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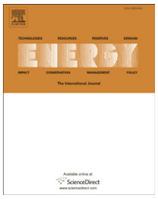

Applying the mixed-mode with an adaptive approach to reduce the energy poverty in social dwellings: The case of Spain

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ABSTRACT

Fuel poverty is a pressing issue in several European countries, and Spain is no exception. Traditionally, it has been associated with cold conditions, but recent studies in the field have stressed its prevalence in warm countries too, during summer. Further, forecasts of climate change for these territories predict more severe summers. This envisages a scenario where low-income families might suffer from fuel poverty due to their inability to afford the energy bill to cool their homes, for tackling which the European Union and its member states are devising strategies. Adaptive comfort models have emerged as a sustainable and resilient approach in this regard. This study aims at clarifying how a change in the behavioural patterns of users, following the adaptive model might reduce the incidence of fuel poverty, compared to the static model based solely on active cooling. For this purpose, a common typology of social dwelling has been simulated in 10 cities representative of the diverse climates of Spain; both the current and future climate change scenarios have been considered. Results indicate that the mixed-mode is effective in alleviating fuel poverty not only in the present scenario, but also in 2050 and 2100, except for the most underprivileged households earning less than 500 € per month. The outcomes of this study will be of use to policy makers, designers, and stakeholders in targeting families in need for specific subsidies to afford a comfortable environment during summer.

1. Introduction

The energy performance of the building stock in Europe is deficient [1,2] mainly due to its aging, with the majority of the structures having been built before the enactment of the first energy standards [3]. Old buildings without proper maintenance demand significant amounts of energy to keep comfort indoors, implying a significant economic burden for their occupants. As a result, negative consequences emerge, among which fuel poverty (FP) stands out as a pressing challenge.

The United Kingdom was the pioneering country in identifying and naming this concept, in 1979 [4], and the most commonly accepted definition is that by the English researcher Brenda Boardman [5] in 1991. Since then, the concept has received widespread support from European countries who are devising policies to alleviate fuel poverty. In Spain, the National Strategy against Energy Poverty 2019–2024 has been developed to reduce fuel poverty cases between 25% and 50% by 2025, vis-a-vis 2017 levels [6]. To meet this goal, a crucial aspect is the method of quantification of fuel poverty cases. Since 1979, many indicators have been developed, based mainly on the direct relationship between the income and the energy expenditure of households. The European Union Energy Poverty Observatory (EPOV), an initiative of the European Commission, has identified four indicators to analyse fuel poverty: high share of energy expenditure in income, low absolute energy expenditure, inability to keep the home adequately warm,

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Abbreviations: 2M, high share of energy expenditure in income; A2, climate change scenario; AEMET, Spanish Meteorological Agency; CP, contracted power; CV(RMSE), coefficient of variation of the root mean square error; EC, the monthly cost of the household energy consumption; ElT, electricity tax the rent of meters; EPOV, Energy Poverty Observatory; ET, energy term; FP, fuel poverty; FPR, fuel poverty ratio; HI, monthly household income; IPREM, public income indicator for multiple purposes; MBE, mean bias error; PVPC, Spanish regulated rate; RM, rent of meters.

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and arrears on utility bills. These indicators consider many combinations leading to fuel poverty, although there is a common pattern in all of them by combining the energy expenditure with thermal comfort conditions [7,8]. In this regard, the family units in a fuel poverty situation usually face many thermal discomfort hours [9], which could cause health problems [10–12]. Therefore, guaranteeing an appropriate balance between thermal comfort and low energy expenditure could imply that many households are not in fuel poverty situations. If building energy performance is improved, fuel poverty cases can be reduced [13]. However, the existing literature asserts that there is a vicious circle by which family units cannot improve their dwellings due to their limited economic resources [14], which, together with the rebound effects [15], could seriously hinder the reduction of fuel poverty cases.

At this point, it is important to consider people's need to use heating and air conditioning systems [16]to maintain appropriate thermal comfort levels. If the climatic conditions and the technical characteristics of buildings contribute to high energy consumption, users will easily be in fuel poverty [17]. As most studies have been conducted in Central and Northern European countries, fuel poverty is usually identified with the winter. Nonetheless, research about the prevalence of fuel poverty in summer is becoming widespread [18,19], particularly in the Southern European regions, where existing research has also shown the difficulties in meeting low energy consumption standards [20]. In addition, users' operational patterns to reduce building energy consumption [21] and the combination of natural ventilation with air conditioning systems (mixed-mode) to acclimatise indoor spaces efficiently [22,23] are essential. These strategies are particularly effective in reducing the cooling demand, as long as the outdoor temperatures are not extreme, but are unfeasible regarding the heating demand [24]. Nonetheless, in view of the climate evolution throughout the 21st century, recent evidence suggests that heating demand will decrease [25], natural ventilation would reduce the risk of overheating [26] and cooling demand will increase to some extent [27,28].

However, natural ventilation could imply thermal discomfort, if the appropriate usage patterns are not clear to users [29]. Therefore, adaptive models could determine the appropriate criteria to establish the periods when natural ventilation or air conditioning systems should be used, thus reducing fuel poverty cases through the decrease in the energy cost of the family units by modifying solely the operational patterns. Past studies, like those by Levie et al. [30] and Yu et al. al [31], have shown that low income households tend to make more use of natural ventilation. Bienvenido-Huertas et al. [32] analysed the effectiveness of the mixed-mode with an adaptive approach in a coastal city in the south of Spain. The results showed the significant effectiveness of using this approach to reduce the fuel poverty cases of family units, particularly those under unfavourable conditions, such as low income or unfavourable orientation of the dwelling. As these results were focused on an isolated case study, the authors deemed it necessary to extend this research line to address the significant research gap on the effect of the mixed-mode and the adaptive models on the energy consumption of the dwellings of low-income family units, and therefore on its effectiveness in reducing fuel poverty across the country.

Accordingly, this study aims to analyse the feasibility of using the mixed-mode with an adaptive approach, as per the European standard EN 16798-1:2019 [33], in 10 cities of Spain with various levels of summer climate severity. The analysis was performed both in the current scenario and for periods throughout the 21st century, to additionally consider the effect of climate change during the lifecycle of a residential building [34].

2. Methodology

The methodology used in the research is summarised in the flowchart in Fig. 1. The next subsections describe the methodology in detail.

2.1. Adaptive thermal comfort models

Adaptive thermal comfort models build upon the adaptability of building users to external climate variations. They basically find application in naturally ventilated buildings [35], although their versatility could also imply the adaptation of setpoint temperatures to the external variations of temperature [36]and the so-called “mixed-mode”, which is a combination of natural ventilation with dynamic setpoint temperatures. Regarding the standards including the adaptive models, ASHRAE 55–2017 [37] and EN 16798-1:2019 [33] are internationally recognized as key documents in the field. The latter is the European standard, which establishes 3 categories according to users' thermal adaptability (Fig. 2 (a)). More specifically, each category is defined for a type of building or user: Category I is applicable to vulnerable users with limited thermal adaptability (e.g., the elderly), category II for new buildings, and category III for existing buildings. Each category establishes an upper and lower limit for the indoor operative temperature (Eqs. (1)–(7)). These limits are calculated using the running mean outdoor temperature (T_{rm}) (Eq. (8)), determined by the weighted average of daily external temperatures. Thermal adaptability finds application under mild external temperatures, and for the European model considered here (EN 16798-1:2019), T_{rm} should be between 10 and 30 °C.

$$\mathit{Optimal\ comfort\ temperature} = 0.33 \cdot T_{rm} + 18.8 \quad [^{\circ}C] \quad (10 \le T_{rm} \le 30) \tag{1}$$

$$\mathit{Upper\ limit}\ (\mathit{Category\ I}) = 0.33 \cdot T_{rm} + 20.8 \quad [^{\circ}C] \quad (10 \le T_{rm} \le 30) \tag{2}$$

$$\mathit{Lower\ limit}\ (\mathit{Category\ I}) = 0.33 \cdot T_{rm} + 15.8 \quad [^{\circ}C] \quad (10 \le T_{rm} \le 30) \tag{3}$$

$$\mathit{Upper\ limit}\ (\mathit{Category\ II}) = 0.33 \cdot T_{rm} + 21.8 \quad [^{\circ}C] \quad (10 \le T_{rm} \le 30) \tag{4}$$

$$\mathit{Lower\ limit}\ (\mathit{Category\ II}) = 0.33 \cdot T_{rm} + 14.8 \quad [^{\circ}C] \quad (10 \le T_{rm} \le 30) \tag{5}$$

$$\mathit{Upper\ limit}\ (\mathit{Category\ III}) = 0.33 \cdot T_{rm} + 22.8 \quad [^{\circ}C] \quad (10 \le T_{rm} \le 30) \tag{6}$$

$$\mathit{Lower\ limit}\ (\mathit{Category\ III}) = 0.33 \cdot T_{rm} + 13.8 \quad [^{\circ}C] \quad (10 \le T_{rm} \le 30) \tag{7}$$

$$T_{rm} = \left(T_{ext,d-1} + 0.8T_{ext,d-2} + 0.6T_{ext,d-3} + 0.5T_{ext,d-4} + 0.4T_{ext,d-5} + 0.3T_{ext,d-6} + 0.2T_{ext,d-7}\right) / 3.8 \quad [^{\circ}C] \tag{8}$$

The adaptive thermal comfort model is mainly aimed at buildings with natural ventilation. However, recent studies have posited the possibility of using it in indoor spaces that operate under mixed-mode (i.e., combining natural ventilation and active cooling or heating). This research considered the application by

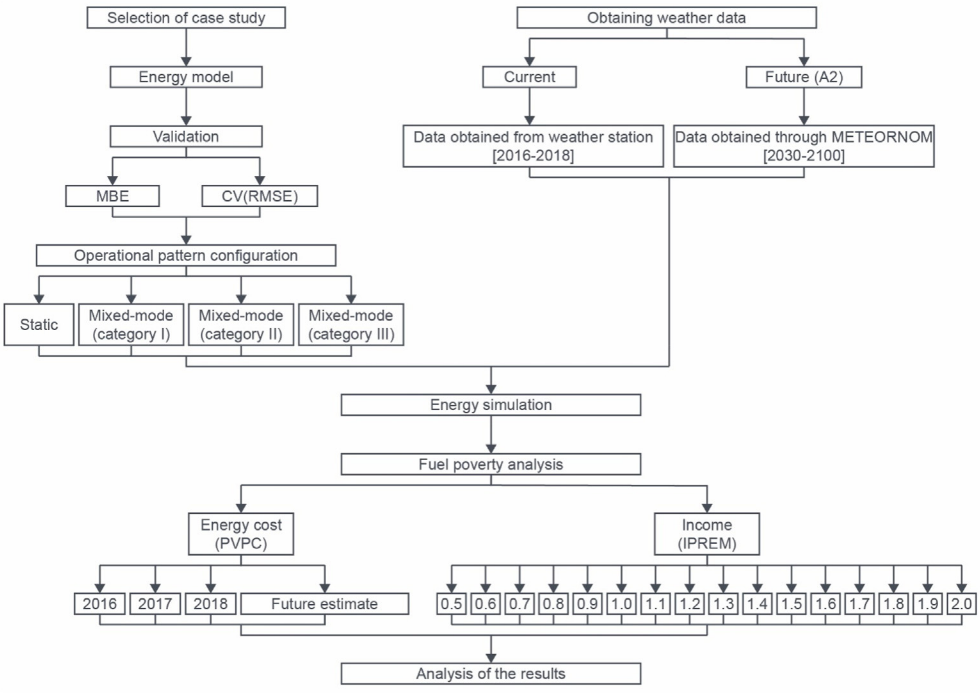


Fig. 1. Flowchart with the steps of this study.

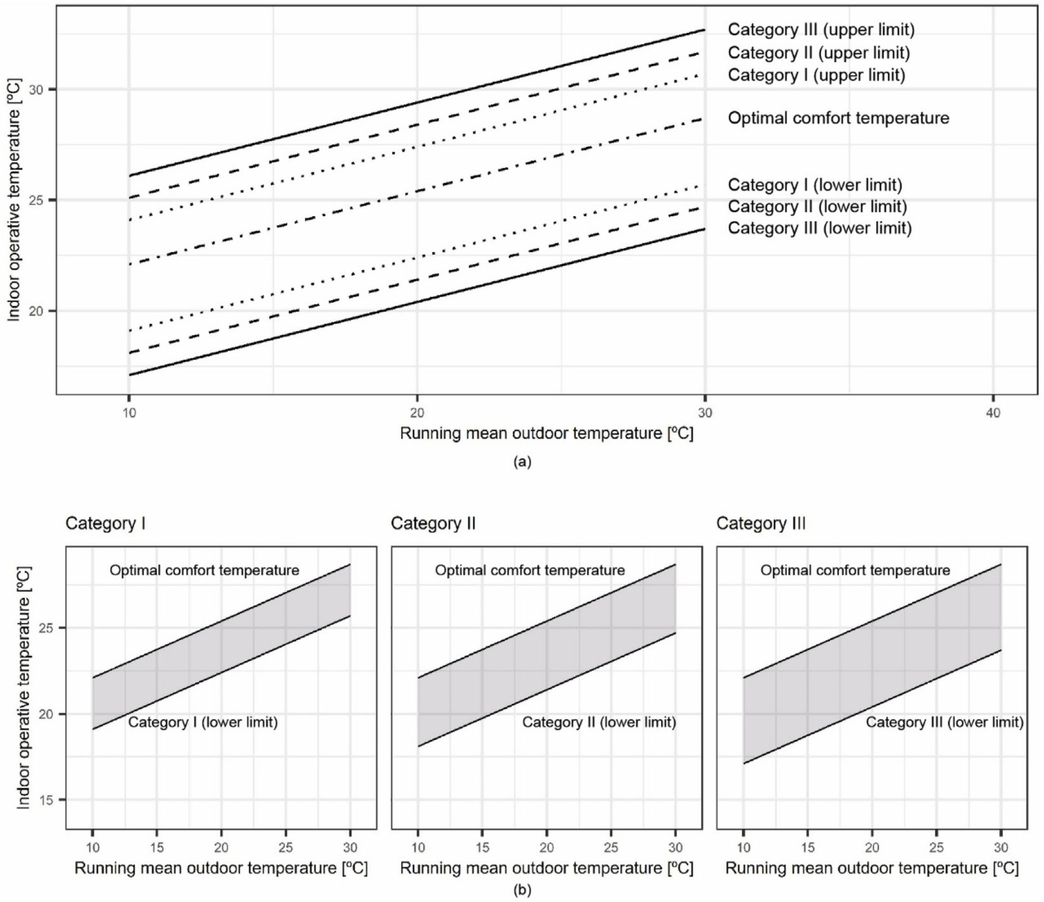


Fig. 2. Adaptive thermal comfort model: (a) upper and lower limits of each category from EN 16798-1:2019, and limit of the optimal comfort temperature, and (b) natural ventilation approaches considering an adaptive approach. The line between the optimal comfort temperature and the lower limit indicates the possible values of the external temperature to ventilate the dwelling naturally.

Bienvenido-Huertas et al. [32]of the adaptive mixed-mode in social dwellings located in coastal zones. This approach considers that the indoor space is naturally ventilated when two conditions are met (Fig. 2 (b)): (i) The operative temperature is above the optimal comfort temperature; and (ii) the external temperature is between the lower limit of the respective category and the optimal comfort temperature. When the operative temperature is above the upper limit, air conditioning systems come into play to ensure that occupants are in comfort. In that event, the setpoint temperature of the air conditioner is set to the upper limit of the adaptive model [36].

2.2. Case study, preliminary validation, and simulation

The mixed-mode approach was applied to a condominium (Fig. 3), a 51-dwelling housing complex for financially deprived families located in Cadiz (Spain). The typology is representative of Spanish social dwellings, featuring apartments with two and three bedrooms, designed for maximum efficiency and economy, with standardized constructive solutions. This complex was finished in 2004, and therefore still met the preceding Spanish standard on building energy efficiency, which dates from 1.979 [38]. Specifically, the thermal transmittance of the façade is 0.70 W/(m^{2}K), and that of the roof, 2.19 W/(m^{2}K).

The building was modelled with Design Builder (Fig. 3) and simulated with the calculation engine Energy Plus. The model was validated according to the criteria established in the ASHRAE Guideline 14—2014. For this purpose, indoor and outdoor temperatures, as well as the energy consumption of one apartment located on the second floor were measured on-site. The simulated data was assessed against the monitored data with the mean bias error (MBE) and the coefficient of variation of the root mean square error (CV (RMSE)), as per ASHRAE Guideline 14—2014. As all parameters were within the prescribed limits (Table 1), it can be considered that the simulated model represents the real building with enough accuracy.

Internal loads were also included in the simulations, and this study adopted the standard schedule of use of the Spanish building code. Two different schedules were considered for the occupancy: weekday and weekend. The value corresponding to 100% of internals loads was set as 3.51 W/m^2 for occupancy, and 4.40 W/m^2 for equipment and lighting (Fig. 4). Regarding the air conditioners, a heat pump with a coefficient of performance (COP) of 4.0 was considered, being representative of an energy-efficient system with an "A" energy label as per the European legislation [39]. Besides, a recent report on the sales of air conditioners in the European market has shown that the majority of the units sold are A-rated [40]. One could argue that the efficiency of this equipment will improve in the future, but this study works on the assumption that it will not change, to maintain consistency in data analysis. Regarding the use of air conditioners, two scenarios were considered: 1) a static model with fixed setpoint temperatures: 27 °C between 0:00 and 7:00, and 25 °C between 7:00 and 0:00 and 2) a mixed-model, as described in Section 2.1, where setpoint temperatures vary dynamically depending on the external oscillations; in this model, the three categories as per EN 16798-1:2019 were considered.

Although the building is in Cadiz, this typology is representative of social dwellings in Spain. Therefore, and to be consistent in the analysis, the simulations were reproduced in 9 other cities, which are representative of the different climate zones as per the Spanish Building Code [41]: Cadiz (zone A3), Bilbao (C1), Canfranc (E1), Grazalema (C2), Huesca (D2), Jaen (C4), Lanzarote (α3), Seville (B4), and Valencia (B3). Letters from A to E indicate the severity of the winter season (A is the least severe), whereas numbers from 1 to 4 indicate the severity of summer (1 is the least severe). Past studies have highlighted that energy performance of buildings in such a climatically diverse country can greatly vary from region to region [42]. In addition, Spanish territories located in a subtropical area deserve special treatment when tackling energy poverty [43]; this particularity is also considered in this study, by using a special index α to denote Lanzarote, located in the Canary Islands.

The climate data used for these 10 cities corresponded to the current and future scenarios. For the current scenario, hourly climate data of the cities between 2016 and 2018 were compiled. The data were obtained through the Spanish Meteorological Agency (AEMET in Spanish), which has a set of automatic weather stations divided by the whole territories that carry out hourly measurements. The data used were previously validated by AEMET. These data were used to generate different EPW files for 2016, 2017 and 2018, in each city. Regarding the climate change scenario, the A2 scenario from the Intergovernmental Panel on Climate Change

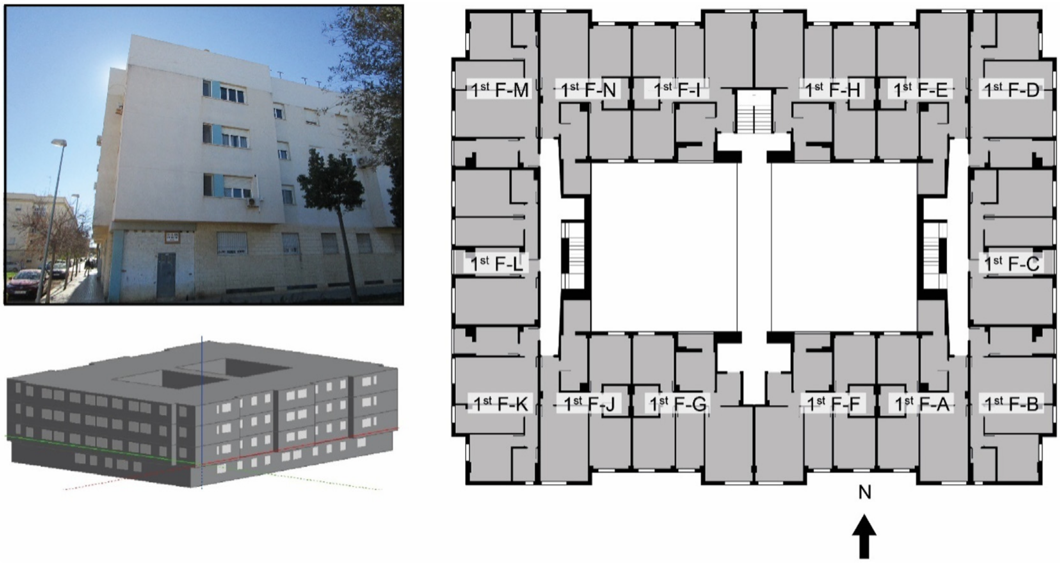


Fig. 3. Case study analysed in the research.

Table 1
Values obtained by the statistical parameters in the validation process.

Variable	Data type	MBE [%]		CV(RMSE) [%]	
		Measured data	ASHRAE 14−2014 criteria	Measured data	ASHRAE 14−2014 criteria
Indoor temperature	Hourly	−4.01	$-10 \le \text{MBE} \le 10$	23.80	<30
Outdoor temperature	Hourly	−2.81		17.83	
Energy consumption	Monthly	1.12	$-5 \le \text{MBE} \le 5$	9.19	<15

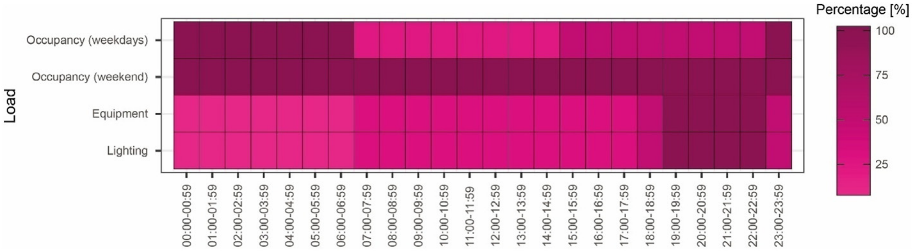


Fig. 4. Load profiles considered in the research.

was used [44]. A2 is among the most unfavourable climate change scenarios developed by the Intergovernmental Panel on Climate Change. This scenario considers a heterogeneous world with very marked demographic and economic increases, leading to a temperature rise between 2 °C and 5.4 °C by the end of the 21st century. Because of its unfavourable characteristics, it has been considered to analyse the impact of climate change on buildings [45–49]. EPW files were generated in the A2 scenario by using METEONORM for 2030, 2040, 2050, 2060, 2070, 2080, 2090 and 2100, to understand in detail the evolution of the mixed-mode adaptive strategies throughout the century. Likewise, the analysis was performed throughout the 21st century, considering the lifespan of the buildings from the last decade of the 20th century. Rincón et al. [50] showed that the average life of Spanish buildings is around 80 years; hence, the building analysed could keep acceptable conditions until the end of the century. This study is based on a simulation process that combined a case study of 51 social dwellings with 4 operational patterns (static and mixed-mode per category from EN 16798-1:2019), 10 cities and 11 climate files (3 for the current scenario and 8 for the future scenario).

2.3. *Analysis of fuel poverty: indicator, energy cost and incomes of the family unit*

The indicator “high share of energy expenditure in income (2 M)” used by the European Energy Poverty Observatory was used to analyse fuel poverty. This indicator considers that the family units are in a fuel poverty situation, when the fraction of the energy expenditure with their incomes is greater than the national median. As for Spain, the study by Sánchez-Guevara Sánchez et al. [51] showed that the threshold value for this indicator is 10%, coinciding with the value established by Boardman [5]. This study therefore considered the threshold value of 10% for 2 M. The fuel poverty ratio (FPR) was determined according to Eq. (9). If the value obtained by Eq. (9) is greater than 10%, the family unit is in a fuel poverty situation (E1. (10)). This assessment is made at a monthly level, so a result is obtained per summer month. This study considered June, July, August and September as the months when the cooling energy consumption is greater [52].

$$FPR = \frac{EC}{HI} \cdot 100 \quad [\%] \tag{9}$$

$$\textit{Case in fuel poverty} \quad \text{if} \quad FPR \geq 2M\ (10\%) \tag{10}$$

where *FPR* is the fuel poverty ratio, *EC* is the monthly cost of the household energy consumption [€], and *HI* is the monthly household income [€].

The household energy consumption was obtained through energy simulations, and the cost of energy consumption was determined according to the cost of the electrical energy for users. For financially deprived families, the Spanish Government established in 2014 a regulated rate, (PVPC by its Spanish acronym), which varies according to the hour of the day [53]. This price determines the price of the energy term (ET) obtained by applying the hourly price of PVPC to the energy consumption:

$$ET = \textit{Energy consumption} \cdot \textit{Price of energy term} \tag{11}$$

There are other concepts included in bills, such as contracted power (*CP*), electricity tax (*ElT*), rent for meters (*RM*), and the value added tax (1.21%). Eq. (12) shows the variables involved in determining EC.

$$EC = 1.21 \cdot (ET + CP + ElT + RM) \tag{12}$$

This study considered that the family unit had contracted a PVPC without hourly discrimination, and the contracted power was 4.6 kW. The hourly values of PVPC were obtained for 2016, 2017 and 2018. For the climate change scenarios, the average value of PVPC in recent years was determined (0.11751 €/kWh) and used to evaluate fuel poverty in future scenarios.

Household income was assessed with the public income indicator for multiple purposes (IPREM in Spanish). IPREM is an index used by autonomous and municipal governments to determine the family units eligible for social benefits such as subsidised housing. This index is determined by the government in accordance with the variation of several macro-economic parameters and is assessed against the household income before taxes. Additionally, the IPREM is multiplied by a factor that informs about the vulnerability of a given household, which varies between 0.5 and 2 in steps of 0.1; the lower the index, the more vulnerable the household. This study considered the IPREM for the period 2010–2016: 626.63 €/month, and the 16 multiplication factors, that is, 16 different household incomes. For example, a given municipality may offer a social dwelling to vulnerable families whose monthly income is below 1.6 times the IPREM; in that case, only families earning less than 1.6 × 626.63 = 1002.6 €/month before taxes would be eligible for that benefit. Even though the IPREM was recalculated in 2018, with an increment of 5.37 €/month, this study did not consider variations in the index either in the present or in future scenarios, to allow for comparison.

3. Results and discussion

Substantial data was obtained from the simulations, whose analysis was organised as follows. Two scenarios were considered: present and future scenarios, in 2050 and 2100. For each, the relation between household income and fuel poverty was analysed considering static setpoint temperatures. The summer months were analysed separately. Following this, the effectiveness of the mixed-mode was assessed against the static model, using the energy consumption and the percentage of families in fuel poverty in relation with the household income as a proxy. This analysis was reproduced in the ten representative cities considered here.

3.1. Current scenario

At the present time and considering static setpoint temperatures, it is evident that low-income households face the risk of falling into fuel poverty; but the most striking result is the remarkable differences between climates. A threshold value of 10%, that is, the 2 M indicator in Spain, was adopted to consider a family as vulnerable (Fig. 5). Two parameters were discussed: the threshold income that places a family into fuel poverty, and the dispersion of data for each income level, which was assessed with the interquartile range.

In northern cities with mild summers, such as Bilbao and Canfranc, only households with very low income levels, below 0.8 times the value for the IPREM (that is, around 600 €), are at risk, which contrasts with the situation in hotter cities. In Sevilla and Jaen, both located in the warm southern region of Andalusia, virtually all families would be at risk of fuel poverty in summer, regardless of their income level. In the rest of the locations, the threshold income oscillated between 1 and 1.4 times the IPREM (between 625 and 877 €). Another important aspect was the dispersion of the data, which was assessed using the interquartile range. Data is less dispersed for high income households and cold cities (Bilbao and Canfranc), as well as in the tropical Lanzarote. Interquartile ranges in these locations are small, always below 2.5%, indicating low variability in the data. In warmer locations (i.e. Jaen, Cadiz, Sevilla, Valencia and Grazalema) this range is wider for low income households, reaching 12.55% in some cases.

Turning now to a deeper analysis of the summer months (June, July, August and September), the most striking result to emerge is the wide difference between cities with cool and warm summers. For each location, all income levels were grouped together, and the percentage of households in fuel poverty as per the 2 M indicator was calculated for the summer of three consecutive years (Fig. 6). Northern cities with cool summers (Bilbao and Canfranc), as well as the tropical Lanzarote would see around 30%–50% of their households falling into fuel poverty, which was in stark contrast with the situation in warmer cities like Sevilla and Jaen, where virtually all socially vulnerable families would face difficulties in affording energy to keep their homes cool during the hottest months of the year. Between these, the rest of the cities would see percentages between 60% and 80%. It is also evident that July and August are the months with a higher incidence of fuel poverty in all locations.

Since it was evident that static setpoints were inextricably related to higher energy consumption and, therefore, to the prevalence of fuel poverty, the analysis moved to the comparison between static and adaptive operational patterns. For each city, the simulated energy consumption of the former was compared with the adaptive approach, considering the 3 categories as per EN 16798-1:2019. Figures in Appendix A depict this relation for categories I, II, and III respectively, which is fitted to a curve, and whose accuracy is assessed by its coefficient of determination.

For all cities and categories, there was a significant correlation between the energy consumption associated with static and adaptive patterns, fitted to a second-degree curve, whose coefficient of determination was 0.8016 and 0.9696, thus displaying a high degree of confidence. The energy consumption as per the adaptive model was always lower than the adaptive model, regardless of the city, which indicates a high potential to reduce the prevalence of energy poverty. The shape of the curves was very similar for all locations when considering category I (Fig. A1), the most restrictive, and they flattened as less restrictive categories were considered: II (Fig. A2), and III (Fig. A3). This suggests that the energy consumption is decoupled from the adaptive setpoint temperatures as the less restrictive categories are considered; these results are likely to be related to the smaller “a” coefficient in the fitted curves in the form of $y = ax^2 + bx + c$. Besides, in the locations with milder summers, such as Bilbao, Canfranc or Lanzarote, the consumption associated with adaptive patterns was virtually null, considering static consumption below 100 kWh for the less restrictive categories.

This suggests that there is a certain relation between the energy consumption using adaptive setpoint temperatures, and the adaptive comfort models. The said equations permit a reliable estimation of the expected savings. For example, in Sevilla, when considering category I, they are in the range of 80% for dwellings with a static consumption of 200 kWh, and of 35% for a static consumption of 800 kWh. This pattern is reproduced with some variations in all locations and for all categories: expected savings are much greater for dwellings with low energy consumption, and the said fitting curves permit their easy estimation.

The next section of the study was concerned with the potential of the adaptive model to rescue vulnerable households from fuel poverty. Fig. 7 compares the percentage of households in fuel poverty as a function of their income level; the comparison is done between a static and three dynamic operational patterns (i.e. categories I, II, and III). For all locations, the difference between the former and the latter is significant, but the most surprising aspect was the effectivity of this approach in warm cities during summer. In Jaen and Sevilla, fuel poverty was a problem for almost all income levels, but the adaptive behaviour would permit establishing a threshold between 0.9. and 1.1 times the IPREM (roughly between 565 and 690 €), under which fuel poverty would affect a considerable number of families. The first set of analyses (Fig. 5) highlighted that in cities with cool summers, only households with an income under 0.8 times the IPREM would be at severe risk of fuel poverty, and this data confirms that 0.8 times the IPREM is the critical value under which all households would be in fuel poverty, irrespective of the adopted category of comfort. In other words, thermal adaptability and natural ventilation would not provide them comfort, and therefore they would need to resort to air conditioning and allocate more than 10% of their income (a mere 500 €), to maintain acceptable conditions inside their homes.

3.2. Climate change scenarios

The previous analysis was reproduced for two future climate

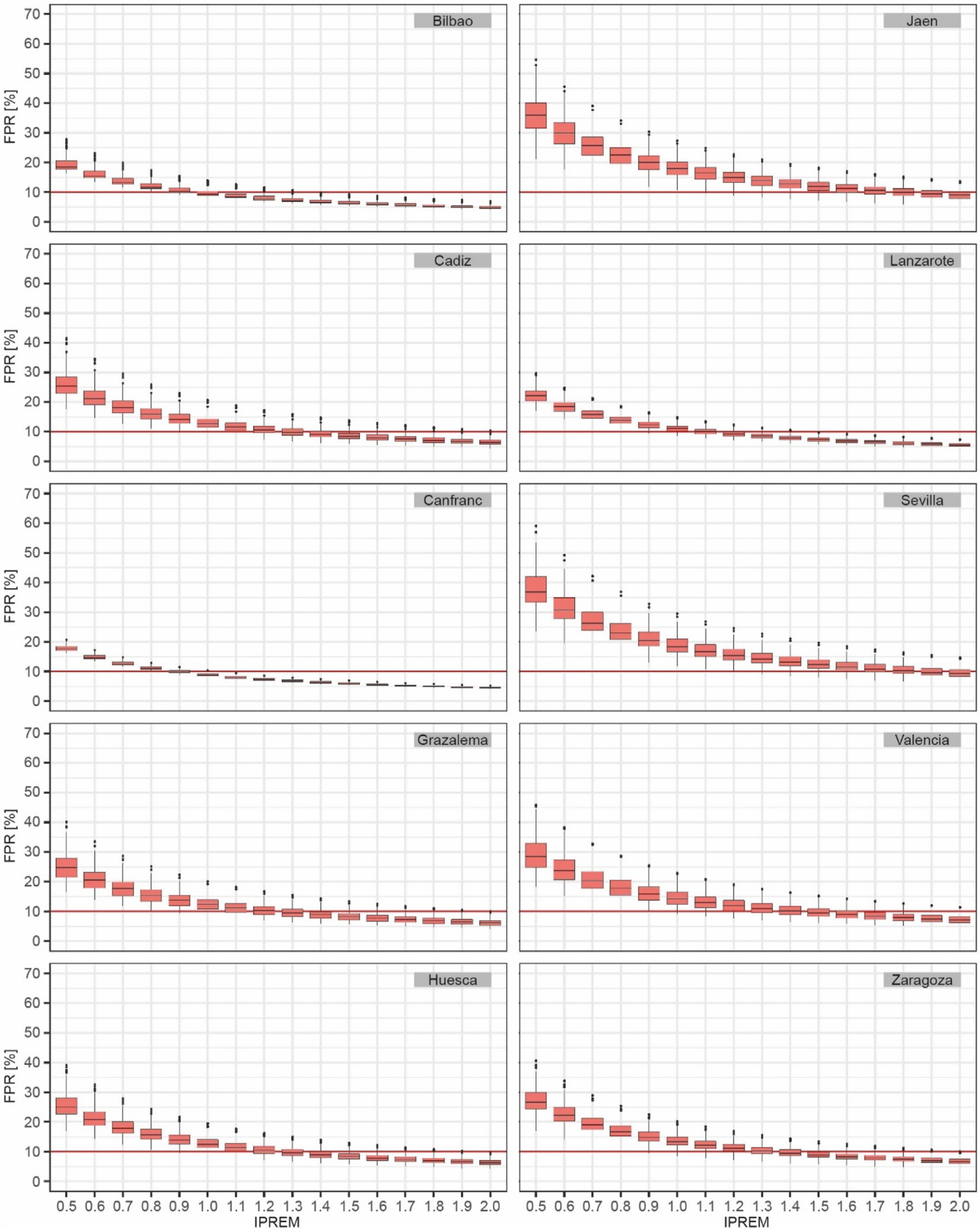


Fig. 5. Box plots with the values related to FPR in the current scenario according to the income level of the family unit (grouped according to the IPREM) for users with static operational patterns. The red line shows the indicator value of the fuel poverty risk corresponding to the 2 M indicator in Spain (10%). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

scenarios, considering the A2 emission scenario in 2050 and 2100. 2050 was chosen because that is the expected deadline for achieving a total decarbonization of the building industry as per the European directive [54], and 2100 because it represents the end of the 21st century.

The risk of fuel poverty in 2050 outlines a similar scenario (Fig. 8). Despite the slight variance in interquartile ranges, no significant differences were found between 2050 and the present scenario. The differences between cities with warm and cool summers are still evident, and vulnerable families in the South of Spain (Cadiz, Sevilla and Jaen) would be in fuel poverty irrespective of their income level. What stands out in this graph is the abrupt change between 2050 and 2100. At the end of this century, not only warm cities, but also families living in the Mediterranean coast (Valencia), or the Northern region of Aragón (Zaragoza and Huesca) would face a certain risk of fuel poverty, notwithstanding their income level. Cities with mild summers will also see a rise in the threshold level of income under which fuel poverty would pose a risk to the family economy: The threshold value would rise from 1 to 1.4 times the IPREM in Bilbao, from 1.2 to 1.5 in Lanzarote, and from 0.9 to 1.0 in Canfranc. Grazalema, although located in the South of Spain, deserves special consideration, as it is in a mountainous area, which creates a special microclimate with mild summers; nevertheless, the threshold value would rise from 1.1 to

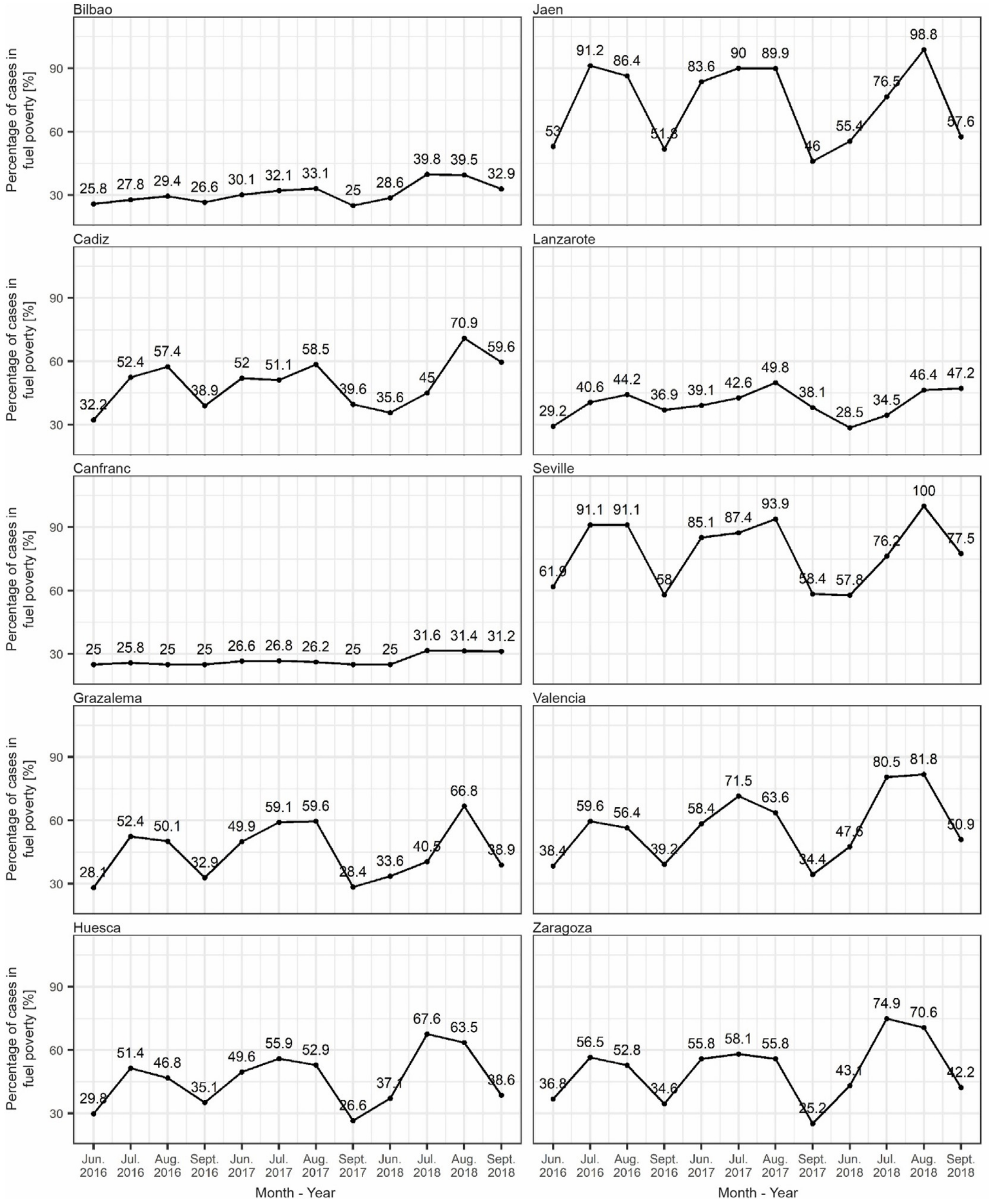
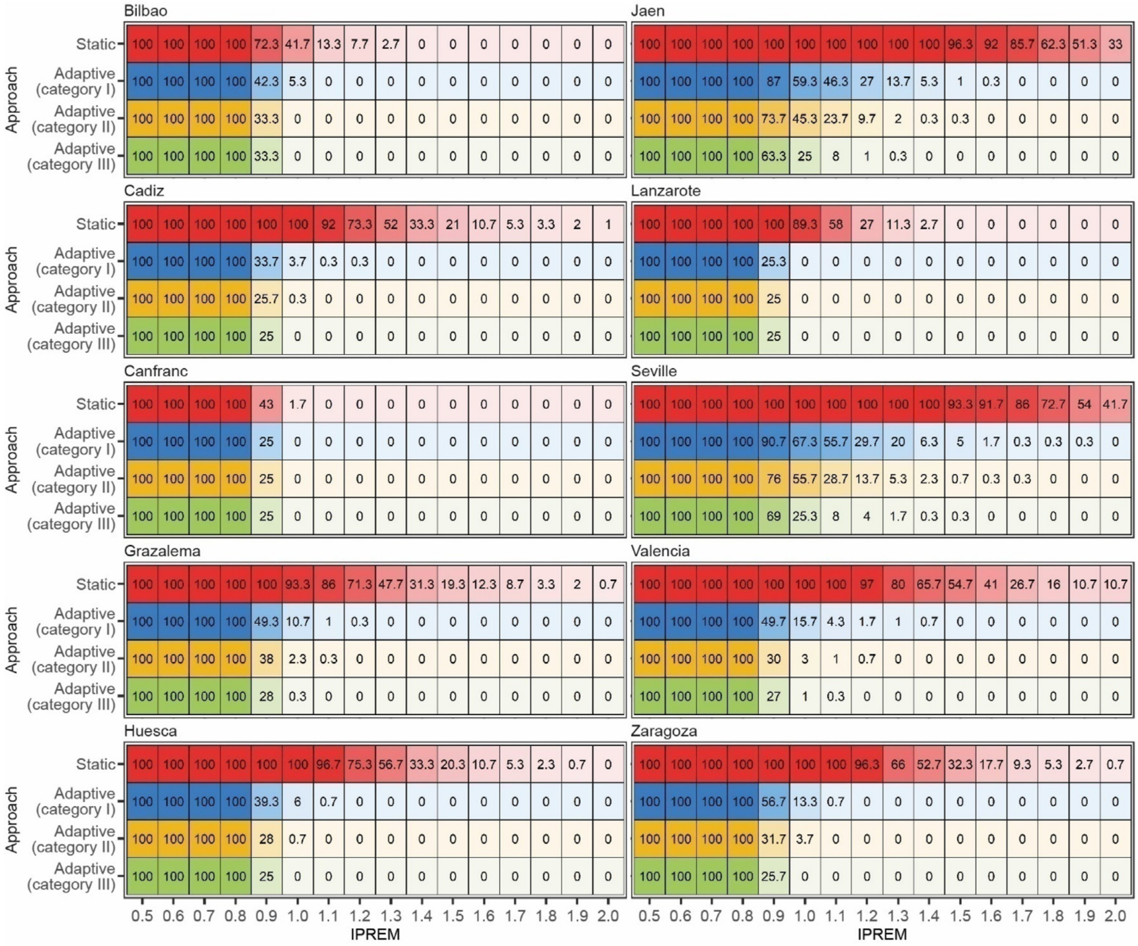


Fig. 6. Evolution of the percentage of fuel poverty cases in the summer months in the current scenario (using static operational patterns).

1.4 times the IPREM. Another aspect that should be highlighted is the greater dispersion of data, particularly for low-income households living in warm cities. The interquartile ranges were wider, and therefore these results should be interpreted with caution.

Figures in Appendix B provide the breakdown of households in fuel poverty during the summer months from 2030 to 2100; the analysis considers all income levels and static setpoint temperatures. They show a steady increase in the number of fuel-poor households for all locations; but the most striking result is that by the end of the century, almost all families living in the South and Eastern cities of Zaragoza, Valencia, Seville, Jaen and Huesca will face difficulties in keeping their homes cool in July and August. In the other cities, which comprise both cooler (Bilbao, Canfranc, and Grazalema) and tropical climates (Lanzarote), the percentage of fuel-poor households will increase gradually, and by 2100, between 50% and 80% of families will need to spend more than 10% of their income, if they want to keep their homes at acceptable temperatures.

In the final part of the analysis, the discussion revolves around the potential of the adaptive model to alleviate fuel poverty during summer months in relation to the income level of households (Fig. 9). The analysis of Fig. 7 discussed the threshold income under which a considerable percentage of families would face financial difficulties, and when the analysis is reproduced for 2050 and 2100, it is evident that the adaptive model can significantly help households in need. The situation might be bearable in 2050 in cooler and tropical climates (Bilbao, Canfranc, Grazalema, and Lanzarote), where a threshold income between 0.9 and 1.3 times the IPREM would draw the line between fuel and non-fuel-poor households. In Cadiz, Huesca, Valencia, Jaen and Zaragoza, wealthier households



Bilbao

Approach	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
Static	100	100	100	100	72.3	41.7	13.3	7.7	2.7	0	0	0	0	0	0	0
Adaptive (category I)	100	100	100	100	42.3	5.3	0	0	0	0	0	0	0	0	0	0
Adaptive (category II)	100	100	100	100	33.3	0	0	0	0	0	0	0	0	0	0	0
Adaptive (category III)	100	100	100	100	33.3	0	0	0	0	0	0	0	0	0	0	0

Jaen

Approach	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
Static	100	100	100	100	100	100	100	100	100	100	96.3	92	85.7	62.3	51.3	33
Adaptive (category I)	100	100	100	100	87	59.3	46.3	27	13.7	5.3	1	0.3	0	0	0	0
Adaptive (category II)	100	100	100	100	73.7	45.3	23.7	9.7	2	0.3	0.3	0	0	0	0	0
Adaptive (category III)	100	100	100	100	63.3	25	8	1	0.3	0	0	0	0	0	0	0

Cadiz

Approach	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
Static	100	100	100	100	100	100	92	73.3	52	33.3	21	10.7	5.3	3.3	2	1
Adaptive (category I)	100	100	100	100	33.7	3.7	0.3	0.3	0	0	0	0	0	0	0	0
Adaptive (category II)	100	100	100	100	25.7	0.3	0	0	0	0	0	0	0	0	0	0
Adaptive (category III)	100	100	100	100	25	0	0	0	0	0	0	0	0	0	0	0

Lanzarote

Approach	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
Static	100	100	100	100	100	89.3	58	27	11.3	2.7	0	0	0	0	0	0
Adaptive (category I)	100	100	100	100	25.3	0	0	0	0	0	0	0	0	0	0	0
Adaptive (category II)	100	100	100	100	25	0	0	0	0	0	0	0	0	0	0	0
Adaptive (category III)	100	100	100	100	25	0	0	0	0	0	0	0	0	0	0	0

Canfranc

Approach	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
Static	100	100	100	100	43	1.7	0	0	0	0	0	0	0	0	0	0
Adaptive (category I)	100	100	100	100	25	0	0	0	0	0	0	0	0	0	0	0
Adaptive (category II)	100	100	100	100	25	0	0	0	0	0	0	0	0	0	0	0
Adaptive (category III)	100	100	100	100	25	0	0	0	0	0	0	0	0	0	0	0

Seville

Approach	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
Static	100	100	100	100	100	100	100	100	100	100	93.3	91.7	86	72.7	54	41.7
Adaptive (category I)	100	100	100	100	90.7	67.3	55.7	29.7	20	6.3	5	1.7	0.3	0.3	0.3	0
Adaptive (category II)	100	100	100	100	76	55.7	28.7	13.7	5.3	2.3	0.7	0.3	0.3	0	0	0
Adaptive (category III)	100	100	100	100	69	25.3	8	4	1.7	0.3	0.3	0	0	0	0	0

Grazalema

Approach	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
Static	100	100	100	100	100	93.3	86	71.3	47.7	31.3	19.3	12.3	8.7	3.3	2	0.7
Adaptive (category I)	100	100	100	100	49.3	10.7	1	0.3	0	0	0	0	0	0	0	0
Adaptive (category II)	100	100	100	100	38	2.3	0.3	0	0	0	0	0	0	0	0	0
Adaptive (category III)	100	100	100	100	28	0.3	0	0	0	0	0	0	0	0	0	0

Valencia

Approach	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
Static	100	100	100	100	100	100	100	97	80	65.7	54.7	41	26.7	16	10.7	10.7
Adaptive (category I)	100	100	100	100	49.7	15.7	4.3	1.7	1	0.7	0	0	0	0	0	0
Adaptive (category II)	100	100	100	100	30	3	1	0.7	0	0	0	0	0	0	0	0
Adaptive (category III)	100	100	100	100	27	1	0.3	0	0	0	0	0	0	0	0	0

Huesca

Approach	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
Static	100	100	100	100	100	100	96.7	75.3	56.7	33.3	20.3	10.7	5.3	2.3	0.7	0
Adaptive (category I)	100	100	100	100	39.3	6	0.7	0	0	0	0	0	0	0	0	0
Adaptive (category II)	100	100	100	100	28	0.7	0	0	0	0	0	0	0	0	0	0
Adaptive (category III)	100	100	100	100	25	0	0	0	0	0	0	0	0	0	0	0

Zaragoza

Approach	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
Static	100	100	100	100	100	100	100	96.3	66	52.7	32.3	17.7	9.3	5.3	2.7	0.7
Adaptive (category I)	100	100	100	100	56.7	13.3	0.7	0	0	0	0	0	0	0	0	0
Adaptive (category II)	100	100	100	100	31.7	3.7	0	0	0	0	0	0	0	0	0	0
Adaptive (category III)	100	100	100	100	25.7	0	0	0	0	0	0	0	0	0	0	0

IPREM

Fig. 7. Heatmap with the percentage of cases in fuel poverty risk in the current scenario according to the income level and behaviour pattern of family units.

would also be affected. Sevilla stands out as a particular case: All families, irrespective of their income, will be fuel-poor during summer in 2050. The adaptive behaviour will greatly help in reducing this threshold income, and considering the differences between cities, it could be said that a threshold income around 0.8 and 1 times the IPREM will differentiate between fuel-poor and non-fuel poor households. The situation will worsen considerably by 2100, especially in warmer climates. Virtually all families will allocate more than 10% of their income towards the energy bill in summer in Cadiz, Huesca, Zaragoza, Valencia, Seville and Jaen. In the rest of the cities, only the most underprivileged families will fall into fuel poverty. Nonetheless, the adaptive model proves to be a feasible approach to tackle this situation; there will be a significant reduction in cases of fuel poverty if either category as per EN 16798:1–2019 is adopted. For some cities, the threshold income would be 0.8 times the IPREM, whereas in those affected by scorching summers, it would be around 1.5 times. Overall, these results indicate that, although fuel poverty will still affect vulnerable households during summer, its incidence could be limited by considering an operational pattern with mixed-mode.

4. Conclusions

This paper aimed at clarifying how the mixed-mode could help in reducing fuel poverty among financially deprived households. The analysis considered a representative typology of social dwellings located in different Spanish cities, whose simulation model was validated against on-site measurements, and considered both the present and future scenarios as per the A2 climate change mission scenario.

The results of this study show that fuel poverty is indeed an acute problem in summer. The traditional static operational pattern, that is, closing windows and operating the air conditioner with fixed setpoint temperatures, will put the most underprivileged households in financial distress, and this situation will be especially serious in Southern and Eastern cities, and in July and August. Thus, the results of this study apply to warm seasons. In the latitudes of Spain, this season corresponds to the summer months, although the current trend is that the warm season is extending into the spring and autumn months. Thus, it is to be expected that the vulnerability of users in warm seasons will be more on a greater number of days of the year. In this sense, the situation will worsen in 2050 and 2100, when the percentage of families in fuel poverty will steadily increase in all climate zones, especially in warmer cities. This study has also clarified that the threshold income level under which families could be fuel poor, following the static operational pattern, would be around 0.8 times the IPREM for northern cities, and 1–1.4 times the IPREM for warmer locations. The regression analysis also confirmed that the mixed-mode, which combines adaptive setpoint temperatures and natural ventilation, can greatly reduce the energy consumption of those dwellings, and that can be modelled as a quadratic function of the consumption as per a static operational pattern. Moreover, the threshold income for fuel-poor families can be lowered to 0.8–1.1 times the IPREM using

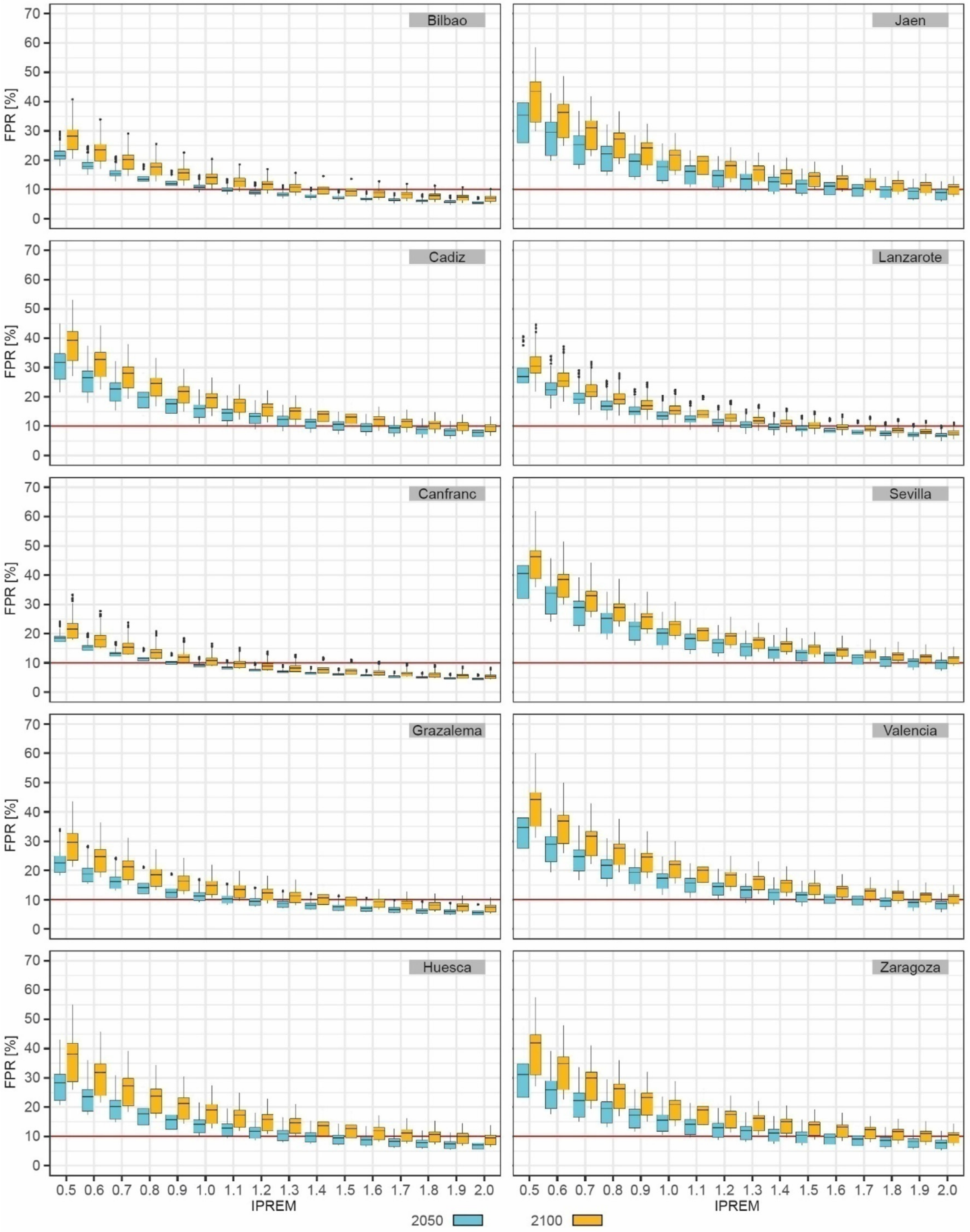
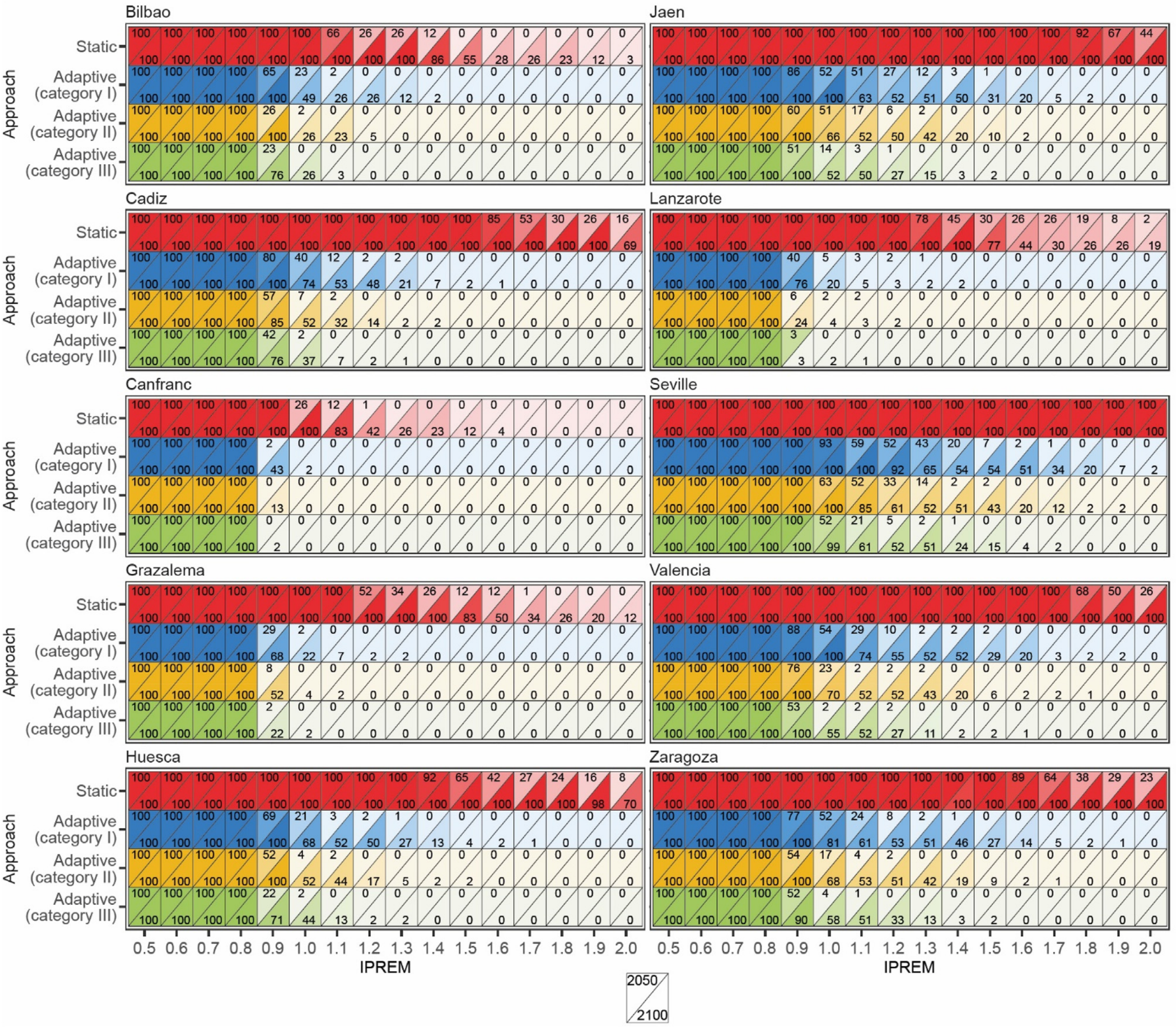


Fig. 8. Box plots with values related to FPR in 2050 and in 2100, according to income level of the family unit (grouped according to the IPREM), for users with static operational patterns. The red line shows the indicator value of fuel poverty risk corresponding to the 2 M indicator in Spain (10%). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

this approach in different locations across Spain.

This research has provided an insight not only into the current scenario, but also a deeper insight into what the future holds in the light of climate change. The minimum income necessary to escape from fuel poverty will rise across the country, and families in the South will need financial assistance regardless of their income, and will definitely face fuel poverty during July and August. In the rest of the cities, the threshold will rise to 1–1.4 times the IPREM. The relevance of the mixed-mode in the future scenarios is supported by the current findings, which prove that households earning less than 1.5 times the IPREM and living in warm cities will be fuel poor; this figure will be 0.8 for those living in cities with cooler summers.

This study provides important insights into the relation between household income and the risk of falling into fuel poverty,



Bilbao

Approach		0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
Static	2050	100	100	100	100	100	100	66	26	26	12	0	0	0	0	0	0
	2100	100	100	100	100	100	100	100	100	100	86	55	28	26	23	12	3
Adaptive (category I)	2050	100	100	100	100	65	23	2	0	0	0	0	0	0	0	0	0
	2100	100	100	100	100	100	49	26	26	12	2	0	0	0	0	0	0
Adaptive (category II)	2050	100	100	100	100	26	2	0	0	0	0	0	0	0	0	0	0
	2100	100	100	100	100	100	26	23	5	0	0	0	0	0	0	0	0
Adaptive (category III)	2050	100	100	100	100	23	0	0	0	0	0	0	0	0	0	0	0
	2100	100	100	100	100	76	26	3	0	0	0	0	0	0	0	0	0

Jaen

Approach		0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
Static	2050	100	100	100	100	100	100	100	100	100	100	100	100	100	92	67	44
	2100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Adaptive (category I)	2050	100	100	100	100	86	52	51	27	12	3	1	0	0	0	0	0
	2100	100	100	100	100	100	100	63	52	51	50	31	20	5	2	0	0
Adaptive (category II)	2050	100	100	100	100	60	51	17	6	2	0	0	0	0	0	0	0
	2100	100	100	100	100	100	66	52	50	42	20	10	2	0	0	0	0
Adaptive (category III)	2050	100	100	100	100	51	14	3	1	0	0	0	0	0	0	0	0
	2100	100	100	100	100	100	52	50	27	15	3	2	0	0	0	0	0

Cadiz

Approach		0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
Static	2050	100	100	100	100	100	100	100	100	100	100	100	85	53	30	26	16
	2100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	69
Adaptive (category I)	2050	100	100	100	100	80	40	12	2	2	0	0	0	0	0	0	0
	2100	100	100	100	100	100	74	53	48	21	7	2	1	0	0	0	0
Adaptive (category II)	2050	100	100	100	100	57	7	2	0	0	0	0	0	0	0	0	0
	2100	100	100	100	100	85	52	32	14	2	2	0	0	0	0	0	0
Adaptive (category III)	2050	100	100	100	100	42	2	0	0	0	0	0	0	0	0	0	0
	2100	100	100	100	100	76	37	7	2	1	0	0	0	0	0	0	0

Lanzarote

Approach		0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
Static	2050	100	100	100	100	100	100	100	100	78	45	30	26	26	19	8	2
	2100	100	100	100	100	100	100	100	100	100	100	77	44	30	26	26	19
Adaptive (category I)	2050	100	100	100	100	40	5	3	2	1	0	0	0	0	0	0	0
	2100	100	100	100	100	76	20	5	3	2	2	0	0	0	0	0	0
Adaptive (category II)	2050	100	100	100	100	6	2	2	0	0	0	0	0	0	0	0	0
	2100	100	100	100	100	24	4	3	2	0	0	0	0	0	0	0	0
Adaptive (category III)	2050	100	100	100	100	3	0	0	0	0	0	0	0	0	0	0	0
	2100	100	100	100	100	3	2	1	0	0	0	0	0	0	0	0	0

Canfranc

Approach		0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
Static	2050	100	100	100	100	100	26	12	1	0	0	0	0	0	0	0	0
	2100	100	100	100	100	100	100	83	42	26	23	12	4	0	0	0	0
Adaptive (category I)	2050	100	100	100	100	2	0	0	0	0	0	0	0	0	0	0	0
	2100	100	100	100	100	43	2	0	0	0	0	0	0	0	0	0	0
Adaptive (category II)	2050	100	100	100	100	0	0	0	0	0	0	0	0	0	0	0	0
	2100	100	100	100	100	13	0	0	0	0	0	0	0	0	0	0	0
Adaptive (category III)	2050	100	100	100	100	0	0	0	0	0	0	0	0	0	0	0	0
	2100	100	100	100	100	2	0	0	0	0	0	0	0	0	0	0	0

Seville

Approach		0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
Static	2050	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
	2100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Adaptive (category I)	2050	100	100	100	100	100	93	59	52	43	20	7	2	1	0	0	0
	2100	100	100	100	100	100	100	100	92	65	54	54	51	34	20	7	2
Adaptive (category II)	2050	100	100	100	100	100	63	52	33	14	2	2	0	0	0	0	0
	2100	100	100	100	100	100	100	85	61	52	51	43	20	12	2	2	0
Adaptive (category III)	2050	100	100	100	100	100	52	21	5	2	1	0	0	0	0	0	0
	2100	100	100	100	100	100	99	61	52	51	24	15	4	2	0	0	0

Grazalema

Approach		0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
Static	2050	100	100	100	100	100	100	100	52	34	26	12	12	1	0	0	0
	2100	100	100	100	100	100	100	100	100	100	100	83	50	34	26	20	12
Adaptive (category I)	2050	100	100	100	100	29	2	0	0	0	0	0	0	0	0	0	0
	2100	100	100	100	100	68	22	7	2	2	0	0	0	0	0	0	0
Adaptive (category II)	2050	100	100	100	100	8	0	0	0	0	0	0	0	0	0	0	0
	2100	100	100	100	100	52	4	2	0	0	0	0	0	0	0	0	0
Adaptive (category III)	2050	100	100	100	100	2	0	0	0	0	0	0	0	0	0	0	0
	2100	100	100	100	100	22	2	0	0	0	0	0	0	0	0	0	0

Valencia

Approach		0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
Static	2050	100	100	100	100	100	100	100	100	100	100	100	100	100	68	50	26
	2100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Adaptive (category I)	2050	100	100	100	100	88	54	29	10	2	2	2	0	0	0	0	0
	2100	100	100	100	100	100	100	74	55	52	52	29	20	3	2	2	0
Adaptive (category II)	2050	100	100	100	100	76	23	2	2	2	0	0	0	0	0	0	0
	2100	100	100	100	100	100	70	52	52	43	20	6	2	2	1	0	0
Adaptive (category III)	2050	100	100	100	100	53	2	2	2	0	0	0	0	0	0	0	0
	2100	100	100	100	100	100	55	52	27	11	2	2	1	0	0	0	0

Huesca

Approach		0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
Static	2050	100	100	100	100	100	100	100	100	100	92	65	42	27	24	16	8
	2100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	98	70
Adaptive (category I)	2050	100	100	100	100	69	21	3	2	1	0	0	0	0	0	0	0
	2100	100	100	100	100	100	68	52	50	27	13	4	2	1	0	0	0
Adaptive (category II)	2050	100	100	100	100	52	4	2	0	0	0	0	0	0	0	0	0
	2100	100	100	100	100	100	52	44	17	5	2	2	0	0	0	0	0
Adaptive (category III)	2050	100	100	100	100	22	2	0	0	0	0	0	0	0	0	0	0
	2100	100	100	100	100	71	44	13	2	2	0	0	0	0	0	0	0

Zaragoza

Approach		0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
Static	2050	100	100	100	100	100	100	100	100	100	100	100	89	64	38	29	23
	2100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Adaptive (category I)	2050	100	100	100	100	77	52	24	8	2	1	0	0	0	0	0	0
	2100	100	100	100	100	100	81	61	53	51	46	27	14	5	2	1	0
Adaptive (category II)	2050	100	100	100	100	54	17	4	2	0	0	0	0	0	0	0	0
	2100	100	100	100	100	100	68	53	51	42	19	9	2	1	0	0	0
Adaptive (category III)	2050	100	100	100	100	52	4	1	0	0	0	0	0	0	0	0	0
	2100	100	100	100	100	90	58	51	33	13	3	2	0	0	0	0	0

Fig. 9. Heatmap with percentage of cases in fuel poverty risk in 2050 and in 2100 according to the income level and behaviour pattern of family units.

being the first one to provide a comprehensive assessment of this socio-economic problem, considering the future climate change scenarios too. Households with an income between 0.8 and 1.5 times the IPREM (roughly between 500 and 939 €) should be classified as “vulnerable”, and those earning less than 0.8 times the IPREM (500 €) should be classified as “especially vulnerable”. These findings have a number of practical implications, considering the salary structure in Spain. According to the latest survey on household income, conducted in 2015 by the National Statistics Institute, 23.8% of Spanish households earn less than 1000 €, and 4.6% less than 500 € [55]; policies specifically targeting fuel poverty could address around one quarter of the Spanish population, and they should be formulated taking into account not only the present situation, but also the future prospects regarding climate change. This study establishes a quantitative framework for detecting fuel poverty *a priori*, thus allowing stakeholders to act well in advance.

This comprehensive study included a great amount of data, and for that reason, its main limitation was the simplification for some variables. At first, the efficiency of the air conditioners, measured by the COP, was fixed at 4.0, which, as stated before, is a representative value for energy-efficient units sold nowadays. However, it could be assumed that in the future, more efficient units with higher COP's will be on the market. Second, household income and energy prices were also considered as a constant, but they could vary in the future. Nonetheless, the results obtained could be representative within the variability range of the price of the ET, similar to the research of Pérez-Fargallo et al. [56] in relation to the social dwellings in Chile. That said, an accurate forecast of those variables for 2050 and 2100 would require a separate econometric analysis, which is beyond the scope of this study. Lastly, the present study has not considered either maintenance cost for the property (i.e. improvements in the thermal envelope), or replacement costs for the air-conditioners during the lifespan of the building, which was estimated at 80 years. Nonetheless, as the energy renovation rate of the existing buildings is still slow [57], meeting the low-carbon goals of the building stock by 2050 is in doubt. Again, these factors should be considered in a separate analysis, which would require accurate estimations as a function of macroeconomic variables. These limitations call for further research aimed at clarifying the influence of the aforementioned variables on the incidence of fuel poverty.

An additional note of caution is due regarding other aspects of the study. Firstly, although the operational patterns are representative of the predominant use of residential spaces, they could differ for specific situations. An example of this could be patterns that emerged from the Covid-19 pandemic [58], due to which teleworking has increased the time spent at home. Second, the results work on the assumption that families always strive to achieve thermal comfort, and for that reason, the assessment of fuel poverty is based on the 2 M indicator. However, other indicators were not analysed, such as the M/2 indicator, which specifically targets households with unusually low energy expenditure. At first sight, they may not be fuel poor, but a deeper analysis reveals that this low expenditure on energy may hide acute poverty, because they would assume thermal discomfort as something inevitable, and use the money for more pressing needs, such as food and water. The existing literature defined this as “heat or eat”, but in this case, we would be talking about “cool or food”.

Despite these limitations, the study certainly adds to our understanding of fuel poverty from a novel perspective, placing the focus on climate consciousness and behavioural aspects, instead on econometric analysis or public policies to tackle climate change merely based on technological upgrades, maintenance or replacement of the building stock and its equipment. This aspect is also related to the reliability of the results in other countries in the Mediterranean area, such as Italy or Greece. Due to economic, climatic and technological similarities, the same savings results are to be expected with mixed mode. In this sense, the results carried out on a European scale [59] have shown the similarities among these countries in the application of adaptive natural ventilation. Likewise, it is to be expected that these results are also valid in developing countries. In this sense, Geng et al. [60] highlighted that the energy efficiency of European countries is better than the world average. Therefore, the application of adaptive strategies can lead to more significant savings in other regions that have a great possibility of applying natural ventilation.

This new understanding should help improve predictions of the impact of climate change on the underprivileged households, and to seize the potential of the mixed mode, combining adaptive setpoint temperatures and natural ventilation. A key policy priority should therefore prioritize two areas: first, investment in low-cost monitoring software in the form of mobile applications, which could inform the dwellers about the actions that would deliver instant savings in the electricity consumption. Second, long-term policies to target the especially vulnerable households, that is, those earning less than 500 €a month, and rescue them from fuel poverty, considering a time span of at least 80 years in the future. In any case, future steps of this research should analyse the possibilities of using optimization processes in a similar way to that used in other sectors [61,62]. Likewise, the energy savings obtained and the construction characteristics in developing countries should be addressed in future works.

Credit author statement

David Bienvenido-Huertas, Conceptualization, Methodology, Writing – original draft. Daniel Sánchez-García, Validation, Visualization, Investigation. Carlos Rubio-Bellido, Formal analysis, Supervision, Funding acquisition. Jesús A. Pulido-Arcas, Data curation, Writing- Reviewing and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

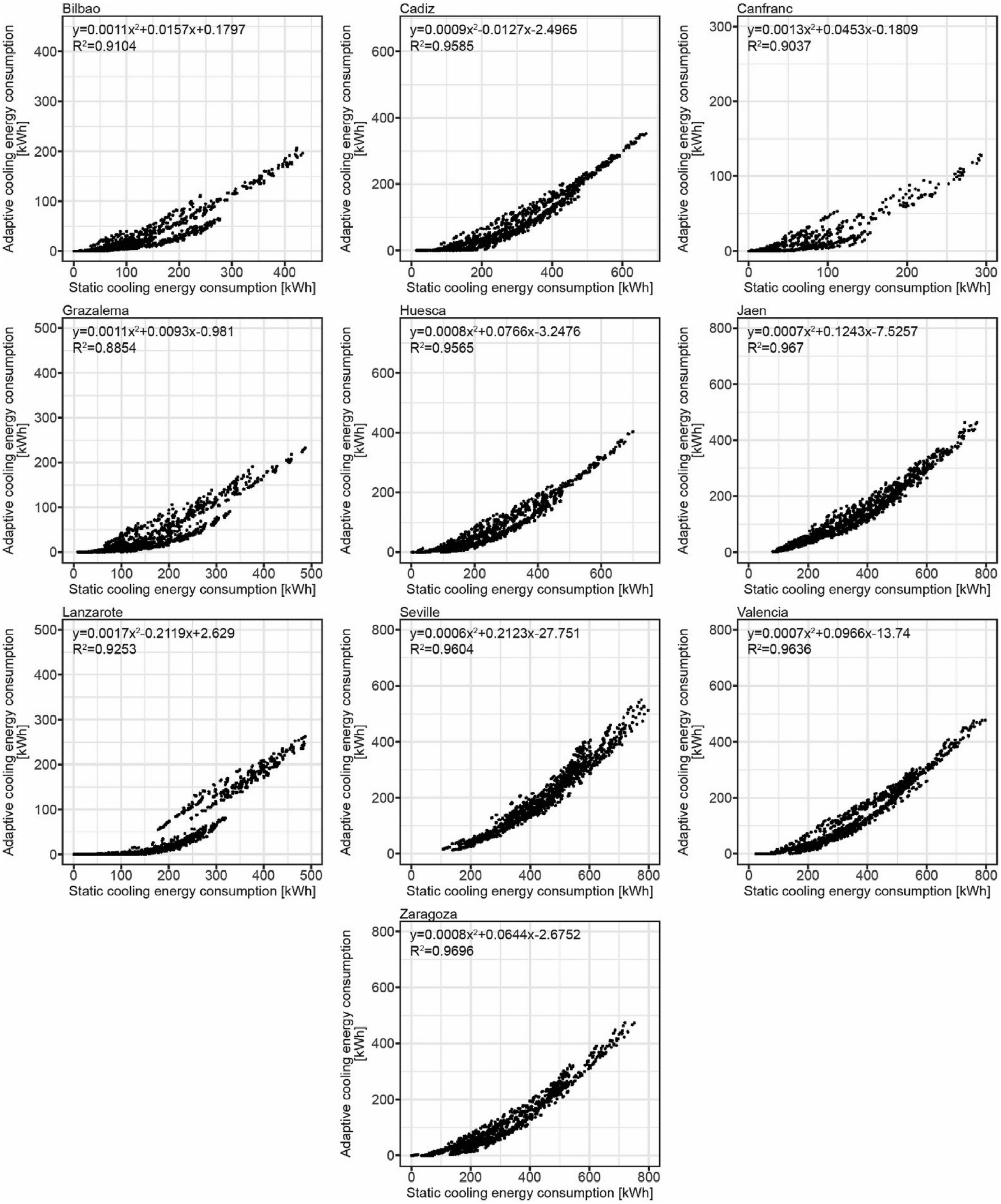

Fig. A1. Point cloud between the energy consumption values obtained with the adaptive patterns of category I (mixed-mode) and the energy consumption with the static patterns (only air conditioning).

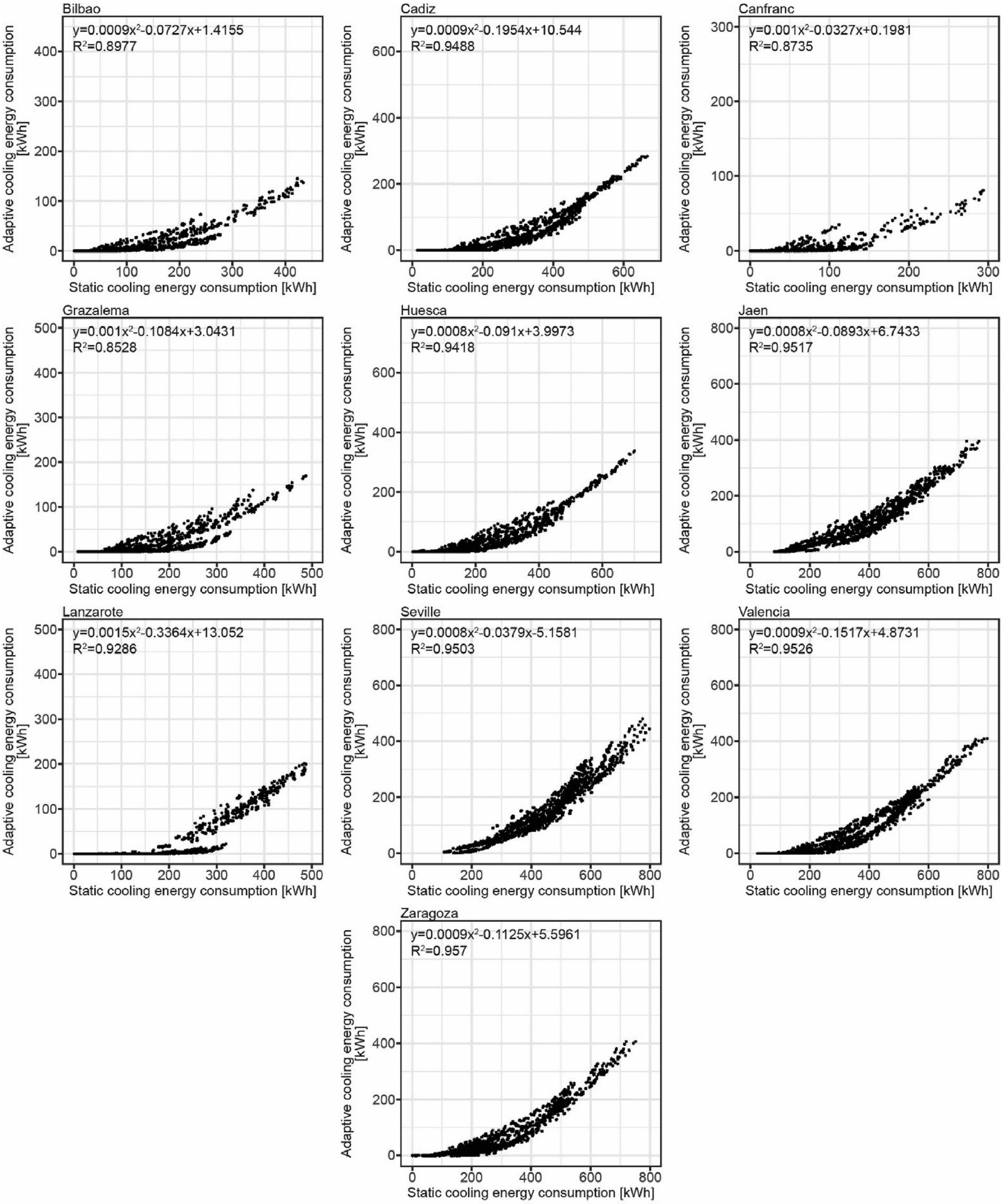

Fig. A2. Point cloud between the energy consumption values obtained with adaptive patterns of category II (mixed-mode) and the energy consumption with the static patterns (only air conditioning).

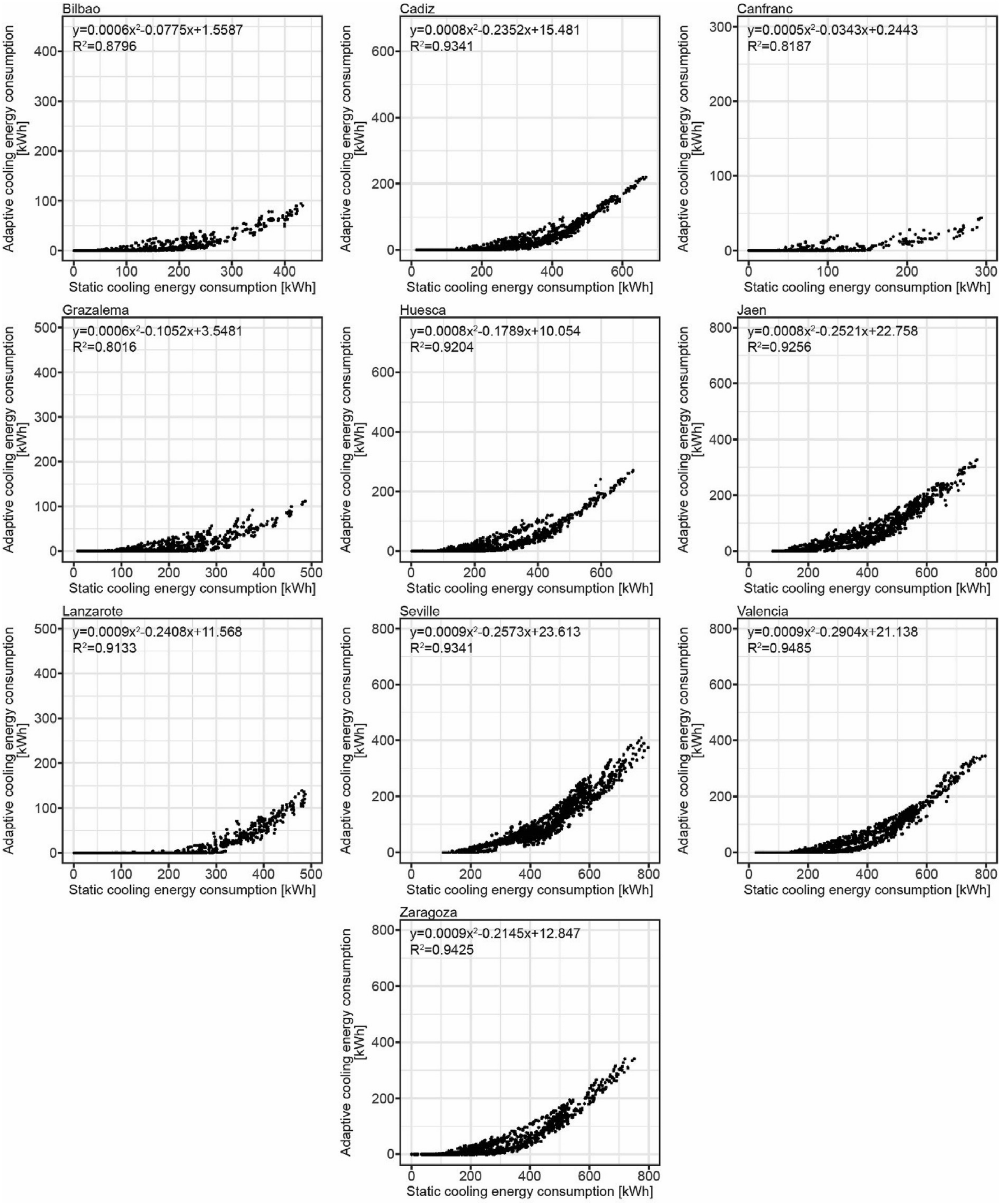

Fig. A3. Point cloud between the energy consumption values obtained with adaptive patterns of category III (mixed-mode) and the energy consumption with the static patterns (only air conditioning).

Appendix B

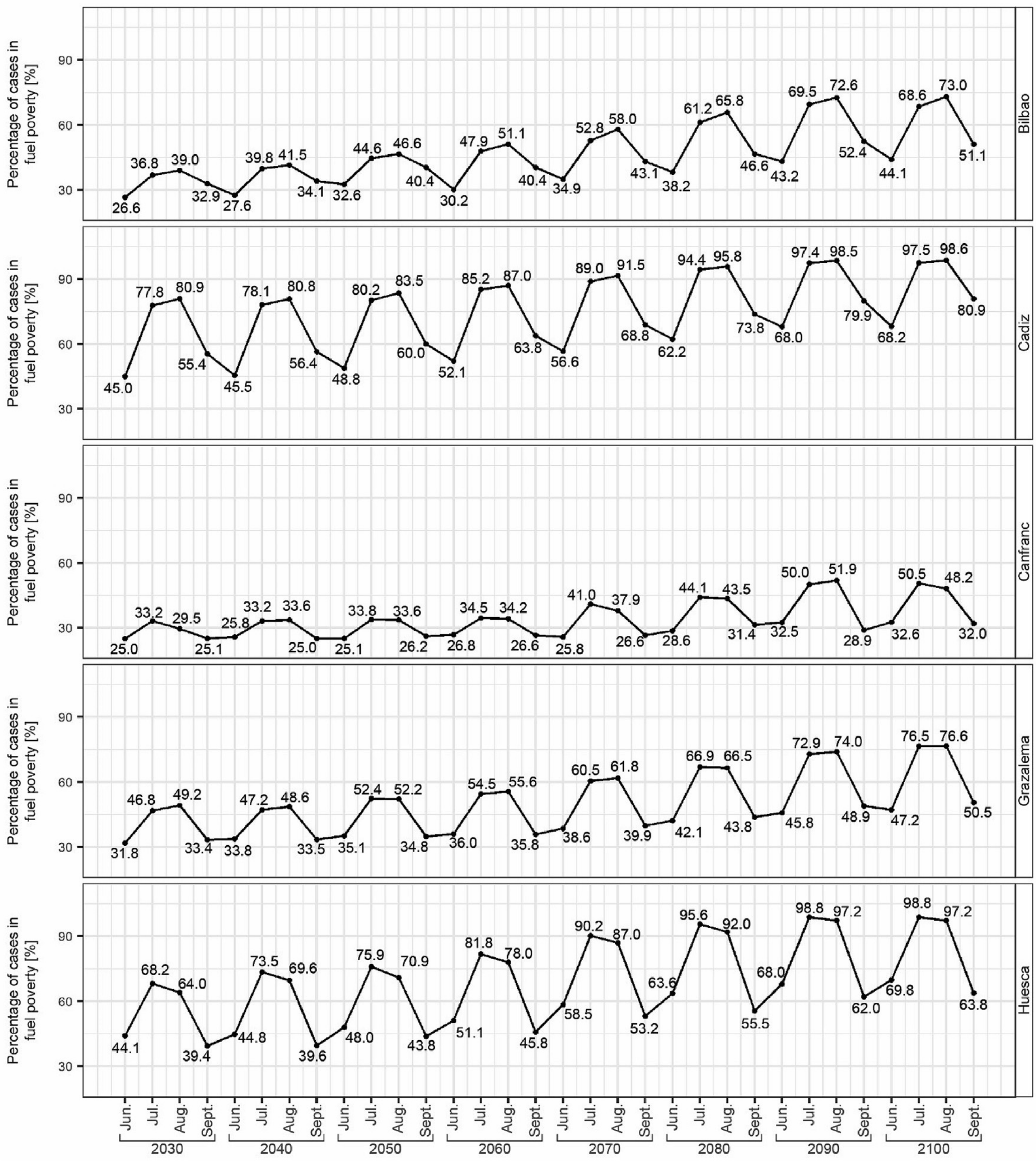

Fig. B1. Evolution of the percentage of fuel poverty cases in the summer months throughout the 21st century using static operational patterns. Results corresponding to Bilbao, Cadiz, Canfranc, Grazalema and Huesca.

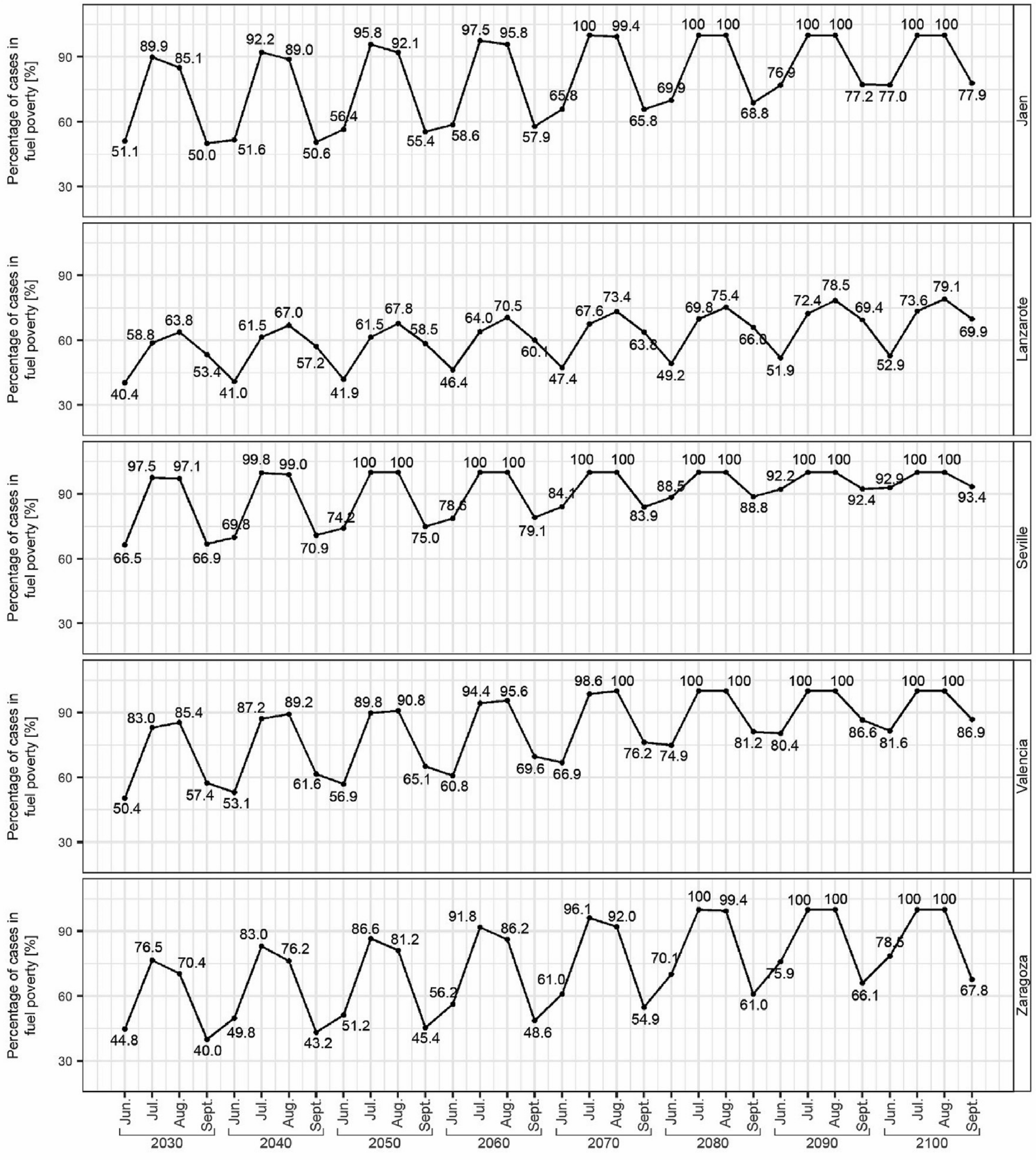

Fig. B2. Evolution of the percentage of fuel poverty cases in the summer months throughout the 21st century using static operational patterns. Results corresponding to Jaen, Lanzarote, Seville, Valencia and Zaragoza.

Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2021.121636.

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