum guaranteed interprofessional wage. An economic growth of the country will improve salaries and reduce energy poverty cases, as other countries have reported [76]. This aspect, together with policies that contribute to lower income inequality, would avoid energy poverty cases [77]. Likewise, unemployment subsidies and electricity social bonds could be insufficient [78–80]. Improving these aspects would imply both a lower percentage of energy poverty cases with low incomes and a better economic situation for family units, thus ensuring greater thermal comfort and better response to possible future scenarios in the south of Spain.

Finally, it is worth highlighting the variability of energy poverty ratios depending on the location of the home. Thus, homes located on ground floors obtained lower values in the energy poverty ratio. These results align with studies in the scientific literature. In this sense, Casquero-Modrego and Goñi-Modrego [81] detected significant variations in the interior temperatures of social housing depending on their location and how it affected the behaviour of users. In some cases, lower than normal utilization of HVAC systems was detected. Likewise, Pérez-Fargallo et al. [82] discussed the need for smart allocation of poor families in housing with low energy demand, such as ground floor housing. Therefore, the results of this study also serve to emphasize the adoption of public policies aimed at the intelligent relocation of families.

5. Conclusions

Energy poverty in hot climatic areas is a problem that presents different characteristics from those in cold areas. In hot climatic zones, the classic rehabilitation measures are not as significantly effective as in the case of cold zones. In these areas, high energy consumption is distributed in a similar way for cold and warm seasons, based on the results reflected in the scientific literature. For this reason, the energy policies of these regions must have a different line of action from that of cold areas. To assess this aspect, the study has carried out a holistic analysis at 3 differentiated levels: (i) building envelope and systems; (ii) income of the family unit; and (iii) user behaviour. The analysis focused on the conditions present in the southern regions of Spain, characterized by a high incidence of energy poverty. The relationships between the technical variables of the built environment and the economic variables of family units living in warm climatic zones has been stressed. Building technical characteristics and income levels should be considered to assess energy poverty. The following conclusions were obtained:

- Families with income levels equal to or lower than the IPREM will always be in a situation of energy poverty. This occurs regardless of the technical characteristics of the dwelling. The improvement of the envelope and HVAC systems meant improvements in energy poverty for families with incomes higher than the IPREM. Therefore, there is a clear relationship between the effectiveness of the building improvement and the family's income level to see if it is an effective measure against energy poverty.
- In the case of low-income families, the incorporation of socioeconomic aid that complements the technical improvement of buildings is essential. It has been confirmed that families with high incomes did not present situations of energy poverty in any of the combinations of buildings obtained. Therefore, it is essential to propose combined measures to improve income together with the improvement of buildings in order to obtain good results.
- In addition to technical and economic issues, it is important to highlight the thermal adaptation of users as a measure to reduce energy poverty. In this sense, the results showed how the use of adaptive patterns was one of the most appropriate measures to reduce cases of energy poverty. This did not happen with the static patterns in which a high number of cases of energy poverty were achieved. Thus, the use of adaptive patterns based on EN 16798-1 could lead to an improvement in the situation of families, without the need to initially implement financial aid or improvements to the building. The combined use of all measures could be the key to achieving coherent action to improve the situation of families in hot climate zones.

To conclude, the results of this study are significant to design an appropriate strategy to remove energy poverty in the dwelling in the south of Spain. Adopting energy renovation strategies is not an effective measure by itself, so appropriate behaviour strategies (based on adaptive thermal comfort models) should be included, as well as social aids. These aspects would be useful to prevent dwelling from being in energy poverty situations in current and future scenarios. It is convenient to clarify that the strategy of the policies resulting from the study presents an application for hot climatic zones. In cold areas, variations in the results are to be expected, since the technological improvement of the building could take on a greater role with respect to operational patterns. This difference in the expected energy savings between energy improvement of buildings and operational patterns depending on the climatic zone has been reflected in previous studies, so the results could be different from those of hot climatic zones. In addition to this aspect, further studies should address some limitations. For instance, the variations presented by assessing energy poverty at different levels. Previous studies have shown that assessing energy poverty in the months of greater demand (e.g., January and July) could vary the results, compared to annual analyses. The monthly analysis could be considered by using parametric criteria in the future context, thus determining the effectiveness of building design and operational pattern to reduce energy poverty in the future. In addition, the significance of income levels and aids should be addressed. Previous studies have shown that economic aids and unemployment subsidies in Spain are not effective by themselves to prevent cases of energy poverty. In this study, the component of financial aid in the energy bill has not been addressed. As a result of the improvement obtained in this study when higher income and building improvements were combined, further studies should parametrically analyse appropriate thresholds for economic aids according to family units' income levels. Finally, the use of renewable energy systems, such as photovoltaics or geothermal [83], should be evaluated. In this study, technical improvement was limited to envelope and HVAC systems. In future studies, the improvement achieved with the use of renewable energy systems and the effect of variations in energy contracts for these systems, such as surplus tariffs, should be addressed.

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Abbreviations

2M: High share of energy expenditure in income
Ada -C2: Adaptive mode, Category 2
Ada -C3: Adaptive mode, Category 3
Ada-C1: Adaptive mode, Category 1
ASHRAE: American Society of Heating, Refrigerating and Air-Conditioning Engineers
COP: Coefficient of performance
EER: Energy efficiency ratio
EPAH: Energy Poverty Advisory Hub
EPOV: Energy Poverty Observatory
EPR: Energy poverty ratio
HVAC: Heating, ventilation and air conditioning
IPREM: Public income indicator of multiple effects
PVPC: Voluntary price for the small consumer
RMOT: Running mean outdoor temperature
SCATs: Smart controls and thermal comfort

Sta-C1: Static mode, Category 1
Sta-C2: Static mode, Category 2
Sta-C3: Static mode, Category 3
U: Thermal transmittance

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