Title:
Adaptive setpoint temperatures to reduce the risk of energy poverty? A local case study in Seville

Abstract:
The reduction of energy poverty is among the main current challenges. One of the recent approaches is based on the reduction of the energy consumption through the climate adaptability of users. This research analyses the possibility of using adaptive setpoint temperatures to reduce the risk of energy poverty. A total of 6,528 cases are considered in the south of Spain in 2015 and 2016 with actual data of temperature, hourly prices from the Voluntary Price for the Small Consumer, and the mean household incomes in both years. The energy consumption and expense are compared to both the static setpoints established by the Spanish Technical Building Code and the adaptive setpoints based on EN 16798-1:2019. In the annual calculation, by using both static and adaptive setpoints, the results show that the situation of energy poverty would only affect the family units belonging to the first decile of incomes. However, a monthly analysis identifies that the coldest or warmest months influence more deciles: for example, January 2015 affected until decile 8. The results also show that adaptive setpoints could reduce the risk of energy poverty in most cases, being more significant in Categories II and III from EN 16798-1:2019, in which this risk is reduced in all months of the year and in all deciles. This study aims to throw light on the use of HVAC systems according to the adaptation of users to reduce monthly the risk of energy poverty.

Highlights

- Performing monthly analyses of energy poverty to find critical months
- A total of 6,528 cases are used to assess energy poverty
- Applying adaptive setpoints to reduce energy poverty

Keywords
Energy poverty; adaptive setpoint temperatures; dwellings; adaptive comfort; electricity price.

1. Introduction

The building stock is characterized by a deficient energy behaviour [1,2]. One of the main aspects of this issue is its age. For instance, in southern countries, 70% of building stock was built in periods before the regulations on energy efficiency [3], thus making the treatment of cases of energy poverty (EP) and appropriate strategies to improve the energy performance of the building stock something of a challenge, particularly considering the financing difficulties of family units of EP [4]. To understand this aspect, EP should be clearly explained. The Spanish government, after a process of mobilization by various sectors [5], defined EP in its National Strategy against Energy Poverty 2019-2024 as the situation in which a household cannot pay the electricity bill (due to a low income), and that situation may be worsened by having an energy-inefficient dwelling [6]. EP may manifest itself through various factors, such as the inability to maintain an adequate temperature in the dwelling, the delay in paying bills, an excessively low energy expenditure, and an expenditure on energy supplies that is disproportionate over the level of income [6]. Many studies have developed the concept of EP since its introduction in 1979 by Isherwood and Hancock [7]. For its quantification and evaluation, the European Energy Poverty Observatory established several indicators: (i) arrears on utility bills, (ii) inability to keep home adequately warm, (iii) low absolute energy expenditure (M/2), and (iv) high share of energy expenditure in income (2M). The 2M indicator is not a static value and can be easily determined according to the characteristics of each country [8]. Furthermore, the use of the criterion of the average percentage of the household energy expenditure at a national level with the 2M indicator is justified within the framework of the 10% threshold established by Boardman [9]. A recent study carried out in Spain determined that the threshold of the 2M indicator in the country was close to the value of 10% [10].

A similar aspect in all indicators is that the risk of EP is not therefore associated with low-income families; it can also be the result of a poor energy performance of buildings [8,11]. In addition, the excessive expense of the energy consumption leads to several impacts, such as the fact that users try to face with a greater number of hours of thermal discomfort [12], thus causing adverse effects in people's physical health [13–15] as well as the risk of death [16,17]. Generally, the impact of EP has been associated with the people's health in cold zones. Recent studies, however, stressed the impact of high temperatures on health [18,19], so it could be a risk for the families in a situation of vulnerability due to the time spent in dwellings. Also, confinement episodes such as the coronavirus pandemic [20] could force people to stay long periods in their dwellings.

After analysing quantified data, over 124 millions of people in the European Union are estimated to be in risk of EP [21]. As for Spain, there are many studies proving the existence of the problem of EP in the country. The first of these studies consisted of cross-sectional analyses carried out in Spain by Ecoserveis through the European fuel Poverty and Energy Efficiency (EPEE) Project [22]. Later, Tirado Herrero [23] evaluated the relationship of job creation linked to interventions as regards energy efficiency in the residential sector, thus making the first diagnosis on EP. Then, a study conducted in 2014 [24] identified an increase of EP in households where unemployed lived. One out of three unemployed households (around 1.2 million of people) spent more than 10% of their incomes in paying domestic energy consumption in 2012, thus leading to an increase of 142% of the number of households in EP in a period of 5 years. In 2015, Sánchez-Guevara Sánchez et al. [25] determined that the 24% of households in the Community of Madrid was in EP and established the energy improvement of the building stock as the most effective measure to alleviate EP. In 2016, the most important study at a national level was conducted [26]. This study showed that 5.1 million of people in Spain (11% of households) could not keep their house warm during winter, thus increasing the number of households in EP by 22% in only two years. Likewise, a recent study by Sánchez-Guevara Sánchez et al. [27] verified the existence of a gender gap related to EP cases in Madrid.

Likewise, the reduction of cases of EP in relation to the fight against climate change is crucial due to the reduction potential of greenhouse gas emissions by decreasing household energy consumption [28] which would mean in turn a reduction of the cases of EP [29]. For example, the promotion of energy efficiency, self-consumption or the energy transition could reduce EP [30]. However, this relation could be limited as, in certain cases, the improvement of energy efficiency in buildings does not imply the extinction of EP cases or alleviation of climate change due to the possible rebound effects generated by the saving in household electricity invoices. These rebound effects are understood as the new expenses of family units living in energy improved buildings [31,32]. So, a rebound effect could be the use of a greater heating setpoint temperature before the energy renovation of the building (e.g., 22 °C instead of 20 °C), which could imply a greater energy consumption [33]. Likewise, another aspect related between EP and climate change is the progressive increase of prices of the electrical energy produced by non-renewable sources to each the energy produced by renewable sources. This increase of rates, although is aimed to encourage the production of clean energy, could influence the increase of EP cases [34]. Another aspect related to the progressive increase in temperatures and EP was indicated in the studies by Sánchez-Guevara Sánchez et al. [35,36], which determined that the progressive modification of climate would result in the establishment of new definitions of EP to include the expected greater cooling energy demand (especially in southern European countries).

An essential aspect of EP is the energy consumption required for users to be within appropriate thermal comfort levels [37]. This thermal comfort guarantees that users are not in situations which could imply the appearance of illnesses. For this purpose, users use heating and cooling systems. So, an appropriate strategy to guarantee a lower number of EP cases is the reduction of HVAC system energy consumption by ensuring appropriate conditions of thermal comfort. There are many studies analysing the possibilities of improving envelopes [38–40] or HVAC systems [41,42] to reduce building energy consumption. However, the implementation of these measures could be a challenge for low-income families [4].

Recent studies stressed the potential of applying adaptive thermal comfort strategies in buildings [43–46]. These studies were based on the possibilities of reduce HVAC system energy consumption by modifying setpoint temperatures [46–48]. Adaptive thermal comfort strategies therefore consider the possibility of using adaptive setpoint temperatures so that there is the possibility of considering thermal adaptability of people under external climate variations. Also, recent studies used these adaptive setpoint temperatures to save residential building energy consumption up to 50% by modifying the operational patterns of HVAC systems: (i) Sánchez-García et al. [45,49] evaluated in Avila, Madrid and Seville the possibility of applying modifications to the operational pattern of the Spanish Building Technical Code by using adaptive setpoint temperatures with the European adaptive thermal comfort standard. Energy savings between 10% and 46% were obtained; (ii) in relation to the optimal determination of the upper and lower limits for adaptive setpoint temperatures, Bienvenido-Huertas et al. [44] analysed the optimal weight to calculate the running mean outdoor temperature in the same cities (Avila, Madrid and Seville), thus obtaining additional savings with the new setpoint temperatures; and (iii) in a recent study, Sánchez-García et al. [50] studied the application of adaptive setpoint temperatures according to the European standard in a case study located in the main cities of Europe. The analysis was performed by evaluating energy savings in the various climate change scenarios provided by the Intergovernmental Panel on Climate Change: Special Report on Emissions Scenarios (SRES) and Representative Concentration Pathways (RCP). Greater savings were obtained in the cooling energy consumption than in the heating energy consumption.

In addition, this type of strategy could greatly vary the analysis of the household energy expenditure. In this regard, Sánchez-Guevara Sánchez et al. [51] indicated that the families using adaptive strategies could modify the Building Energy Rate (BER) and payback periods. This aspect is based on the energy savings achieved with a more sustainable and appropriate use of HVAC systems, thus guaranteeing users' thermal comfort.

1.1. Aim of this study

An analysis framework to evaluate the decrease in EP cases with adaptive setpoint temperatures is required for a dual purpose: (i) to consider adaptive setpoint temperatures as a mitigation strategy for EP risks; and (ii) to consider this type of users' behaviour in household EP evaluations. For this reason, social dwellings built throughout the 20th century in the south of Spain were analysed because of both the deficient energy performance of the existing building stock and the progressive risk of EP in the region [52]. Likewise, the reduction of the energy consumption in warm zones, such as the south of Europe, and the achievement of nearly zero energy consumption buildings is a challenge [53]. The analysis of the risk of EP and the possibility of using adaptive setpoint temperatures would therefore ensure a better energy performance of the building stock, thus guaranteeing always the thermal comfort of users without making economic investments. This research analysed a combination of 6,528 cases. The cases were simulated with EnergyPlus by using actual temperature data for 2015 and 2016 and based on both the hourly rates from the Voluntary Price for the Small Consumer and the mean household incomes in both years. Also, the potential of reducing the cases of family units allocating more than 10% of their incomes to electricity invoices by adopting adaptive setpoint temperatures.

The structure of this paper starts with the methodology included in Section 2. This section details the thermal comfort models analysed in this research, as well as the case studies, climate data, income values, and the procedure used to determine the energy cost. Section 3 discusses the results by analysing first the results of energy poverty by considering some patterns of static setpoint temperatures, and then, the effect of considering adaptive setpoint temperatures. Section 4 summarises the main conclusions.

2. Methodology

2.1. Thermal comfort model

Currently, the Spanish regulation as regards energy efficiency of buildings (the Spanish Building Technical Code (CTE) [54]) considers an operational pattern of setpoint temperatures by users based on a static thermal comfort model (see Fig. 1). This aspect implies that the use of setpoint temperatures does not change according to the external temperature and always have the same pattern: (i) in cold periods, the heating temperature is 20 °C during the day and 17 °C at night, and (ii) in hot periods, the cooling temperature is 25 °C during the day and 27 °C at night. These operational patterns ensure the thermal comfort of users with efficient setpoint temperatures. However, several studies stressed the high energy consumption associated with the use of these setpoint temperatures [38,45] as temperatures implying a greater consumption of HVAC systems (e.g., 25 °C in cooling) are associated with the hours of the greatest demand (e.g., 4 p.m.).

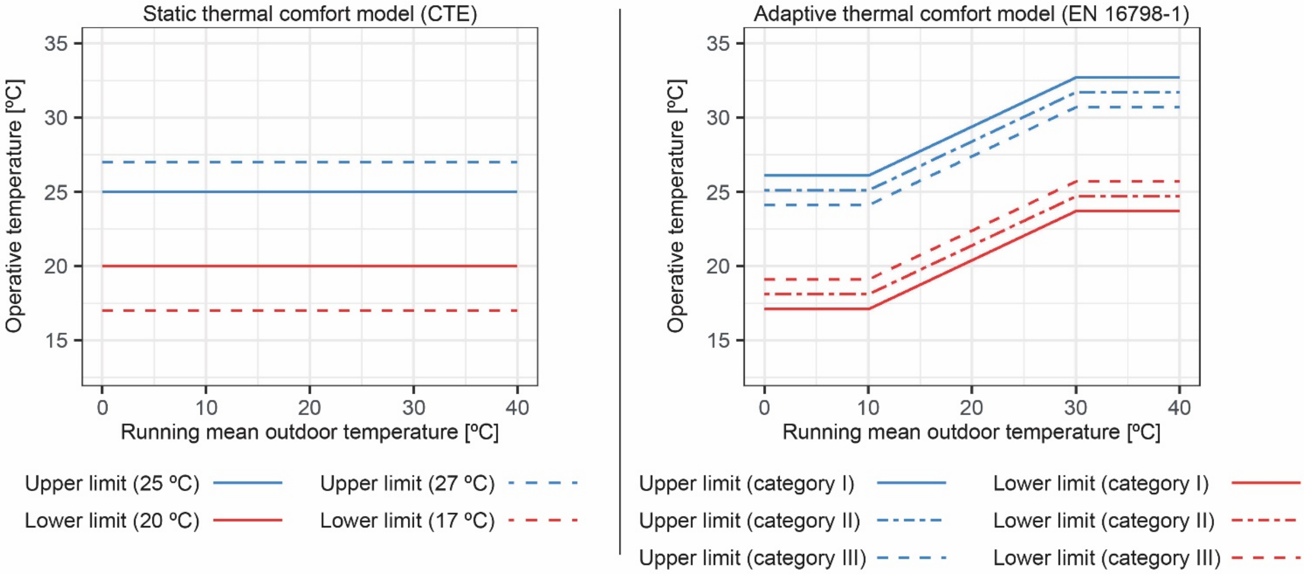

Fig. 1. Values of static (CTE) and adaptive setpoint temperatures (EN 16798-1:2019).

In addition, the potential of using adaptive setpoint temperatures as a measure to reduce the building energy consumption without making economic investments is also stressed [38]. Several studies, such as those by Parkinson et al. [55] and Hoyt et al. [56], showed the great potential of energy saving obtained by nudging the setpoint temperatures. This aspect could be an opportunity to reduce the cases of EP in most vulnerable population groups. Adaptive setpoint temperatures are setpoint temperatures that vary according to the oscillations of the daily external temperature of the previous days and are obtained according to an adaptive thermal comfort model. As for Europe, the adaptive thermal comfort model is included in EN 16798-1:2019 [57]. This standard is the modification of the previous adaptive thermal comfort standard (EN 15251:2007 [58]) and establishes 3 categories of lower and upper limits among which the operative temperature should oscillate. Each category belongs to different levels of thermal acceptability, so category I corresponds to users with a lower thermal adaptation than those from category III, whose limits present a greater thermal gradient. The limit values of each category are obtained through linear correlations with respect to the running mean outdoor temperature (T_{rm}) (see Eqs. (1)-(6)). T_{rm} is obtained by a weighted sum of daily mean external temperatures from the previous days (see Eq. (7)). Also, T_{rm} will not be only useful to obtain the limits of the internal operative temperature, but also to determine whether the adaptive comfort model from EN 16798-1:2019 could be applied. In this regard, EN 16798-1:2019 establishes that the adaptive comfort model could be applied if T_{rm} is between 10 °C and 30 °C.

$$Upper\ limit\ (Category\ I) = 0.33 \cdot T_{rm} + 20.8 \quad [°C] \quad (10 \le T_{rm} \le 30) \tag{1}$$

$$Lower\ limit\ (Category\ I) = 0.33 \cdot T_{rm} + 15.8 \quad [°C] \quad (10 \le T_{rm} \le 30) \tag{2}$$

$$Upper\ limit\ (Category\ II) = 0.33 \cdot T_{rm} + 21.8 \quad [°C] \quad (10 \le T_{rm} \le 30) \tag{3}$$

$$Lower\ limit\ (Category\ II) = 0.33 \cdot T_{rm} + 14.8 \quad [°C] \qquad (10 \leq T_{rm} \leq 30) \tag{4}$$

$$Upper\ limit\ (Category\ III) = 0.33 \cdot T_{rm} + 22.8 \quad [°C] \qquad (10 \leq T_{rm} \leq 30) \tag{5}$$

$$Lower\ limit\ (Category\ III) = 0.33 \cdot T_{rm} + 13.8 \quad [°C] \qquad (10 \leq T_{rm} \leq 30) \tag{6}$$

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

2.2. Procedure to obtain the dataset

The dataset analysed in this research has been obtained through a dynamic simulation and analysis of the EP risk based on grouping the region's income by deciles. Fig. 2 summarizes the steps followed in the study. First, a case study of social housing was combined with 16 types of façade. Each of these combinations was analysed in 8 orientations and with 51 types of HVAC systems, generating a total of 6,528 combinations according to the type of façade, orientation and HVAC system. Then, each combination was analysed using a thermal comfort model (static or adaptive) in two different years (2015 and 2016). With the energy consumption data obtained, the energy expenditure associated with each combination was calculated. Also, the EP risk was determined in the deciles of income obtained. For this purpose, the maximum and minimum data of each decile were used to simplify the discussion of the results. EP was assessed at an annual and monthly scale.

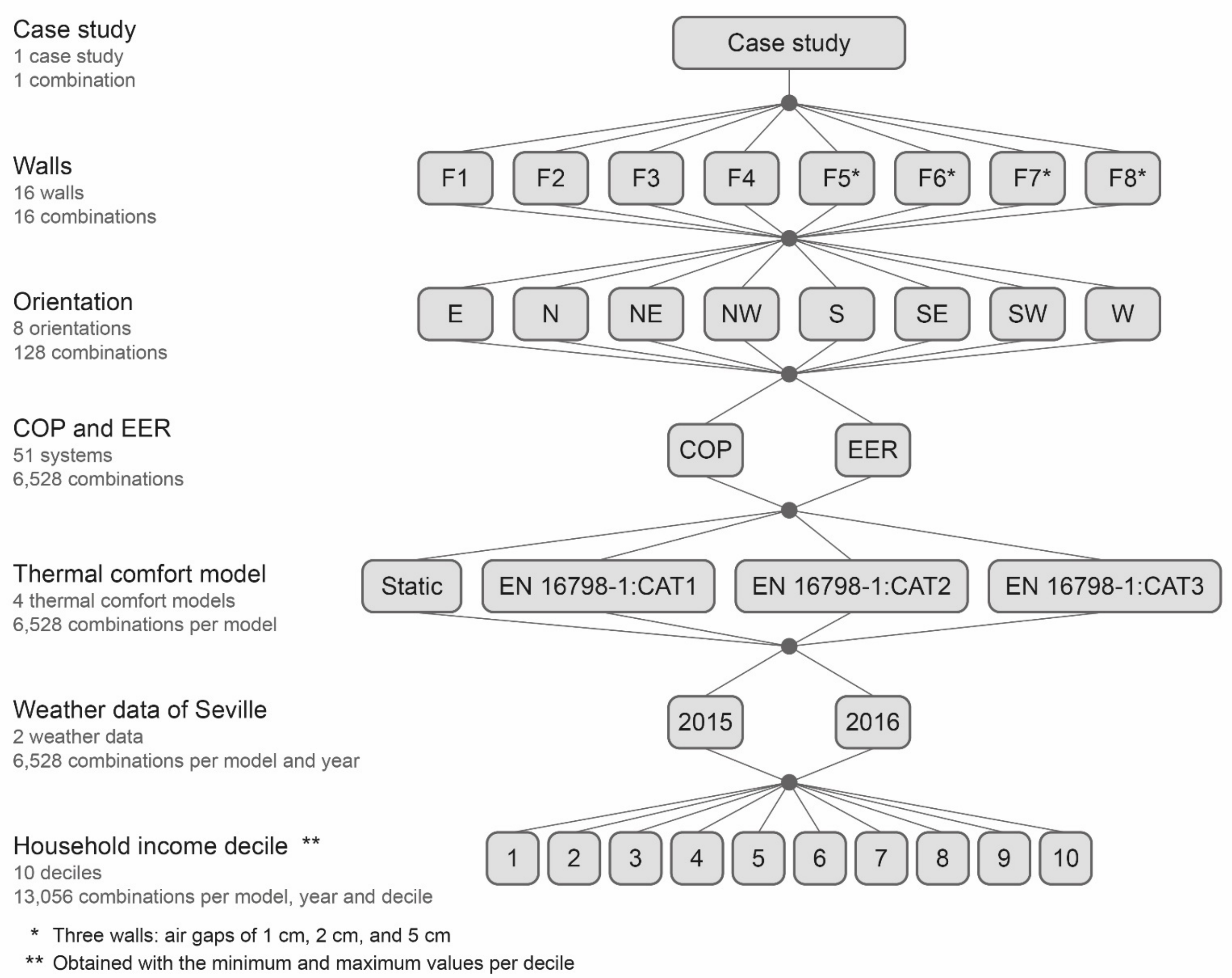

Fig. 2. Workflow of the process to obtain the cases.

2.2.1. Case study

The goal of this study is to analyse the impact of adaptive thermal comfort models in energy poverty risk of social dwellings from the 20th century in the south of Spain. The study area is the city of Seville because of its great building stock of social dwellings built before the first regulation as regards energy efficiency in Spain (the NBE-CT-79 [59] in 1979). At the beginning of the 20th century, Seville had a housing deficit [60]. After the Spanish Civil War, there was a demographic increase which in turn increased the number of buildings in the city, particularly social dwellings [60]. For example, a total of 13,000 social dwellings were built in the period between the Spanish Civil War and 1950 [61]. After analysing the construction year of the building stock in Seville, the high number of buildings built before the NBE-CT-79 was verified [59]. According to the Spanish Institute of Statistics [62], 66.43% of the building stock existing in the city was built before the NBE-CT-79. This aspect shows the high percentage of buildings in Seville with a low energy performance as buildings before the NBE-CT-79 were characterized by not having insulation in their designs, but a high thermal transmittance [1].

Table 1. Number of buildings built in Seville per period.

Period	Number of buildings
Before 1900	1,001
From 1900 to 1920	696
From 1921 to 1940	2,645
From 1941 to 1950	3,157
From 1951 to 1960	8,906
From 1961 to 1970	11,593
From 1971 to 1980	9,609
From 1981 to 1990	7,000
From 1991 to 2001	6,860
From 2002 to 2011	5,139

For this reason, this analysed the social dwellings built in Seville before the NBE-CT-79. A representative case study of these dwellings was chosen (see Fig. 3). The case study is a dwelling located on the fourth floor in a building built in the seventies in the Triana district (Seville). The surface of the dwelling is 65 m^2, so it is representative of most social dwellings of the period [63].

Nevertheless, this case study was not analysed as the only case study as the model designed was used to be combined with several factors which presented various combinations of representative cases of the existing social dwellings in Seville. First, the dwelling was analysed with various façade typologies. Fig. 4 includes the 8 façade typologies analysed. These typologies correspond to the most representative façades of the building stock of social dwellings from the 20th century in Seville which were included in cataloguing studies [63]. The designs of façade with air gap (i.e., designs F5, F6, F7, and F8) were analysed with 3 thicknesses of air gap: 1, 2, and 5 cm. So, the total number of façades were 16. Regarding windows, the design was a metal framework without a thermal bridge break and monolithic glasses of 3 mm of thickness because it is the most used window typology in social dwellings before 1979. The shading elements of the case study are the balconies of the building itself. Also, each design of case study (i.e., the case study with a façade design) was analysed in 8 orientations in the 4 cardinal points (E, N, S, and W) and their bisectors (NE, NW, SE, and SW)

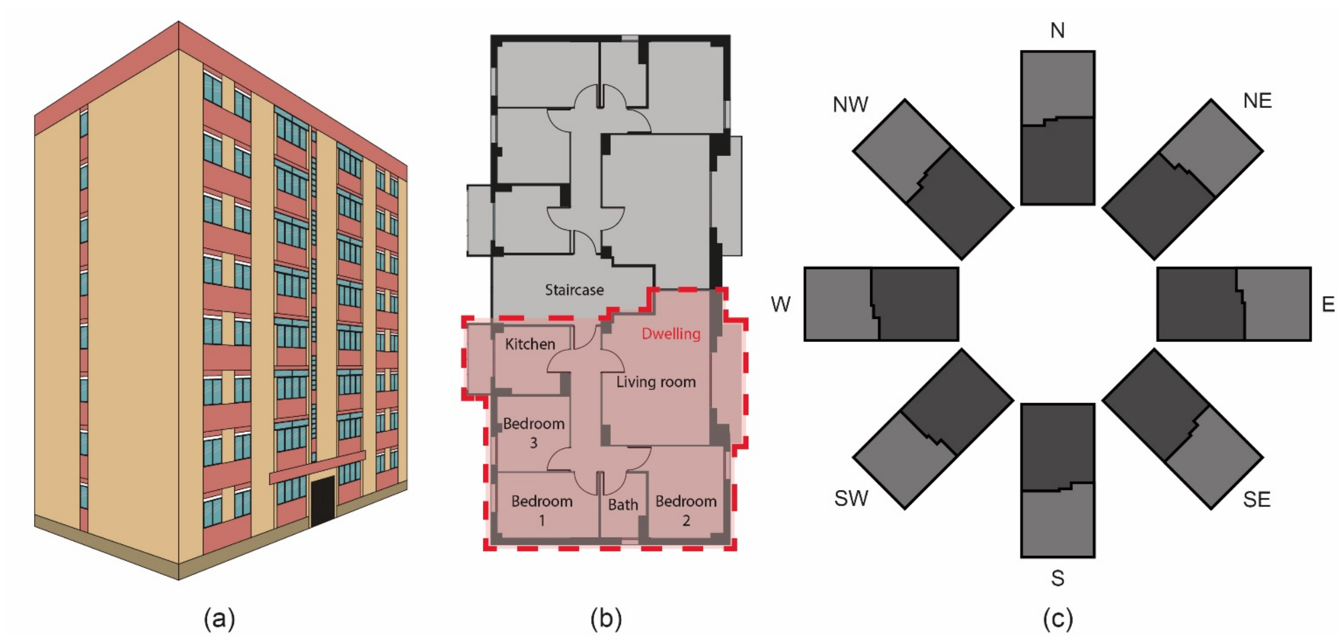

Fig. 3. Case study used in this research: (a) 3D view of the building, (b) the dwelling analysed, and (c) modification of orientations in the case study.

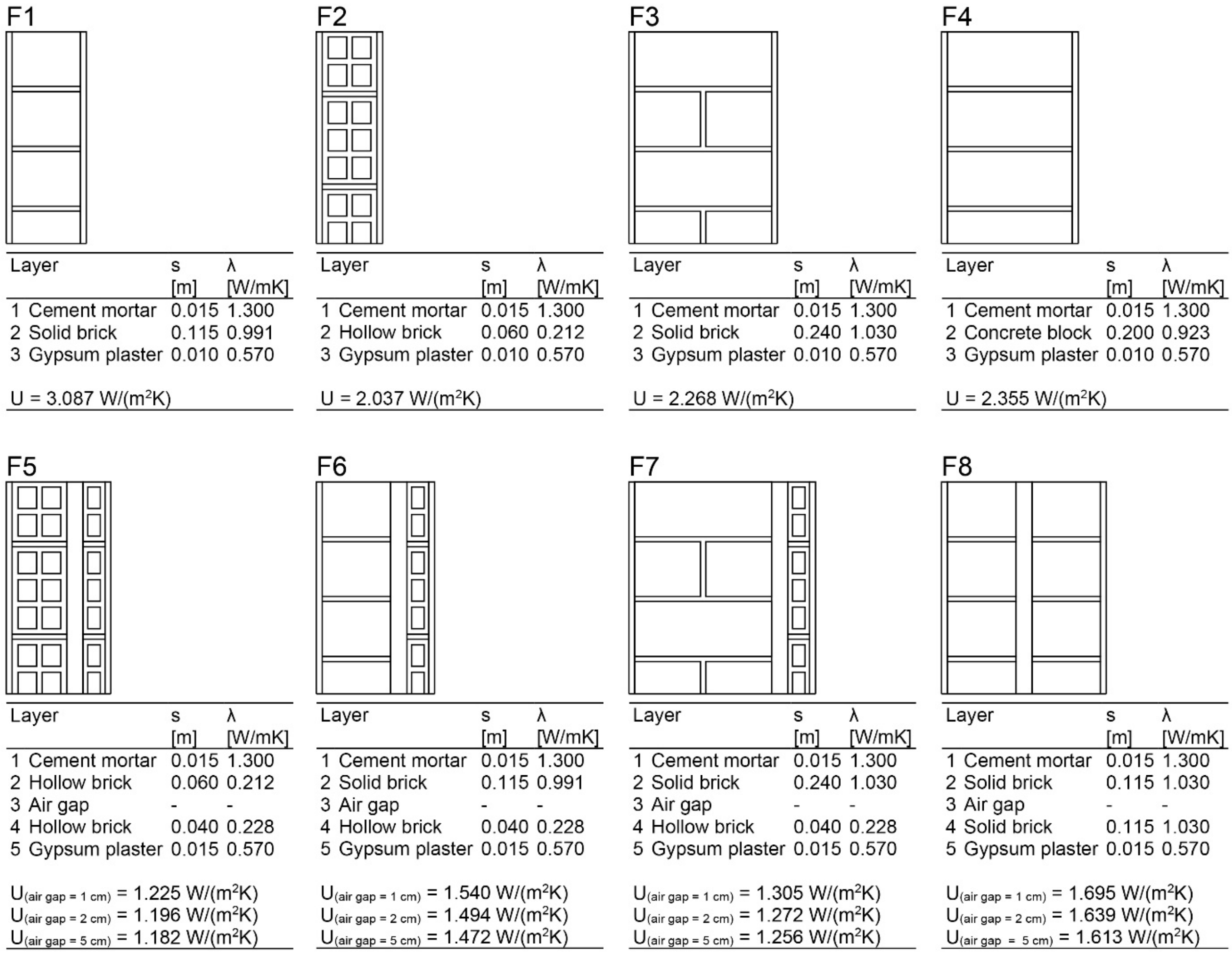

Fig. 4. Façades considered in this research. s and λ are the thickness and the thermal conductivity of layers.

Regarding the size of the unit family, it corresponds to a family of two adults and one minor. This household size is representative of the average size of Spanish households. In this sense, the Spanish Institute of Statistics [64] indicated that the average size of Spanish households is 2.5. Therefore, the consideration of a family unit of two adults and one minor is representative with the average data for the country. The load profile defined in the CTE for residential use was used (see Table 2). This use profile was considered representative of the way of use of Spanish dwellings. The occupancy of the case study varies depending on the day: from Monday to Friday, the occupancy varies between 0.54 W/m² and 2.15 W/m², whereas in weekends the case study has an occupancy of 2.15 W/m². The load from both lighting devices and equipment has the same use profile, which varies between 0.44 W/m² and 4.40 W/m² according to the hour of the day. The possibility of natural ventilation in the night hours (between 0:00 and 6:59) of summer of 4 ach was considered. Regarding heating and cooling systems, the operative temperature was always within the thermal comfort limits of each model: either CTE (static model) or EN 16798-1:2019 (adaptive model) (see Table 3). This aspect implied that users never presented a thermal discomfort. The adaptive setpoint temperatures were independently analysed for the 3 categories from EN 16798-1:2019. Due to the possibility variation by using heating and cooling system throughout the year, the possibility of being used at any moment of the year was considered. This aspect is different from the criteria of use included in the CTE, which establishes that the use of air conditioning system is only limited to the months between June and September. Regarding heating and cooling systems, there were different systems of heat pump which varied Coefficient of Performance (COP) and Energy Efficiency Ratio (EER) indexes. There were also combinations of heat pump for cooling and heating through by electricity radiators based on the most used types of HVAC system by the residents in the south of Spain [65]. There was therefore a combination of 51 systems.

Table 2. Hourly distribution of loads in the case study.

Loads		Time period					
		0:00 – 6:59	07:00 – 14:59	15:00 – 17:59	18:00 – 18:59	19:00 – 22:59	23:00 – 23:59
Sensible load (W/m²)	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
Latent load (W/m²)	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 (W/m²)	Weekdays and weekend	0.44	1.32	1.32	2.20	4.40	2.20

Equipment (W/m²)	Weekdays and weekend	0.44	1.32	1.32	2.20	4.40	2.20

Table 3. Thermal comfort models and setpoint temperatures.

Model	Category	Setpoint temperature	
		Upper limit	Lower limit
CTE	-	27 (0:00 – 06:59) 25 (07:00 – 23:59)	17 (00:00 – 06:59) 20 (07:00 – 23:59)
EN 16798-1:2019	Category I	Eq. (1)	Eq. (2)
	Category II	Eq. (3)	Eq. (4)
	Category III	Eq. (4)	Eq. (6)

By combining 16 façade designs, 8 orientation, and 51 systems, there was a total of 6,528 cases. In each, the energy consumption obtained by heating and cooling system, and lighting and other devices was analysed. The heating and cooling consumption was obtained based on the static model from CTE and on the 3 categories from EN 16798-1:2019. These simulations were performed with EnergyPlus v9.1. In these simulations, the definition of EnergyPlus Weather (EPW) files was important. As income data of families in Seville were available for 2015 and 2016 (for further information, go to subsection 2.3.), the case studies were analysed for the climate conditions of these two years. For this purpose, hourly data of temperature and moisture from 2015 and 2016 in Seville were obtained through the Spanish Meteorological Agency (see Fig. 5). These data were used to generate EPW of Seville for 2015 and 2016. So, this study analysed the results obtained in 6,528, analysed with 4 thermal comfort models (one static model and three adaptive models) and in two years (2015 and 2016). It is important to stress the variations in the external temperature that 2015 and 2016 present (see Table 4). In 2015, the two first months of the year were characterized by low temperatures, whereas in 2016, the minimum temperatures were in general greater than those from 2015. Likewise, July 2015 was characterized by recording the greatest temperatures throughout the year, whereas in 2016, the values recorded in July and August were almost identical.

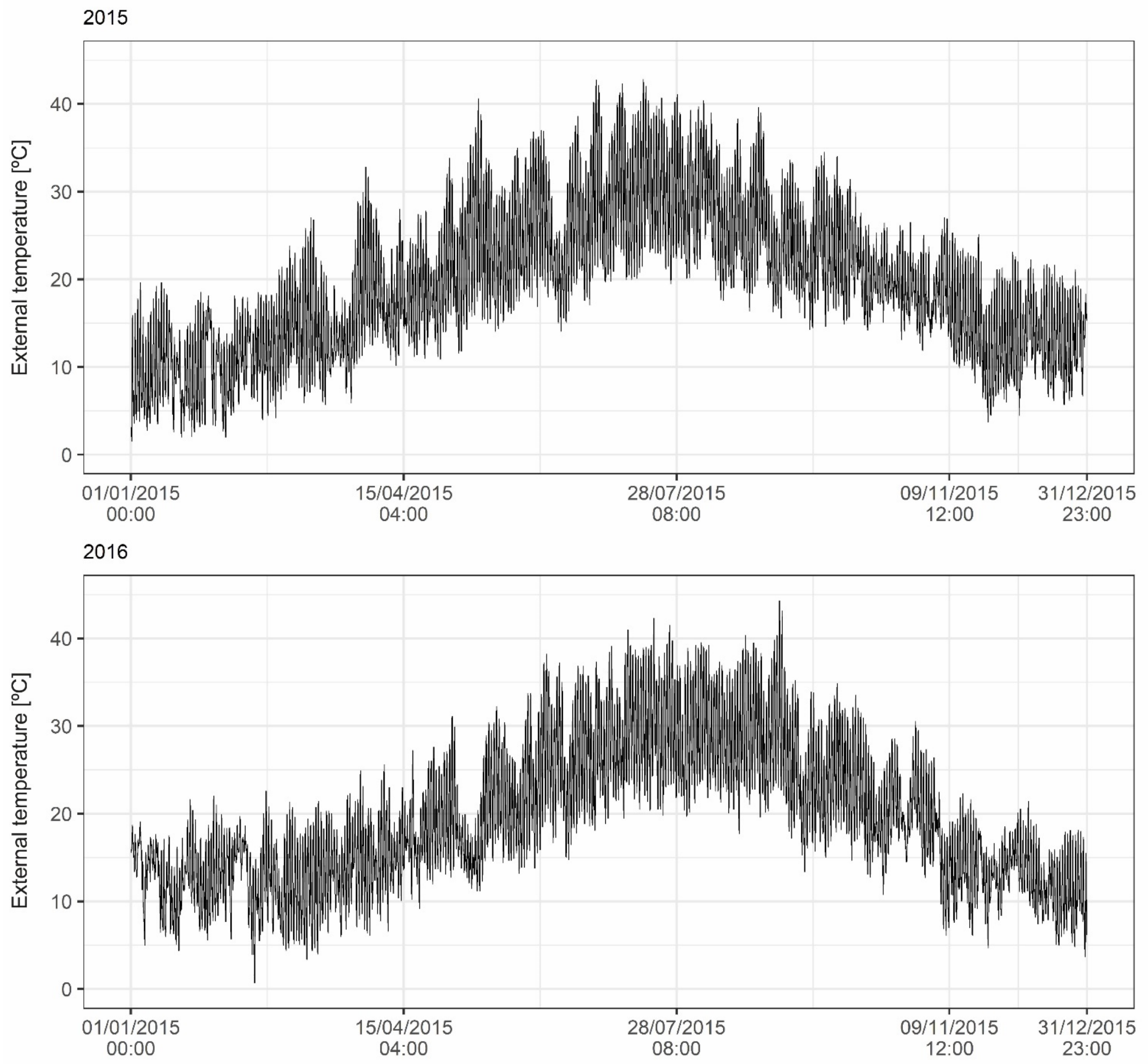

Fig. 5. External temperature values recorded in Seville in 2015 and 2016.

Table 4. Summary of the mean temperature values in 2015 and 2016.

Period	2015			2016		
	Mean temperature	Mean temperature of minimum values	Mean temperature of maximum values	Mean temperature	Mean temperature of minimum values	Mean temperature of maximum values
January	10.4	4.4	16.4	13.1	9.1	17.2
February	11.4	5.8	16.9	13.1	8.1	18.1
March	15.5	8.6	22.3	13.4	6.7	20.1
April	18.9	12.7	25.0	16.8	11.2	22.4
May	24.0	15.7	32.3	20.0	14.1	26.0
June	26.3	18.4	34.2	26.0	18.1	33.9
July	30.3	21.7	38.9	29.8	21.8	37.7
August	28.4	21.0	35.7	29.8	21.9	37.7
September	23.9	17.2	30.6	26.1	18.5	33.7
October	20.6	16.0	25.3	21.6	15.8	27.4
November	16.3	10.1	22.3	14.7	9.9	19.5
December	14.3	8.3	20.2	13.0	8.4	17.5
Annual	20.0	13.3	26.7	19.8	13.6	25.9

2.2.2. Determination of the energy poverty risk: indicator, income values and energy price

To determine cases at energy poverty risk, 2M indicator was used. As indicated in Section 1, the study by Sánchez-Guevara Sánchez et al. [10] determined that the value associated with this indicator in Spain is 10%. Therefore, those households that spend more than 10% of their income on the electricity bill are at EP risk. For this purpose, the energy poverty ratio (EPR) is determined (see Eq. (8)) and compared with the value of 2M in Spain (see Eq. (9)):

$$EPR = \frac{HECE}{I} \cdot 100 \quad [\%] \tag{8}$$

$$Case\ in\ energy\ poverty \quad \text{if} \quad EPR \geq 2M\ (10\%) \tag{9}$$

where $HECE$ is the household energy consumption expenditure [€] and I is the household income [€].

To calculate EPR, determining the income of families and the economic expense in relation to the energy consumption is required. Regarding family incomes, the Spanish Institute of Statistics has annual mean incomes of families in each census units into which Spanish municipalities are divided [66]. These data are available for 2015 and 2016. So, the annual mean incomes of census units of Seville were available for these two years (see Fig. 6). As Fig. 6 shows, census units do not coincident to each building. The reason is that census units are divisions of the cities to disseminate the statistical information and to organise other aspects, such as electoral processes. Therefore, the value indicated for each census unit corresponds to the average of the data surveyed by the families included in each census unit.

EPR was analysed by distinguishing the income deciles of the families in Seville. The maximum and minimum values of each decile were determined in this analysis and were in turn analysed. A total of 13,056 cases were therefore analysed per decile: 6,528 cases for the minimum value of distribution and 6,528 cases for the maximum value of distribution of each decile.

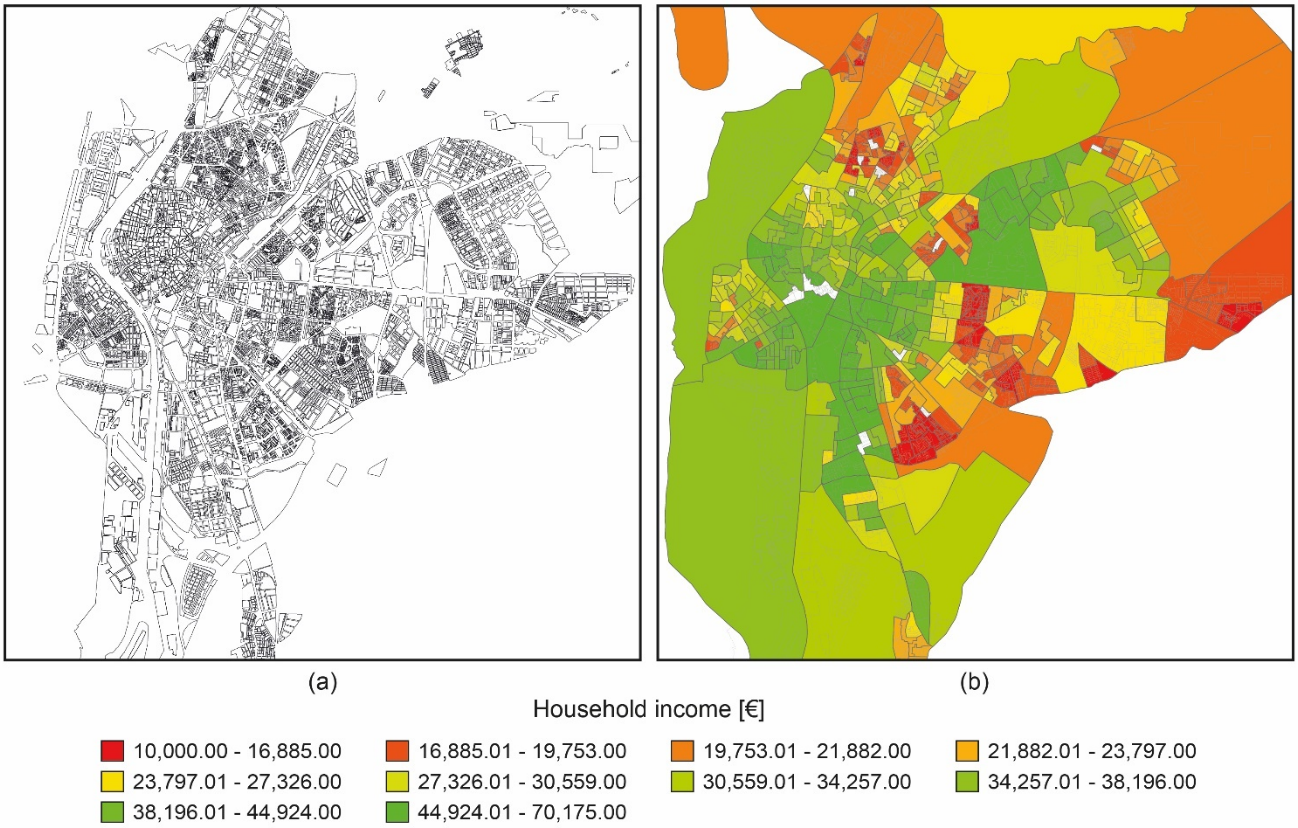

Fig. 6. Distribution of mean incomes per household in Seville: (a) map of the city of Seville, and (b) distributions of mean incomes per household in 2016 in various census units of the city.

The other variable required to determine EPR is the economic expense of the family in relation to the energy consumption. This expense can be understood as the sum of the energy consumptions multiplied by the price corresponding to each, as well as other additional costs associated with the energy invoice. As for social dwellings, all the energy consumption is based on electricity, so the consumption of other fossil fuels, such as natural gas, was not considered. In this regard, the type of contract of the users of these dwellings in 2015 and 2016 was through the Voluntary Price for the Small Consumer (PVPC in Spanish), without hourly discrimination and with a contracted power of 5.75 kW. Since 2014, there is the possibility of contracting through PVPC, whose electricity price is regulated by the Spanish Government [67] and whose price varies according to the hour of the day. The following concepts are distinguished in the energy invoice through PVPC: (i) energy term; (ii) power term; (iii) electricity tax; (iv) rent of the digital meter; and (v) value added tax.

The price of the energy term is obtained by multiplying the energy consumed by the dwelling by the price of the energy term (obtained by summing the grid access and the production cost of the electrical energy (see Eq. (10)). Given that the hypothesis considered in this research is the contract of PVPC, the price of the energy term could be known in the hours of the years 2015 and 2016 (see Fig. 7).

$$ET = EC \cdot PET \quad (10)$$

Where ET is the energy term [€], EC is the energy consumption of the dwelling [kWh], and PET is the price of the energy term [kWh/€].

The power term is a fixed price that the user should always pay by having the contracted power. This price is obtained by multiplying the contracted power (in this research, 5.75 kW) by both the days including the invoicing period and the power term of the PVPC (see Eq. (11)). This power term includes the price of the power term of the grid access (0.104229 €/(kWday)) and of the marketing margin (0.010959 €/(kWday)).

$$PT = 5.75 \cdot ND \cdot (0.104229 + 0.010959) \quad (11)$$

Where PT is the power term [€], and ND is the number of days of the invoicing period.

Other concept included in the price of the PVPC invoice is the electricity tax (ElT). This tax is applied to the sum of the energy and power terms, with a value of 5.1127% (see Eq. (12).

$$ElT = 0.051127 \cdot (ET + PT) \quad (12)$$

Finally, the total amount of the electricity invoice that should be paid by the users of a dwelling will be obtained by the sum of the energy term (ET), of the power term (PT), and of the electricity tax (ElT), as well as the rent of the electricity meter (EMR) and the value added tax applied (see Eq. (13)). To rent meters, a price of 1.11 €/month was considered, and the value added tax has a percentage value of 21%.

$$HECE = 1.21 \cdot (ET + PT + ElT + EMR) \quad (13)$$

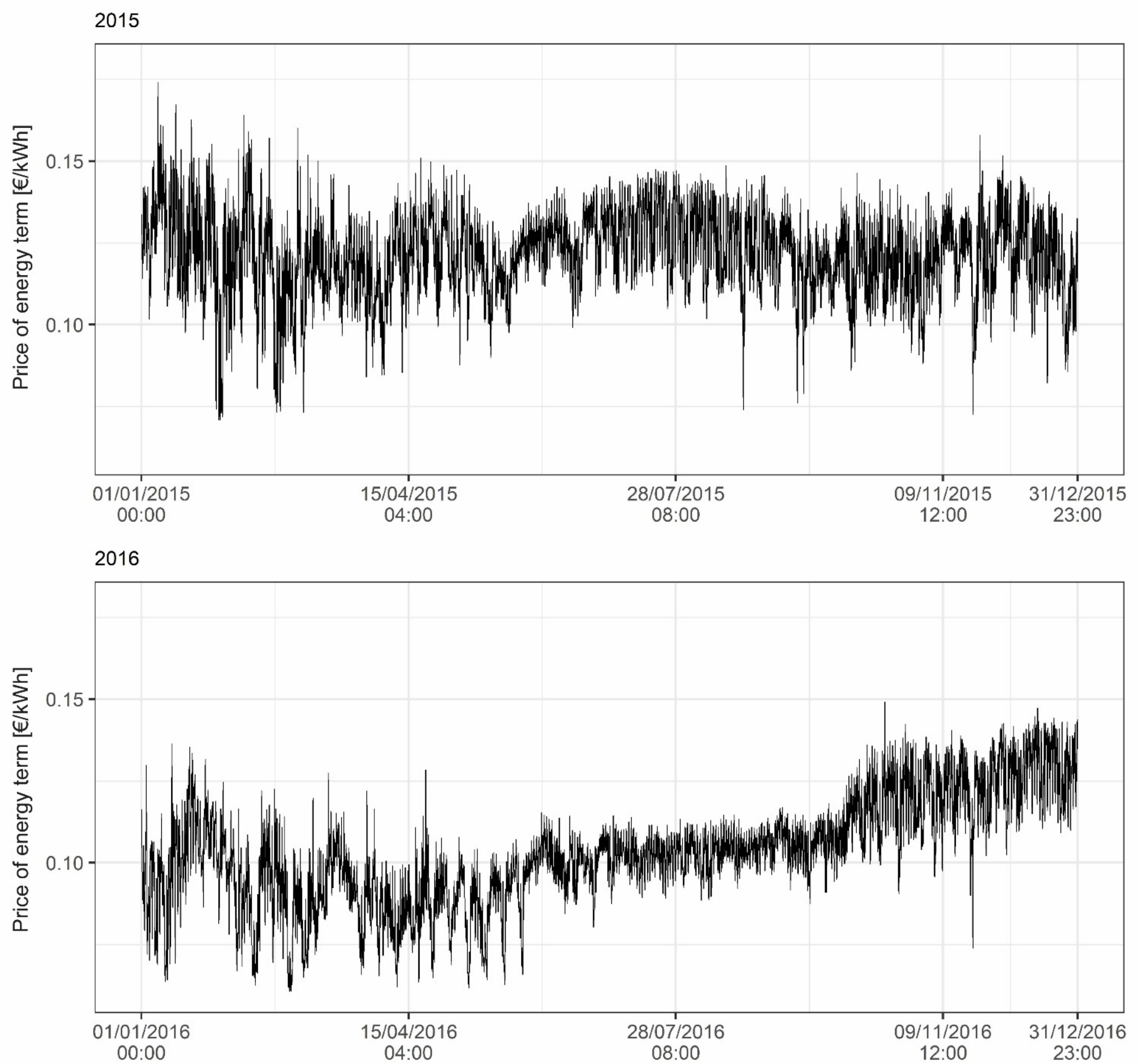

Fig. 7. Values of hourly PVPC in 2015 and 2016.

3. Results and discussion

3.1. Energy poverty risk with operational patterns of static setpoint temperatures

The EP risk was analysed in the social dwellings using static setpoint temperatures. The first step was the analysis of the distribution in deciles of the incomes of households in Seville in 2015 and 2016. Through this organisation (an usual practice in other countries with greater risk of economic poverty in their inhabitants, such as Chile [68]), the annual incomes of the most vulnerable households are found. Fig. 8 represents the box plots of the 10 deciles obtained in each year, and Table 5 includes the maximum and minimum of the distributions of each decile. The heterogeneity of household incomes can be proved, with values from €9,591 to €66,577 in 2015 and from €10,001 to €70,175 in 2016. There are therefore differences between the families with low and high annual incomes of €56,986 and €60,174 in 2015 and 2016, respectively. Likewise, the maximum value of the first decile in both years is slightly greater than €17,000 annually, which reflects the low incomes associated with this group despite the increase of the income values in 2016. In general terms, there was an improvement of the incomes in 2016, with a mean increase of €512.78 This aspect could be directly related to a greater percentage of population working. According to data from the Spanish Institute of Statistics [69], the employment rate in Seville increased between 0.20% and 1.49% in 2016 with respect to 2015, whereas the unemployment rate in Seville decreased between 2.05% and 3.89% (see Table 6).

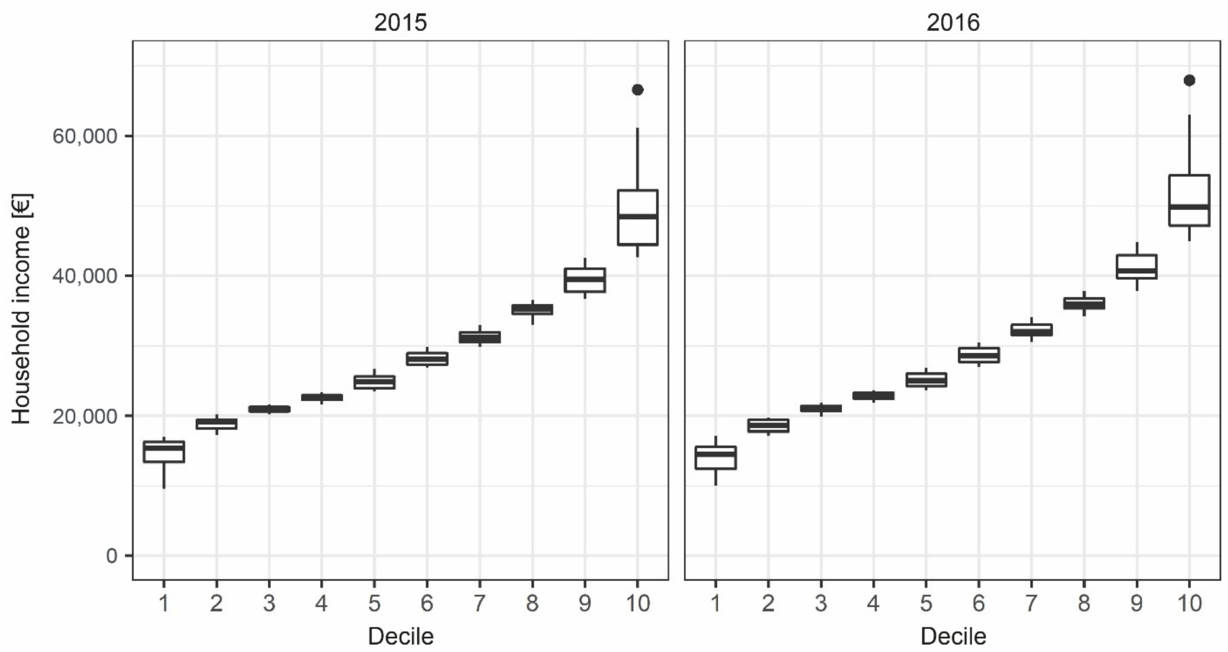

Fig. 8. Distributions of the income deciles in Seville in the years 2015 and 2016.

Table 5. Maximum and minimum values of the distributions obtained per income deciles in Seville in the years 2015 and 2016.

Decile	Mean household incomes [€]			
	2015		2016	
	MIN	MAX	MIN	MAX
D1	9,591	17,032	10,001	17,136
D2	17,246	20,204	17,150	19,852
D3	20,210	21,626	19,865	21,882
D4	21,628	23,381	21,898	23,681
D5	23,453	26,701	23,682	26,856
D6	26,871	29,790	26,984	30,518
D7	29,881	32,977	30,527	34,136
D8	33,013	36,531	34,216	37,813
D9	36,663	42,623	37,816	44,856
D10	42,662	66,577	44,924	70,175

Table 6. Evolution of employment and unemployment rates in Seville in the years 2015 and 2016.

Year	Term	Employment rate	Unemployment rate
2015	Term 1	40.74	32.38
	Term 2	42.79	29.31
	Term 3	41.25	31.23

	Term 4	42.69	29.08
2016	Term 1	42.23	28.49
	Term 2	43.02	27.01
	Term 3	41.69	28.02
	Term 4	42.89	27.03

After analysing the values obtained in EPR, the values obtained in 2015 and 2016 (full year) were analysed. For this purpose, the sum of electricity invoices throughout each year was analysed, EPR was determined by using annual incomes. As mentioned in Section 2, the analysis was individually conducted per decile, analysing the maximum and minimum income values of each (Table 4). Fig. 9 represents the distributions of annual values of EPR obtained per decile. Considering that the threshold value of EP risk is when EPR exceeds the value of 10%, only the first decile presented cases of energy poverty in 2015 and 2016. In this regard, from the 13,056 cases of the first decile, 34.03% and 9.47% presented values over 10% in 2015 and 2016, respectively. However, the EP risk was analysed in detail in social dwellings. For this purpose, the risk presented by dwellings in all the months of the year was assessed. Figs. 10 and 11 represent the value distributions of EPR in the months in 2015 and 2016, and Table 7 shows the percentage of cases with energy poverty risk. The results were monthly different with respect to an annual scale, varying the EP risk according to the year and month. This aspect therefore showed the possible limitations of the annual analysis of the EP risk by hiding the possible variations of EP risk suffered by households.

After analysing the results, it was proved that the months characterized by a greater heating demand (winter months) and the months with a greater cooling demand (summer months) generated a greater number of cases. In this regard, there were cases with energy poverty risk in January 2015 up to decile 8. This month was characterized by presenting low external temperatures, so the façade solutions with a low thermal resistance facilitate the heat loss through the exterior, thus generating a greater energy expense in families. As the level of incomes is lower, the percentage of cases in EP is greater until reaching 63.43% of the cases of decile 1. However, the heating period was not the greatest contributor to EP cases in social dwellings in Seville, but the cooling period. This aspect could be prove in the remaining cold months (January, February, March, and December) as the percentage of EP cases had a significant decrease, with decile 1 being a percentage ranging between 4% and 29.32%, whereas in hot months (June, July, August, and September), the percentage of EP cases ranged between 21.19% and 62.92% in the first decile. So, the energy consumption of air conditioning system is that generating the greatest EP risk in these case studies, and in period of high external temperatures (such as July in 2015), there were EP cases up to decile 5. However, the great vulnerability by using air conditioning system is for families belonging to the first decile. The fact that the greatest risk was in hot periods could be more important in future climate change scenarios predicted throughout the 20th century, which will increase the external temperatures.

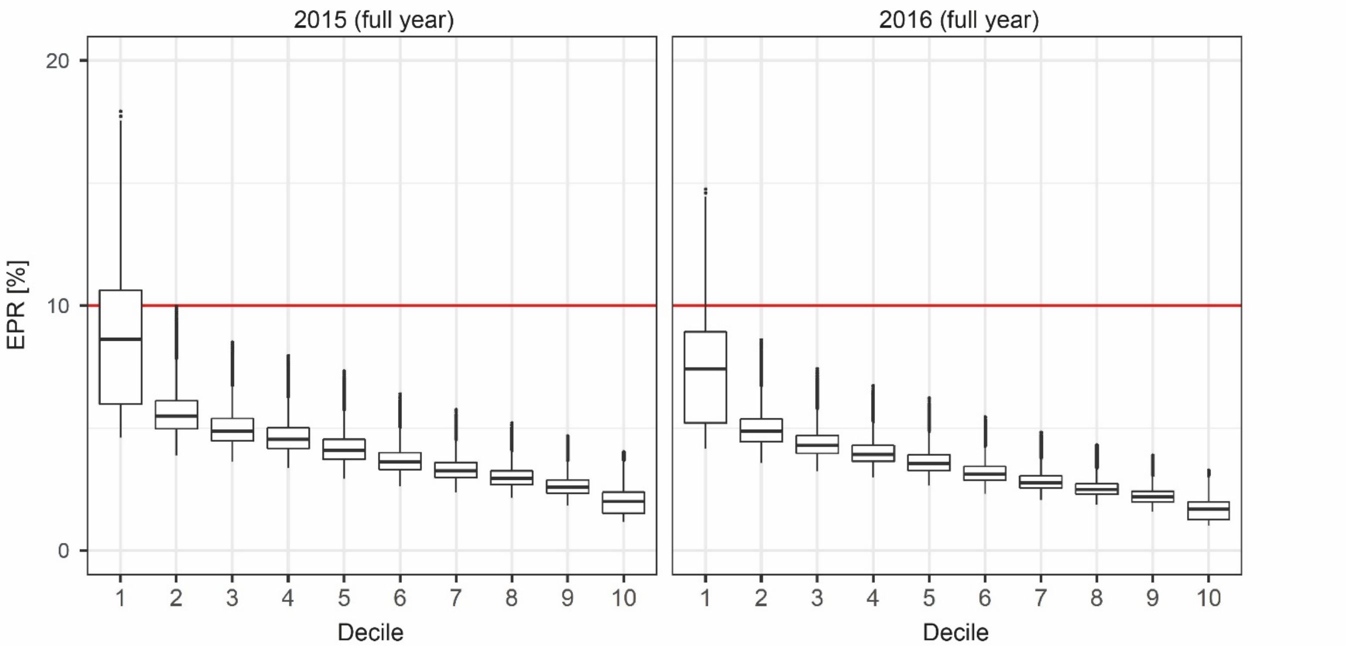

Fig. 9. Distributions of the values of EPR per deciles by considering the operational patterns of static setpoints by users. The red line represents the line of 10%.

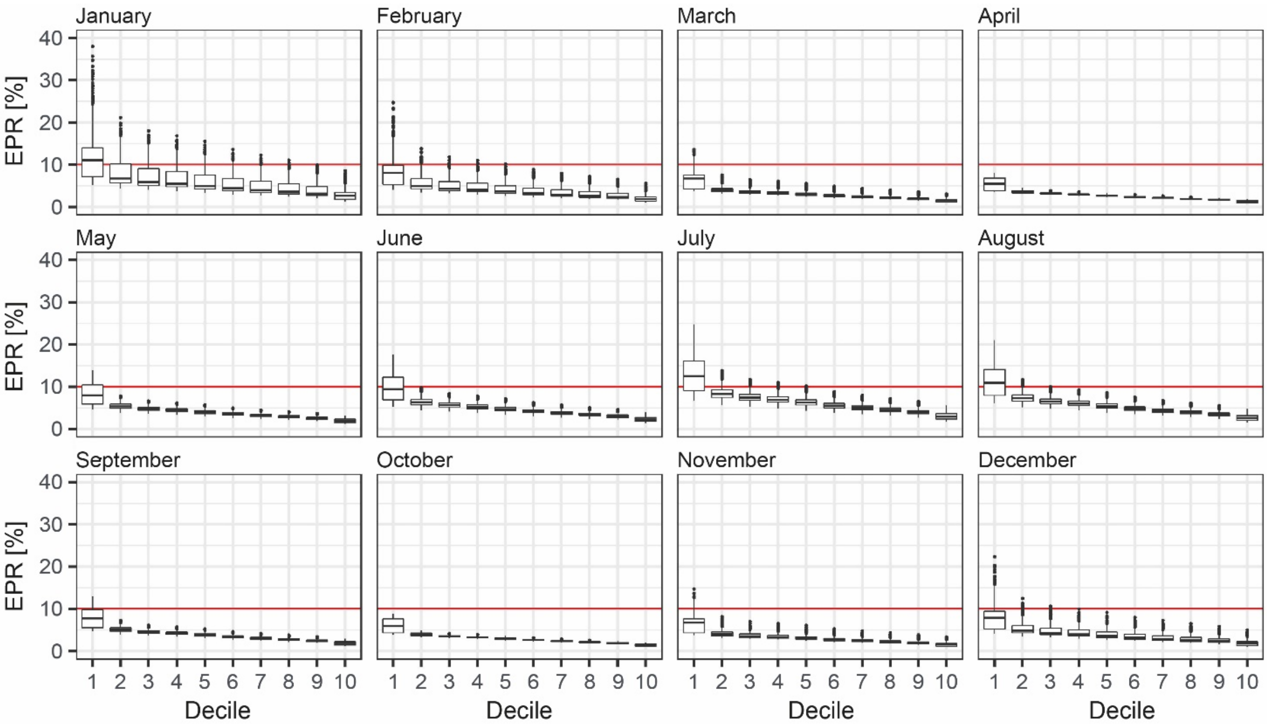

Fig. 10. Distributions of the values of EPR per deciles in the months of the year 2015 by considering the operational patterns of static setpoints by users. The red line represents the line of 10%.

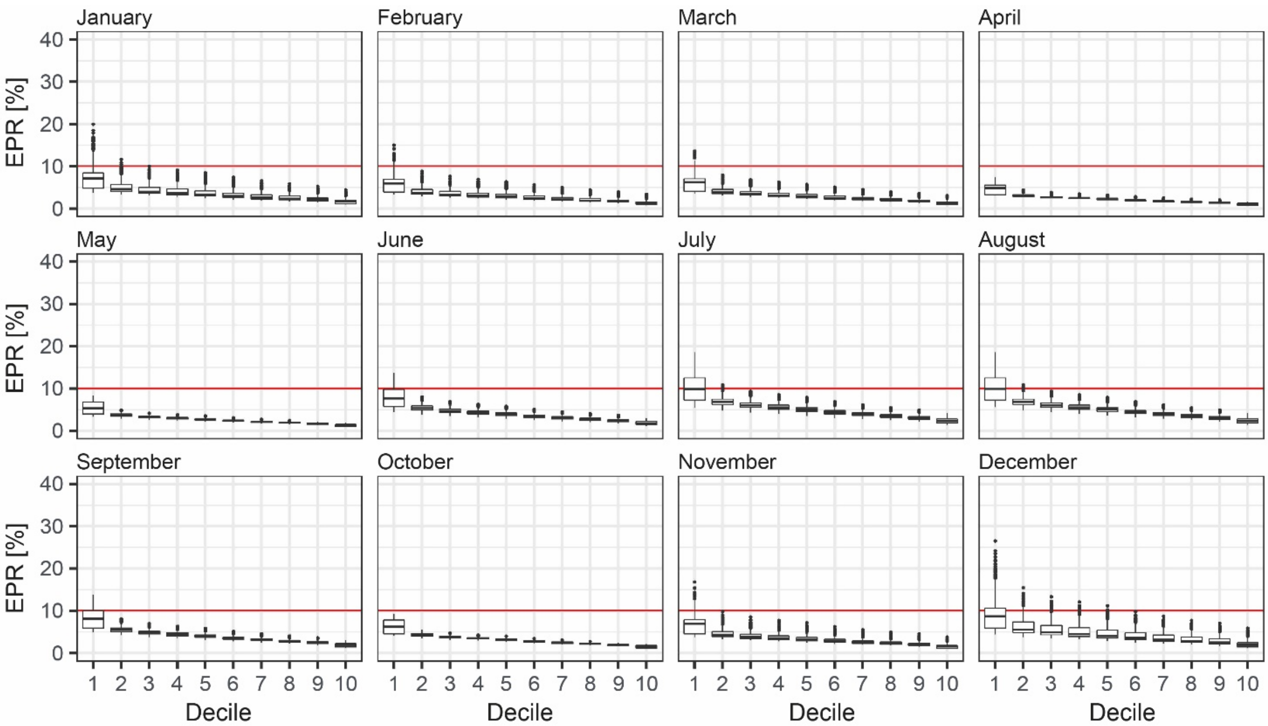

Fig. 11. Distributions of the values of EPR per deciles in the months of the year 2016 by considering the operational patterns of static setpoints by users. The red line represents the line of 10%.

Table 7. Percentage of cases with EP risk by considering static behaviour patterns.

Year	Period	Percentage of cases with EP risk (greater than 10%) [%]									
		D1	D2	D3	D4	D5	D6	D7	D8	D9	D10
2015	Full year	**34.03**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	January	**63.43**	**25.61**	**16.13**	**11.17**	**6.62**	**3.03**	**1.52**	**0.41**	0.00	0.00
	February	**23.97**	**2.76**	**1.10**	**0.55**	**0.14**	0.00	0.00	0.00	0.00	0.00
	March	**4.00**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	April	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	May	**31.84**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	June	**48.02**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	July	**62.92**	**12.68**	**1.47**	**0.34**	**0.02**	0.00	0.00	0.00	0.00	0.00
	August	**51.55**	**1.17**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

	September	**20.62**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	October	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	November	**4.83**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	December	**20.80**	**1.10**	**0.14**	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2016	Full year	**9.47**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	January	**15.29**	**0.55**	**0.14**	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	February	**4.55**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	March	**4.00**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	April	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	May	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	June	**21.19**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	July	**49.23**	**0.28**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	August	**49.73**	**0.22**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	September	**24.44**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	October	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	November	**8.26**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	December	**29.32**	**5.79**	**2.21**	**0.97**	**0.28**	0.00	0.00	0.00	0.00	0.00

3.2. Variation of EP risk by adopting adaptive behaviour patterns

There were many cases in the first decile of incomes by adopting static behaviour patterns in the use of HVAC systems. The improvement to adopt resilient behaviour patterns of users through adaptive setpoint temperatures was focused on the results of the first decile. Fig. 12 represents the percentage variations in the number of EP cases in the various deciles and months.

First, the analysis of the annual results of the first decile showed that the use of adaptive setpoint temperatures generated different effects according to the category used (i.e., according to users' thermal expectations). In this regard, category I (corresponding to the narrowest thermal comfort limits) decreased the number of annual cases in EP risk of 43% in 2015 and 40.8% in 2016. Although these percentages were significant, the increase of thermal tolerance ranges (i.e., the extension of thermal comfort limits) could generate a more significant decrease in the number of EP cases, so that category II implied a decrease between 74.3% and 82.3%, and category III between 92.5 and 98.5%. The latter could imply a decrease of EP annual cases.

However, the annual analysis was not required to show the variable behaviour of the EP risk in the months of the year, as seen with the static setpoints. The monthly analysis showed that the effectiveness of the alleviation of EP with adaptive setpoint temperatures depended on the month and the category used. Category I could therefore increase the number of EP cases in cold periods as the values obtained for the heating setpoint temperature through the correlation of the lower limit (Eq. (1)) could obtain values greater than those used for the static setpoint temperatures (17 °C and 20 °C depending on the hour of the day). Nevertheless, the other two categories reduced the number of cases with EP risk in cold periods. As for the first decile, category II achieved reductions between 10.4% and 20.3% in the cold months from 2015 and between 16.1% and 40.6% in the cold months from 2016, whereas category III achieved greater reductions in the number of cases between 45.9% and 90.9%. In the remaining deciles, the adoption of adaptive setpoint temperatures for heating had the same tendency as in the first decile: category I could increase the number of EP cases, whereas the other two categories decreased the cases, with a tendency to disappear the EP cases in the deciles with the greatest incomes.

These results showed the potential of using adaptive setpoint temperatures to reduce EP cases in cold periods. However, the great potential of using these energy saving strategies was in the summer months, which were the most favourable months for the appearance of EP cases in the social dwellings of the region analysed. In this regard, the use of any category from EN 16798-1:2019 achieved reductions of the number of EP cases of the first decile. In the most unfavourable months in the summer of each year (July in 2016 and August in 2016), the use of category I reduced the cases between 20.6% and 43%, category II between 29.1% and 70%, and category III between 38.7% and 92%. In the remaining months there were greater percentage reductions than those from the most unfavourable months, as well as an extinction of the EP cases found in the other deciles with more incomes. These results therefore showed the potential of using adaptive setpoint temperatures to reduce the EP risk in the social dwellings analysed without making economic investments to improve the energy performance of buildings, such as the improvement of the façade, the replacement of windows or the replacement of HVAC systems with other systems with a greater performance. Only in those cases in which EP cases are not eliminated by implementing adaptive setpoint temperatures, the possibility of the energy improvement of the building should be assessed. The results of this research are based on the hypothesis of a total thermal comfort during all the hours of the year, as well as of certain occupancy patterns and loads. The actual behaviour of users of these social dwellings could vary as they can stay a longer time outside during the less cold periods, so the EP found in the study would be reduced. Nonetheless, these results are useful to prove the effect of the modification of operational patterns of HVAC systems on the EP risk, thus guaranteeing users' thermal comfort. It is important to emphasize that subjective factors not considered in this study could affect the effectiveness of this measure (e.g., the customs of each region and socio-economic or cultural factors). Another aspect not considered is the size of the family unit. For this study, the size of the family unit was considered fixed for all combinations of income deciles and operational patterns. Presumably, different family sizes could modify and limit the effectiveness of adaptive strategies.

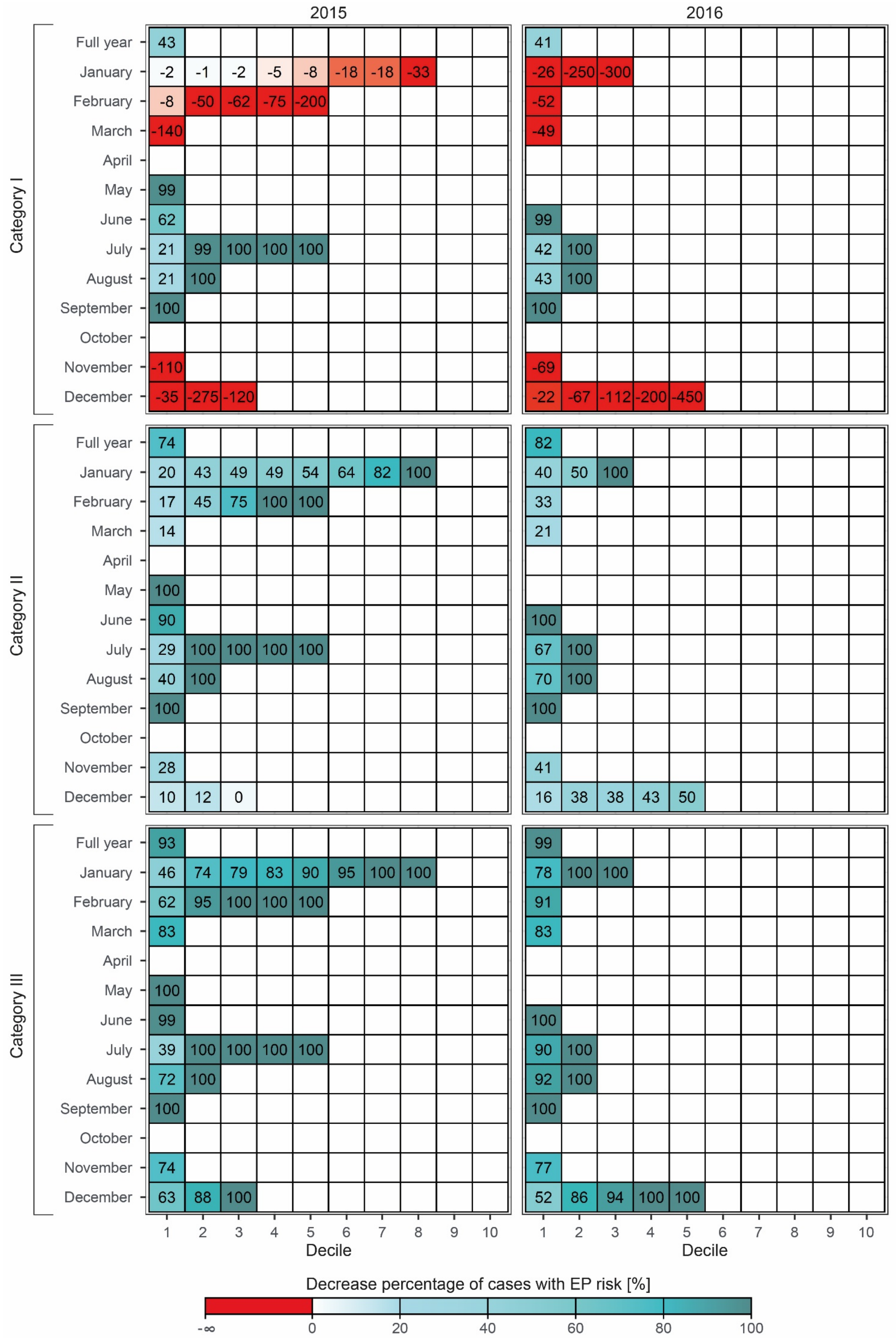

Fig. 12. Heatmap with the decrease percentage of cases with EP risk. Positive values correspond to a reduction of cases (100% of the total elimination of EP cases), and negative values correspond to an increase of cases.

4. Conclusions

This study aims to go more deeply into the application of adaptive setpoint temperature to reduce the energy poverty risk. For this, the investigation analysed a combination of 6,528 cases in Seville (Spain). The cases were simulated in EnergyPlus using real temperature data from 2015 and 2016. With the hourly rates of the Voluntary Price for the Small Consumer and with the average household income in 2015 and 2016, the potential for reducing energy poverty was analysed by using adaptive setpoint temperatures.

Based on the 6,528 cases studied during 2015 and 2016 and by considering the results, the indicators related to incomes and expenses depend on the conditions of the moment. As a result, there are more cases of energy poverty in 2015 than in 2016, despite the greater percentage of unemployed and a little bit harder climate in 2015.

Secondly, annual data are not enough to diagnose the energy poverty in detail. It is possible that the analysis of the annual calculation does not find cases in certain months of the year, as established by the results. When hourly values of energy price and climate conditions are used, the results should have at least a month dimension. There could be situations affecting a great percentage of deciles, particularly in the most extreme months.

Another aspect to be emphasized is the possibility of detecting cases of energy poverty in the summer months. In Seville, where temperature values greater than 40 °C can be reached, the consumption of air conditioning systems could be high, thus resulting in an excessive cost for families. These results therefore suggest the need to establish new criteria and definitions of energy poverty in warm conditions, similar to what was reported by Sánchez-Guevara Sánchez et al. [35].

Finally, the use of adaptive setpoint temperatures could be an appropriate strategy to reduce the building energy consumption and to guarantee users' thermal comfort. The reduction in energy consumption is an adequate strategy to reduce cases of energy poverty because it is a measure without economic cost. However, the effectiveness of reducing energy poverty depends on the users' thermal adaptation (users with a less thermal adaptation may have less possibility of reducing energy poverty). In this sense, category I of EN 16798-1: 2019 obtained a decrease in the number of energy poverty of up to 43%, while category II was up to 82.3% and the category III was up to 98.5%. Even though the adaptive setpoint temperatures managed to reduce the cases of energy poverty in all months of the year, it was found that they are more effective in reducing energy poverty in the summer months. The use of the categories of EN 16798-1: 2019 makes it possible to achieve reductions in the risk of energy poverty in families in the first decile. Thus, this measure could be adequate to act quickly in vulnerable families in the summer months. The subjective factors (cultural or psychological) could also limit the application of these measures. Nonetheless, the great potential of adopting adaptive measures in the event of energy poverty is notable. Finally, the results can be associated with false positives: those families with adaptive operational patterns which are evaluated by static operational patterns through standardized processes (such as those for Building Energy Rating). This aspect could imply that energy consumption is overestimated and that the household could be considered to be at energy poverty risk.

To conclude, this research could be used to develop new studies based on the control of setpoints to reduce the energy poverty risk without affecting adequate thermal comfort levels. The conscious use of HVAC systems considering climate change will be the result of new research studies. In addition, the generation of predictive models based on the data analysed in this paper will throw light on very low-cost interventions without changing the constructive structure of buildings. Likewise, the relationship between the months of the year and the cases of energy poverty may be a trigger for a greater number of deaths. For this reason, future studies should monthly analyse the possible relationship between the mortality rate and the cases of energy poverty throughout the country. Finally, the relationship between the effectiveness of adaptive strategies, the size of the family unit, and sociocultural and economic factors should also be analysed in future works.

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