# Potential of energy flexible buildings: evaluation of DSM strategies using building thermal mass

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## Abstract

Energy flexible buildings through smart demand-side management (DSM) or smart demand response (DR) using efficient energy storage, are currently one of the most promising options to deploy low-carbon technologies in the electricity networks without the need of reinforcing existing networks. Although, many ignore the potential, economic and energetic benefits these alternatives could hold for buildings, users and tariffs.

In the study carried out a control system of demand management measures is analyzed, based on the use of the buildings' thermal mass as thermal storage (preheating, precooling and night ventilation). This demand management system is analyzed in five existing residential buildings in the so-called reference scenario (construction, user and current prices). Subsequently, comes the analysis of the optimal management strategy choice from the system, when facing changes in the housings' constructive characteristics and electric tariffs.

The dynamism of the management system stands out from the results achieved, as well as the dependence of the possible strategy choices on the climate zones. In the reference situation, the maximum economic savings obtained after the implementation of the management system correspond to 3.2% for heating and 8.5% for cooling. In this same manner, when the buildings are previously rehabilitated, the savings can double even generating energy savings. Finally, it can be concluded that the low installation costs of these measures make them a winning solution, as long as the electric pricing and user behaviour allow the required flexibility.

***Keywords:*** *Demand side management; Building as thermal battery; Demand flexibility; Economic load dispatching; Demand response*

# 1 Introduction

In this era of uncertainty, when speaking of energy planning consumer demand, has emerged as a central figure, since it can be seen as a means of balancing the energy supply and demand of electricity, by providing the system with flexibility whose responsibility no longer falls only on the generation infrastructure. Traditionally, the demand has been addressed by requiring green-rated buildings and energy efficient equipment. Conversely, retrofitting solutions for existing buildings can be a more costly and challenging task [1]. Around 40% of the energy is consumed by the buildings and they are responsible for 36% of greenhouse gas emissions [2]. The ultimate aim is buildings with a balance of zero energy or net positive energy [3], buildings that produce at least as much energy as they consume, involve high energy efficiency and on-site renewable energy (RE) generation [4].

The energy flexibility of a building could significantly contribute to the minimization of tempory mismatches between generation and demand, caused by intermittent renewable generation. It is defined as the ability to manage its demand and generation according to local climatic conditions, user needs and energy networks requirements [5]. Faced with these requirements, the concept of Demand Side Management (DSM) [6] appears as a proactive way to increase the energy efficiency among users in the long-term [7], and can reduce both the electricity peak power demand and the electricity consumption [8,9].

The most prominent DSM methods include reducing peak loads (peak clipping or peak shaving), shifting load from on-peak to off-peak (load-shifting), increasing the flexibility of the load (flexible load shape), and reducing energy consumption in general strategic conservation), as stated by Müller et al. [10]. Besides, it is necessary to analyze how it is possible to improve energy storage strategies to make them more efficient and, to reach low cost alternatives. Additionally, demand side management provides an active integration of the user into the market by influencing its load profile, making more conscious and efficient use of energy. For example, Müller et al. [11] and Gelazanskas et al. [12] proposed more interesting strategies.

There are countless publications on DSM and there is a noticeable increase in recent years on the number of published papers about this issue. However, they emphasize different aspects. For example, many studies focus on price based DSM, quantifying the suitability and impact of DSM approaches under variable prices or real-time pricing [13–17]. Conversely, other publications emphasize the influence of DSM on Smart Grids, developing different frameworks for its integration into micro grids or Smart Grid environments [12,18–26], based on research and practice [27] addressing the behavioural changes of energy end-users.

On the other hand, Fernández et al. [28] make a comparison between renewable generation and DSM, suggesting that DSM exhibits the best performance in terms of economic efficiency and environmental sustainability, reducing peak loads and losses in the system. The estimation of this paper are: electric appliances consume around 62% of the electricity of a home in Spain, where unattended appliances such as washing machines are responsible for 21%. As a result, they consume 13% of the total electricity demand. This means that being able to program these appliances to work at non-peak times could achieve considerable savings at no cost.

In fact it has been shown that the impact of DSM programs is significant: it can be appreciated mostly in aggregated households [29]. $CO_2$ emissions could also give customers an environmental motivation to shift loads during peak hours. Also, an empiric estimation of three different DSM measures is developed by Khanna et al. [30]: electricity pricing, energy label programs and information feedback mechanisms. As an alternative, the approach discussed by Khoury et al.

[31]. It determines an optimal schedule of operation for predictable devices. At the beginning of each day, the energy flows are forecasted, modifying the consumption of the house accordingly. Furthermore, significant savings can be achieved with actions such as changing the settings of the thermostats or retrofitting projects. Shiftable loads are heating, cooling air conditioning, washing machines, dryers and dishwashers [32]. Command and control of heating and cooling systems are becoming a cost-effective viable option, particularly applicable to the existing building stock [1]. So, one of the major topics to be investigated in this field is the potential of DSM in existing buildings, and the requirements to achieve the maximum savings.

In addition, all programs intended to influence the customer's use of energy are considered DSM and can be addressed to reduce demand at peak times, seasonal consumption or alter the time of use [33]. In general, they encourage the end user to be more energy efficient. DSM can also help to reduce network congestion and the need for investment in new generation equipment [28]. Then, this field closely follows the paradigm of what type of characteristic should have user behaviour of buildings to invest in these programs.

DSM often works best when there is storage available for the user. The storage in these demand management strategies is especially important as it is mainly about the movement of loads and uses of energy at periods other than production. Applicability of each one of them has been analyzed according to certain conditions, in particular the cost of installation and operation. There are three types, basically: electrical batteries; thermal energy storage TES using water tanks; and thermal energy storage using thermal inertia of buildings [34–37]. The first one remains an expensive option but it is the most used. The second one takes advantage of domestic heat water needs to become an easy and viable solution [11,35,38], through pre heating and cooling, or storing the energy in tanks [1]. TES systems have shown a capability to shift electrical loads from high-peak to off-peak hours, which is the reason why they are a powerful instrument in DSM, especially in the presence of renewable energies [33]. Storage can also help to flatten the customer's load profile. Therefore, effective TES can potentially impact several categories of DSM, including peak load shifting, valley filling and strategic conservation [39]. And finally, the most innovative is the use of the internal thermal mass of buildings [40,41]. In this work, it is studied the latter.

There are also many studies which stress the importance of storage within a DSM framework. For instance, the study presented by Quareshi et al. [39] assesses the impact of using Phase Change Materials (PCM) in buildings to leverage its thermal energy storage capability, claiming that significant advantages can be obtained for space heating applications. On the other hand, Wolisz et al. [42] analysed the potential of Thermal Energy Systems (TES) in buildings, integrating conventional storage technologies like hot water tanks as well as the structural thermal storage capacity of a building itself. The calculations are based on a thermal building simulation in Modelica. The study developed by Arteconi et al. [43] presents an existing installation of a TES system coupled with heat pumps, performing simulations to show the load shifting potential of the storage while assessing energy and cost savings. [32] Also, showing some impressive results regarding load shifting, arguing that the peak load of a dwelling can be reduced on average by 24% and 13.5% as a result of washing machine and dishwasher load shifting respectively. Last, the potential to improve the balancing between electricity used for heating and local production of a Net Zero Energy Building (nZEB) by active used of the structural thermal storage capacity of the building is analyzed by Reynders et al. [44]. This study shows the possibilities of structural thermal storage but, results are not replicable in existing building.

Literature shows that the DSM potential is function of the availability of thermal mass and the geometry of the building [44]. However, the use of the thermal mass only enables short-term storage. Therefore it is not able to reduce seasonal mismatches of energy production. The DSM potential is higher for the massive buildings compared to lightweight buildings, and it could be expected that the efficiency of the structural storage is higher for well insulated buildings. Le Dreau et al. [34,45] analyze the influence of interior mass and envelope quality of buildings in heating energy flexibility. However, cooling energy is not studied, and the decision of refurbishment yes or not is not clear. There are many works about thermal storage in the building structure [35,40,44,46,47]. The most discussed topics are: benefits in thermal comfort and a small reduction of building demand [46,47]; effect of intermittent operation schemes [47]; district heating approach [35]; and change in user behaviour [40].

Activating the structural thermal storage demands for the active control of the indoor temperatures and the total energy use increases [44], since the use of structural storage might result in increased transmission and ventilation losses. The building could be preheated and its storage capacity activated by increasing the indoor temperature set-point when the price of the electricity is low. Alternatively, the set-point could be lowered with high electricity prices, releasing the stored energy and thus reducing the electricity demand.

Another way in which DSM can work is by relying on the inherent property of buildings, for example by changing the temperature thanks to their thermal mass or disengaging heating or cooling for short periods, especially when the air flow within the building is maintained [1]. So, there are some rules which should be considered related to DSM [1], but it is not about weather and building thermal behaviour aspects. For example, improving the performance of a building through building automation requires adequate measurements and justification of the economic gains it could offer before its realization, which could differ depending on the user behaviour. The study presented in [48] suggests that results from observations and product research for residential homes indicates that the investment cost of building automation ranges from 500 to 2000 Euros, depending on the building type.

The literature review revealed a significant knowledge gap in this area: there are not many studies on the performance of thermal storage systems in residential buildings (heating & cooling), user behaviour or thermal characteristics of buildings valuing the potential savings obtained both economic and energetic. Moreover from the existing research initiatives, most do not talk about energy or economic savings, studies tend to analyze the storage performance, but not linked to savings obtained or their dependences.

This study addresses this knowledge gap by presenting systems used for DSM thermal energy storage in five different buildings, in different climatic conditions, with the refurbishment of the thermal envelope of the buildings or not, and the study of the most relevant parameters (electricity tariffs, nightcooling, preheating, precooling…).

Additionally, it proposes a new energy controller to optimize and analyze:

- Effect of tariffs: a study of different electricity tariffs in Spain
- Operation of heat pumps (duration and setpoints)
- Equilibrium between energy savings and costs.
- Importance of rehabilitation in DSM solutions (thermal energy storage using buildings as a battery).

The objective of the work is evaluating an algorithm that automatically manages the activation of a heat pump in response to the most appropriate strategies according to pricing and operating conditions. It is interesting to see if a balance can be reached between the cost savings, the increase in energy consumed, the thermal comfort of the occupants and the contribution to the reduction of the peak loads. The study shows different results and conclusions, highlighting the important influence of various factors on the results obtained, such as user behaviour, constructive quality of the building and electricity pricing.

The literature review revealed a possible knowledge gap in this area: there are not many studies on the thermal storage systems performance in residential buildings (heating & cooling) and the thermal characteristics of buildings, valuing the potential savings obtained for both energy and economics. And those that exist, do not talk about energy or economic savings, only analyze the storage performance, but the works do not link to the achieved savings or their dependences.

# 2 Methodology

## 2.1 Overview

The implemented methodology allows analizing the potential use of the buildings' thermal mass as an energy storage system ('building as a battery') through the application of different measures of demand management. For this purpose, an intelligent manager has been implemented to decide the optimal operating scenario based on the climatic conditions, the use given by the users and the different measures to analyze (preheating, precooling and night ventilation). These measures are based on the equipment' operative control, their setpoint variations and swiching the system' air extraction on and off during the night hours.

The decision-maker selects the optimal strategy based on the building's geometrical and constructive characteristics, the areas climate, tariffs and operating conditions. Therefore, the objective of the decision maker is to achieve savings in costs as well as reducing the network overload during periods of higher consumption, by shifting loads towards non peak hours, or hours of lower consumption. In this way, the building acts as a battery, offering passive thermal storage.

This demand management system is analyzed in five real residential buildings from the so-called reference scenario (construction, users and current tariffs). Subsequently, the optimal management strategy chosen by the system, facing changes in construction characteristics and electricity pricing is analyzed.

Figure 1 shows the layout of the methodology carried out for the development of this study.

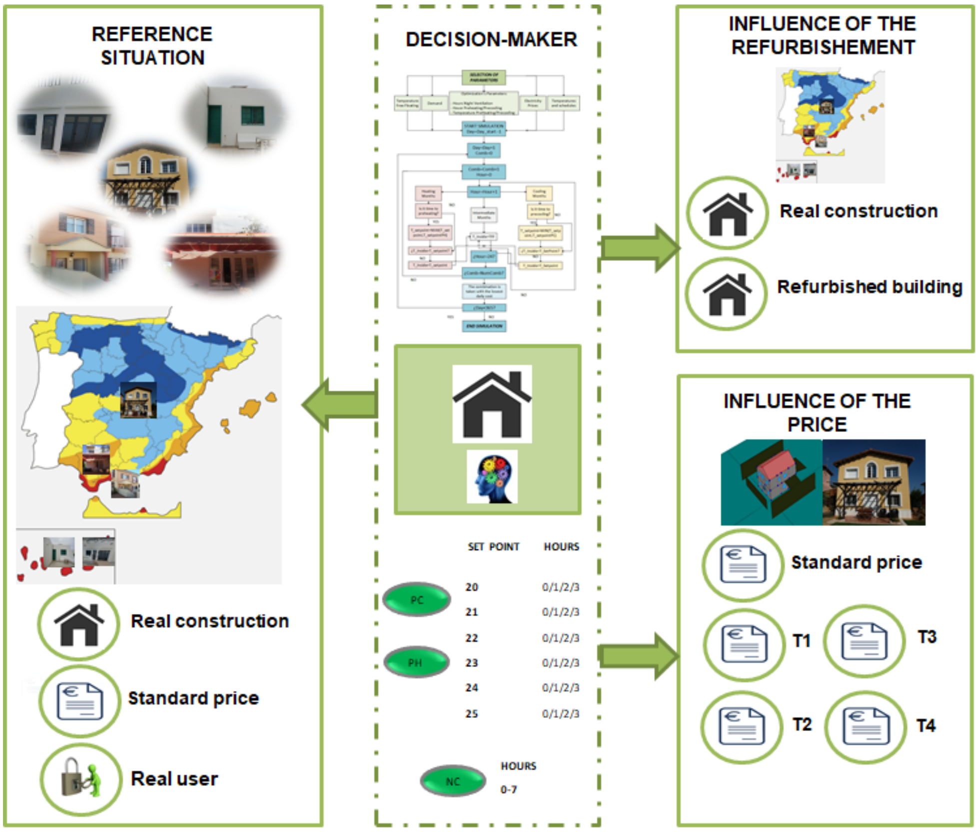


Figure 1. Methodology

## 2.2 Decision-maker

### 2.2.1 Basic principles

The manager's objective (decision-maker in figure 1) is to choose the most appropriate strategy for the daily operation, taking into account the established use of the building. The most appropriate strategy is the one that minimizes daily operating costs while maintaining the same level of comfort during occupation hours. This optimization allows evaluating the potential and intelligence of the control systems for thermal conditioning and night ventilation in the buildings and the actual capacity of the buildings as thermal storage systems. At the end of the day, the system decides the optimal strategy of operation for the next day. This decision is made at the end of the day, in the final hours.

The manager has implemented a simulation algorithm, as shown in figure 2. This algorithm requires the following parameters:

- Building Energy model using the detailed Unified LIDER-CALENER software tool (HULC) [49].
- Chosen electric tariffs
- Operating hours and conditioning instructions.
- Night ventilation: air flux is extracted from houses and the extractors consumption.

It should be noted that the algorithm calls the detailed building simulation tool HULC [49]. This call validates the historical temperature data and energy demands until the present moment and simulates the different scenarios of operation, occupation and climatic conditions to be analyzed. The result of this simulation is the energy consumption and the response of indoor air for each strategies. In this way, the algorithm can compute the hourly cost and decide on the optimal strategy.

Centralized electric heat pumps are used to keep comfortable conditions entirely in every room of houses, except the bathrooms, the kitchen and the corridor. The air conditioning systems have been simulated using the heat pump model of DOE2 [50]. This procedure is used in EnergyPlus [51] or TRNSYS [52]. Models require to define the Energy Efficiency Ratio EER and the nominal capacity. The value of EER is 2 for every system, and their nominal capacity depends on each dwelling. They have been sized analyzing peak cooling needs, obtained from the energy needs of the different buildings using the proposed simulation tool [49]. Likewise, the coefficients from the operation curves (showing the effects of partial load and variation due to the outdoor conditions) have been taken from the proposed default values by EnergyPlus for the heat pumps.

The proposed controller (see figure 2) automatically manages the activation of the heat pump in response to the most appropriate strategies according to the pricing and operating conditions. Algorithm takes known parameters shown at the top of figure 2. Then, simulation starts at the end of the day, before the study, taking as certain the results of the past day. In this simulation, all the possible operation strategies are analyzed. The simulation of possible future scenarios includes up to 3 days following the current one, so that the optimal strategy (lower daily cost) for the day to study takes into account its repercussions in the coming days. Because it has been estimated that the time constants for the buildings to study are between 48 and 72 h [53].

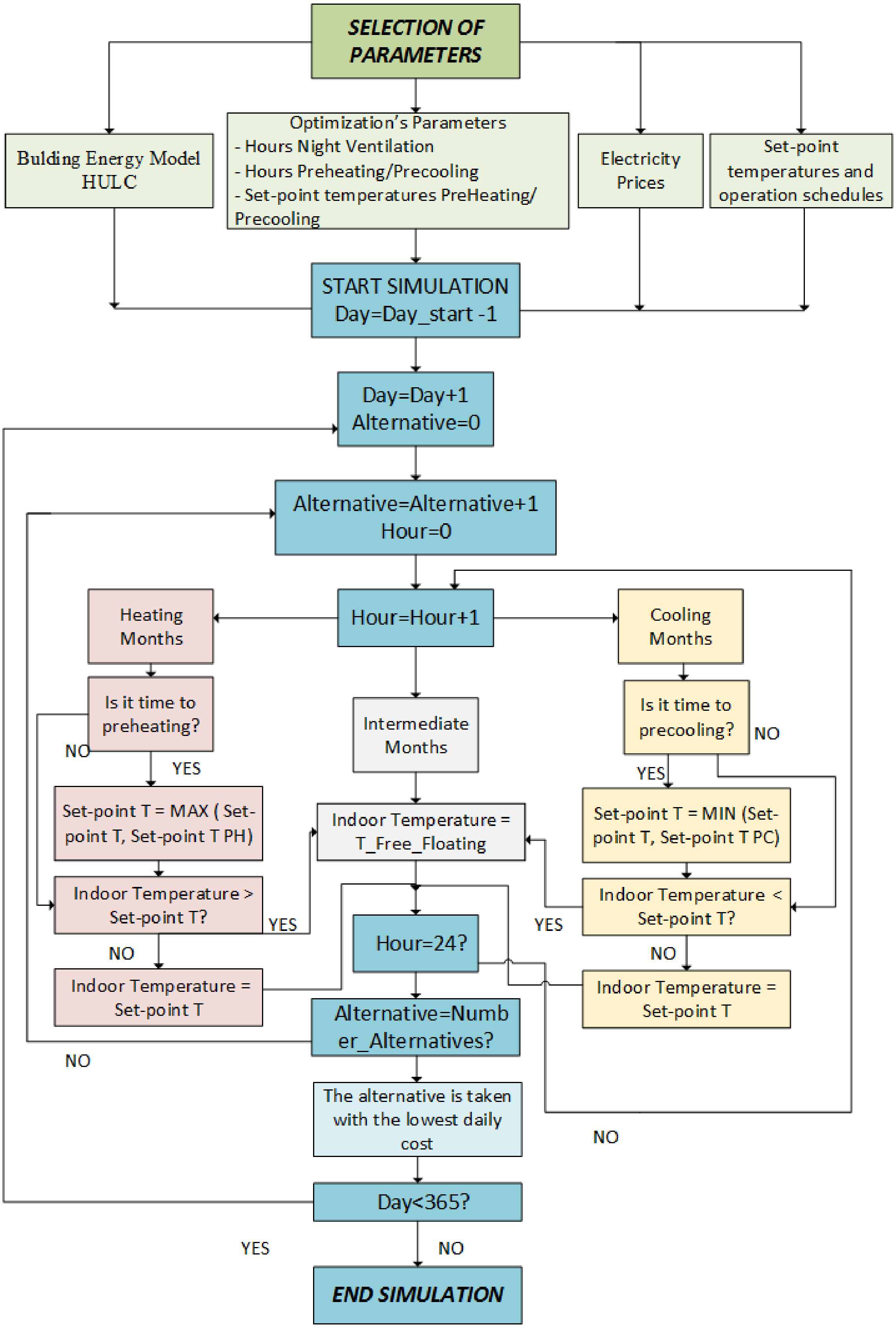


Figure 2. Management algorithm

### 2.2.2 Strategies

In work carried out the measures of demand management studied are preheating, precooling and nightcooling. These measures use the structural thermal capacity of the buildings as a means of thermal storage, complementing, the cooling regime, with the use of lower external temperatures during the night (night ventilation). These measures have been chosen because of their low cost and installation feasibility on existing buildings.

Night ventilation appears to be one of the more promising passive cooling techniques [54,55]. If the outdoor air temperature at night is low enough, natural or mechanical ventilation can be used to cool the exposed thermal mass of a building. By doing this, improved thermal conditions are provided for the following day.

Preheating and precooling, are similar techniques, carried out at opposite times during the year. In these techniques, the internal mass of building is preheated or pre-cooled, according to the regime in question. Heat pumps turns on during the hours prior to the occupation of the building. The objective of these strategies is the reduction of the buildings' energy demand, or the modification of the demand curve, shifting the loads from peak hours to valleys.

Figure 3 shows a preheating situation for 3 hours before the start of the operation period. In this one can observe the energy gain from the air to the room and at the same time on the mass of the building. As mentioned above, said mass is used as heat storing means during a given period. This measure does not achieve a significant reduction in energy demand, but it manages to move the demand curve to more convenient periods for economic reasons or the stabilization of the global energy demand.

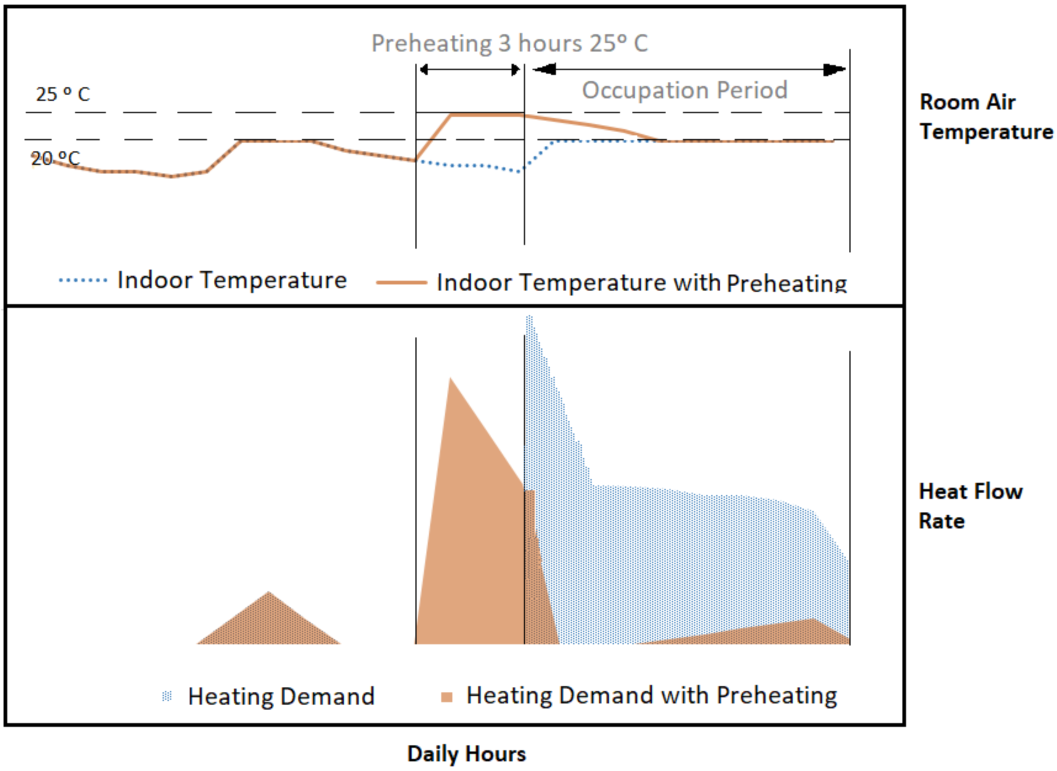


Figure 3. Schematic representation of a mass storage building event preceding the occupation period.

Existing literature has shown that preheating or precooling strategies can achieve great benefits [56–58]. However, it does not detail the influential factors in them that would allow an "a priori" decision on the implementation feasibility for these measures. In work carried out, the potential of these measures will be analyzed, as well as the influence of different factors that influences their choice. Below, the measures carried out in the study are presented. Table 1 presents the preheating and pre-cooling strategies. These measures contemplate the temperature set choices and the operation hours (start-up of the air conditioning equipment hour/s before the occupation). Given that during occupation hours it has been assumed that users set the equipment to 20ºC in heating mode and 25ºC in cooling mode.

| | SET POINT TEMPERATURE (°C) | No. OF OPERATION HOURS |
|---|---|---|
| PREHEATING (PH)<br>PRECOOLING (PC) | 20 | 0/1/2/3 |
| | 21 | 0/1/2/3 |
| | 22 | 0/1/2/3 |
| | 23 | 0/1/2/3 |
| | 24 | 0/1/2/3 |
| | 25 | 0/1/2/3 |

Table 1. Preheating and precooling strategies

Table 2 shows the number of operating hours for night ventilation. This strategy contemplates the number of hours before the 7 hours of operation. For example, if the decision maker decides on 2 hours of night ventilation, it means that the strategy would start at 5 o'clock. The operation of the system is at constant flow, provided that the temperature on the outside of the building is lower than on the inside.

| NIGHT VENTILATION (NV) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| No. OF HOURS | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |

Table 2. Night Ventilation strategies

## 2.3 Buildings energy model

As previously mentioned, the demand management system is analyzed in five real residential buildings (table 3) in the so-called reference scenario (current situation). Subsequently, the effect from the choices of the optimal management strategy made by the system is analyzed while facing changes in construction characteristics and electricity pricing.

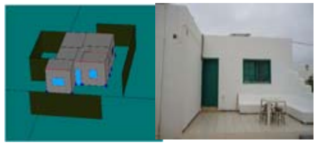
An analysis has been necessary to model the buildings, these models have been developed with an accurate consideration of the geometry, materials, orientation, exposed surfaces of ceilings, walls, and floors is available. The building models were developed in detail with the Unified LIDER-CALENER software tool (HULC by its Spanish acronym), which is the official building energy certification tool in the country [49], using the current constructive solutions.

The reason for using this software is two fold: first, this tool follows a transient and hourly base assessment that has been validated via the Bestest [59], it has been used to obtain the Building's

Energy Performance Certificate from hundreds of thousands of buildings in Spain, and it has also been used by many studies in the recent literature [60–67]. In the same manner, this tool was developed by the author's research group, which allowed to make certain modifications that enabled the present study.

The study required several visits to each of the houses, from the district which allowed to collect the necessary data of the actual construction, geometry, occupancy, current tariffs and the internal gains of the buildings, which were then used for the detailed modelling of the buildings (see table 3).

Additionally, the chosen buildings are distributed in different climatic zones, the classification appears in table 3 according to the climatic zones in Spain CTE-DB HE B1 [68] and adhering to Köppen's climatic classification of [69,70]. The studied buildings take into account this global classification, 2 of them located in Csa (Seville and Malaga), one BSk (Madrid) and BWh (Canary Islands). Csa, is a climatic zone very representative of coastal areas, represents 10% of the world distribution. BWh, a more arid climate and encompasses the world locations with such characteristics, desert, corresponding to 25%. Finally, BSk, is also a dry climate, but not as extreme as the previous one, it contains 15% of the world distribution. We have mainly treated areas with warmer climates, representing the current climate change situation around the world and the rising trend of the global average temperature, global warming, with high number of publications in recent years [71,72].

| **ID** | | **Location** | **Description** | **Climate Classification CTE** | **Climate Classification K-G** |
|---|---|---|---|---|---|
| **Dwelling 1** |  | La Graciosa Island (Lanzarote) | Single-family house of 2 floors, semi-detached house.<br>Surface: 88 m²<br>Orientation: Southeast<br>Year of construction: 2005-2006 | α3 | BWh |
| **Dwelling 2** |  | La Graciosa Island (Lanzarote) | Single-family isolated house of 1 floor<br>Surface: 60 m²<br>Orientation: Southeast<br>Year of construction: 2005-2006 | α3 | BWh |
| **Dwelling 3** |  | Lozoyuela (Madrid) | Single-family isolated house of 2 floors.<br>Surface: 158 m²<br>Orientation: Northwest<br>Year of construction: 2004-2005 | D3 | BSk |

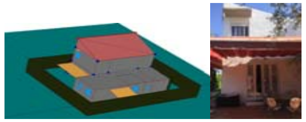
| | | | | | |
|---|---|---|---|---|---|
| **Dwelling 4** |  | Alhaurín de la Torre (Málaga) | Single-family house of 2 floors, semi-detached house<br>Surface: 182 m²<br>Orientation: North<br>Year of construction: 2004-2006 | A3 | Csa |
| **Dwelling 5** |  | Espartinas (Sevilla) | Single-family isolated house of 2 floors.<br>Surface: 230 m²<br>South orientation<br>Year of construction: 1997 | B4 | Csa |

Table 3. Description of buildings

## 2.4 User Behaviour

The current energy system where energy is mostly centrally generated on the one hand, and is consumed by individual users on the other, offers a framework in which users can play a significant role, achieving considerable energy savings. In this context, we can safely mention the famous proverb “knowledge is power” is of particular significance, as different studies demonstrate energy savings when the user plays an active role [73–78]. Besides, energy awareness [79] and empowered consumers to effectively manage their household energy consumption and encourage conservation strategies [80] that could guarantee energy savings higher than 20%.  So, it has been a requirement of this study to guarantee different reliable and representative user profiles for the case study. For that it

The study has been carried out by measuring the dwellings and defining use patterns, aiming to reflect the real behavior of the buildings. Due to this, a presence sensor has been installed at the entrance of each home for 45 days. With the information from this sensor, the percentage of occupation days have been calculated with their respective hours (see figure 4). In this way, the most probable occupation schedule has been defined when the occupation percentage exceeds 60 %, and it will be assumed for the dwellings under study. Figure 4 shows the profile of occupation taken for working days (Monday to Friday) and weekends or holidays (Saturdays and Sundays).

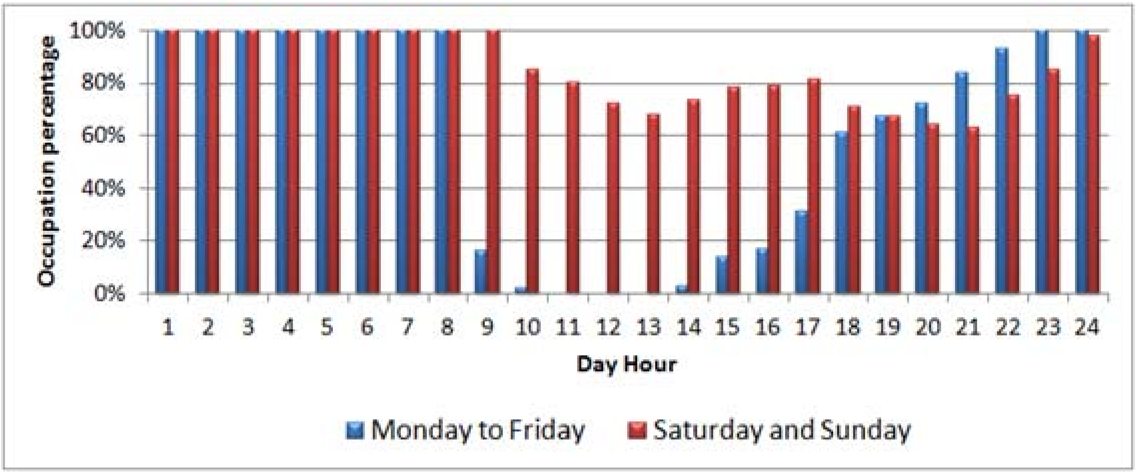


Figure 4. Occupation in function of percentage of analized days (measured data)

The user’s behaviour affects from the internal sources of occupation to lighting and equipment; ventilation and the standard operation of the conditioning system. The conditioning of the houses is carried out whenever occupation takes place except in summer when the conditioning equipment is turned off in the interval between 1-7h. The set-points established for summer and winter have been 25ºC and 20ºC respectively, according to the standards.

## 2.5 Electricity tariffs

The electricity sector faces significant challenges in the soon future, with changes in the use of electricity, the ageing of infrastructure and a higher amount of intermittent and renewable electricity generation. To face these challenges, demand side management combining the analysis of the electricity rates can play an important role. In the literature, there are different types of rates (dynamic pricing) that offer an alternative to the traditional ones, Critical Peak Pricing (CPP), Real-Time Pricing (RTP) and Time-of-Use (ToU) tariffs [81]. Of the rates mentioned, ToU is the most used and allows an easy link with the consumer [82-84] The Spanish electricity market has different prevalent rates:

- Standard tariff. It is the most usual tariff for the Spanish electricity market and the current rate for the sample of homes studied. It consists of two periods, the first one from 13:00 to 22:00 hours, both included for 0.16 € / kWh; the other, the remaining hours, at 0.08 € / kWh.

- Tariff 1-Free short period (T1): 2 free hours per day, both in winter and in summer from 7:00 PM to 8:00 PM, both included. The remaining hours at € 0,140711 / kWh.

- Tariff 2 - Flexible use period (T2): choose the 8 hours you want in which a reduced rate applies. The price of cheap hours at 0.07461 € / kWh and faces at 0.168531 € / kWh. According to the occupation profiles, for all dwellings the section from 15:00 to 22:00 is chosen as the valley period.

- Tariff 3-Fixed rate (T3): fixed daily rate of 0.114 € / kWh. In addition, for the study carried out, a fictitious rate called Rate 4 is proposed:

- Tariff 4-Renewables (T4): Fictitious rate where the price of electricity in the valley is zero. The rest of the hours the price corresponds to the tip of the standard.

In the present study, the demand management system is analyzed in the so-called reference scenario (standard tariff). Subsequently, the effect in the electric pricing of choosing the optimal management strategy suggested by the system is analyzed.

# 3 Results

## 3.1 Evaluation of the strategies in the reference scenario

The demand-management system is evaluated in five existing residential buildings for the so-called reference scenario. This reference situation is detailed in Table 4, and consists on the selection of study rates and study strategies. The objective is to analyze the implications that occur in the choice of preheating, precooling and night ventilation strategies defined previously in section 3.2.2.

| ID | BUILDING (Actual Status) | CLIMATE | Tariff | DECISION MAKER | | |
|---|---|---|---|---|---|---|
| | | | | Strategies | Setpo | Hours |
| 1 | Dwelling 1 | α3-BWh | Standard | PH / PC / NV | 20-25 | 0-3 / 0-3 / 0-7 |
| 2 | Dwelling 2 | α3-BWh | Standard | PH / PC / NV | 20-25 | 0-3 / 0-3 / 0-7 |
| 3 | Dwelling 3 | D3-BSk | Standard | PH / PC / NV | 20-25 | 0-3 / 0-3 / 0-7 |
| 4 | Dwelling 4 | A3-Csa | Standard | PH / PC / NV | 20-25 | 0-3 / 0-3 / 0-7 |
| 5 | Dwelling 5 | B4-Csa | Standard | PH / PC / NV | 20-25 | 0-3 / 0-3 / 0-7 |

Table 4. Case studied in reference scenario.

### 3.1.1 Detailed study of strategies (preheating, precooling and nightcooling)

For the detailed analysis of the strategies, the results obtained for one of the simulated buildings (dwelling 3 of table 3) are presented in detail. This building consists of a detached house of 2 floors located in Madrid with users and standard pricing.

First, the preheating alternatives presented previously in Table 4 have been analyzed. The variables for decision making chosen have been the number of hours of operation outside the period set by the user and the setpoint temperature for each one of them. In figure 5, the percentage of days for the heating season are shown, with the possible combinations. The blue column is equivalent to days where the management algorithm has considered as an optimal situation not to choose preheating strategies. As noted, this represents almost 60% of the days. The rest of the days, some of the possible measures have been chosen, correspond mainly to weekends.

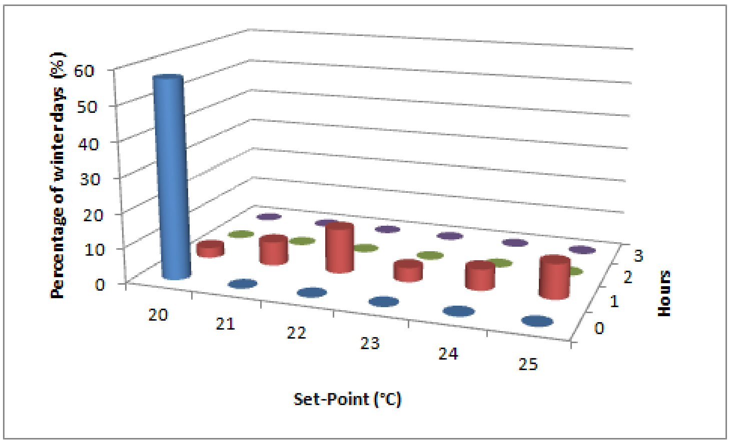


Figure 5. Percentage of winter days that take each of the preheating strategies

Figure 6 shows two consecutive days corresponding to a weekend. As it can be seen, the conditioning of the space occurs from 1:00 pm, just when the peak rate begins.

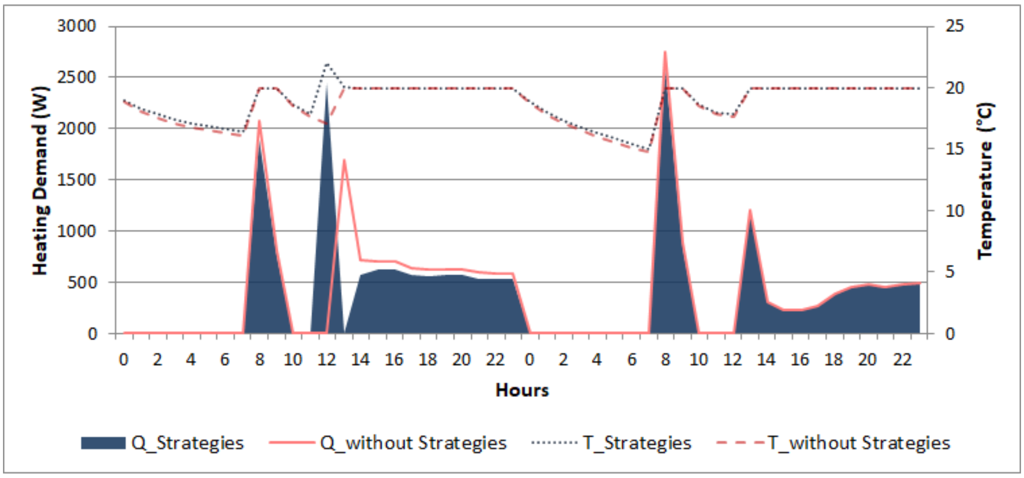


Figure 6. Representation preheating user 1 during a weekend

On the first day figure 6 shows the manager has chosen to preheat for one hour as an optimal strategy, allowing the start of conditioning later and with lower values at the peak rate hours. However, the next day (Sunday) the decision maker does not choose any of the proposed alternatives. This fact allows concluding that a dynamic management of the system has been carried out.

Next, the alternatives presented above for precooling (with / without night ventilation) have been analyzed in tables 1 and 2. Figure 7 shows the percentage of days from the cooling season where each of the alternatives have been chosen. The blue column shows to be equivalent to the days where the management algorithm has considered as an optimal situation not to choose precooling strategies (without night ventilation), representing almost 40% of the days. For the rest of the days, strategies lasting one hour have been chosen with different setpoint temperatures.

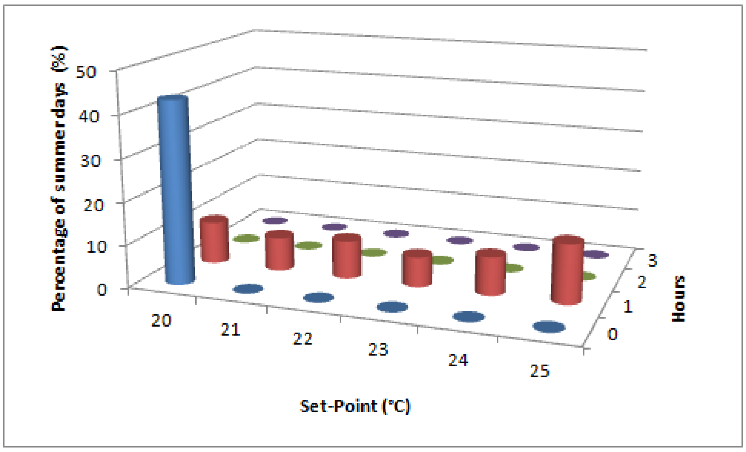


Figure 7. Percentage of summer days that takes each of the precooling strategies user 1

If the percentage of days where the management algorithm has considered the optimal choice for night ventilation strategies (with/without precooling, see figure 8) is analyzed, it can be observed measures incurred in low additional cost, increasing the percentage of days where these strategies can be chosen.

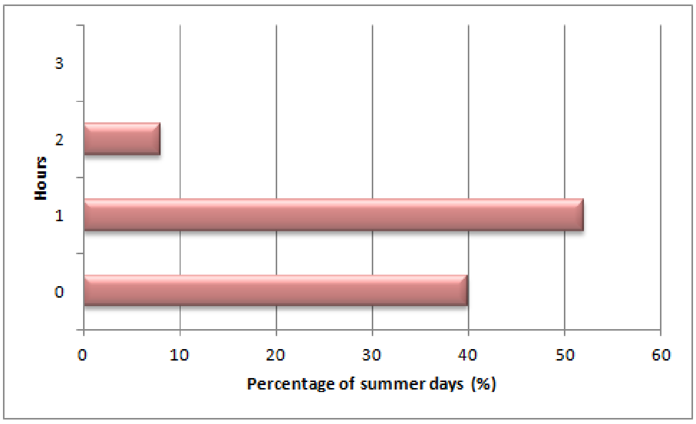


Figure 8. Percentage of summer days that takes each of the night ventilation strategies

Also, the results from the study carried out (see figure 8) show although up to seven hours of night ventilation are proposed, the hours usually do not exceed the tree hour duration because structural thermal storage can only be short-term.

Next, in Figure 9 the effect of night ventilation is analyzed. So, figure 9 shows five consecutive days. The first two days are operated with one hour of night ventilation and the rest with two hours. In the last two days (figure 9), it is observed that night ventilation virtually eliminates the cooling needs for hours 7 and 8. Besides, it is observed that the first day of precooling in the valley period cancels startup demand during the peak period. On the rest of the days, the cooling has been carried out during the valley period (preecooling) and it has been canceled during the stoping period. For this reason, precooling is more interesting during the weekend (first day), when there has not been such a sharp stop between the valley and the peak period.

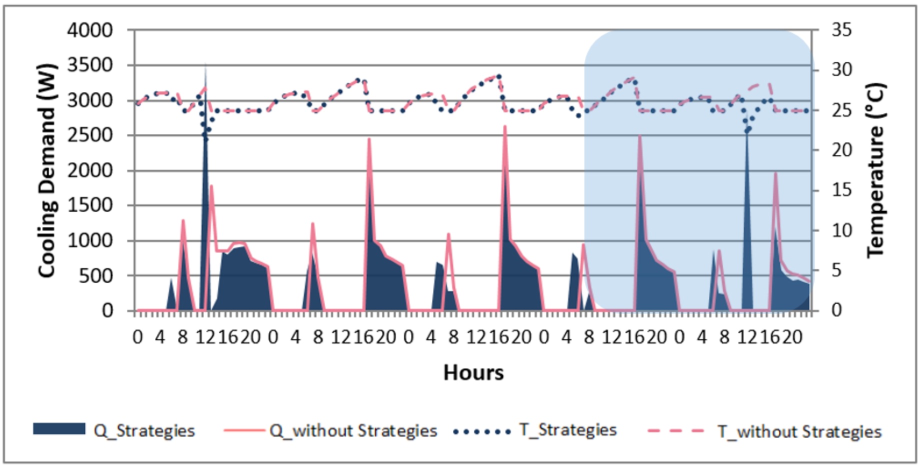


Figure 9. Representation precooling and night ventilation

### 3.1.2 Optimum results of the management system (decision-maker)

The overall results obtained for the different buildings studied are shown below (see table 3). Figures 10 and 11 show the strategies that the management system chooses as the optimal operating strategy every day. Figure 10 corresponds to the month of January and figure 11 corresponds to the month of July. The month of January was chosen as the representative month for heating, because it is the month with higher heating demand. The same procedure has been carried out for cooling. Names of the applied strategies correspond to PC or PH depending on whether it is precooling or preheating, the number of operating hours and the established setpoint temperature.

Figure 10 shows the choice of the most representative management system for the studied month has been PH-0-20. This option proves to be equivalent to the non-implementation of preheating strategies. It also highlights the dynamism of the management system and the dependence between the manager's choice and the climate zones.

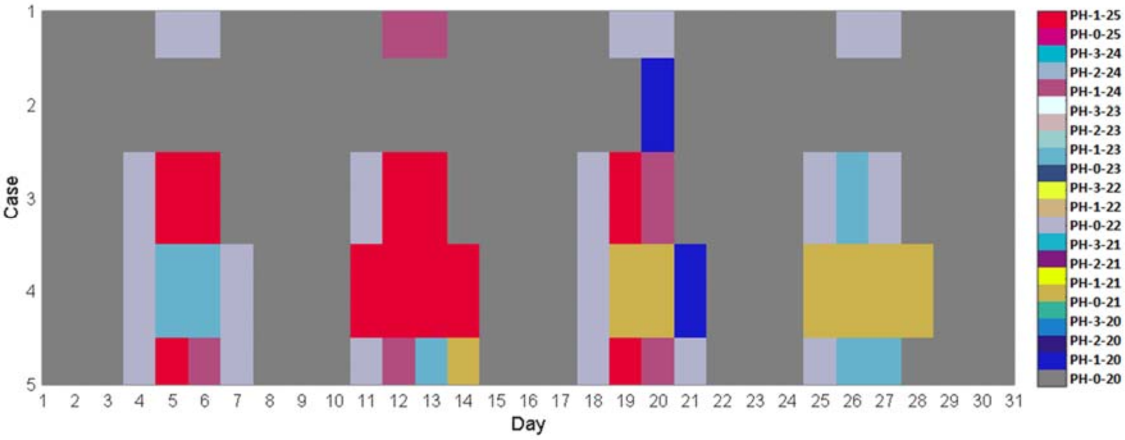


Figure 10. Selection strategies for preheating. January

Figure 10 shows the choices of the management system for a representative cooling month. Generally, the figure shows precooling strategies lasting one hour dominate in the choices selected. It also highlights the dynamism of the management system and dependence on the choice of the manager with climate zones.

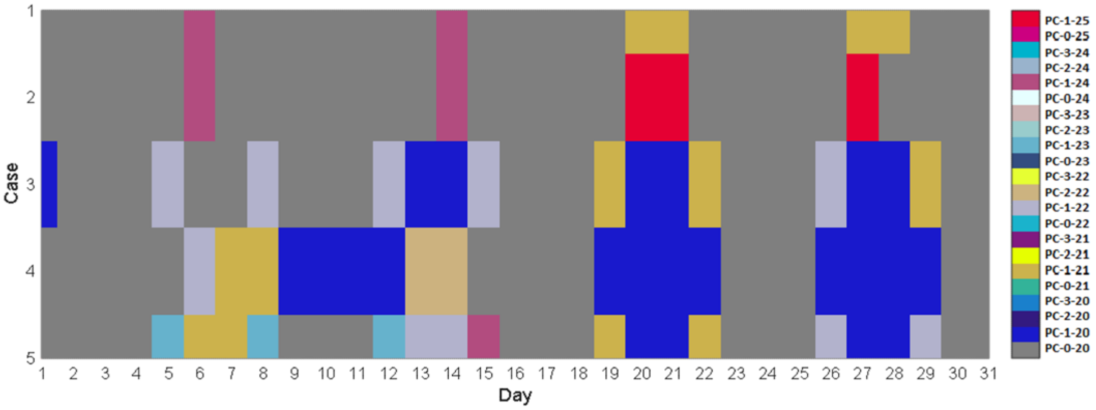


Figure 11. Selection strategies for precooling. July

Figure 11 does not show the daily choice for night ventilation hours chosen because it is a winning strategy in all cases. The package of improvement for cooling has been generally referred to as precooling and/or nightcooling. As can be seen in figure 12, in only 26% of cases, the manager decides not to perform night ventilation. These days tend to be days with unfavourable external weather conditions.

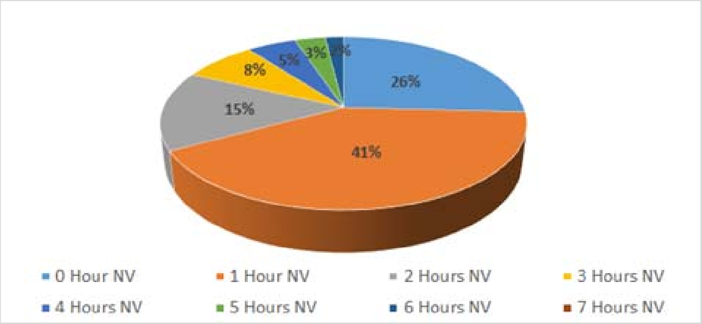


Figure 12. Percentage of days in July that take night ventilation (NV) strategies

Finally, Figure 13 shows the percentages of economic savings that result after the implementation of each measure selected by the manager in the different operating regimes (figures 10 and 11). As can be seen in this figure, the dwelling with the highest percentage of savings for heating (3.2%) correspond to dwelling number 3. In this dwelling the preheating choice last one hour with set temperatures of 25°C. Likewise, the housing with the highest percentage of savings for cooling (8.5%) corresponds to house number 4. In this case, the main strategy is last one hour of precooling with 20ºC of setpoint temperature (with/without night ventilation). In addition, the results show again the dependence between the management strategy carried out and the climate zone. See, for example, houses 1 and 2 located in Lanzarote. These do not have economic savings in heating, but they do in cooling due to the areas' climatic characteristics.

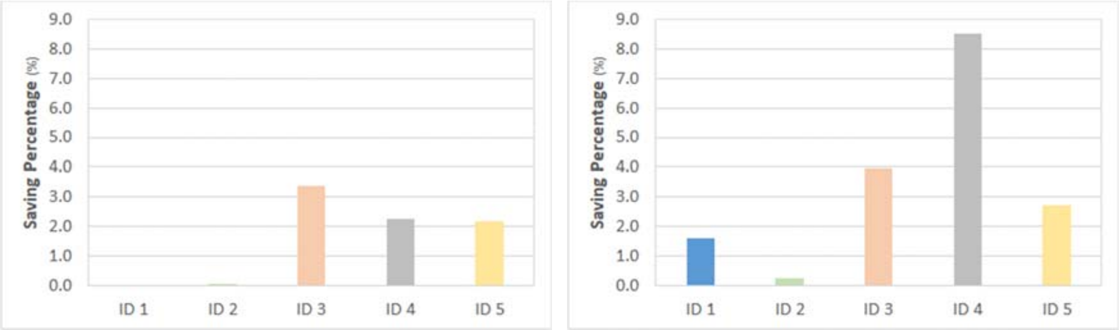


Figure 13. Percentage of energy savings after implementing a management system for heating (left) and cooling (right).

## 3.2 Evaluation of the strategies in conditions other than the reference

### 3.2.1 Effect of rehabilitation

After the analysis of the constructive solutions from the initial scenario, it is observed that these are characterized by low constructive qualities. Therefore, the study carried out analyzes the potential of the DSM measures in the five houses with the current construction and after a possible energy rehabilitation (improvements on the construction qualities).

Improvement of the envelope is based on the optimization of insulation thickness and quality of the windows. Applying these measures to each of the buildings presented previously in table 3, results in the percentages of savings shown in table 5 (only after energy rehabilitation).

| ID of dwelling | | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| Energy Savings percentage (%) | Heating needs | 68.6 | 53.3 | 15.2 | 50.2 | 54.5 |
| | Total (heating+cooling) needs | 26.1 | 20.7 | 7.2 | 16.7 | 18.1 |

Table 5. Savings achieved on the energy needs from each of the houses with the proposed rehabilitation.

Next, the effect of the demand management measures on the building's before and after rehabilitation measures have been compared. Table 6 shows the percentages of economic savings obtained for the different homes (current scenario and rehabilitated scenario) after the implementation of the demand management system (by the decision-maker) as well as the number of days where the manager selects the different strategies. As can be seen in table 6, the number of days where the manager chooses a potential strategy increases in buildings with better constructive quality.

| | | ***Heating Savings (%)*** | ***Cooling Savings (%)*** | ***Nº. PH Days*** | ***Nº. PC Days*** | ***Nº. NV Days*** |
|---|---|---|---|---|---|---|
| **ID1** | *Actual* | 0 | 1.6 | 38 | 23 | 70 |
| | *Refurbished* | 0.6 | 14.4 | 43 | 48 | 119 |
| | *Actual* | 0.1 | 0.2 | 9 | 15 | 85 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **ID2** | *Refurbished* | 0.7 | 2.4 | 22 | 39 | 101 |
| **ID3** | *Actual* | 3.4 | 3.9 | 65 | 63 | 110 |
| | *Refurbished* | 4.5 | 8.0 | 45 | 120 | 120 |
| **ID4** | *Actual* | 2.3 | 8.5 | 58 | 44 | 106 |
| | *Refurbished* | 2.3 | 24.5 | 33 | 87 | 120 |
| **ID5** | *Actual* | 2.2 | 2.7 | 75 | 48 | 74 |
| | *Refurbished* | 6.7 | 8.4 | 54 | 54 | 98 |

Table 6. Comparison between existing building before and after of refurbishment plan

Another interesting result of table 6 is the climatic influence. In case 1, 2 and 4, the refrigeration consumption is much higher than the heating demand. In contrast, cases 3 and 5 have shown similar results for heating and cooling. However, all of the savings in cooling have been higher than in heating, a consistent result in the Mediterranean climate presenting a great opportunity for night ventilation.

As a consequence of the rehabilitation, the implementation of this system produces more considerable economic savings in all the rehabilitated buildings (see figure 14)

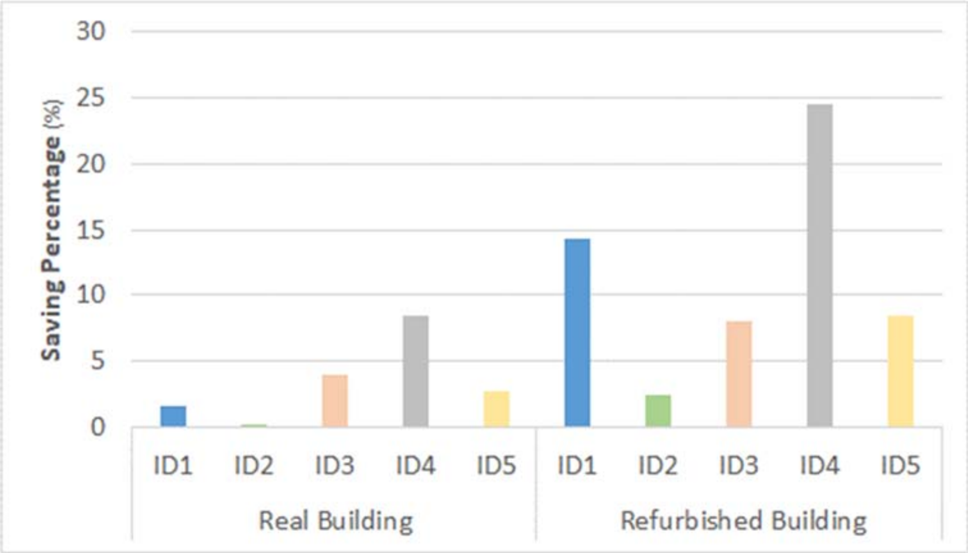


Figure 14. Building influence

Likewise, the results of this section show that it is possible to obtain a balance between the costs reduction and a possible reduction of the house's energy consumption, which is an advantage in contrast to conventional measures of demand management.

### 3.2.2 Effects of pricing

Finally, the influence of applying another rating is analyzed. This study includes other existing tariffs from the Spanish electricity market, presented in section 2.5 Electricity Tariffs located above.

From the results obtained, it can be seen for the case of the third building with all the rates (see table 7). Generally speaking, it is observed that pricing is an influential element, both on the decision making of the different alternatives and in the potential for economic savings. It is distinguishing two types of rates, one of them where the number of strategies increases and therefore so do the savings, others where greater savings are achieved without increasing the number of decisions, simply due to the rates.

| | ***Standard*** | ***T1*** | ***T2*** | ***T3*** | ***T4*** |
|---|---|---|---|---|---|
| *Heating Savings (%)* | 3 | 4 | 9 | 10 | 69 |
| *Cooling Savings (%)* | 4 | 47 | 38 | 24 | 54 |
| *No. PH Days* | 65 | 0 | 150 | 0 | 150 |
| *No. PC Days* | 63 | 121 | 76 | 0 | 121 |
| *No. VN Days* | 105 | 46 | 52 | 59 | 115 |

Table 7. Electricity pricing influence

Figure 15 shows that tariff 4 is the highest percentage of economic savings obtained both in heating and cooling. This percentage is due to the rates of the tariff and the increase in the number of strategies that the decision maker selects as optimal (see table 7).

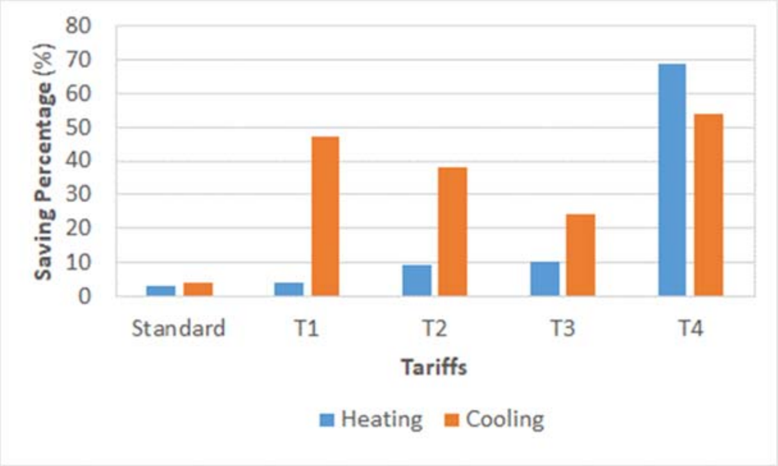


Figure 15. Tariff influence

The result presented in figure 15 suggests the importance of electricity rates in the economic potential of these measures. Since the energy potential is quite limited and it is zero or negative in many cases. That is to say, the Energy stored during the hours of low cost may not be recovered during the hours of high cost and occupation, due to defective building characteristics.

## 4 Conclusions

Buildings can act as active elements in innovative city systems where it is possible to connect vehicles, utilities, renewable energy sources and energy storage for sustainable growth and development. In this same matter, buildings could be energy exchange hubs with generation, storage and conversion capabilities, if they provide energy demand flexibility, but they require smart technologies and energy management. This work is focused on the study of the most common energy demand management measures with the least cost (energy flexibility), analyzing a sample of actual buildings in several climatic zones. These buildings are studied in their initial situation and after rehabilitation measures have been applied, allowing to quantify the current economic and energetic saving potential of these measures. Additionally, the sensitivity of these results to the changes in the constructive quality of the building, climatic conditions, user behaviour and contracted electricity pricing is analyzed.

The main conclusios of this study are:

- The results obtained highlight the dynamism of the management system, as well as the dependence of the possible strategies choices on the climatic zones. It translates into preset decisions that can only be considered by taking into account real events.

- In the reference situation, the maximum economic savings obtained after the implementation of the management system correspond to 3.2% for heating regime and 8.5% for cooling. It is important to highlight the potential of night ventilation. It reduces considerably the energy demand for cooling. And this strategy has a high probability of being chosen by the decision maker given the low implementation costs and the high energy saving potential.

- The results from constructive quality improvements carried out during the study show that the implementation of this system produces higher economic savings in all the rehabilitated buildings analized.
- From study of electricity prize: it can be observed the influence of the decision making process between the different alternatives and the potential for economic savings.
- It is implicit in the results that renewable production of electricity can maximize the economic savings (rate 4). It would be of future interest to study the use of the thermal mass of buildings to store the surplus of renewable energy produced and not consumed, complementing as well the energy storage in lithium batteries.

The results obtained show the potential of implementation regarding frequently used devices in smart homes to reduce the cooling needs of low-income families in climatic conditions reaching summer temperatures outside the comfort limits, presenting energy demand savings higher than 30%. However, the current costs associated with this type of devices complicates the unyielding efforts to obtain substantial economic benefits in the short term. Combining night ventilation strategies and smart house devices has not yet been studied extensively. Therefore research should focus on the subject to develop knowledge in future studies. Although these measures are not commonly considered in demand management, the authors of this paper consider that the interaction between the DSM and traditional energy efficiency measures is of vital importance, due to the high impact they have on the houses energy consumption in the summer reducing air conditioning use, which has a high electric demand. This total electricity consumption can be reduced thanks to measures that relate energy demand side management and night ventilation. Producing an additional reduction in demand peaks, with the economic and environmental benefits that this entails.

Finally, the integration with renewable energy sources can maximize savings; showing the growing interest of storing the unused photovoltaic surplus in buildings. Combining renewable energy production, thermal and electric energy storage in buildings proves to be an area that requires further research work.

# 5 Acknowledgementes

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