Mitigating energy poverty: potential contributions of combining PV and building thermal mass storage in low-income households

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Abstract

The issue of energy poverty has devastating implications for the society, and it has been aggravated in the past years due to the economic crisis and the increase of energy prices. Among the most affected are those with low incomes and living in inefficient buildings. Unfortunately, the bitter reality is that sometimes this part of the population are facing the next question: Heating, or eating? The declining prices of distributed energy technologies such as photovoltaics provides an opportunity for positive social change. Although their use does not address energy poverty directly, substantial contributions may be made.

Measurements of indoor temperatures in a social housing district of southern Spain in 2017 have revealed the unbearable temperatures that the occupants have to endure, both in summer and winter. Using this district as a case study, the present work aims to evaluate the benefits of exploiting its rooftop PV potential to cover part of the electricity consumption of the district (reducing the energy bills), and use the surplus electricity to supply power for the heat pumps in the district. Optimal alternatives regarding maximum PV production, maximum self-sufficiency ratio and minimum investment costs have been found, considering as well different options when sharing the available electricity surplus to improve the thermal comfort of the occupants. As far as the authors know, no previous study has followed an approach aimed at energy poverty alleviation such as the one presented in this work. The results show that using the surplus electricity to heat or cool the whole dwellings would improve the thermal comfort of the occupants in average up to 11 % in winter and 26 % in summer. If all the PV generation was used or more buildings in the area were employed to install PV modules, improvements up to 33 % in winter and 67 % in summer could be obtained, reducing at the same time the thermal comfort differences among the dwellings of the district.

Keywords: energy poverty; fuel poverty; PV potential; thermal comfort.

1 Introduction

1.1 Background

Cities have become one of the cornerstones in fighting climate change due to their increasing electricity demand. Although in the past this was mostly covered by using fossil fuels in large centralized power plants, the use of renewable energies is becoming widespread due to their proven contribution to mitigate global warming and the fact that they provide local, clean and abundant sources of energy. The transition to smart microgrids which make use of distributed renewable energy generation systems such as photovoltaic (PV) or wind energy is also being promoted, and there is a huge potential to utilize them not only to satisfy demand and provide decentralized generation, but also to help tackling fuel poverty and achieving emission reductions [1]. Due to its decreasing prices and market availability, photovoltaic generation is frequently considered to be the best candidate on a large scale.

Despite the enormous benefits of renewable energy systems (RES), there is a drawback that should be considered: an extensive use inserts uncertainty into the grid due to their dependency on weather conditions. A large amount of intermittent renewable energy in the energy system is a major challenge, since supply and demand must match at any time [2]. For this reason there is a need for power reserve, and energy storage systems play a central role since they provide the means to balance energy generation and demand. Buildings can be part of the solution in future smart grids, offering different storage potentials in the structure itself (thermal storage) or in individual units such as water tanks or batteries [3], which also allow load shifting strategies.

The high energy consumption of the building sector, climate change and energy poverty are the major problems encountered in the built environment in Europe [4]. The three sectors are strongly interrelated, presenting significant synergies. When using buildings to service power flexibility requirements, case study based specifics should be considered [5]. According to [6], demand response in HVAC systems focuses on individual buildings, but their building-group performance, which is the real concern to the grid, has not been systematically evaluated. The number of studies on load matching has increased rapidly in the past years and most of them use approaches such as energy storage (batteries or thermal storage) and demand side management. However, the literature also shows that research is mostly focused on individual buildings when it comes to load matching [7]. Retrofit programs reduce carbon emissions to some degree, but the bigger challenge is addressing habitual household energy consumption [8]. In addition, retrofitting measures in social houses are usually undertaken by the housing company, so they require to be communicated, assimilated and accepted by the tenants [9].

1.2 Energy poverty

In spite of the rising electricity consumption in cities, there is a part of the population that is particularly vulnerable. Energy poverty refers to the situation in which a household is unable to maintain a proper level of indoor thermal comfort as a consequence of a combination of three causes: low income, high energy prices or poor energy efficiency of housing [10]. This affects the capacity of the occupants to consume energy so as to keep the proper indoor environmental conditions, thus deteriorating their health and quality of life. For these reasons, energy poverty is a serious problem in the European Union and the whole world. In parallel, the term fuel poverty is traditionally used to imply the inability to cover the heating or cooling needs. In addition, the role of the occupants for achieving energy savings is increasingly recognized and even more important in the social housing sector [11].

The problem of energy poverty has been aggravated in the past years, particularly in Spain, due to the economic crisis and the increase of energy prices. As a result, part of the population cannot cover their energy needs, reaching very low or very high indoor temperatures that may have a severe impact on their health and result in an increase of illnesses or even mortality. According to the study in [12], 5.1 million people in Spain, which means 11% of the households, claim that they are incapable of maintaining a proper indoor temperature in winter. Another of the used indicators shows that 7% of the Spanish households live in a situation of energy poverty. Andalusia, where the present study takes place, is the region in Europe with the highest solar energy potential [13]. However, heating is necessary in most European countries, even those in the south of the continent such as Spain.

In particular, social housing and low-income households are the most vulnerable, since they present social and financial constraints and need to be one of the main targets when actions towards mitigating energy poverty are carried out. For example, a field investigation in [10] showed that the energy consumption in social dwellings was lower than expected not due to a good performance of the dwellings, but to a lowering of the indoor comfort levels. The study in [14] also shows that low income households showed minimum heating consumptions much below the normal thresholds. The work presented in [15] revealed that electricity demand responds positively to income, and negatively to electricity and gas prices. The study in [16] presents the state of the art regarding the energy demand and indoor environmental quality of low income households in Europe. Last of all, [17] evaluates the effect of customized consumption feedback in low-income households, confirming the importance of information and efficiency indicators.

1.3 District PV potential and load matching

Although the use of solar PV does not address fuel poverty directly, it can provide a great contribution towards diminishing the electricity demand in a social housing context. For instance, [18] showed that deploying solar panels in low-income housing units would contribute to energetic autonomy, reduce grid dependency and help to change the cultural perception towards renewable energy alternatives. In addition, [1] explores PV generation and how it can be used to provide added value in terms of demand reduction and contribute to a reduction in fuel poverty.

Until recently, there was no significant concern for grid operators due to low PV adoption rates. However, this is changing due to the increase of energy generation from PV systems, which is not usually aligned with the electricity demand. There are also concerns regarding the prevalence of PV in electricity networks. Concurrent with increasing electricity prices, the rewards for exported solar electricity are falling, thus local PV self-consumption is gaining attention [19]. [20] developed a methodology for predicting the impact of net metering restrictions on the deployment of residential solar systems. In this context, self-consumption with storage allows to highlight the prosumer concept (consumers that are also capable of producing their own energy), since this strategy may be interesting from a technical and economical perspective [21]. However, there may be conflicting interests between the users and the grid, since higher returns to PV owners lead to higher net load variance burdening the grid while smoothing the load profile leads to diminishing returns for the PV owners [22].

Household or community energy storage are two promising storage scenarios for residential electricity prosumers [23]. An interdisciplinary review of community energy storage is presented in [24]. Also, a new framework to integrate community storage units in an existing residential community system with rooftop PV is proposed in [25], and [19] compares the results of storage adoption at the level of individual households to storage adoption on the community level using the aggregated community demands, highlighting the need for energy policy to develop market mechanisms that facilitate the deployment of community storage. This study also illustrates that community storage decreases the total amount of storage deployed, decreasing surplus PV generation and therefore increasing self-sufficiency. Even though battery storage systems implemented with PV have been widely documented in literature since the costs have been decreasing and their reliability has improved, most authors agree that it is still an unprofitable option for many users [22].

There are many alternatives for determining the PV potential of a district. For instance, [26] presents a review of existing methods that aim at evaluating aspects such as passive heating and PV potential, [27] uses a combination of support vector machines and Geographic Information Systems (GIS) to estimate the PV potential for urban areas, or [28] design a novel method to obtain the optimum community energy storage systems for end user applications. In [29] the relevance of facades and other vertical features in the urban environment for solar power generation is analyzed. The study in [30] shows a method to conduct PV potential analyses in high detail using publicly available building data and aerial images in combination with image recognition techniques without having to rely on 3D model data. However, the use of 3D city models combined with simulation functionalities allows to quantify energy demand and renewable generation for very large set of buildings in a more accurate way, as it has been shown by studies such as [31–33].

Since PV systems supply power only during the day, which means only approximately half of the hours of the year, it is necessary to analyze when the power is supplied compared to the demanded load [34]. Demand patterns affect the optimal PV orientation, so choosing it should not only be based on maximizing energy production (as is frequent in most designs), but also on expected demand patterns and market prices [35]. Even in buildings with the same level of yearly generation and consumption, the mismatch between the demand and PV generation profiles leads to large power flows between the household and the grid, creating network problems and causing economic losses to the end-users [36]. The study in [22] showed that the aggregation of the demand and PV potential from different building surfaces in the urban context translates into a better demand-supply match, therefore minimizing storage needs. In addition, an analysis of the performance of a PV-Trombe wall studying the impact of several PV parameters on the electricity generation can be seen in [37], determining optimal tilt angles and suggesting how solar energy can be in charge of energy savings within a building.

Using a combination of air-conditioning use with the operation of time-shiftable appliances, [38] investigate the potential for residential consumers to lower community-level peak demand through home energy management systems. Another option to improve self-consumption is rescheduling appliances, typically washing machines, clothes dryers and dishwashers. However, the main conclusion reached in [39] is that there is an overall small contribution when carrying out that approach, and that radically different market conditions would be needed to make them advantageous for the grid. [40] present a novel control algorithm for joint energy demand and thermal comfort optimization in PV microgrids. The study in [41] shows a novel control algorithm for joint demand response management and thermal comfort optimization in microgrids with renewable energies and storage. In [42], a novel method for quantifying the available demand flexibility of buildings is proposed, including a probabilistic analysis to specify the stochastic nature of energy demand, weather, construction type and comfort constraints.

1.4 Aim of the study

The case study of the present work is a social housing district of 235 households in the province of Seville, in southern Spain. The city where the district is located has an average income of 12900 €/household per year, and the unemployment rate is very high (22.90% in January 2018). The climate is severe both in summer and winter and the thermal efficiency of the buildings is rather poor, thus the households that will be assessed are living in conditions of extreme energy poverty. A monitoring campaign was carried out during the whole year of 2017, obtaining measurements of total electricity consumption and indoor temperature of the living room and a bedroom in 10 representative dwellings of the district at hourly intervals. The measurements revealed the unbearable temperatures that the occupants have to endure both in summer and winter, and the need for thermal comfort improvement measures.

It is very common to carry out thermal mitigation strategies by rehabilitating the existing building stock: increasing the thermal insulation, improving the thermal bridges or reducing the air infiltrations (winter), as well as using solar control strategies or night ventilation (summer). However, this work seeks to offer a different alternative, which could either substitute or, even better, work hand in hand with traditional retrofitting strategies.

The purpose of the present study is to assess the benefits of exploiting the rooftop PV potential of the district so as to improve the thermal comfort of the occupants and mitigate extreme low and high indoor temperatures, and at the same time reduce their energy bills. This will be done by using the solar PV generation to cover part of the district's energy consumption, and the rest of the electricity (which would otherwise be exported) to supply power for the heat pumps (HP) of the households in the district instead. In this way, rather than using electrical storage as is frequent in most studies, the present work takes advantage of the thermal mass storage capacity of the buildings themselves and at the same time improves the thermal comfort levels of the occupants. The thermal behavior of the buildings will be characterized by using very detailed simulation models of the 37 typologies in which the 235 dwellings of the buildings were categorized.

Several alternatives will be analyzed in energy and economic terms for exploiting the PV potential of the district, changing the orientation and inclination of the PV panels as well as the separation between adjacent rows. This will be done with the purpose of determining the optimal options regarding maximum PV production, maximum self-sufficiency ratio and minimum investment costs. Once the optimal PV strategies are detected, 5 different alternatives to share the available electricity surplus of the district will be considered to improve the thermal comfort of the occupants.

This paper is structured as follows. In Section 2, a description of the case study and the experimental measurements is presented, followed by the description of the proposed method and strategies. The analysis of results regarding the PV potential and thermal comfort improvement strategies is then discussed in Section 3. Finally, we conclude with a brief summary in Section 4. The current work aims to shed some light into whether it might be beneficial to install large PV systems in order to improve the thermal comfort in districts at risk of energy poverty.

2 Case study: modelling and simulation

2.1 Description of the case study

The social housing district under study is owned by the Agency for Housing and Rehabilitation in Andalusia (AVRA). It is composed of 235 dwellings distributed among the buildings in the area, which were built in 1983. The thermal envelope and windows have a poor quality (for instance U_{walls}=1.77 W/m^{2}K). The district of 235 dwellings has been divided into 37 different typologies. This means that every dwelling in the district belongs to one of the typologies, which have been distinguished according to geometry of the dwelling, orientation and floor number. Table 1 shows a summary of the considered typologies. A representation of the district and some of the detailed building models created for the present study can be seen in

Figure 1. As it can also be observed, the roofs of the buildings in the upper-right corner are tilted, while the rest are flat.

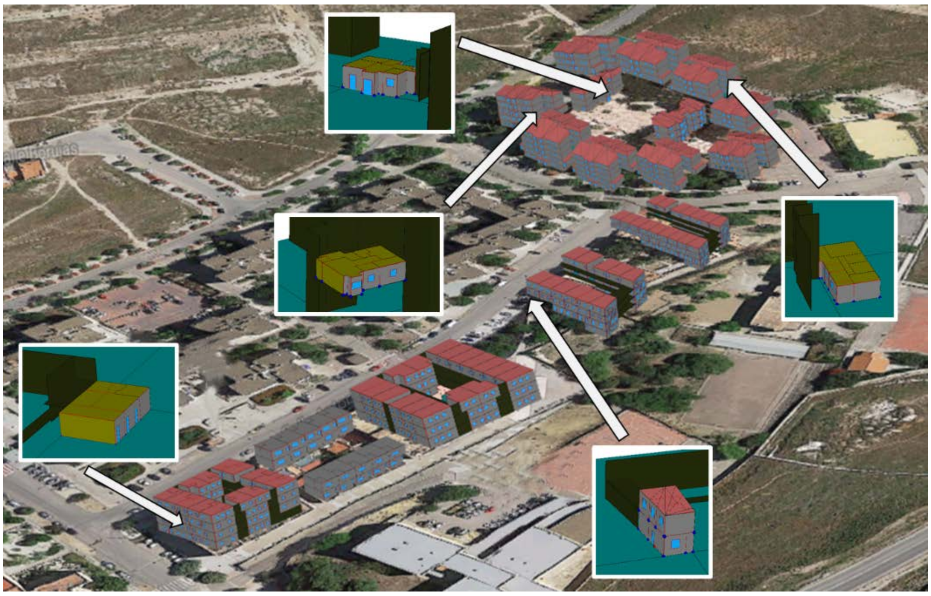


Figure 1: Representation of some of the detailed models in the district.

TYPOLOGY	ORIENTATION	AREA [m2]	FLOOR	NUMBER OF DWELLINGS IN THE DISTRICT
TYPOLOGY 1	SOUTH-WEST	66	GROUND FLOOR	7
TYPOLOGY 2	NORTH-WEST	66	GROUND FLOOR	9
TYPOLOGY 3	NORTH-EAST	61	GROUND FLOOR	4
TYPOLOGY 4	SOUTH-EAST	61	GROUND FLOOR	2
TYPOLOGY 5	SOUTH-WEST	78	INTERMEDIATE	8
TYPOLOGY 6	NORTH-WEST	78	INTERMEDIATE	6
TYPOLOGY 7	NORTH-EAST	78	INTERMEDIATE	6
TYPOLOGY 8	SOUTH-EAST	78	INTERMEDIATE	9
TYPOLOGY 9	SOUTH-WEST	66	INTERMEDIATE	13
TYPOLOGY 10	NORTH-WEST	66	INTERMEDIATE	14
TYPOLOGY 11	NORTH-EAST	66	INTERMEDIATE	15
TYPOLOGY 12	SOUTH-EAST	66	INTERMEDIATE	14
TYPOLOGY 13	SOUTH-WEST	66	UPPER FLOOR WITH ROOF	9
TYPOLOGY 14	NORTH-WEST	66	UPPER FLOOR WITH ROOF	9
TYPOLOGY 15	NORTH-EAST	66	UPPER FLOOR WITH ROOF	4
TYPOLOGY 16	SOUTH-EAST	66	UPPER FLOOR WITH ROOF	4
TYPOLOGY 17	NORTH-WEST / SOUTH-WEST	56	GROUND FLOOR	2
TYPOLOGY 18	NORTH-EAST / SOUTH-EAST	56	GROUND FLOOR	2
TYPOLOGY 19	NORTH-WEST / SOUTH-WEST	56	INTERMEDIATE	2
TYPOLOGY 20	NORTH-EAST / SOUTH-EAST	56	INTERMEDIATE	2
TYPOLOGY 21	NORTH-WEST / SOUTH-WEST	56	UPPER FLOOR WITH ROOF	2
TYPOLOGY 22	NORTH-EAST / SOUTH-EAST	56	UPPER FLOOR WITH ROOF	2

TYPOLOGY 23	NORTH-WEST	75	GROUND AND FIRST FLOOR	3
TYPOLOGY 24	NORTH-WEST	75	GROUND FLOOR	2
TYPOLOGY 25	NORTH-EAST	57	GROUND FLOOR	2
TYPOLOGY 26	NORTH-EAST	65	GROUND AND FIRST FLOOR	2
TYPOLOGY 27	NORTH-WEST	75	INTERMEDIATE FIRST FLOOR	4
TYPOLOGY 28	SOUTH-EAST / NORTH-EAST	51	INTERMEDIATE FIRST FLOOR	2
TYPOLOGY 29	SOUTH-EAST / NORTH-EAST	52	INTERMEDIATE SECOND FLOOR	2
TYPOLOGY 30	NORTH-WEST	56	INTERMEDIATE FIRST FLOOR	6
TYPOLOGY 31	NORTH-EAST	75	INTERMEDIATE FIRST FLOOR	9
TYPOLOGY 32	NORTH-WEST	73	INTERMEDIATE + UPPER FLOOR WITH ROOF	23
TYPOLOGY 33	NORTH-EAST	73	INTERMEDIATE + UPPER FLOOR WITH ROOF	27
TYPOLOGY 34	NORTH-WEST / NORTH-EAST	64	INTERMEDIATE + UPPER FLOOR WITH ROOF	2
TYPOLOGY 35	NORTH-WEST / SOUTH-EAST	64	INTERMEDIATE + UPPER FLOOR WITH ROOF	2
TYPOLOGY 36	SOUTH-EAST / NORTH-WEST	64	INTERMEDIATE + UPPER FLOOR WITH ROOF	2
TYPOLOGY 37	SOUTH-EAST / SOUTH-WEST	64	INTERMEDIATE + UPPER FLOOR WITH ROOF	2
				235

Table 1: Characteristics of all the dwelling typologies in the district.

2.2 Experimental measurements: justifying the need for intervention

A monitoring campaign was designed to assess the level of indoor comfort in the district. Measurements were taken in 10 representative dwellings, recording the indoor air temperature every hour during the whole year 2017. On the other hand, household electricity consumption has a very strong temporal variation not captured with consumption data from monthly bills, so high-resolution data from smart meters is paramount. Therefore, the electric power consumption in each dwelling (D) was recorded through a smart meter every hour of the year, determining the total household electricity consumption. The characteristics of the chosen dwellings can be seen in Table 2.

Dwelling	Area [m2]	Number of occupants	Installed sensors
D1	78	3	-Smart meter. -Living room temperature. -Bedroom temperature.
D2	78	5	
D3	56	4	
D4	56	1	
D5	75	4	
D6	73	4	
D7	56	3	
D8	73	3	
D9	66	1	
D10	73	7	

Table 2: Characteristics of the monitored dwellings.

For the whole period of the study, weather data is also available through a nearby weather station, providing hourly values of outdoor temperature, humidity, and solar radiation. The minimum outdoor air temperature (see Figure 2) was recorded on the 18th of January (-0.79 ˚C), while the higher temperature was recorded on the 13th of July (42.4 ˚C).

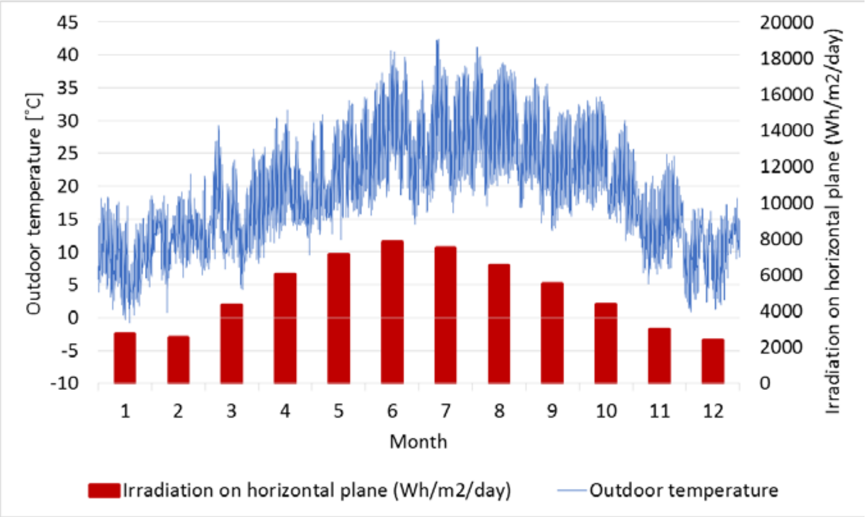


Figure 2: Outdoor temperature and daily irradiation on horizontal plane.

Since most of the studied dwellings were not air-conditioned, the indoor temperatures were persistently high or low for many days in a row. Door-to-door surveys revealed that some of the occupants even moved their cushions to the living room floor in summer, due to the unbearable temperatures in their bedrooms during the night which made it impossible to fall asleep.

Even though all the dwellings have a split air conditioner in the living room, most of them also have an electric stove under the living's room table, which is very frequent in Spain. Under the wrong assumption that using the stove incurs in lower costs, most of the dwellings do not make use of the split air conditioners in winter: either they don't use heating at all, or they only use the electric stoves. The hourly temperatures of the living rooms in the monitored dwellings can be seen in Figure 3. As shown, the indoor temperatures in all the dwellings are certainly far beyond the comfort zone most of the time, even though some of them make use of the split air conditioners for short periods.

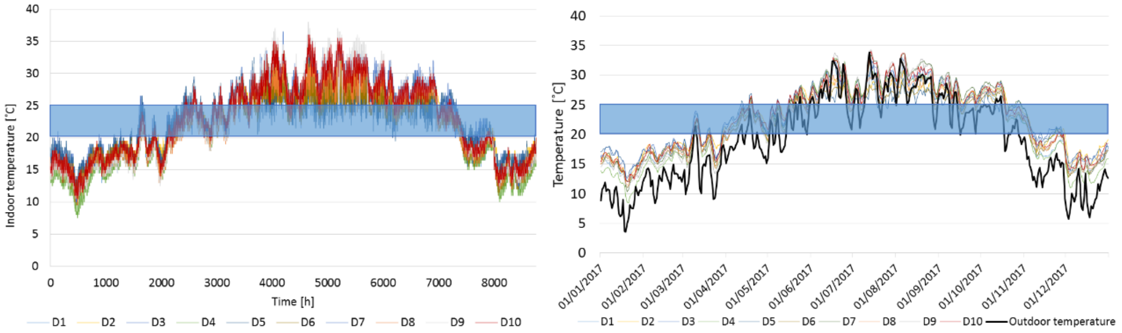


Figure 3: Hourly temperatures of the living rooms in the monitored households (left) and average daily temperatures (right).

On the other hand, the temperature of one bedroom in each monitored dwelling was also measured. In contrast with the measurements of the temperatures in the living rooms, it can be seen that none of the bedrooms in the dwellings are air-conditioned (see Figure 4). The differences between dwellings are mainly due to orientation (solar gains) and internal gains. The percentage of time outside the comfort zone in all the dwellings can also be seen in Figure 5. The results reveal the poor conditions in which the occupants of these households live, with several months in a row where the thermal comfort is violated 100 % of the time.

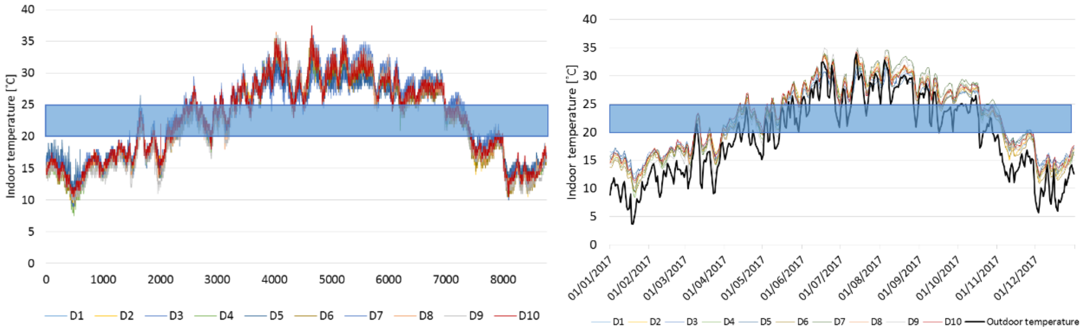


Figure 4: Hourly temperatures of the bedrooms in the monitored households (left) and average daily temperatures (right).

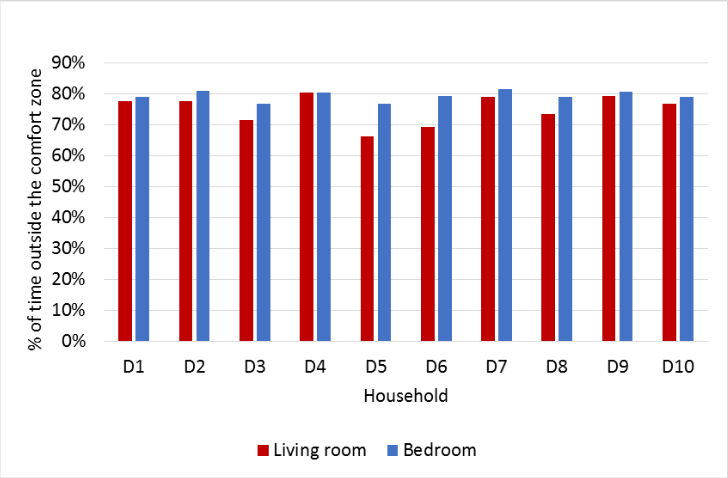
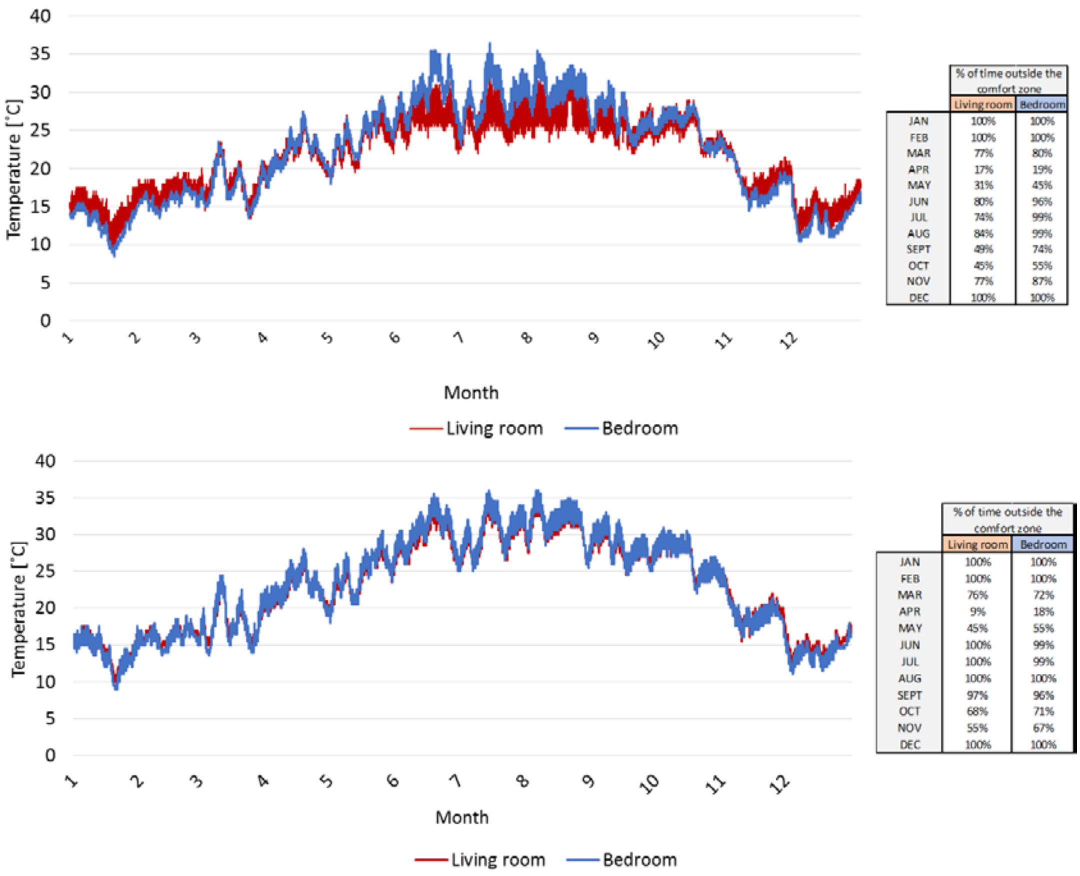


Figure 5: Percentage of time outside the comfort zone of all the households.

If we focus on individual dwellings, a clear difference can be observed between those whose living room is air-conditioned, and those that make no use of heating or cooling. This can be seen in Figure 6, which shows the difference of temperatures between the living room and the bedroom in dwellings D6 and D7. While D6 uses the split air conditioner, D7 uses no heating or cooling whatsoever, which translates into very similar temperatures in both of its rooms.



	% of time outside the comfort zone	
	Living room	Bedroom
JAN	100%	100%
FEB	100%	100%
MAR	77%	80%
APR	17%	19%
MAY	31%	45%
JUN	80%	96%
JUL	74%	99%
AUG	84%	99%
SEPT	49%	74%
OCT	45%	55%
NOV	77%	87%
DEC	100%	100%

	% of time outside the comfort zone	
	Living room	Bedroom
JAN	100%	100%
FEB	100%	100%
MAR	76%	72%
APR	9%	18%
MAY	45%	55%
JUN	100%	99%
JUL	100%	99%
AUG	100%	100%
SEPT	97%	96%
OCT	68%	71%
NOV	55%	67%
DEC	100%	100%

Figure 6: Comparison of temperatures in the conditioned household D6 (up) and the non-conditioned household D7 (down).

On the other hand, the household electricity consumption measured by the smart meters in each dwelling at hourly intervals allows to understand their behavior in a better way. One interesting outcome is to observe the relationship between the electricity consumption and the differences of temperature in the living room and bedroom of an air-conditioned household. Figure 7 shows such an example of this comparison. In this case, the household consumption has been filtered to show the hourly consumption values only if a difference of temperature of more than 1˚C is observed between both rooms. As it can be seen, there is a clear correspondence between the energy consumption and the temperature increase in the living room.

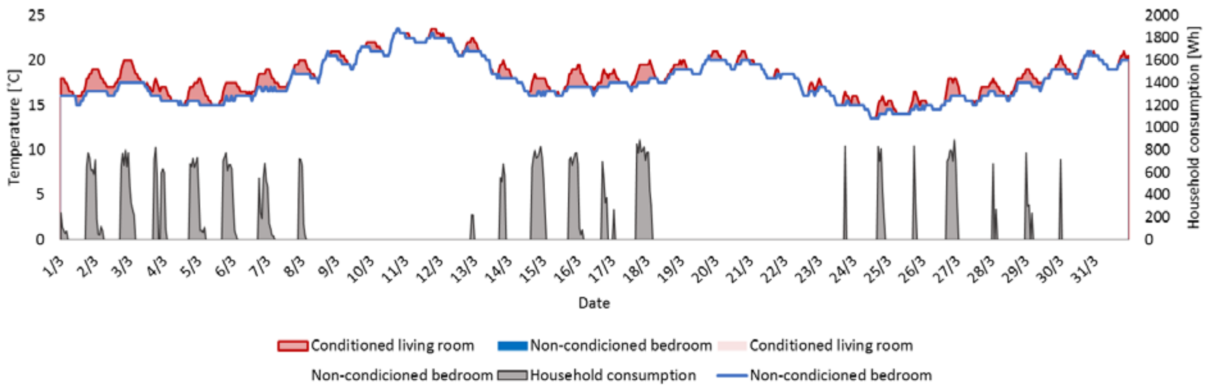


Figure 7: Hourly comparison of temperatures and consumption in dwelling D6.

The monitoring of 10 representative dwellings allows to estimate the total electricity consumption of the district in an accurate way. As we aggregate different household electricity consumption profiles, the result for the district is a smoother profile whose shape will match better the PV generation. In order to show the measurements of the 10 dwellings, an average daily energy consumption profile per household in the district which accounts for all appliances and lighting consumptions in the dwellings has been produced, distinguishing between each month (see Figure 8). Peaks can be observed at lunch (around 15h) and dinner time (21-22h). These average profiles have been obtained considering only the consumption measurements in each individual dwelling when the difference between the temperatures in its two monitored rooms is lower than 1˚C, so as not to take into account hours with air conditioning consumptions.

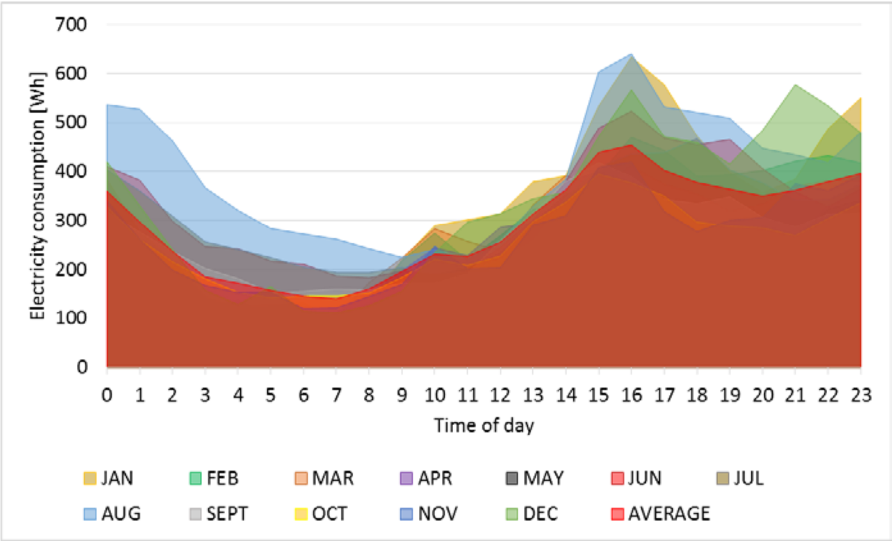


Figure 8: Average monthly energy consumption per household in the district.

In order to calculate the total electricity consumption of the district (without taking air-conditioning into account), the average consumption of the 10 monitored dwellings has been calculated for each hour of the year, discarding those consumptions when the difference of temperature between the monitored rooms of the household was higher than 1˚C. Once the average consumption is calculated each hour, the total consumption has been estimated by extrapolating the result to the whole district, composed of 235 buildings. The resulting hourly consumption profile of the district for the whole year is shown in Figure 9.

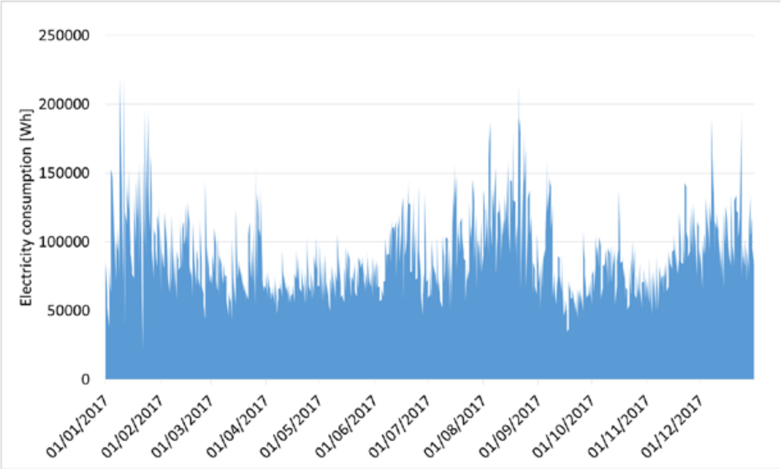


Figure 9: Electricity consumption of the district for every hour of the year.

2.3 Methodological description

From the point of view of the present work, the PV potential of the district could be used to mitigate the consequences of low income and high energy prices on its inhabitants, which restrict their energy consumption especially when it comes to heating or cooling the dwellings. In this case, the solar power generation will be used to cover partially the electricity demand of the district. No electrical storage will be considered.

If the PV generation is lower than the demand, then all the PV generation will be used and the rest of the electricity necessary to cover the demand of the district will be obtained from the grid at its regular price. Conversely, if the PV generation exceeds the demand there will be exported energy. Traditionally this is handled by using net metering, which allows users with surplus electricity to feed the electricity that they do not use back into the grid, obtaining benefits in the process. Given the intricate regulatory and practical situation in Spain in this respect, the proposal of this study is to use the electricity surplus to feed the heat pumps in the district instead. In this way, the thermal storage capacity of the buildings is used and the thermal comfort of the occupants can be improved. The control strategy of the proposed system is summarized in Figure 10.

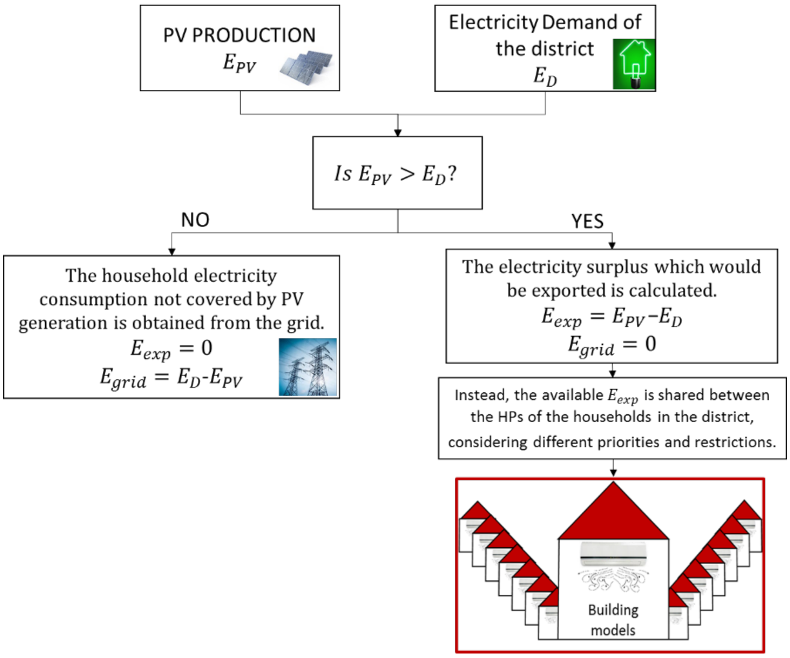


Figure 10: Control diagram of the proposed strategies.

On another note, two indicators will be used to analyze the match between the district's electricity consumption and the PV generation:

-Self-consumption ratio: share of the solar supply that is directly consumed in the district.

$$SCR = \frac{\sum PV_{production} - \sum PV_{exported}}{\sum PV_{production}}$$

-Self-sufficiency ratio: share of the district demand covered by the solar supply.

$$SSR = \frac{\sum PV_{production} - \sum PV_{exported}}{\sum E_D}$$

To determine the Life Cycle Costs (LCC) of each analyzed scenario, a time span which includes the capital investment, operation and maintenance costs was considered. The following parameters are used: investment period of 25 years, inflation rate of 3% and maintenance and costs of 1% of total investment of the project. The electricity cost from the grid is 0.209 €/kWh. The total investment costs are calculated by considering the price of the installed PV modules and inverters in each case. In addition, an increment of 40 % will be considered so as to take into account other costs such as wiring or installation.

The values for the LCC were obtained with the following equation:

$$LCC = Initial_{investment} + \left(Costs_{operation} + Costs_{maintenance}\right) \cdot \sum_{t=1}^{25} \frac{1}{(1+r)^t}$$

where "t" is the year, and "r" is the inflation rate.

The PV modules chosen for the present study are the model Atersa A-250P (250W), and the inverters are Fronius Eco 25.0-3-s (25 kW), with costs of 182 Euros and 3690 Euros respectively.

2.4 PV potential simulation

Although the PV potential of a district is frequently estimated through the use of 3D models for example, the relatively simple layout of the case study in the present work allowed to design the PV system in a simpler but also more detailed way. This was done by using *Helioscope* [43], a web-based PV system design tool that integrates shading analysis, simulation and CAD in one package. It allows to estimate the yearly energy production taking into account losses due to weather, shading, wiring, component efficiencies, panel mismatches and aging. It provides recommendations for equipment and array layout, and the discrete number of PV modules that can fit into a solar field is calculated, considering parameters such as the orientation and inclination of the modules or the separation between adjacent rows.

It should be mentioned that the buildings of the district which have tilted roofs (see Figure 1) will not be used to install PV modules, since the presence of solar thermal panels as well as other obstacles does not allow it. Considering, therefore, only the flat roofs, an example of a PV layout in the district under study using Helioscope can be seen in Figure 11. Since all the buildings have the same height, shading due to distant objects was not considered, only shading between the own PV modules. The total roof area of the district is 2300 m^2 approximately.

Figure 11: Example of layout of the district in Helioscope: south orientation in the flat roofs.

Although the PV modules are usually oriented to maximize the annual solar power supply, this may not optimize other indicators such as self-consumption, grid imported electricity or revenue. Thus, the present study varies the tilt and azimuth of the PV modules installed in the horizontal rooftops of the district, so as to assess in detail the match between the solar power supply and the electricity consumption of the district as well as evaluate different alternatives that will entail different PV yields in summer and winter (which will in turn influence the improvement of the thermal comfort of the occupants). Apart from varying the tilt and orientation of the PV modules, it is also interesting to evaluate the influence of the separation between rows in the horizontal rooftops of the district. This is done in Helioscope through the use of the span-to-rise ratio, which is based on the front-to-back distance between modules divided by the height at the back of the module bank. Therefore, this ratio is sensitive to whether the bank has multiple modules and the tilt of the module, since either of these will increase the rise distance. Raising the span-to-rise ratio increases the distance between rows, thus less PV modules will be installed, reducing the PV yield. However, increasing the ratio also reduces the shading losses, so various alternatives should be analyzed when focusing on maximizing the PV potential.

2.5 Thermal behavior of the dwellings

In order to analyze the thermal behavior of the district in detail, a building model for each of the 37 typologies has been developed. This means that a model with an accurate consideration of the geometry, materials, orientation, exposed surfaces of ceilings, walls, and floors is available for each of the 235 dwellings. The dwelling models were developed in the detailed Unified LIDER-CALENER software tool (HULC by its Spanish acronym), which is the official building energy certification tool in the country [44]. The real constructive solutions were used.

The reason for using this software is twofold: first, this tool follows a transient and hourly base assessment that has been validated via the Bestest [45], it has been used to obtain the Building Energy Performance Certificate of hundreds of thousands of buildings in Spain, and it has also been used by many studies in the recent literature [46–53]. And second, this tool was developed within the research group of the authors of the present work, which allowed to make certain modifications so as to be able to carry out the present study. As an example, a validation of the model of dwelling D4 (which corresponds to Typology 22) is presented in Figure 12, which compares the real measurements of the dwelling in 2017 with the simulation results of its free-floating temperature (no air conditioning system) when using the real climatic data. As it can be seen, the results provided by the software are highly accurate.

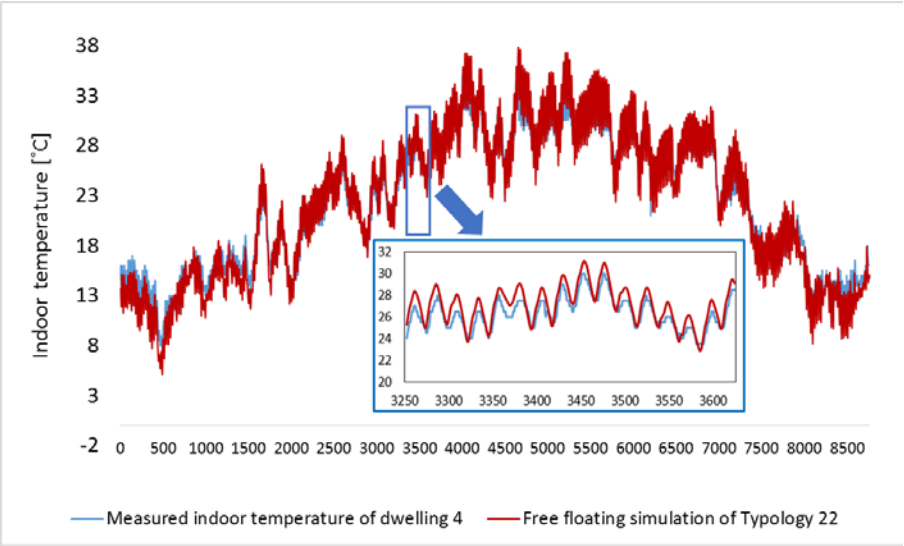


Figure 12: Validation with HULC of the measured indoor temperature of dwelling 4 for the whole year.

2.6 Description of the proposed strategies

2.6.1 Optimal PV potential strategies

In the present work, different alternatives that influence the PV production will be analyzed using the buildings with horizontal roofs. Many studies carry out a very detailed analysis for the optimization of the orientation and the tilt angle of the PV modules. For example, a very interesting review of tilt and azimuth angles considering design parameters, simulations and mathematical techniques for different applications can be seen in [54]. Other studies such as [55–57] determine the optimum tilt angles and orientation for solar photovoltaic arrays, in order to maximize incident solar irradiance for specific periods or latitudes. However, the present work reduced the amount of possibilities considered to 3 different tilt angles and 4 different orientations, since a detailed optimization was not its primary objective.

The options considered for the inclination of the PV modules are: latitude -10˚, latitude + 0˚ and latitude +10˚. For the PV module orientation, the following options (which adapt to the shape of the roofs) will be studied:

- North-East orientation of the PV modules (66˚).
- South-East orientation of the PV modules (156˚).
- South orientation of the PV modules (180˚).
- South-West orientation of the PV modules (246˚).

Two alternatives for module spacing will be also used: span-to-rise=1.5 and span-to-rise=2, to check whether it is better to increase the distance between rows (less PV modules installed but reduced shading losses) or not. The proposed alternatives will be analyzed with the aim of estimating their effect on the following variables:

- Number of panels that can be installed.
- Annual/winter/summer solar energy supply.
- Matched electricity consumption.
- Self-consumption ratio.
- Self-sufficiency ratio.
- Life Cycle Cost.

Once all the alternatives have been examined, three of them will be chosen regarding the following criteria: maximization of self-sufficiency (SSF), maximization of exported PV production (SUPPLY) and minimization of the investment costs (INV). This will be done focusing only on the PV production and electricity demand of the district.

2.6.2 Thermal comfort strategies

The previously mentioned chosen strategies will be then used for the thermal comfort improvement analysis of the dwellings, using weather data of a representative year. However, one question that should be answered is the following: if there is surplus production (exported energy), who should benefit from the available electricity? This study does not seek to propose a detailed course of action regarding this issue (just like sharing in the reality the PV production between dwellings with different electricity consumptions), since it would be a task for studies with different purposes.

Bearing in mind that the focus is on quantifying the improvement of the thermal comfort of the occupants in the district, the following strategies are proposed:

- All the 235 dwellings in the district receive the same amount of electricity to feed their heat pumps (proportional). An indoor temperature restriction is considered: the heat pump of a dwelling can only be used at any time of the simulation if the thermal comfort of the occupants is guaranteed (20-25˚C). If this condition is not fulfilled, the energy that this dwelling would receive is shared by the remaining dwellings instead. If all the 235 dwellings have already been considered in a certain timestep and there is still a surplus, it will be quantified. This strategy will be named as “Prop”.
- A fixed amount of electricity (500 Wh or 1000 Wh) is used to feed the heat pump of each dwelling. In this case, the number of dwellings n_{HP} that can be fed considering

the available electricity is calculated at the beginning of each timestep, and the n_{HP} buildings with the lowest indoor temperature (in winter) or highest indoor temperature (in summer) will activate their heat pumps. The same indoor temperature restrictions as for the first strategy are considered. These strategies will be named as "Q=500" and "Q=1000".

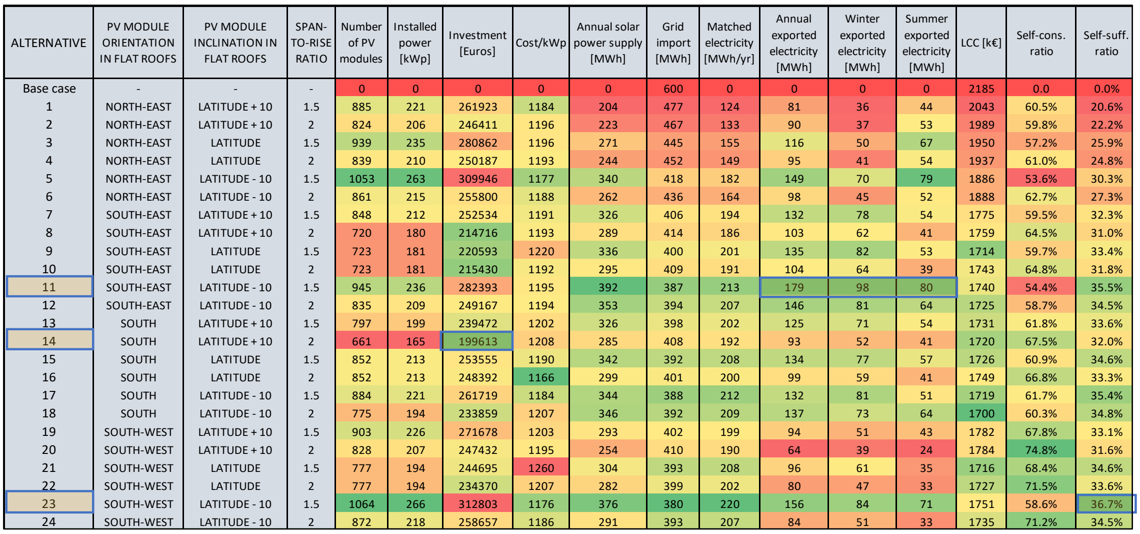
- The indoor temperature of all the dwellings in the district is checked at the beginning of the timestep. First, the dwelling with the lowest indoor temperature in winter (or highest in summer) is heated until reaching a certain set-point temperature. The necessary consumption in order to do so is accounted for. Then, the next dwelling is chosen and so on, until all the exported PV electricity has been used. Two options will be considered: one with a set-point temperature of 25 ˚C in winter and 20 ˚C in summer, and another one with 22.5 ˚C for both summer and winter periods. These strategies will be named as "T=20/25" and "T=22.5".

In summary, these 5 thermal comfort improvement strategies will be simulated for each of the chosen optimal PV strategies (maximization of self-sufficiency, maximization of exported PV production and minimization of the investment costs), making a total of 15 alternatives. An average Coefficient of Performance (COP) of 2 will be considered for all the heat pumps in the district, which is a rather conservative value. Then, several indicators will be shown so as to make a proper performance assessment and comparison between the different options. The total excess degree hours for example will account for the sum of temperature differences in the whole season between the indoor temperature and the comfort temperature (below 20 ˚C in winter and above 25 ˚C in summer).

3 Analysis of results

3.1 PV potential calculations

Once all the PV potential calculations proposed in the previous section have been completed in Helioscope, the next step is to calculate all the variables involved. The number of PV modules that can be installed in the district is provided by the software, as well as the installed power and the solar power supply, calculated for every hour of the year. The annual results can be seen in Figure 13, with colors that highlight the best alternatives in each column independently.



ALTERNATIVE	PV MODULE ORIENTATION IN FLAT ROOFS	PV MODULE INCLINATION IN FLAT ROOFS	SPAN-TO-RISE RATIO	Number of PV modules	Installed power [kWp]	Investment [Euros]	Cost/kWp	Annual solar power supply [MWh]	Grid import [MWh]	Matched electricity [MWh/yr]	Annual exported electricity [MWh]	Winter exported electricity [MWh]	Summer exported electricity [MWh]	LCC [k€]	Self-cons. ratio	Self-suff. ratio
Base case	-	-	-	0	0	0	0	0	600	0	0	0	0	2185	0.0	0.0%
1	NORTH-EAST	LATITUDE + 10	1.5	885	221	261923	1184	204	477	124	81	36	44	2043	60.5%	20.6%
2	NORTH-EAST	LATITUDE + 10	2	824	206	246411	1196	223	467	133	90	37	53	1989	59.8%	22.2%
3	NORTH-EAST	LATITUDE	1.5	939	235	280862	1196	271	445	155	116	50	67	1950	57.2%	25.9%
4	NORTH-EAST	LATITUDE	2	839	210	250187	1193	244	452	149	95	41	54	1937	61.0%	24.8%
5	NORTH-EAST	LATITUDE - 10	1.5	1053	263	309946	1177	340	418	182	149	70	79	1886	53.6%	30.3%
6	NORTH-EAST	LATITUDE - 10	2	861	215	255800	1188	262	436	164	98	45	52	1888	62.7%	27.3%
7	SOUTH-EAST	LATITUDE + 10	1.5	848	212	252534	1191	326	406	194	132	78	54	1775	59.5%	32.3%
8	SOUTH-EAST	LATITUDE + 10	2	720	180	214716	1193	289	414	186	103	62	41	1759	64.5%	31.0%
9	SOUTH-EAST	LATITUDE	1.5	723	181	220593	1220	336	400	201	135	82	53	1714	59.7%	33.4%
10	SOUTH-EAST	LATITUDE	2	723	181	215430	1192	295	409	191	104	64	39	1743	64.8%	31.8%
11	SOUTH-EAST	LATITUDE - 10	1.5	945	236	282393	1195	392	387	213	179	98	80	1740	54.4%	35.5%
12	SOUTH-EAST	LATITUDE - 10	2	835	209	249167	1194	353	394	207	146	81	64	1725	58.7%	34.5%
13	SOUTH	LATITUDE + 10	1.5	797	199	239472	1202	326	398	202	125	71	54	1731	61.8%	33.6%
14	SOUTH	LATITUDE + 10	2	661	165	199613	1208	285	408	192	93	52	41	1720	67.5%	32.0%
15	SOUTH	LATITUDE	1.5	852	213	253555	1190	342	392	208	134	77	57	1726	60.9%	34.6%
16	SOUTH	LATITUDE	2	852	213	248392	1166	299	401	200	99	59	41	1749	66.8%	33.3%
17	SOUTH	LATITUDE - 10	1.5	884	221	261719	1184	344	388	212	132	81	51	1719	61.7%	35.4%
18	SOUTH	LATITUDE - 10	2	775	194	233859	1207	346	392	209	137	73	64	1700	60.3%	34.8%
19	SOUTH-WEST	LATITUDE + 10	1.5	903	226	271678	1203	293	402	199	94	51	43	1782	67.8%	33.1%
20	SOUTH-WEST	LATITUDE + 10	2	828	207	247432	1195	254	410	190	64	39	24	1784	74.8%	31.6%
21	SOUTH-WEST	LATITUDE	1.5	777	194	244695	1260	304	393	208	96	61	35	1716	68.4%	34.6%
22	SOUTH-WEST	LATITUDE	2	777	194	234370	1207	282	399	202	80	47	33	1727	71.5%	33.6%
23	SOUTH-WEST	LATITUDE - 10	1.5	1064	266	312803	1176	376	380	220	156	84	71	1751	58.6%	36.7%
24	SOUTH-WEST	LATITUDE - 10	2	872	218	258657	1186	291	393	207	84	51	33	1735	71.2%	34.5%

Figure 13: Obtained results in all the analyzed strategies. In each column, green cells represent the best options while red cells represent the worst ones. The marked alternatives are those chosen for the thermal comfort study.

First of all, it should be mentioned that choosing the optimal parameters is paramount in order to maximize the solar supply, which varies up to 48 % among the studied alternatives. On the other hand, the differences between them regarding grid import, matched electricity and self-sufficiency ratio are not very significant. The reason behind this is that the electricity consumption of the social housing district is low, especially when compared to the PV generation obtained during sunshine hours after the installation of the PV modules. Remembering that the exported energy and its potential revenue is not being computed in these calculations for the reasons noted above, the considered alternatives still show payback periods around 7 years. Other conclusions that may be reached are mentioned below:

- The base case, which considers the provision of all electricity from the grid, is the one with the highest LCC.
- A lower inclination angle of the PV modules leads to more modules being installed, since the separation between rows is less restrictive. The north-east and south-west orientations also favor the number of modules that can be installed due to the shape of the roofs. The same happens with the span-to-rise ratio: the simulations with a value of 1.5 allow the installation of more modules. In most cases this results in an increase of the solar power supply, but also an increase on the LCC. The reason is that although more PV panels are installed, the shading losses increase if a span-to-rise ratio of 1.5 is used. Therefore, the results need to be carefully analyzed in order to choose the optimal options.
- In most cases, the maximum power supply in summer and annually is achieved with an inclination of latitude-10˚.
- In general, using the PV layouts with the north-east orientation results in less annual solar power supply as well as matched generation, exported electricity and self-sufficiency ratio. In addition, they are the ones with worse LCCs.
- The matched electricity and self-sufficiency ratio is higher when the south-west layout orientation is used (thus the grid import is lower in these cases). The reason is that the electricity demand of the district is higher after midday, favoring the south-west orientations which generate more energy during those periods.

After considering in detail all the results from the PV alternatives that have been analyzed, three of them have been chosen for the thermal comfort study (see Figure 13):

- Alternative 11: it was selected since it offers the highest solar power supply both in summer and winter.
- Alternative 14: it has the lowest investment cost and almost the lowest LCC, since it is the alternative with the lowest number of PV modules installed. This option is optimal from an economic point of view, but offers a lower solar power supply.
- Alternative 23: it shows the highest self-sufficiency ratio and matched electricity, as well as the lowest grid import. This is due to the fact that it is the option with more PV modules installed (and higher investment costs).

3.2 Thermal comfort improvement of the chosen strategies

As mentioned in Section 2.6.2, the three optimal PV strategies that have been selected will be now used to analyze the potential benefits of using their exported PV production so as to improve the thermal comfort of the occupants, considering five different alternatives. Therefore, a total of 15 simulations will be conducted. Each simulation analyzes on an hourly basis the thermal behavior of each of the 235 dwellings during the 8760 hours of the year. The decision of which heat pumps should be activated, which depends on the strategy, is taken every timestep. As an example, Figure 14 illustrates simulated indoor temperatures and consumptions in dwelling 130 for some of the analyzed strategies in the PV optimal case that maximizes the exported PV production (SUPPLY). It can be seen how during the day, the exported PV production (Q) given to this dwelling is used to supply heat, which results in an increase of the indoor temperatures. It can also be seen how on the 21 of March this dwelling was not chosen for the strategy T=20/25, since other dwellings of the district had a higher priority due to their lower indoor temperatures. Once all the alternatives have been simulated, several indicators are calculated.

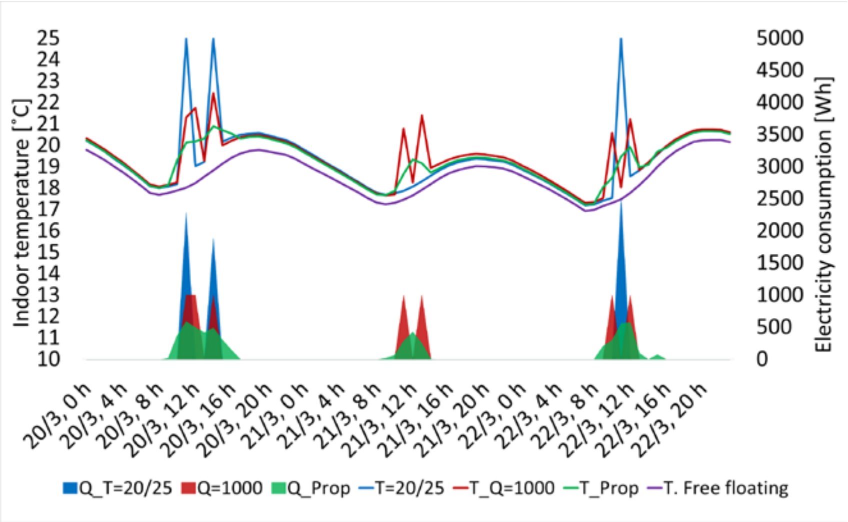


Figure 14: Example of simulated indoor temperatures and consumptions in the dwelling 130 for some of the analyzed strategies (case maximization of exported PV production).

The energy storage capacity of the structural mass becomes clear (see Figure 15) when the indoor temperature fluctuation under full free floating conditions (purple curve) and the indoor temperature fluctuation when the heat pump operates (green curve) are compared. The effect of the thermal mass is proportional to the difference between both curves when the heat pump is switched off (shaded area). It can be seen how this difference is obviously higher in hours immediately after the heat pump operation.

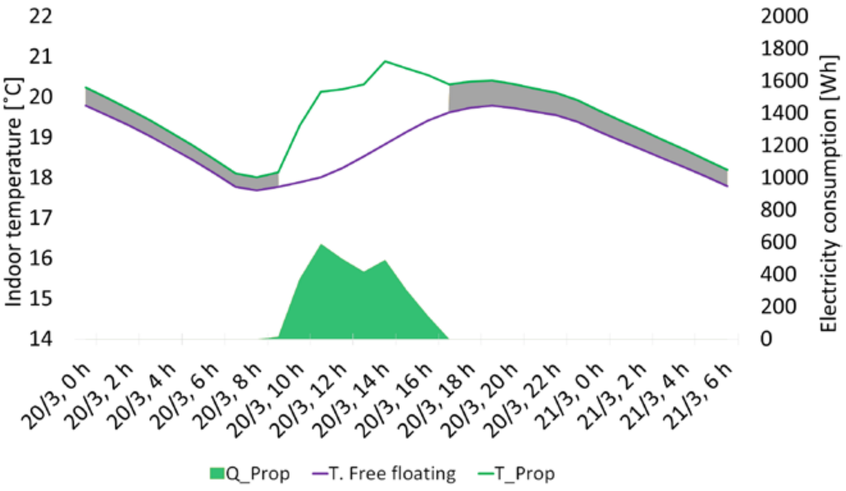


Figure 15: Example of thermal energy storage before and after the heat pump operation in the dwelling 130.

The results of all the strategies are given in Table 3, which shows among others the average total excess degree hours and average percentage of time outside the comfort zone of the dwellings in the district for each alternative. First of all, as we can see the three PV optimal strategies (SUPPLY, INV and SSF) have a different amount of available electricity, which influence the thermal comfort improvements. The percentage of energy used is computed in each simulation. This indicates the amount of available electricity that has been used during the whole year in the heat pumps of the district. A 100 % is never achieved, since it could happen that during a certain timestep all the buildings have already been heated/cooled and there is still surplus electricity, for example if Q=500 Wh and the PV production is higher than 117500 Wh, or if the temperature requirements of the strategies are not met so the dwelling cannot be used. The number of activated dwellings varies depending on the followed strategy, and the highest values can be found for the strategy "PROP", since there are no priorities to heat/cool the dwellings and the same amount of energy is given to each of them.

				Winter				Summer			
	Available exported electricity [MWh]	Percentage of the energy used [%]	Average number of activated dwellings	Excess degree hours [˚C·h]	Reduction [%]	Percentage of time outside the confort zone [%]	Reduction [%]	Excess degree hours [˚C·h]	Reduction [%]	Percentage of time outside the confort zone [%]	Reduction [%]
BASE CASE	-	-	-	17405	0.0%	76.3%	0.0%	11369	0.0%	72.3%	0.0%
SUPPLY_PROP	178.8	92.19	222	15448	11.2%	68.8%	7.5%	8402	26.1%	61.7%	10.5%
SUPPLY_Q=500		90.02	133	15475	11.1%	69.3%	7.0%	8479	25.4%	62.2%	10.1%
SUPPLY_Q=1000		85.42	65	15530	10.8%	69.6%	6.7%	8459	25.6%	62.7%	9.6%
SUPPLY_T=20/25		96.81	45	15812	9.2%	69.9%	6.4%	8671	23.7%	62.1%	10.2%
SUPPLY_T=22.5		88.23	64	15760	9.4%	69.5%	6.8%	8646	24.0%	62.0%	10.3%
INV_PROP	92.6	95.54	226	16197	6.9%	72.5%	3.8%	9772	14.0%	66.9%	5.4%
INV_Q=500		95.33	92	16206	6.9%	72.7%	3.6%	9719	14.5%	66.8%	5.5%
INV_Q=1000		89.81	45	16262	6.6%	73.0%	3.3%	9751	14.2%	67.1%	5.2%
INV_T=20/25		97.5	26	16452	5.5%	73.2%	3.1%	9896	13.0%	66.8%	5.4%
INV_T_225		89.22	40	16405	5.7%	72.8%	3.5%	9874	13.2%	66.8%	5.5%
SSF_PROP	155.7	92.66	222	15884	8.7%	69.9%	6.4%	8669	23.7%	62.9%	9.4%
SSF_Q=500		90.78	130	15903	8.6%	70.3%	6.0%	8711	23.4%	63.2%	9.1%
SSF_Q=1000		86.07	64	15951	8.4%	70.7%	5.6%	8693	23.5%	63.4%	8.9%
SSF_T=20/25		97.32	61	16146	7.2%	70.7%	5.6%	8941	21.4%	63.2%	9.0%
SSF_T=22.5		85.47	43	16112	7.4%	70.5%	5.8%	8883	21.9%	62.8%	9.5%

Table 3: Overview of the average obtained results in the district.

The highest reduction of total excess degree hours is found for the case "SUPPLY_PROP" (optimal PV case that maximizes the exported PV production, and shares the available energy between all the dwellings equally). The reason is that compared to the other strategies, the increase of temperatures produced by the heat pumps in the dwellings is lower, which translates into lower thermal losses. If a dwelling is heated/cooled only sporadically, the energy will be wasted rapidly. But, if a dwelling is repeatedly used, its thermal inertia allows to store the energy in a more adequate way. A 11.2 % reduction of the total excess degree hours in winter and 26.1 % in summer (more available electricity) may be achieved, reducing the percentage of time outside the comfort zone in 7.5 % and 10.5 % respectively. Although these results may not seem very appealing, the influence that these reductions of total excess degree hours have on the health of the occupants should be taken into account, since illnesses are associated with higher thermal comfort violations as mentioned in the literature review in Section 1.

Besides, these results could be rather misleading. Although it is true that the strategy "PROP" is the best alternative when looking at the whole district, the electricity in this case is shared equally between all the buildings. This means that for example a dwelling with better solar access than another one is given the same amount of energy. Therefore, although when looking at the whole district the average total excess degree hours is lower in "PROP", the dwellings with worse indoor conditions do not have a higher priority. Figure 16 shows the range of total excess degree hours of all the dwellings in the district for each strategy in the case "SUPPLY", as well as their distribution, which is similar in the studied alternatives. As it can be seen, although the average of the district in the case "PROP" is lower, there are buildings with much higher total excess degree hours compared to the other alternatives. For this reason, the alternative T=20/25 is considered as a more suitable option, since it is also able to reduce the differences of thermal comfort between the dwellings of the district, favoring those which have worse indoor conditions.

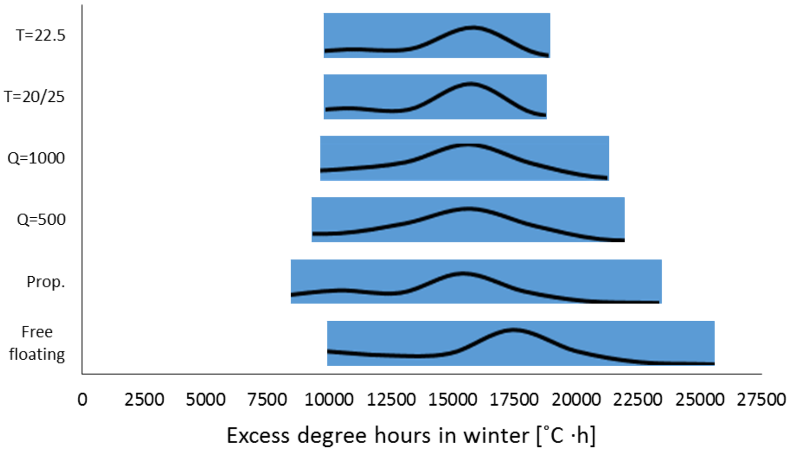


Figure 16: Comparison of total excess degree hours of the households for each strategy (case maximization of exported PV production).

Last of all, another interesting outcome of the present study is to know what the results of thermal comfort improvement would be, had the assumptions been different. The strategy T=20/25, considered as a consequence of the previous results as the most appropriate one to reduce the differences of thermal comfort in the district, will be used in the following scenarios:

- Only the living rooms will be considered, instead of heating/cooling the whole dwellings. The PV production still covers the district demand partially just like in previous cases.
- All the electricity generated by the PV modules will be used for the heat pumps instead of covering partially the electricity demand of the district, heating or cooling the whole dwellings.
- The potential PV generation if the buildings with tilted roofs had been used will also be considered, increasing the available electricity (still covering partially the electricity demand of the district and heating/cooling the whole dwellings).

The results (see Table 4) show that if only the living rooms of the district are considered, the comfort improvements are much higher (reductions of average excess degree hours of 34 % in winter and 72.6 % in summer). The reason for this is the lower amount of energy necessary to heat/cool the living rooms compared to the whole dwellings, which also decreases the percentage of energy used. An example of the hourly indoor temperatures achieved in the living room of a dwelling compared to its free floating temperature is illustrated in Figure 17, showing the benefits of such a strategy. As for the case that doesn't partially cover the demand of the district, higher reductions are also achieved (from 9 % to 24 % in winter and from 24 % to 44 % in summer). Last of all, if the PV potential of the buildings with tilted roofs had been used, a reduction of almost 33 % could be achieved in winter and 67 % in summer, heating or cooling the whole dwellings.

				Winter				Summer			
	Available exported electricity [MWh]	Energy used [%]	Average number of activated dwellings	Excess degree hours [˚C·h]	Reduction [%]	Time outside the confort zone [%]	Reduction [%]	Excess degree hours [˚C·h]	Reduction [%]	Time outside the confort zone [%]	Reduction [%]
Base Case	-	-	-	17405	0.0%	76.3%	0.0%	11369	0.0%	72.3%	0.0%
Whole district (previous case)	178.8	96.8	45	15812	9.2%	69.9%	6.4%	8671	23.7%	62.1%	10.2%
Only living rooms	178.8	67.6	153	11428	34.3%	55.5%	20.8%	3117	72.6%	34.7%	37.6%
All PV generation is used	392.2	94.1	62	13263	23.8%	63.1%	13.2%	6370	44.0%	51.8%	20.5%
Including generation of tilted roofs	698.4	80.7	123	11680	32.9%	56.9%	19.4%	3774	66.8%	38.2%	34.1%

Table 4: Results of the analyzed options.

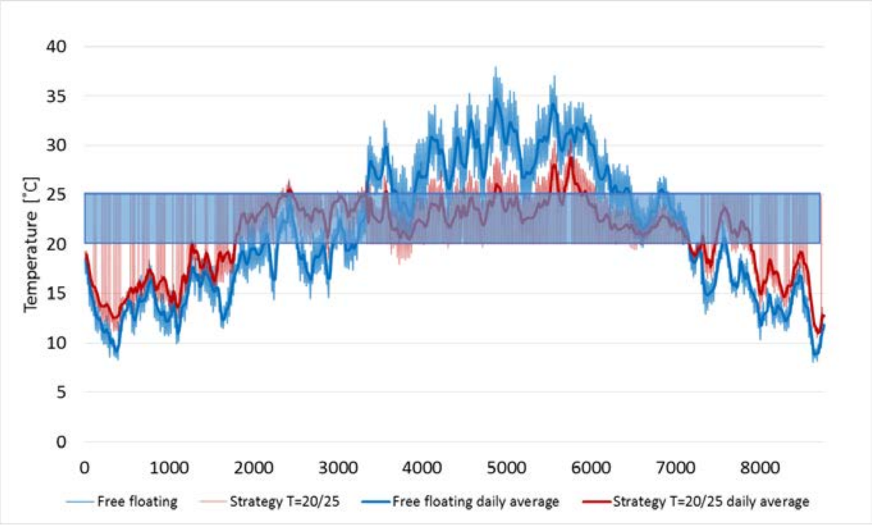


Figure 17: Hourly and daily free floating temperature of the living room in dwelling 147 VS temperatures achieved with strategy T=20/25.

4 Conclusions

In the present work, a novel approach in order to improve the thermal comfort of the occupants in a district at risk of energy poverty has been developed. Taking advantage of the rooftop PV potential in the area, the solar supply is used to cover part of the electricity consumption of the households during the day, reducing their energy bills. Then, instead of using electric storage, the proposal is to use the surplus electricity to supply energy for the heat pumps in the district, heating or cooling the whole dwellings.

First, the optimal strategies from an electrical and economical point of view were chosen, changing the orientation and inclination of the PV modules as well as their separation in order to maximize the solar supply, minimize the investment or maximize the self-sufficiency ratio of the district. The results showed that the solar power supply was maximized by using a south-east orientation, while using a south orientation with less PV modules installed led to the lowest investment, due to the relatively low consumption of the district compared to the PV generation. The self-sufficiency ratio was maximized using a south-west orientation, which favors the solar power supply when the consumption of the district is higher.

After choosing the PV optimal strategies, the surplus electricity in those alternatives was used to share the electricity between the heat pumps of the 235 dwellings of the district. Heating or cooling the whole dwellings, the results showed that the thermal comfort of the occupants could be improved in average up to 11 % in winter and 26 % in summer. If all the PV generation was used, a reduction of 24 % in winter and 44 % in summer could be obtained. On the other hand, if more buildings could be employed to install PV modules, improvements up to 33 % in winter and 67 % in summer could be expected. If only the living rooms of the district were heated, up to 34 % and 73 % reduction in winter and summer respectively could be achieved. In all the cases considered, the thermal comfort differences among the dwellings of the district are reduced significantly, particularly in some of the proposed strategies.

The outcomes of the present work show the potential benefits of the approaches that have been introduced when it comes to tackling energy poverty, even without considering a previous implementation of traditional thermal mitigation strategies. In future work, the synergies between the approaches shown in the present study and traditional retrofitting strategies will be further analyzed. The reason for this is that the results of thermal comfort improvement shown here will most probably improve if thermal mitigation strategies are previously implemented, due to the reduction of the thermal losses of the buildings which allows to store the energy inside the buildings for longer periods. These proposed alternatives could be used by policy-makers in the future, reducing the energy bills of occupants with monetary restrictions and at the same time improving substantially their thermal comfort.

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