Evaluation of energy flexibility of buildings using structural thermal mass

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Academic course: 2016 - 2017

Master of renewable energy and energy sustainability

Dedication

This work is dedicated to my wife Ivetheyamel and my sons Camila and Santiago, who inspire me to get better every day.

Acknowledgements

I thank Joana Ortiz, Ph.D, IREC researcher for all assistance provided me in this process.

Part of this work stems from the activities carried out in the framework of the IEA-EBC Annex 67 (International Energy Agency – Energy in Buildings and Communities program) about Energy Flexibility in Buildings.

INDEX

1. Overview....1
2. State of the art....2
   2.1 Energy policy of the European Union....2
   2.2 Energy flexibility in buildings....3
3. Method....5
   3.1 Objective....5
   3.2 Model description....5
   3.3 Scenario....6
      3.3.1 Reference scenario....7
      3.3.2 ADR – Events scenario....7
   3.4 Key Performance Indicators....8
      3.4.1 Available structural storage capacity (C_{ADR} [kWh])....8
      3.4.2 Storage Efficiency (η_{ADR} [-])....9
      3.4.3 Thermal Comfort index:....11
      3.4.4 Electricity consumption....11
      3.4.5 Electricity cost.....11
4. Results and discussion....12
   4.1 Cases “+1D/2H” and “-1D/2H”....12
      4.1.1 Upward ADR event....12
      4.1.2 Downward ADR event....14
      4.1.3 Comparison of upward and downward....16
   4.2 Effect of temperature variation....17
   4.3 Effect of event duration....19
5. Conclusions....22
6. References....24

1. Overview

In order to mitigate the effects of climate change and to focus on sustainable development in the field of energy, the EU is committed to increase renewable energies and energy efficiency, as we see in the objectives "20/20/20" and in the strategies for 2030. Renewable energies solar and wind have had a great advance; however they are very unpredictable because they depend on the climatic conditions, which represent a disadvantage in its use. The development of these energies could be compromised by the problems that could cause in the stability of the electrical network if its penetration is high. There is a great deal of research focused on improving this situation of instability through energy storage and distribution. The demand management has been identified as a tool for the balance between energy generation and demand. It has been found in the construction sector a great opportunity, taking advantage of the fact that in 2020 all new buildings must be nearly Zero Energy Building (nZEB). The trend is that buildings will become energy producers, and to capable to store it. Then, determining the flexibility of a building's energy demand becomes the key to proposing energy consumption strategies that favor the stability of the power grid and the cost of energy.

There are several alternatives to store energy in a building. Its thermal inertia can be widely used in heating and cooling systems, which represent the greatest demand for energy in a home. This study is focused on determining the energy flexibility of the heating system operation a nZEB using its structural mass. The energy flexibility has been tested implementing advanced control strategy without compromise the thermal comfort of the users. It has been evaluated with the indicators of available storage capacity and the energy storage efficiency proposed by Reynders[1].

2. State of the art

2.1 Energy policy of the European Union

Energy is indispensable for the life of human beings. The energy access and security of supply are keys to the development of modern societies. The dependence on fossil fuels, the level of imports and the environmental impact of their use are some of the major challenges facing the European Union (EU); without neglecting aspects such as the price of energy, the increase of energy demand, the reliability of electric systems, climate change, among others. Against this background, the EU establishes an energy policy[2] aimed at achieving an integrated energy market, security of supply, and sustainability of the energy sector.

As alternatives to energy production low in CO2 emissions and the reduction of greenhouse gases (GHG), the EU launched the so-called "20-20-20 climate-energy package"[3][4][5]]. It agrees to reduce GHG emissions by at least 20%, to use at least 20% of renewable energy sources (10% in transport), and to improve energy efficiency by 20%; All these objectives must be achieved by 2020 and measured by reference to 1990. By 2030 [6], it has already set a new target of reducing 40% of GHGs and at least 27% of energy consumption must be of renewable sources.

In the framework of these policies, the EU aims to move towards an energy future: low in CO2 emissions, reliable, sustainable, and independent; where renewable energy, energy storage, and smart grid will play a very important role. The great deployment of solar and wind energy could be affected by the variability they have and the instability that could occur in the smart grid, as they have greater penetration in the market. The climatic conditions and the difficulty of storage are the main disadvantages, which face this type of energies.

Under this situation new concepts such as energy flexibility and nearly zero energy buildings (nZEBs) emerge. These buildings play a very important role in the generation, storage, distribution and consumption of energy; becoming small energy centers; helping to manage supply and demand; giving energy flexibility to the system; and obtaining a decentralized, renewable, interconnected and variable economy.

The EU has provided that, as of 31 December 2020[7], all new buildings will nearly zero energy building (nZEB). A nearly zero energy building is defined as “a building that has very high energy performance. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby” [8].

The role of buildings in the management of renewable energy is becoming more important; they can act as energy generators, as energy storage, or as controllers of demand. Through an active demand response (ADR) event, demand can be managed, to reduce energy demand to reduce peak demand or to avoid system failures[9]. The demand responds to the habits of the consumers and this can be modified by different strategies. As a result nZEBs are projected as renewable energy sources, with storage capacity and demand flexibility.[10][11].

2.2 Energy flexibility in buildings

Energy flexibility is defined as "*the ability to manage its demand and generation according to local climate conditions, user needs and grid requirements*" [12]. De Coninck, defines it as "the possibility to deviate the electricity consumption from the business as usual (BAU) consumption at a certain point in the time and during a certain time span".[13]

Several authors have presented indicators and methodologies to quantify the energy flexibility[13][14][1][15]. It is generally considered the quantification of 3 aspects of energy flexibility: time, energy quantity and storage efficiency. These parameters determine how long can be delayed or forced the operation of Heating, Ventilating and Air Conditioning (HVAC) systems, without jeopardizing thermal comfort, the amount of energy that increases or decreases during this period, and the losses or efficiency of storage.

The structure of a building (walls, floor, roof and furnishings) can also be considered as a thermal storage system. A study by Braun[16] notes that both energy costs and electrical use can be substantially reduced by adequate control of the thermal storage of the building. Reynders[17], in his study of the impact of residential building design parameters on the structural energy storage potential (STES) for the ADR, develops a quantification method based on 4 performance indicators: the available storage capacity, storage efficiency, power shifting capability and state of charge. The heat that can be stored during an ADR event and the efficiency of this storage depends not only on the structure of the building, but also on the properties of the heating and ventilation systems, the climatic conditions of the environment and the behavior of users. Available capacity and storage efficiency provide important information for the design of buildings and power grids. In addition, the power change capability and the load state quantify instantaneous flexibility in an operative phase.

A strategy of flexibility is to control the loads. It is possible to change part of the peak period load to the period of lower demand, or to maximize the use or accumulation of energy when the energy price is lower or vice versa. Most of the thermal energy will be stored in the intrinsic structure and furniture when the temperature increases.

The energy demand in residential buildings is mainly composed by heating, cooling, domestic hot water, lighting, and the use of electrical appliances. A large part of this demand can be shifted over time and, therefore, increase its flexibility. Taking advantage of the thermal inertia of building, it can be used to move the thermal loads of heating or cooling at certain intervals without compromise the thermal comfort. The effect of this shifty depends on thermal mass, heat loss, internal gains, user pattern and actual climatic conditions.

The research developed into the energy flexibility that buildings can offer to help stabilize power grids and facilitate the penetration of renewable energy is in its early stages. There is still no overview of the amount of energy flexibility that buildings according to type and use can offer to the electrical system. In this context, the International Energy Agency (IEA) and Energy in Building and Community Program (EBC) launched the Annex 67 Energy Flexible Buildings program[12], which aims to increase knowledge, provide possible solutions that energy flexibility in buildings can offer, and provide the means to exploit and control this flexibility. It also aims to develop a methodology to characterize the energy flexibility of buildings, including on-site generation research, energy storage, load management, user behavior and user acceptance through simulations, laboratory tests and demonstrations in real buildings.

3. Method

3.1 Objective

The purpose of this project is to investigate the behavior of the energy flexibility of a residential building in Mediterranean climate, through the activation of its structural thermal mass by controlling a heating load to:

- Implement different ADR strategies in the heating system operation.
- Evaluate energy flexibility through the indicators: available storage capacity and storage efficiency.
- Investigate how to represent the energy flexibility.
- Identify which is the best flexibility strategy to reduce the energy cost.

3.2 Model description

A residential building[18][19][20] located in Terrassa (Barcelona, Spain) has used to evaluate the energy flexibility. Table 1 shows the main characteristics of the building, which coincide with the characteristics of a nZEB: high energy efficiency building.

The apartment is located on the first floor of the building with two external facades facing north and west; it is divided into 3 bedrooms, a living room, a kitchen, a study, a hallway and a bathroom as shown in Figure 1. The building is modeled in TRNSYS, including the external environment and its corresponding shade. Further details on the hypothesis of the construction model are described in[10][21].

Table 1
Main characteristics of the building

Parameter	Unit	Values
Floor area	m^2	108.5
Window area	m^2	19.6
Protected volume	m^3	263.6
U-value walls	W/m^2K	0.2
U-value windows	W/m^2K	2.5
g-value windows	-	0.5
Ventilation	-	Natural
Solar protections	-	Blinds (all openings), Awing (west facade)
Heating and DHW		Heat Pump
Lighting system		LED

The heating (SH) and domestic hot water (DHW) is produced by an air-water heat pump with a COP of 5.25. The emitters of the system are water radiators, and once the water flow stop, the radiator continues to emit heat until the water it contains cools down. The radiators are controlled by a single thermostat placed in the living room.

***Figure 1**:* 3D model, photo and floor plan of the study case building.[10]

The occupancy profile has been adapted according to the habits of the family, as shown in the table 2.

Table 2
Occupation profile

Occupancy Day zone	Occupancy Night zone	Non-occupancy zone
06:00 – 09:00 and 19:00 – 21:00	21:00 – 06:00	09:00 – 19:00

The weather data used for the simulation are from a weather station located in the city centre of Terrassa (official weather station nº 189C, “Agencia Estatal de Meteorología”).

3.3 Scenario

In this study, a set of cases are defined to evaluate the energy flexibility in a nZEB by the operation of the heating system. These cases involve the boundary conditions, the behavior of the occupants and the reference scenario. The indicators analyzed quantify the energy flexibility by analyzing a deviation from a reference scenario.

The thermal mass of the house is activated by performing ADR events. Reynders defines an ADR event as "an active, temporary deviation from normal behavior without violating comfort requirements". This can be interpreted as a short-term increase or decrease of the temperature set point. The temperature control is performed by a traditional thermostat, which is implemented a day-night program according table 2.

Table 4 shows an overview of the evaluated cases.

3.3.1 Reference scenario

It is considered as a reference scenario the normal operating conditions of the heating system: the setpoint during occupancy day hours is 21.5 ºC and 20.5 ºC at occupancy night or when the apartment is empty. These temperatures correspond to the middle of the comfort range, as table 3 shows.

Table 3
Category and temperature ranges to maintain thermal comfort in day and night[22].

Category	**Operative temperature ranges (°C)**	
	Day range. Assumptions: 1.2 met, 1 clo, 0.1 m/s	**Night range. Assumptions: 0.8 met, 2.5 clo, 0.1 m/s**
Cat. II	19.2 - 23.8	17.8 - 22.7

3.3.2 ADR – Events scenario

The ADR events consist in changing the setpoint temperature for a certain time, in order to shift the heating load. To define the ADR events is need to determine 3 parameters:

- The setpoint variation. Increase or decrease the setpoint, and how many degrees.
- The duration of the event, for how long the setpoint will be modified.
- When the ADR event will be done, e.g. at 01:00 or 17:00 of the day.

Table 4
List of cases

Cases	Temperature setpoint occupancy day (ºC)	Temperature setpoint occupancy night and non-occupancy (ºC)	Temperature Setpoint variation (ºC)	Duration of the ADR event (h)	Projection horizon (h)
+1D/1H	21.5	20.5	+1	1H	24 H
-1D/1H	21.5	20.5	-1	1H	24 H
+1D/2H	21.5	20.5	+1	2H	24 H
-1D/2H	21.5	20.5	-1	2H	24 H
+2D/2H	21.5	20.5	+2	2H	24 H
-2D/2H	21.5	20.5	-2	2H	24 H
+1D/3H	21.5	20.5	+1	3H	24 H
-1D/3H	21.5	20.5	-1	3H	24 H
+1D/5H	21.5	20.5	+1	5H	24 H
-1D/5H	21.5	20.5	-1	5H	24 H

The cases presented in Table 4 correspond to:

- Events with different variations in setpoint temperature and same period duration.
- Events with the same variation in setpoint temperature but different duration time.

At each hour of the day, an event was implemented, for each case; and the flexibility analysis was performed within a 24-hour horizon, counted from the start of the event.

The simulation of these cases aims to: identify the behavior of energy flexibility during each hour of the day; define when and how much energy can be stored or decreased consumption; when the maximum energy flexibility occurs and when it is zero; when and under what conditions the cost of energy is minimized; i.e. to help increase the knowledge of energy flexibility, to propose strategies that help to manage demand in the best way.

3.4 Key Performance Indicators

For this study, the indicators of energy flexibility considered are available storage capacity and storage efficiency. In addition, indicators of thermal comfort, electricity cost and energy consumption are analyzed in order to evaluate the ADR events from different points of view.

3.4.1 Available structural storage capacity (C_{ADR} [kWh])

The available structural storage capacity for active demand response is defined “as the amount of heat that can be added to the structural mass of a dwelling, in the time-frame of an ADR event, without jeopardizing thermal comfort”.[1]

To quantify available storage capacity and storage efficiency Reynders is based on: a reference scenario in which the setpoint temperature is the minimum set to maintain thermal comfort; and in the increase of the temperature setpoint during the simulation of the ADR events[1], as shown in figure 2.

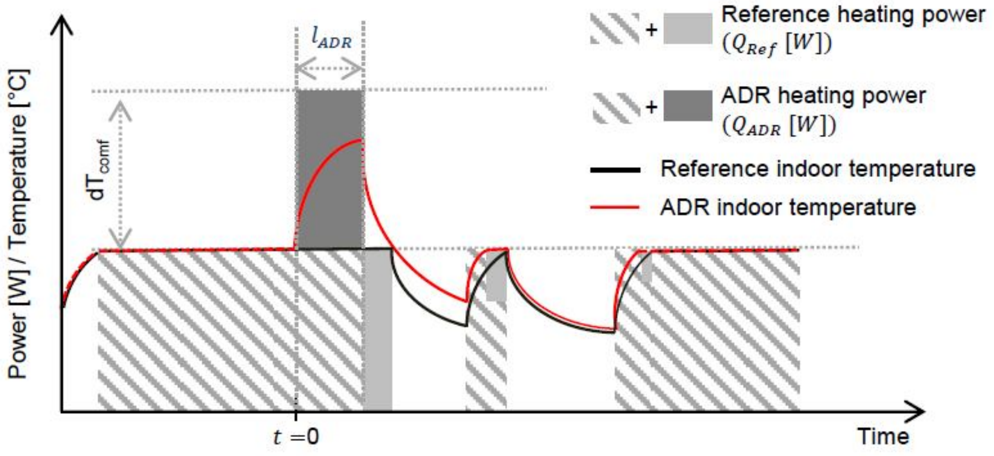

Figure 2: Scheme of the simulation experiment used to quantify the available storage capacity and the storage efficiency[1]

The available storage capacity is determined, as the integral, of the difference between the heating power ADR (Q_{ADR}) and the heating power of the reference scenario (Q_{REF}), setting the minimum allowable comfort temperature as reference, and increasing the temperature set point "dT" (ºC) for the duration of the "l_{ADR}" event (s). The table 5 shows an analysis of the possible values of the indicator.

$$C_{ADR} = \int_0^{l_{ADR}} \left(Q_{ADR}(t) - Q_{REF}(t)\right) dt \text{ , Equation 1}$$

Table 5

Analysis of the possible values of the available storage capacity

C_{ADR}	Upwards	Downward
>0	The heating power supplied during the time of the event is greater than the reference power, i.e. heat is stored.	Unlikely
=0	The heating power supplied during the event is equal to the reference power, ie no available storage capacity	The heating power supplied during the event is equal to the reference power, ie no available storage capacity
<0	Unlikely	The heating power supplied during the event was lower than the reference, ie the heat demand was lower

3.4.2 Storage Efficiency (η_{ADR} [-])

The storage efficiency is defined as "the fraction of the heat that is stored during the ADR event that can be used subsequently to reduce the heating power needed to maintain thermal comfort".[1]

$$\eta_{ADR} = 1 - \frac{\int_0^{hor} \left(Q_{ADR}(t) - Q_{REF}(t)\right) dt}{\int_0^{l_{ADR}} \left(Q_{ADR}(t) - Q_{REF}(t)\right) dt}, \text{Equation} \quad 2$$

Equation 2 was proposed by Reynders and was designed to evaluate only upward events. However, in our experiment, we are performing both events, upward and downwards. In order to obtain comparables values of efficiencies in both cases, the Equation 3 is proposed.

$$\eta_{ADR} = 1 - \frac{\int_0^{hor} \left(Q_{ADR}(t) - Q_{REF}(t)\right) dt}{\left|\int_0^{l_{ADR}} \left(Q_{ADR}(t) - Q_{REF}(t)\right) dt\right|}, \text{Equation} \quad 3$$

The integral in the denominator is equal to the available storage capacity (C_{ADR}), shown as the dark grey area in Figure 2. The numerator of the equation represents the rebound effect (RE). For upward events, it corresponds the heat stored during the ADR event that is not recovered after a long period; for downward events, RE represents the saved energy during the ADR event that is needed after a long period.

Table 6 shows an analysis of the possible values of the indicator.

Table 6

Analysis of the possible values of the energy efficiency

n_{ADR}	Upwards / Downward
>1	The heat consumption, at the projection horizon, when the ADR event is performed, is lower than the reference scenario (saving heat)
=1	The consumption of heat, in the projection horizon, when the ADR event is performed, is the same as the reference scenario.
<1	The heat consumption, at the projection horizon, when the ADR event is performed, is greater than the reference scenario.

3.4.3 Thermal Comfort index:

This index is defined as, the number of times that the air temperature of the dwelling is outside the comfort range; according to category II of the recommended indoor environment in (UNE-EN-15251)[22]. It is measured by the following equation and expressed as a percentage.

$$P_{OUT} = \frac{\sum^{hor} p_t * OUT_t}{\sum^{hor} p_t * t} \Bigg| \begin{matrix} OUT_t = 1; T_{c,min} < T_i < T_{c,max} \\ OUT_t = 0; T_i > T_{c,max} \vee T_i < T_{c,min} \end{matrix} \text{; Equation 4}$$

P_{OUT}: Percentage outside of range

p_t: occupation:

T_i: Indoor temperature

$T_{c,min}$: Minimum comfort temperature

$T_{c,max}$: Maximum comfort temperature

3.4.4 Electricity consumption

The difference in electrical consumption is determined as the integral of the difference between the electric power of the event ADR (E_{ADR}) and the electric power of the reference scenario (E_{REF}), for the whole projection horizon. It is expressed in kWh.

$$DEC = \int_0^{hor} \left(E_{ADR}(t) - E_{REF}(t)\right) dt \text{, Equation (5)}$$

3.4.5 Electricity cost.

The difference in electricity cost has been calculated using a variable energy price (Voluntary Price for the Small Consumer, PVPC, for its acronym in Spanish) (€/kWh). The PVPC are hourly values and changes according to the energy market.[23]

$$EC = \int_0^{hor} \left(E_{ADR}(t) - E_{REF}(t)\right) * PVPC(t) * dt \text{, Equation (6)}$$

4. Results and discussion

In all cases, the thermal comfort index P_{OUT} was 0%, i.e. the thermal comfort was never jeopardized.

4.1 Cases "+1D/2H" and "-1D/2H"

A complete analysis of the cases "+1D/2H" and "-1D/2H" is developed in the following section.

4.1.1 Upward ADR event

The results of an upward scenario are shown, where the temperature setpoint has increase 1ºC for two hours. The event "3" (figure 3) is used as an example to explain the results of the indicators over a 24-hour horizon. Figure 3 represents the set point of the reference scenario (REF SET POINT) and the setpoint of the ADR event (EVENT SET POINT); the air temperature for the reference scenario and for the ADR event (REF TEMP, EVENT 03 TEMP respectively); and the heat power of both scenarios (REF HEAT POWER, EVENT 03 HEAT POWER).

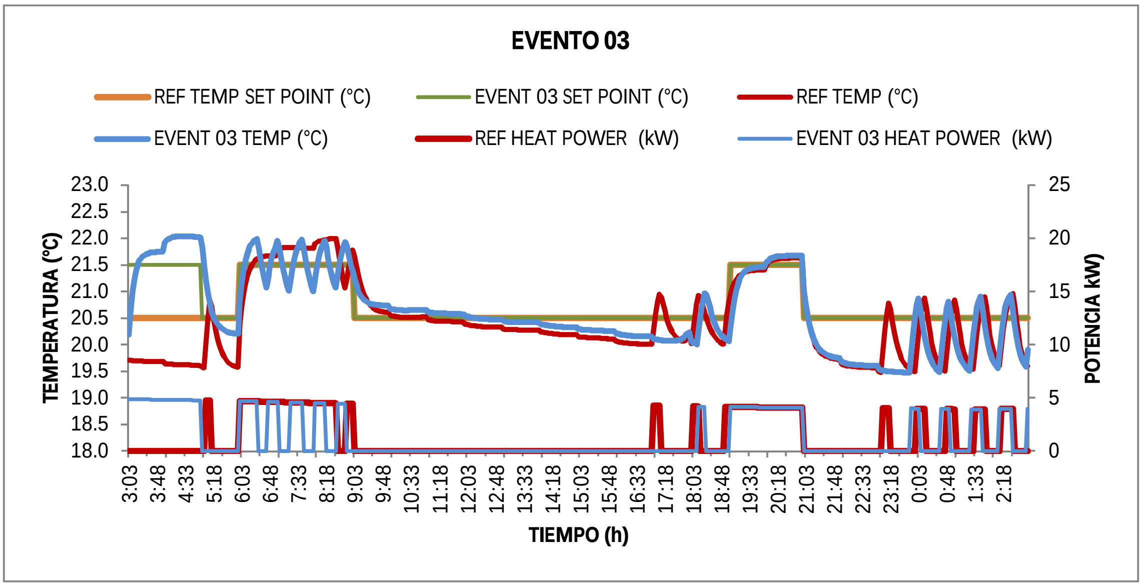

Figure 3: Representation of the temperature set point, the air temperature and the heating power by the reference scenario and event "03"

In the reference scenario is possible to observe how the heating power is switch on. It is occurs all time when the setpoint temperature is higher (occupied day time), and in few smaller intervals when the setpoint is lower (night and non-occupied). The air temperature never is outside the comfort range.

The ADR event starts with the setpoint change from 20.5 ° C to 21.5 ° C at 03:03 hours, and maintains this value for 2 hours. If the ADR scenario is compared with the reference scenario, it is possible to observe how the change in the set point allowed to stored energy. This is feasible, because in the reference scenario the heating is not working. The different behavior of the temperature and heating power curves between 05:00 and 09:00 hours allowed to identifying that the stored energy during the ADR event is used in this period.

Table 7
Results of the indicators measured in event "3"

Indicator	Measure
$C_{ADR} = \int_0^{2h} (Q_{ADR}(t) - Q_{REF}(t))dt$	9.41 kWh
$ER = \int_0^{24h} (Q_{ADR}(t) - Q_{REF}(t))dt$	1.58 kWh
$\eta_{ADR} = 1 - \frac{\int_0^{24h} (Q_{ADR}(t) - Q_{REF}(t))dt}{\int_0^{2h} (Q_{ADR}(t) - Q_{REF}(t))dt}$	83%
$DEC = \int_0^{24h} (E_{ADR}(t) - E_{REF}(t))dt$	0.18 kWh
$EC = \int_0^{24h} (E_{ADR}(t) - E_{REF}(t)) * PVPC(t)dt$	-2.56 (€)

The results of the indicators for event "3" are shown in the table 7 and are interpreted as follows: The available storage capacity is 9.41 kWh; it means that during the ADR event, the building is able to store 9.41 kWh more than the reference scenario. The rebound effect is 1.58 kWh; it means that in the ADR event, in a period of 24 hours, the building has consumed 1.58 kWh more than reference scenario. Consequently the storage efficiency is 83%. Although electricity consumption is higher in the ADR scenario, the energy cost is 2.56 € lower than the reference scenario.

Figure 4 shows the results of the 24 events carried out in the case "+1D/2H". Each event is evaluated in a 24-hour period. The results of every event are positioned in the starting time of the ADR event. For example, the indicators of a 24-h evaluation of the ADR event implemented at 13:03 are represented in Figure 4 at 13:03.

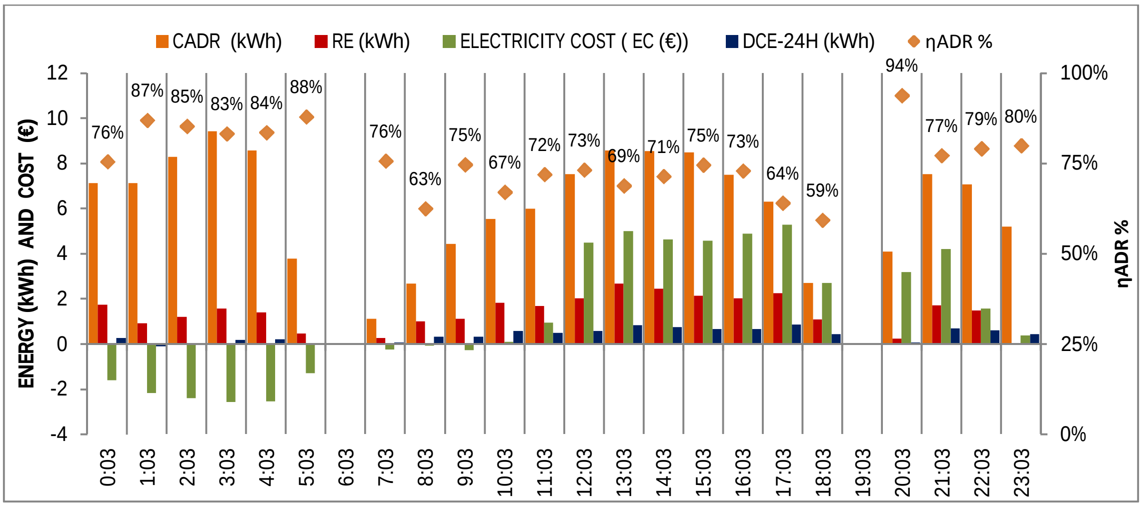

Figure 4: Representation of the indicators of capacity and efficiency of storage, electricity cost and energy consumption by the 24 ADR events of the case "+ 1D / 2H"

In Figure 4 is possible to identify that the building has available storage capacity at the night and non-occupied periods. These periods correspond to the lowest setpoint. The ADR events performed at 06:03 and 19:03 hours do not have storage capacity, i.e. the heating power in the events is equal to the reference. The ADR events that present a better efficiency and greater cost savings correspond to those made between 00:03 and 05:03. The others ADR events provide equal or higher energy cost. The energy consumption in the ADR events is equal or higher than the reference scenario. The ADR event done at 03:03 hours show higher storage capacity (C_{ADR} = 9.41 kWh) and cost savings (2.56 €) with an efficiency of 83%.

4.1.2 Downward ADR event

The results of a downward scenario is shown, where the temperature setpoint has decreased 1 ºC for two hours. The event "19" (figure 5) is used as an example to explain the results of the indicators over a 24-hour horizon.

The reference scenario is the same as described in section 4.1.1. The figure 5 shows that the event starts at 19:03 hours with the change setpoint from 21.5 ° C to 20.5 ° C, and maintaining this value for 2 hours. This change of setpoint allows switch off the heating power and move the load to the next hours (21:00 to 23:00). After the 23:00 hours the behavior between both scenarios is similar.

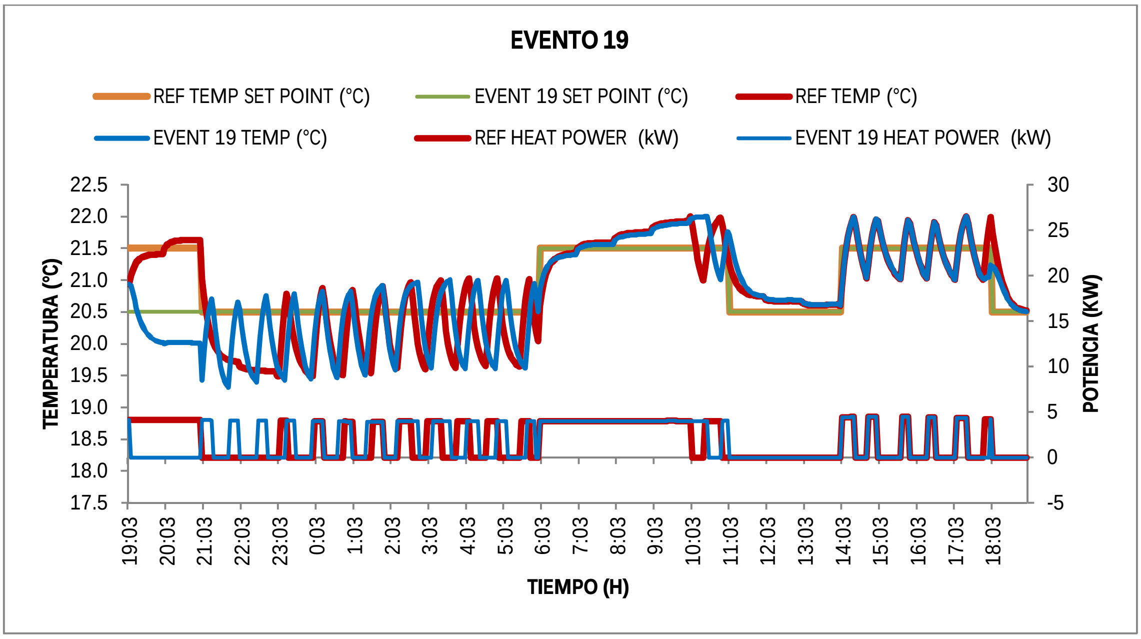

Figure 5: Representation of the temperature set point, the air temperature and the heating power by the reference scenario and event "05"

Table 8

Results of the indicators measured in event "19"

Indicator	Measure
$C_{ADR} = \int_0^{2h} (Q_{ADR} - Q_{REF})dt$	-7.82 kWh
$ER = \int_0^{24h} (Q_{ADR} - Q_{REF})dt$	-1.62 kWh
$\eta_{ADR} = 1 - \frac{\int_0^{24h} (Q_{ADR} - Q_{REF})dt}{\left\| \int_0^{2h} (Q_{ADR} - Q_{REF})dt \right\|}$	121%
$DEC = \int_0^{24\,h} (E_{ADR} - E_{REF})dt$	-0.60 kWh
$EC = \int_0^{24h} (E_{ADR} - E_{REF}) * PVPC * dt$	-5.83 (€)

The results of the indicators for event "19" are shown in the table 8 and are interpreted as follows: The available storage capacity is -7.82 kWh; it means that during the ADR event, the building is able to save 7.41 kWh more than the reference scenario. The rebound effect is -1.62 kWh; it means that in the ADR event, in a period of 24 hours, the building has consumed 1.62 kWh less than reference scenario. Consequently the storage efficiency is 121%. The electricity consumption is 0.68 kWh lowest in the ADR event, and the energy cost is 5.83 € lower than the reference scenario.

Figure 6 shows the results of the 24 events carried out in the case “-1D/2H”. Each event is evaluated in a 24-hour period. The results of every event are positioned in the starting time of the ADR event.

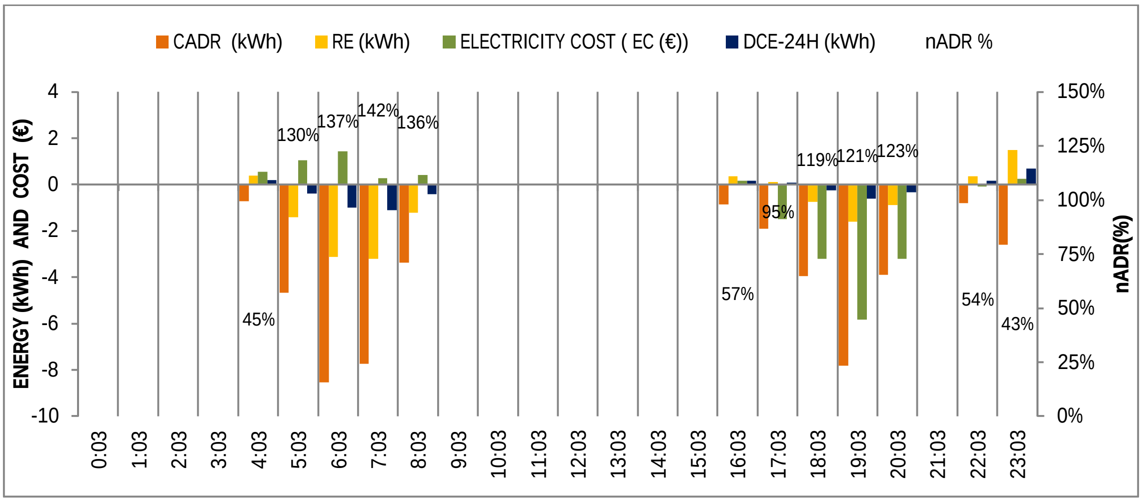

Figure 6: Representation of the indicators of capacity storage, efficiency storage, electricity cost, and energy consumption by the 24 ADR events of the case "- 1D/2H"

In Figure 6 it is possible to identify that the building has energy flexibility during the daily occupied hours or in the periods near them. It is feasible because the temperature set point is higher during these events. The building doesn’t have energy flexibility if the ADR events are performed when the temperature set point is lower. The events carried out in the morning have the highest availability storage capacity and the highest efficiency; however their costs are higher than reference scenario. It is because, the load is moved to hours where the energy price is higher. The ADR events performed in the afternoon are the ones with the highest saving costs. The energy consumption in the ADR events is equal or lower than the reference scenario. The ADR event done at 19:03 hours has the higher storage capacity (C_{ADR} = -7.82 kWh) and cost savings (5.83 €) with an efficiency of 121%.

4.1.3 Comparison of upward and downward

Figure 7 shows the available capacity storage and efficiency storage, and figure 8 shows electricity cost for upwards and downwards events.

The hours with high storage capacity in the upward events are the ones with lower storage capacity in the downward events, and vice versa. The downwards events have higher saving costs than the upwards events. The hours between 00:03 and 05:03 are favorable for energy storage, and the hours between 17:03 and 20:03 are favorable to reduce energy consumption.

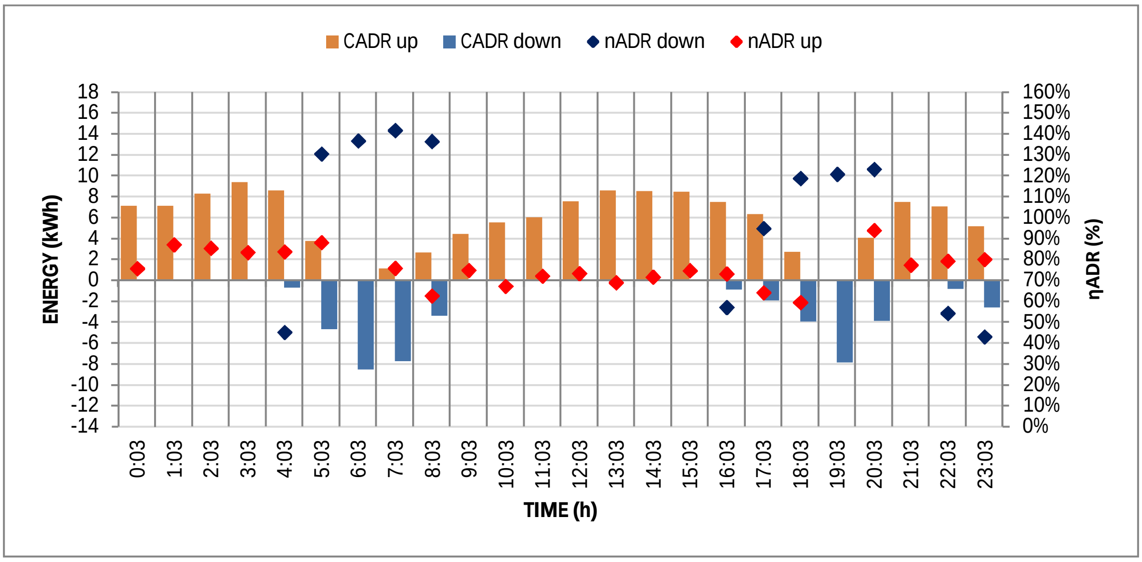

Figure 7: Representation of the indicators of capacity storage and efficiency storage for the 24 ADR events of the cases "+1D/2H" and "- 1D/2H"

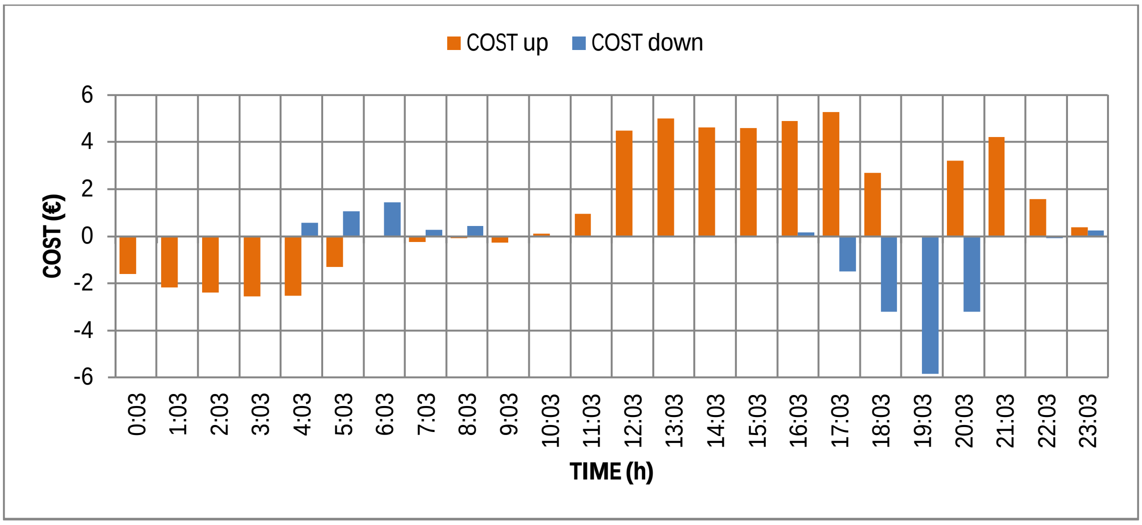

Figure 8: Representation of electricity cost for the ADR events of the cases "+1D/2H" and "-1D/2H"

4.2 Effect of temperature variation

In this section the behavior of the energy flexibility is analyzed for the setpoint variation of 1 and 2 °C. The analyzed cases are: +1D/2H, -1D/2H, +2D/2H, and -2D/2H. The results of these cases are shows in the figure 9 and 10.

In the upward events, while the temperature increases: the storage capacity increases, the efficiency is the same or decreases, and there are no significant changes in the energy costs.

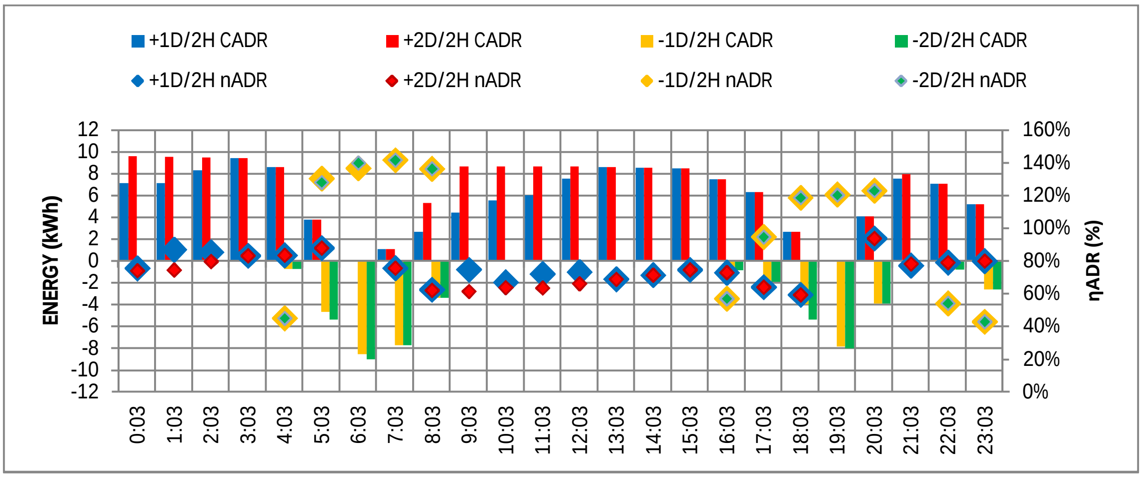

Figure 9: Representation of the indicators storage capacity and storage efficiency, for the cases "+1D/2H", "-1D/2H", "+2D/2H", and "-2D/2H"

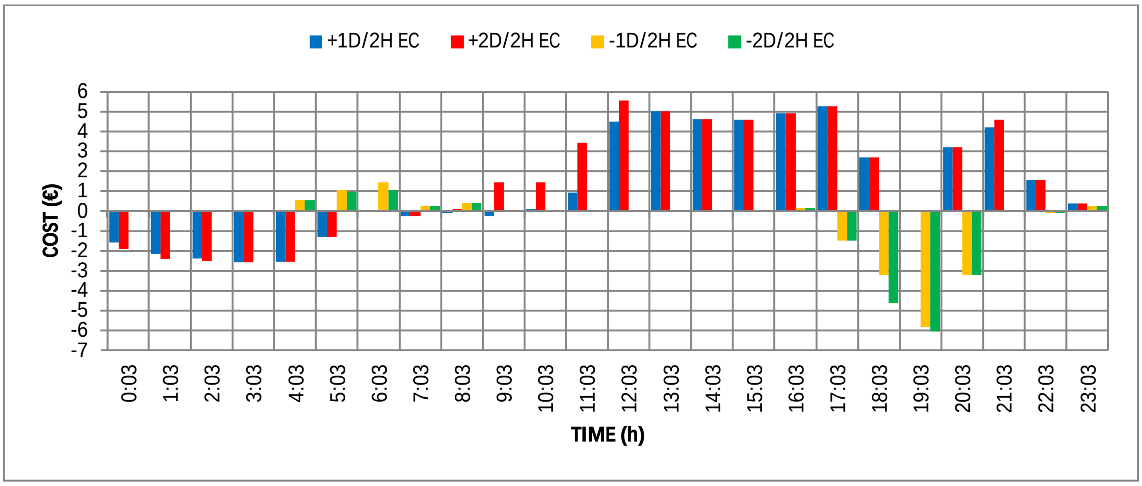

Figure 10: Representation of the electricity cost for the cases "+1D/2H", "-1D/2H", "+2D/2H", and "-2D/2H".

In downwards events, while temperature increases: storage capacity, efficiency, and cost have very similar results; except at the event performed at 18:03. At this time, if the temperature is decreased by 2 ° C, the energy flexibility and saving costs are higher.

The option of change of the temperature setpoint in 2 ° C is the one that presents better results of energetic flexibility, for both upwards and downwards events.

4.3 Effect of event duration

In this section we analyze the behavior of energy flexibility in events of 1, 2, 3, and 5 hour's duration. The analyzed cases are the following: +1D/1H, +1D/2H, +1D/3H, +1D/5H, -1D/1H, -1D/2H, -1D/3H, and -1D/5H

Figure 11 shows the results of storage capacity and storage efficiency for upward events. As the duration of the event increases, the storage capacity also increases. The events 5-hours duration has the greatest capacity of storage; nevertheless, if the event is carried out between the 02:03 and 06:03 hours the efficiency is smaller. The efficiency depends on the temperature setpoint in the event duration. In events with higher set points the efficiency is lower and vice versa.

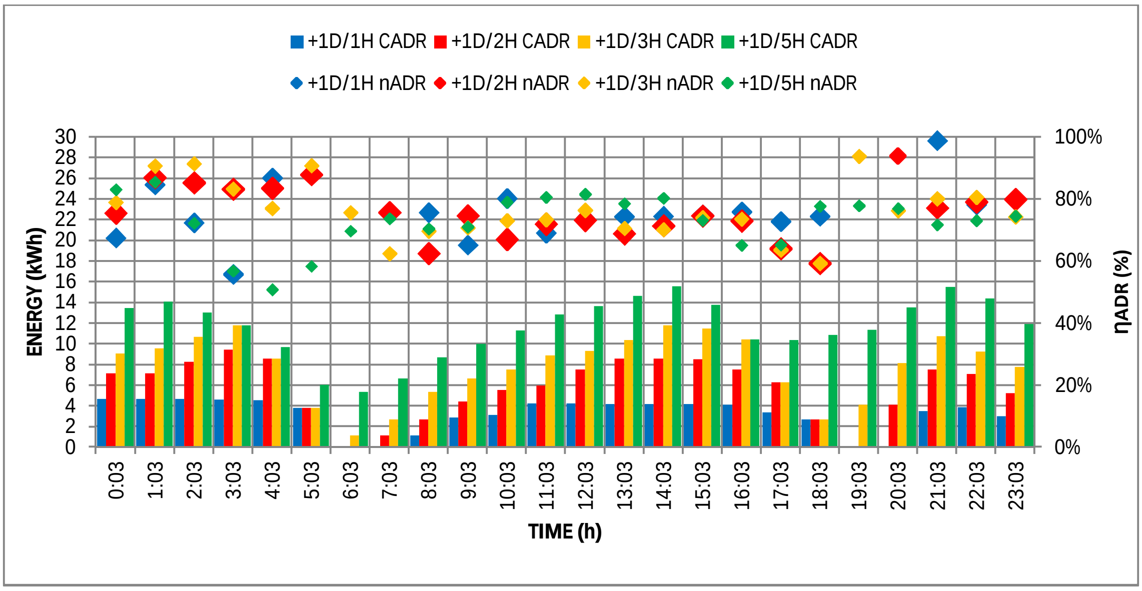

Figure 11: Representation of the indicators of capacity and efficiency of storage, of the cases "+1D/1H", "+1D/2H", "+1D/3H", and "+1D/5H"

The cost of electricity (Figure 12) depends of storage capacity, storage efficiency and electricity price. All cases have saving costs between 00:03 and 05:03 hours. According to the results of energy cost, at daily hours it is not convenient to store energy, because de electricity price is higher.

The selection of appropriate duration of energy flexibility events depends on the time where the ADR event is performed. For example, 5 hours event performed at 01:03 shows the highest saving cost (4.17 € per day), and 5 hours event performed at 05:03 shows the lowest saving cost (1 € per day). Event must be performed in order to obtained highest saving cost.

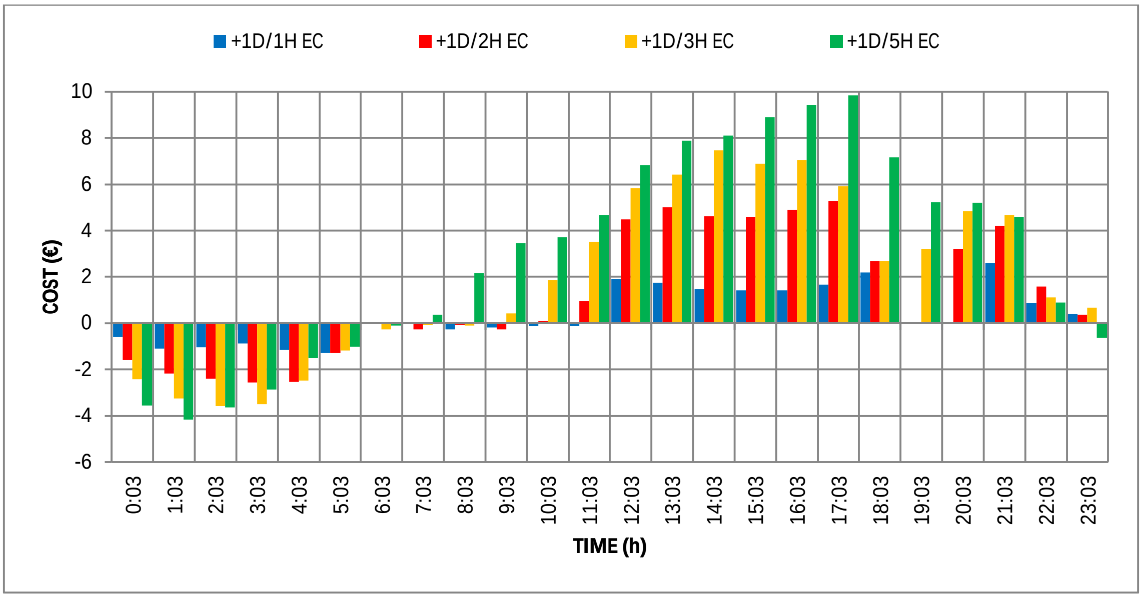

Figure 12: Representation of electricity cost for the cases "+1D/1H", "+1D/2H", "+1D/3H", and "+1D/5H"

Figure 13 shows the results of storage capacity and storage efficiency for downward events.

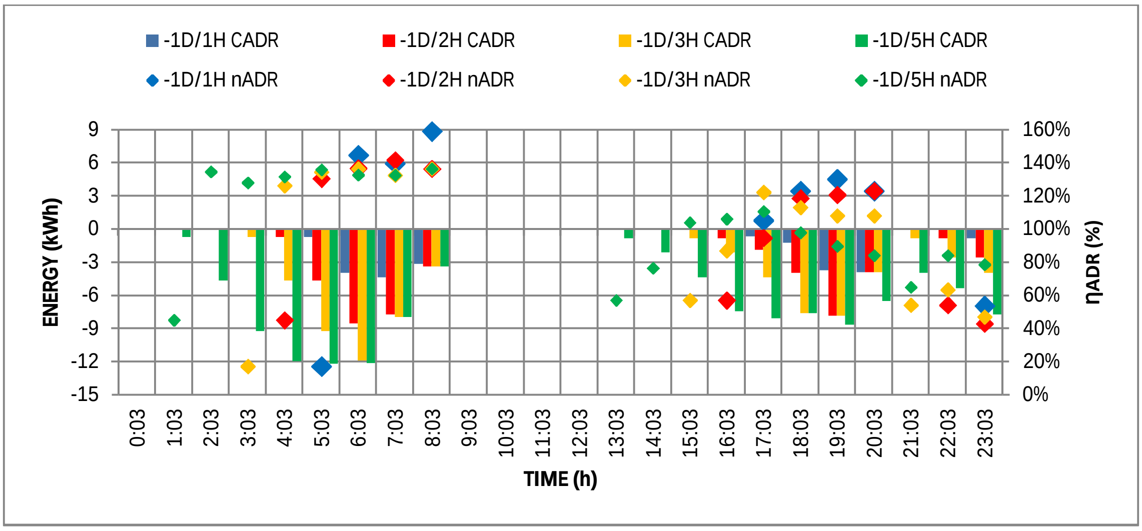

Figure 13: Representation of the indicators of capacity and efficiency of storage, of the cases "-1D/1H", "-1D/2H", "-1D/3H", and "-1D/5H"

As happens in upwards events, in downwards events, increasing event duration increases storage capacity. The efficiency varies widely; it is because, the duration of the ADR event includes zones with different temperature set points. Although the events performed between 1:03 and 8:03 have efficiency higher than 100%, their cost is also higher than the reference scenario; it is because, the load is shifted to hours where the energy price is higher. Generally the longest events have the highest saving costs, as shown in figure 14. For example, 5 hours event performed at 19:03 shows the highest saving cost (-7.29 € per day).

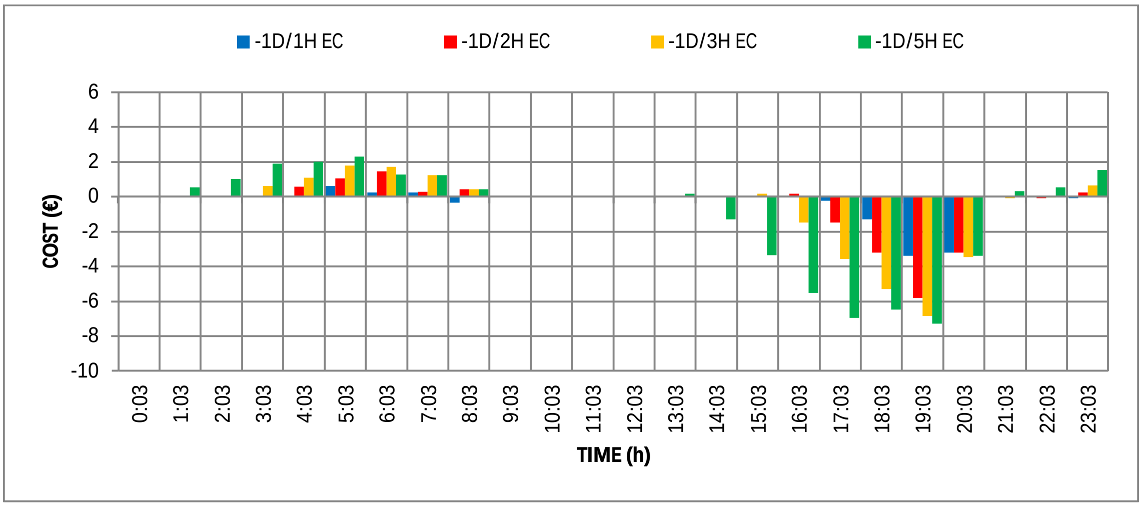

Figure 14: Representation of the electricity cost indicator for the cases "-1D/1H", "-1D/2H", "-1D/3H", and "-1D/5H"

5. Conclusions

The study analyzes the behavior of the energy flexibility applied in a residential nZEB located in a Mediterranean climate. The energy flexibility is analyzed implementing different modulations of the setpoint temperature, so called ADR events (Active Demand Response). The ADR events are performed in a day-night thermostat control in different configurations: 1 or 2ºC of temperature modulation (increase or decrease), and 1, 2, 3 and 5 hours of duration.

According the results, it is possible to identify some common patterns between all the cases:

- There is an opposite behavior of energy flexibility between upward and downward events; i.e. if in a certain upward event the storage capacity is high; in the same moment, the downward event will provide a lower storage capacity, and vice versa.
- In upward events performed in periods without occupation or at night time, the storage capacity increases; it is because the event includes the lowest temperature setpoint. On the contrary, if the event includes the highest setpoint, the storage capacity decreases significantly. The events with greater saving costs are those carried out between 00:03 and 05:03 where the energy price is lower.
- Downward events present the greatest energy flexibility in the occupied day periods, where the temperature setpoint is higher. The building does not have energy flexibility in most of the night and of non-occupied periods. The result of storage capacity and storage efficiency are better in the ADR events performed in the morning than the ones performed in the afternoon; however the electricity cost is higher. This is because in the morning hours the load is moved to hours with higher energy prices, and in the afternoon, the load is moved to lower price hours (night).
- Events with temperature variations do not present significant differences in the energy flexibility and the storage capacity and storage efficiency have similar behaviors in both cases. Probably, the reason is that the system needs more than 2 hours to reflect the effect of 2ºC of modulation, in comparison with 1ºC.
- Comparing the cases with different duration, in general, the longest duration events (5 hours) are the ones with the greatest storage capacity; however not always the longer events are the best option in terms of storage efficiency and

energy consumption. A balance between ADR duration, the capacity efficiency, energy consumption and the energy cost must be found.

- In +1D/2H case, the event performed at 03:03 hours has the maximum available storage capacity (9.41 kWh) and economic savings (2.56 € per day)
- In -1D/2H case, the event performed at 19:03 hours has the maximum available storage capacity (-7.82 kWh) and economic savings (5.83 € per day)
- The 5-hours event performed at 19:03 provides the maximum saving costs (7.29 € per day).
- The comfort index demonstrates that all the ADR events have provided comfort conditions and the operative temperature of the occupied hours are inside the comfort range.
- In general, the energy flexibility events have a rebound effect and the energy consumption is greater than the reference scenario. However, there is not a direct relationship between the energy consumption and the energy cost, because the energy price varies with time.
- All events that offer energy flexibility do not necessary have economic saving in the electricity cost, due to the energy price variation.

The selection of the best flexibility strategy depends on the time at which the ADR event is took place. This type of analysis helps to increase the knowledge of energy flexibility, in order to be able to define an appropriate strategy for shifting the heating load. Further research is needed in this topic, as for example to analyze the behavior of energy flexibility combining different ADR event in the same day and how to quantify the flexibility in those cases; or to evaluate the energy flexibility in summer applying the ADR event to the cooling system.

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Abstract.

The de-carbonization of energy and the higher penetration of renewable energies in the energy mix lead to the search for new alternatives in the generation and distribution of energy. One of these alternatives is the demand managed; through the energy flexibility that residential nZEB can offer. The nZEBs are a reality in the EU, and it is believed that in the not too distant future they will play a very important role in the stability of the electrical system; becoming small centers of energy, capable of generating and storing energy. In this study an analysis of the energy flexibility of a residential nZEB was carried out, by controlling a heating load. The variables taken into consideration for the analysis were the setpoint temperature and the event duration. In total, 240 active demand response modulations (ADRs) were performed in 10 different scenarios. The evaluation of the energy flexibility was done through the indicators of available storage capacity and storage efficiency proposed by Reynders.

The comfort index demonstrates that all the ADR events have provided comfort conditions and the operative temperature of the occupied hours are inside the comfort range.

In upward events performed in periods without occupation or at night time, the storage capacity increases; it is because the event includes the lowest temperature setpoint. On the contrary, if the event includes the highest setpoint, the storage capacity decreases significantly.

Downward events present the greatest energy flexibility in the occupied day periods, where the temperature setpoint is higher. The building does not have energy flexibility in most of the night and of non-occupied periods

In general, the energy flexibility events have a rebound effect and the energy consumption is greater than the reference scenario. However, there is not a direct relationship between the energy consumption and the energy cost, because the energy price varies with time. All events that offer energy flexibility do not necessary have economic saving in the electricity cost, due to the energy price variation

Resumen.

La des-carbonización de energía y la mayor penetración de las energías renovables en el mix-energético, conlleva a buscar nuevas alternativas en la generación

almacenamiento y distribución de energía. Una de estas alternativas es la gestión de la demanda, a través de la flexibilidad energética que pueden ofrecer los nZEB residenciales. Los nZEBs son una realidad en la UE, y se cree que en un futuro no muy lejano desempeñarán un rol muy importante en la estabilidad del sistema eléctrico; convirtiéndose en pequeños centros de energía, capaces de generar y almacenar energía. En este estudio se realizó un análisis de la flexibilidad energética de un nZEB residencial, mediante el control de una carga de calefacción. Las variables tomadas en consideración para el análisis fueron la temperatura de consigna y el tiempo de duración de los eventos. En total se realizaron 240 modulaciones de respuesta a la demanda activa (ADR por sus siglas en inglés) en 10 diferentes escenarios. La evaluación de la flexibilidad energética se la realizó mediante los indicadores de capacidad de almacenamiento disponible y eficiencia de almacenamiento propuestos por Reynders.

El índice de confort demuestra que todos los eventos ADR han proporcionado condiciones de confort; y que la temperatura operativa de las horas de ocupación está dentro del rango de confort.

En los eventos donde el ajuste de temperatura es hacia arriba, y que se llevaron a cabo en periodos de ocupación de noche o de no ocupación tienen mayor capacidad de almacenamiento; esto es porque el evento se realiza con una menor consigna de temperatura. En los eventos que incluyen una mayor consigna de temperatura la capacidad de almacenamiento disminuye significativamente.

En los eventos donde el ajuste de temperatura es hacia abajo, presentan mayor flexibilidad energética en periodos de ocupación de día, que corresponden a una mayor consigna de temperatura. El edificio no ofrece flexibilidad energética en la mayoría de los periodos de ocupación de noche y de no ocupación.

En general todos los eventos presentaron un efecto rebote y el consumo de energía fue mayor que el escenario de referencia; sin embargo no hay una relación directa entre el consumo de energía y el costo de la energía, debido a que el precio de la energía está en función del tiempo. No todos los eventos que ofrecen flexibilidad energética tienen ahorro en el costo de la electricidad, debido a la variación del precio de la energía.