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WP3 - Technology Integration in Smart Managed Plus Energy Buildings and Neighbourhoods

D3.4 GUIDELINES FOR REALIZING ENERGY FLEXIBILITY

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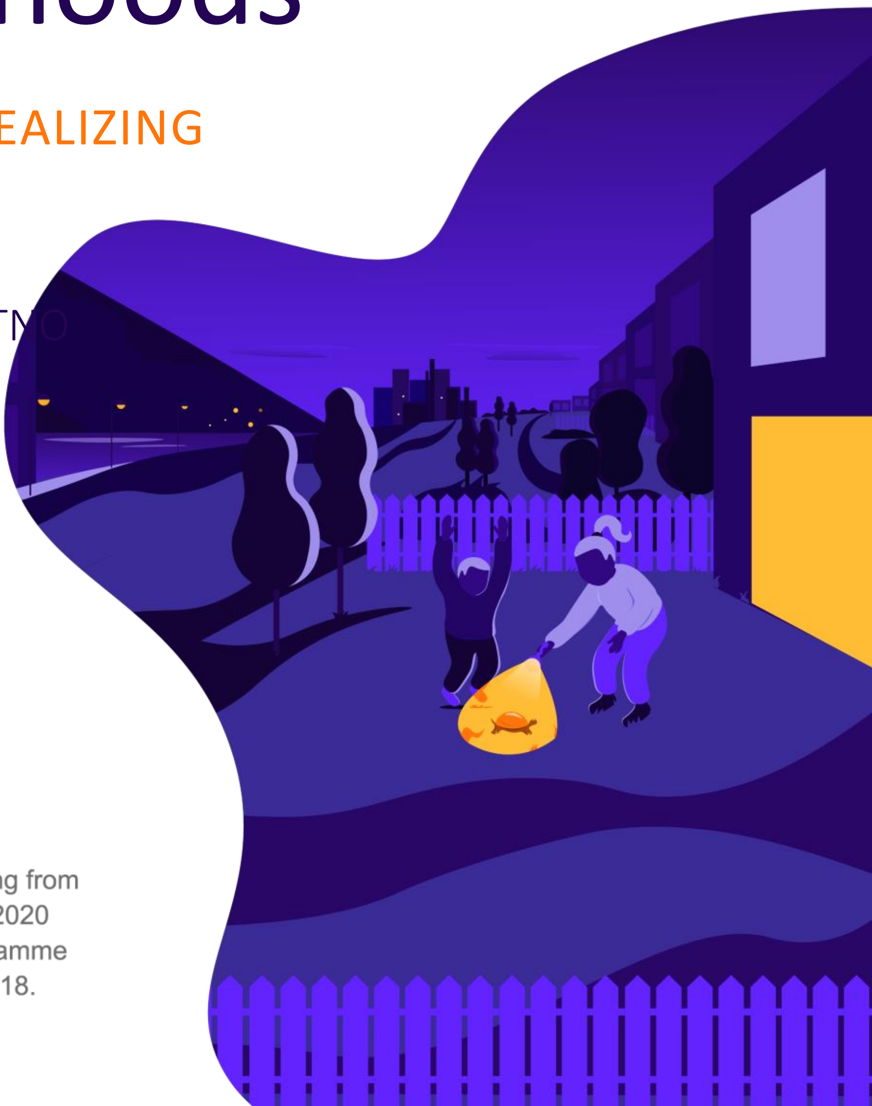

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Executive Summary

The objective of this deliverable is to provide generic guidelines for utilizing the energy flexibility of building components, by investigating the flexibility potential of the Dutch and Spanish demos at the component level. For each demo, components which can provide energy flexibility were identified, and their potential for flexibility was quantified via dynamic building simulations.

Specifically, the report focuses on utilizing the flexibility of HVAC systems (i.e. space heating) or domestic hot water (DHW) production, to promote the consumption of on-site generated solar energy and to reduce the imported electricity from the grid. Therefore, in addition to a set of generic flexibility KPIs (e.g. storage capacity, efficiency and flexibility index), solar-specific KPIs such as supply cover factor and extra import from the grid were presented in the report and are used in evaluating the energy flexibility.

To investigate the energy flexibility potential of each building component, a series of dynamic simulations were performed, where the normal operation of the building components, as determined by a reference scenario, is altered in a systematic manner. This is done either by introducing Active Demand Response (ADR) events on a daily basis which modulate the setpoints for space heating or domestic hot water production (in the Dutch demo), or by introducing a penalty signal that triggers a setpoint shift (in the Spanish Demo). The flexibility KPIs were then calculated under various boundary conditions related to occupant's behaviour. The effect of external conditions (i.e. outdoor temperature and solar radiation) was also investigated.

The flexibility potential of a component is strongly dependent on the design of the system, occupant's behaviour, the comfort constraints, the penalty signal and control algorithms used. The space heating can provide more flexibility in the heating season if the heating system includes a storage as in the case of the Spanish demo with centralized heating. If the goal is to shift the energy consumption to the night hours, the flexibility control strategy may lead to a higher total energy consumption if the thermal losses to the outside environment are substantial, which however corresponds to overall lower CO_2 emissions. The domestic hot water production offers flexibility throughout the whole year, although its flexibility capacity can be limited by the actual DHW demand, by the capacity of the tank and by the comfort restriction. Imposing a stricter comfort bound on e.g. a temperature setpoint would limit the magnitude of the allowable setpoint shift, thereby decreases the available flexibility capacity. The insights derived from the flexibility analysis in the two demos were formulated in terms of guidelines for flexibility, and will be taken into account in designing smart control systems in work package 4 – Flexibility measures in different climate zones and markets.

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1. Roles and Responsibilities

Name	Role	Responsibility
TNO	Task 3.4 leader, coordinator of deliverable contents, contributor	Inventory of active building components for the Dutch demo case, method for evaluating energy flexibility potential, simulation of flexibility scenarios for the Dutch demo case, setting up guidelines for energy flexibility, coordination
IREC	Contributor	Inventory of active building components for the Spanish demo case, method for evaluating energy flexibility potential, simulation of flexibility scenarios for the Spanish demo case, setting up guidelines for energy flexibility
DTU	Reviewer	Review of the deliverable

2. Introduction

Objective

The objective of task 3.4 is to provide guidelines to realise significant energy flexibility in multi-storey apartment buildings. This report specifically focuses on shifting the energy load in time, using available active building components, to promote the consumption of locally-generated solar power (to limit the export of the generated electricity to the grid) and to reduce the electricity import from the grid.

Description of the deliverable

This deliverable aims to address three central questions:

- Which active building components can be used for energy flexibility?
- How is energy flexibility potential characterized and computed?
- What are external boundary conditions/occupants' behaviours that affect energy flexibility potential, and how can they be translated into guidelines?

The report focuses on the Dutch and Spanish demo cases and provides a description of available active components in the two demos along with their operational range and constraints. In general, shifting energy loads at a certain moment in time either has an upward or downward effect on energy use and has a rebound effect at a later moment. To quantify the flexibility potential a set of key performance indicators (KPIs) which capture various characteristics of load shifting is presented. These include generic KPIs such as storage capacity, storage efficiency and flexibility index, as well as the solar-specific KPIs such as the supply cover factor and the extra electricity imported from the grid.

The flexibility potential of the Dutch and Spanish demos is investigated by performing dynamic simulations using digital twins of both demo cases. For each of the available building components a series of simulations is performed, in which the normal operation of the component, as determined by a reference scenario, is altered in a systematic manner. Two Parallel methodologies, one based on introducing the active demand response (ADR) events, and the other based on a penalty-aware controller coupled to a penalty signal, are presented. An ADR event refers to a certain change in the operation of a component (for example shifting a temperature setpoint up or down by a fixed amount) for a limited duration of time. In the flexibility analysis, a chosen ADR event, with a given setpoint shift and duration, is applied on a daily basis starting from the same hour each day. It will be then investigated how the buildings' response to such a fixed strategy is affected by variable external conditions. The penalty-based approach follows a similar principle where the setpoint shift is dictated by a penalty signal which, for simplicity, is assumed to have a fixed daily pattern. Therefore, both methodologies lead to a fixed daily pattern of setpoint shift, based on which the flexibility potential of the component can be evaluated using the flexibility KPIs. These approaches provide insight for the next step, i.e. implementation of adaptive strategies and model predictive control, which is the topic of the subsequent work packages.

Besides the design parameters, the flexibility potential of an active component heavily depends on boundary conditions such as outdoor weather conditions (e.g. outdoor air temperature and solar radiation), occupant behaviour (e.g. preferred level of ventilation, indoor temperature, domestic hot water demand) and comfort constraints (e.g. the allowable tolerance around the preferred setpoint values). Characterizing the effect of boundary condition thus forms the core of the flexibility analysis in this report. The insights derived from the analysis are formulated in terms of guidelines for utilizing the energy flexibility, which can inform the design of smart control systems by addressing the following questions:

- What strategies are useful to achieve a high energy flexibility for a particular component (with the focus on promoting the consumption of locally generated solar energy)?

- What is the effect of boundary conditions on the flexibility potential of each component?
- Which component has the largest potential for energy flexibility under different circumstances?

The report is structured as follows:

- Chapter 3: Inventory of active building components
- Chapter 4: Key Performance Indicators (KPIs) for energy flexibility
- Chapter 5: Methods for energy flexibility characterization
- Chapter 6: Scenario definition
- Chapter 7: Simulation results Dutch demo case
- Chapter 8: Simulation results Spanish demo case
- Chapter 9: Conclusions and guidelines for energy flexibility

3. Inventory of active building components

Flexibility can be exploited if there are active components that allow for shifting energy demand within time. Therefore, as a first step, an inventory is made of the active components available in the demo cases, including the operational range and constraints for the components' conditions.

In the Dutch demo case, the active components available are the ground source heat pump in each apartment, used for space heating and for domestic hot water production, and the electric appliances. The inventory of the operational range and constraints of all active components in the Dutch demo case can be found in Annex A. It is noted that for the Dutch demo the flexibility of electric appliances is not considered in this research as it will only be determined by the assumptions that are made about the use of these appliances in time. In case of space heating and domestic hot water production the use in time is controlled by the thermostats in the room and domestic hot water tank (DHW tank) respectively.

In the Spanish demo case, the active components available are the 3 air-to-water heat pumps, that are supply source for the central heating and DHW system. There is 1 water tank for the DHW (2000L) and 1 water tank for the heating system (1000 L), that are the main components providing the energy flexibility at building level. Therefore, the flexibility potential is provided through the set-points of heat pumps, tanks, and apartments' thermostats, affecting the DHW system and space conditioning. The inventory of the operational range and constraints of all active components in the Spanish demo case can be found in Annex B.

4. Key Performance Indicators (KPIs) for energy flexibility

In this chapter the Key Performance Indicators (KPIs) that are used to quantify the energy flexibility are described. Most of the KPIs in this section (supply cover factor, flexibility index, rebound efficiency, peak delivered and export powers and POR) were already presented in D3.1. Other KPIs (storage capacity and efficiency, imported electricity from the grid) have been additionally presented in this report. The KPIs are calculated based on the simulated time series data. They quantify different aspects of flexibility and serve as instruments for the guidelines.

Storage capacity and storage efficiency

Storage capacity and storage efficiency are defined in relation to the Active Demand Response (ADR) events [1][2]. An ADR event is referred to an induced change in the normal operation pattern of an active component for a limited period of time. For example, assuming that the temperature setpoint for heating normally obeys a certain "reference scenario", leading to a heating power $P_{ref}(t)$, an ADR event of duration l_{ADR} can be created by increasing (upward flexibility, Figure 1, left) or decreasing (downward flexibility, Figure 1, right) the temperature setpoint by e.g. 1°C, starting at the time $l_{DR.start}$ until $l_{DR.end} = l_{DR.start} + l_{ADR}$. The ADR event leads to an altered heating power $P_{DR}(t)$.

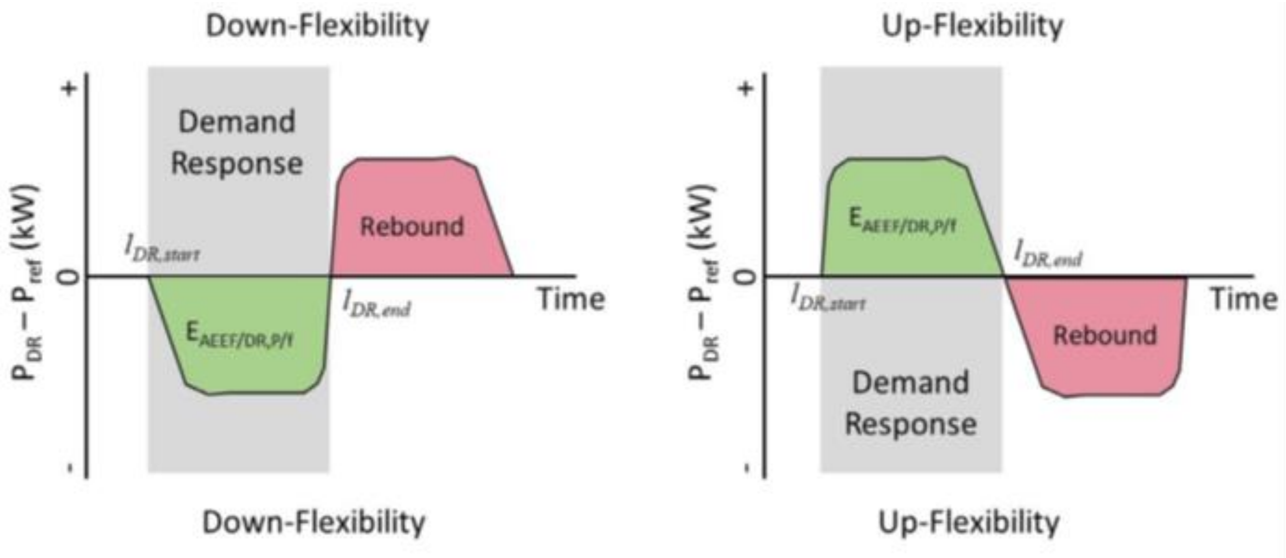

Figure 1: ADR events in the case of downward flexibility (left) and upward flexibility (right) [1].

Storage capacity quantifies the amount of extra energy used (in the case of upward flexibility) or the energy saved (in the case of downward flexibility) during the ADR event compared to the reference scenario (green area in Figure 1).

Calculation:

$$C_{ADR} = \int_{l_{DR.start}}^{l_{DR.end}} (P_{DR} - P_{ref})dt, \tag{1}$$

where:

P_{ref} – consumed power in the reference scenario (kW)

P_{DR} – altered consumed power as a result of introducing an ADR event (kWh)

In this study the ADR events occur regularly, starting from the same hour every day. In this case Equation (1) is generalized as

$$C_{ADR} = \sum_i \int_{t_{DR.start,\ Day_i}}^{t_{DR.end,\ Day_i}} (P_{DR} - P_{ref})dt \tag{2}$$

Storage efficiency characterizes the magnitude of the rebound effect (the red area in Figure 1) compared to the extra energy used/energy saved (the green area in Figure 1).

Calculation:

$$\eta_{ADR} = 1 - \frac{\int_0^{\infty}(P_{DR} - P_{ref})dt}{|C_{ADR}|} \tag{3}$$

Supply cover factor

The supply cover factor is the relation between the energy produced on-site and directly used and the total on-site produced energy.

Calculation:

$$\gamma_{supply} = \frac{E_{prod,used}}{E_{prod,tot}} = \frac{\int min\,[P_{prod}(t), P_{used}(t)]\ dt}{\int P_{prod}(t)\ dt} \tag{4}$$

where:

$E_{prod,used}$ – self-consumed on-site production (kWh)

$E_{prod,tot}$ - total electricity produced on-site (kWh)

P_{prod} - on-site produced power (kW)

P_{used} – on-site consumed power (kW)

When energy storage elements are present in the system, e.g. a battery, this needs to be considered in the definition of the used power, as the power used to charge the storage adds to power consumption in the building. For example, in case of a PV system and a battery, the supply factor can be computed with the following Equation:

$$\gamma_{supply} = \frac{\int min\,[P_{PV}(t), P_{used}(t) + P_{bat}(t)]\ dt}{\int P_{PV}(t)\ dt} \tag{5}$$

where

P_{PV} – is the on-site (photovoltaic) production (kW)

P_{bat} - is the power sent to the battery (positive if charging) or incoming from the battery (negative if discharging) during the interval of time of evaluation (kW)

To characterize the effect of the energy flexibility on the usage of the generated solar energy, the difference between the supply cover factors for the ADR scenario and the reference scenario is calculated:

$$\Delta\gamma_{supply} = \gamma_{supply}^{ADR} - \gamma_{supply}^{ref}, \tag{6}$$

where

γ_{supply}^{ref} – supply cover factor in the reference scenario

γ_{supply}^{ADR} – supply cover factor in the ADR scenario

Imported electricity from the grid

The extra energy import from the grid in the ADR scenario with respect to the reference scenario is calculated as

$$\Delta E_{import} = E_{import}^{ADR} - E_{import}^{ref} \tag{7}$$

where

E_{import}^{ref} – Electricity imported from the grid in the refence scenario (kW)

E_{import}^{ADR} – Electricity imported from the grid in the ADR scenario (kW)

Flexibility index

Flexibility index symbolizes the fractional savings, that is possible to achieve when applying the flexibility control strategy. Flexibility index 0 symbolises zero improvement in the flexibility scenario, meaning that both the base and flexible case had equally much penalties. Flexibility index 1 indicates that flexible case accumulated penalty is close to 0.

Calculation:

$$FI = 1 - \frac{C1}{C0} \tag{8}$$

$$Cn = E * \lambda \tag{9}$$

Where:

FI – flexibility index

$C1$ – Accumulated penalty of flexible case, penalty unit

$C0$ – Accumulated penalty of base case, penalty unit

Cn – Accumulated penalty, penalty unit

E – Energy consumption, kWh

λ – penalty signal, penalty unit/kWh

Efficiency of rebound energy

This indicator represents the fractional increase of energy consumption between flexible and the reference (base) case. This indicator can be evaluated based on many different terms: whether by final or primary energy, thermal or electrical consumption, at different points on the demand side etc. It is expected that E1>E0 (the energy consumption of flexible case is greater than of the base case), due to the energy rebound effect.

Calculation:

$$Reff = 1 - \frac{E_1}{E_0} \tag{10}$$

Where:

E_1 – energy consumption of flexible case (kWh)

E_0 - energy consumption of base case (kWh)

Interpretation:

1) Reff < 0 if $E_1 > E_0$
2) Reff > 0 if $E_1 < E_0$

Peak delivered and peak exported power

The peak delivered and the peak exported power KPIs are extreme values of the net duration curve. The maximum positive value is the peak delivered, while the maximum negative value is the peak export. If there is no net export, then the peak export is equal to zero.

Calculation:

$$P_{max,del,i} = \max\,[P_{net,i}(t)] \qquad (11)$$

$$P_{max,exp,i} = -\min\,[P_{net,i}(t)] \qquad (12)$$

Where:

$P_{max,del,i}$ – Peak delivered power: peak power of energy delivered to the grid by the energy carrier i

$P_{max,exp,i}$ – Peak exported power: peak power of energy exported to the grid by the energy carrier i

$P_{net,i}$ – net power by energy carrier i

POR (Percentage outside the range, thermal comfort)

To evaluate the thermal comfort, the percentage of time that temperatures are out of the ranges specified in the categories of EN 167989-1-2019 following the adaptive comfort, should be estimated for buildings with and without cooling systems for the heating and cooling seasons. Table 1 represents the comfort categories, and for new buildings the thermal comfort should be inside category II (IEQ_{II}) [3].

Table 1: Thermal comfort categories based on Adaptive comfort model EN 167989 [3].

Category	Upper and lower limits
IEQ_{I}	upper limit: $\Theta_o = 0{,}33\ \Theta_{rm} + 18{,}8 + 2$ lower limit: $\Theta_o = 0{,}33\ \Theta_{rm} + 18{,}8 - 3$
IEQ_{II}	upper limit: $\Theta_o = 0{,}33\ \Theta_{rm} + 18{,}8 + 3$ lower limit: $\Theta_o = 0{,}33\ \Theta_{rm} + 18{,}8 - 4$
IEQ_{III}	upper limit: $\Theta_o = 0{,}33\ \Theta_{rm} + 18{,}8 + 4$ lower limit: $\Theta_o = 0{,}33\ \Theta_{rm} + 18{,}8 – 5$

Where:

$\Theta rm =$ Outdoor Running mean temperature for the considered day (°C) which can be calculated by:

$\Theta rm = (1\text{-}\alpha)\,\{\Theta_{ed\text{-}1} + \alpha\,\Theta_{ed\text{-}2} + \alpha^2\,\Theta_{ed\text{-}3}\}$

$\Theta ed - 1 =$ daily mean outdoor air temperature for previous day

$\alpha =$ constant between 0 and 1 (recommended value is 0,8)

$\Theta ed - i =$ daily mean outdoor air temperature for the i-th previous day

In case that daily running mean outdoor temperatures are not available, the following formula can be used: $Qm = (Q_{ed\text{-}1} + 0.8\ Q_{ed\text{-}2} + 0.6\ Q_{ed\text{-}3} + 0.5\ Q_{ed\text{-}4} + 0.4\ Q_{ed\text{-}5} + 0.3\ Q_{ed\text{-}6} + 0.2\ Q_{ed\text{-}7})/3.8$

Where:

$\Theta o =$ indoor operative temperature, ˚C

$\Theta rm =$ running mean outdoor temperature, ˚C

$\Theta c =$ Optimal operative temperature, ˚C

Where the limits apply when $10 < \theta_{rm} < 30$˚C

5. Methods for energy flexibility characterization

Active Demand Response (ADR) simulation and analysis

In general, shifting energy loads at a certain moment in time either has an upward or downward effect on energy use and has a rebound effect at a later moment. The effect of a shift in use of active components on energy use and the rebound effect heavily depends on boundary conditions, e.g. the outside air temperature, the time of the day, the occupant behaviour, etc.

To investigate the effect of boundary conditions several reference scenarios are designed, that cover typical periods (e.g. heating season). The reference scenarios typically cover a longer period, such that the boundary conditions (simulated and measured) represent the natural variation in practice.

The potential for energy flexibility is quantified via dynamic building simulations by introducing Active Demand Response (ADR) events (see [1]), which change the operation pattern of an active component for a limited period of time with respect to the reference scenario. This includes, for example, changing the temperature setpoint for space heating or domestic hot water. It should be noted that adaptive strategies are not considered in this report, as the goal of this work is to quantify the flexibility potential, and not finding the optimal way to utilize the available flexibility (which would be studied in the subsequent work packages). Therefore, in this study it is assumed that the ADRs occur every day at the same hour and with the same duration during the simulation period, and they are designed to stay within the comfort boundaries to guarantee that comfort is maintained. Since the external conditions and boundary conditions are varying in time, a fixed ADR strategy would result in a time-dependent response as well. This allows to quantify the effect of external and boundary conditions on the flexibility potential of components, which is one of the goals of this deliverable. In addition, the effect of the starting time and the duration of ADRs on the flexibility potential is studied. For each of the buildings' components mentioned in Chapter 3, a series of computer simulations are performed, where the magnitude, duration, and the starting time of the ADR events, as well as the boundary conditions, are varied systematically. For example, when assessing the energy flexibility for space heating, simulations are performed with either increasing or decreasing the thermostat setpoint within the acceptable comfort range, for either 4 or 6 hours, under different boundary conditions (neighbour temperature, ventilation level, etc.). In addition, the ADR start time is varied across each hour of each day during the simulation period. This allows for quantifying the day-to-day variation in flexibility potential, due to variable external conditions. The flexibility potential can then be quantified using the KPIs that are described in Chapter 4. The analysis is performed at the component level, in the sense that for each component only the electricity consumption of that component is included in the computation of the flexibility KPIs.

Simplified penalty signals

The simplified penalty signal methodology used in this work expresses flexibility as a continuous signal along the year. It is assumed that the flexible scenario has a penalty-aware control strategy and therefore is reacting to the change in penalty function. The simplified penalty signals' method used in this work represents an idealistic penalty signal in order to evaluate the maximum flexibility potential, that is normalized between the peak and the base line. The base line marks a constant penalty that cannot be avoided. In case of price penalty signal the base line is around 0.10 €/kWh (Figure 2), and for the solar penalty signal, the base line is 0 (Figure 3).

The evaluation process for energy flexibility is described following:

1. Determination of the penalty signal

Figure 2 illustrates the process to define the penalty signals. The example shows the process with a price penalty: first the energy price is monitored (top figure), secondly the energy price is being normalized (middle figure), and finally the idealized price penalty is proposed, resulting in penalty signal 1 when there are highest energy prices, 0 when the energy price is the lowest, and 0.5 in case of intermediate prices.

2. User restrictions

Secondly, the comfort range is evaluated, based on adaptive model, which determines the upper and lower temperature limit, as expressed in Figure 4. Operative temperature must stay between those constraints.

3. Control strategy

Finally, the control strategy is determined providing the operational conditions of the active elements that respond to the penalty signal. Figure 5 presents an example of control strategy, where the households' heating set-points and set-backs vary depending on the penalty signals.

4. Presentation of the results

The results of simulations can be expressed as accumulated energy or accumulated penalty (Figure 6). Accumulated energy can be evaluated based on many different terms: whether by final or primary energy, thermal or electrical consumption, at different points on the demand side etc. The difference between the total accumulated energy of base case and flexible case is the rebound energy. Accumulated penalty is observed when multiplying energy with the corresponding penalty signal. The difference between total accumulated penalty of the base case and flexible one is the possible benefit that can be observed when applying the penalty aware control strategy.

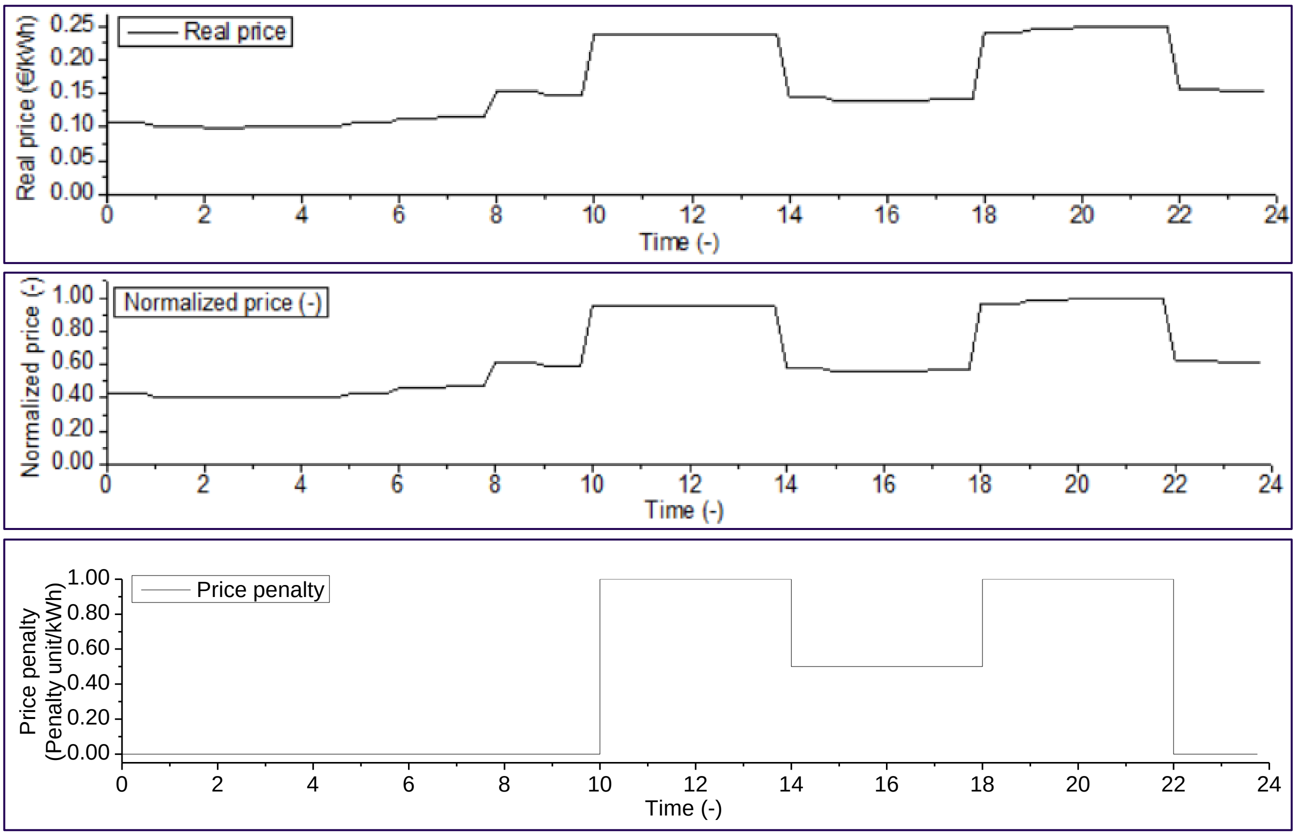

Figure 2: Determination process of penalty signal: energy price (top), normalized energy price (middle), idealized price penalty signal (bottom).

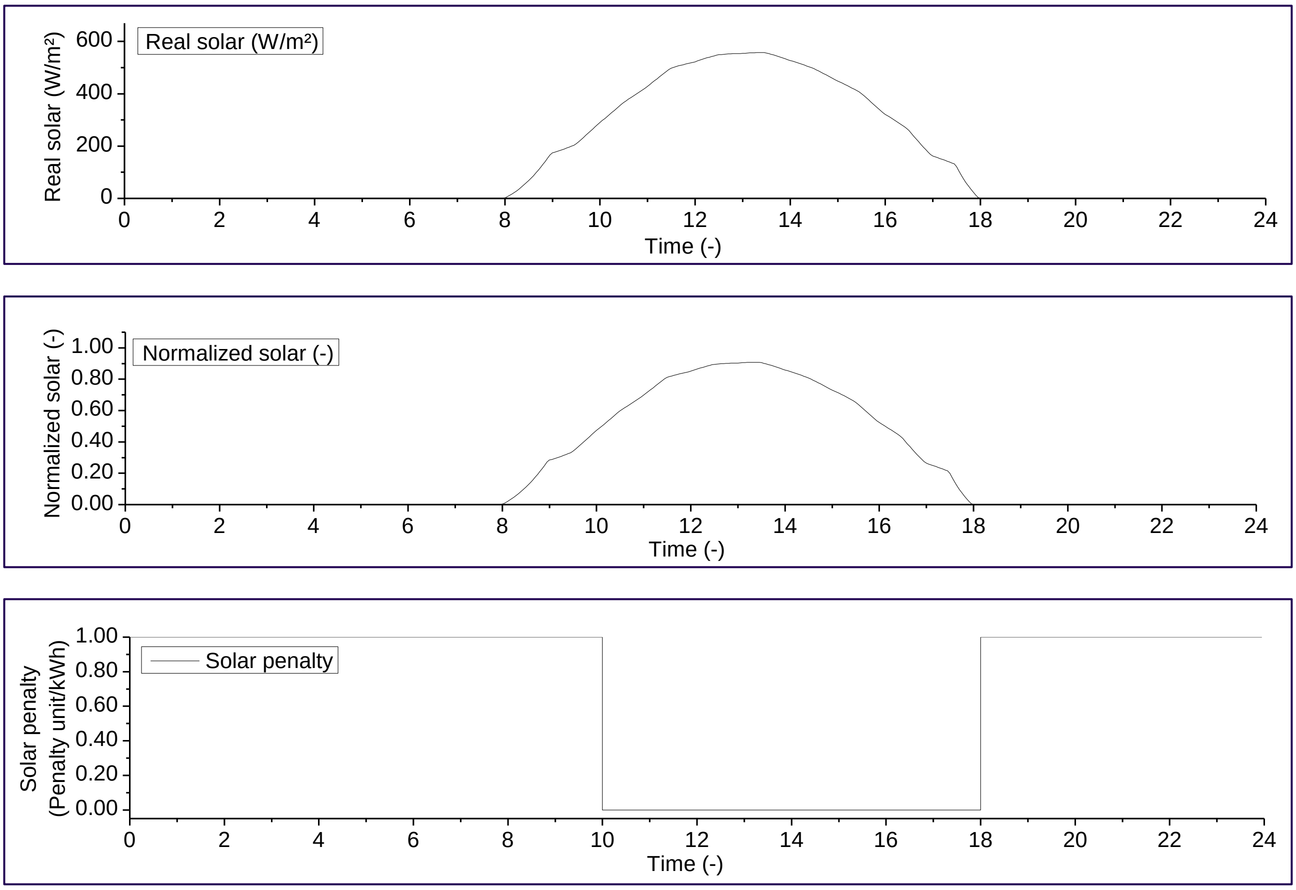

Figure 3 Determination process of solar penalty signal: real solar radiation profile (top), normalized solar radiation profile (middle), idealized solar penalty signal (bottom).

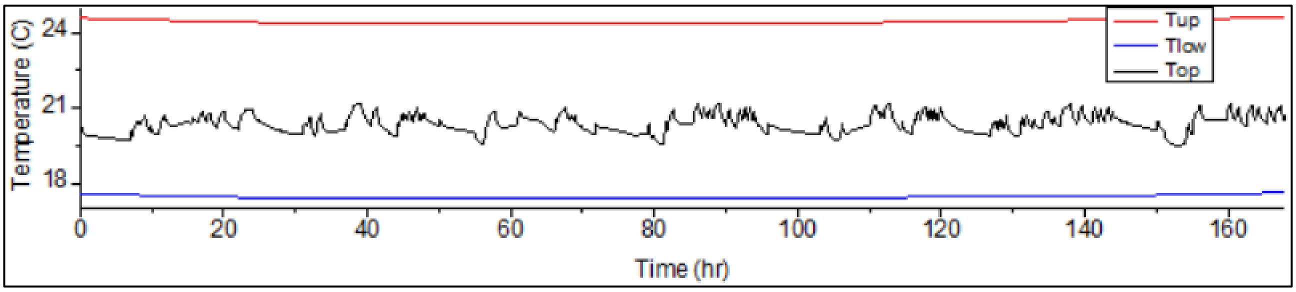

Figure 4: Comfort range based on Adaptive comfort model.

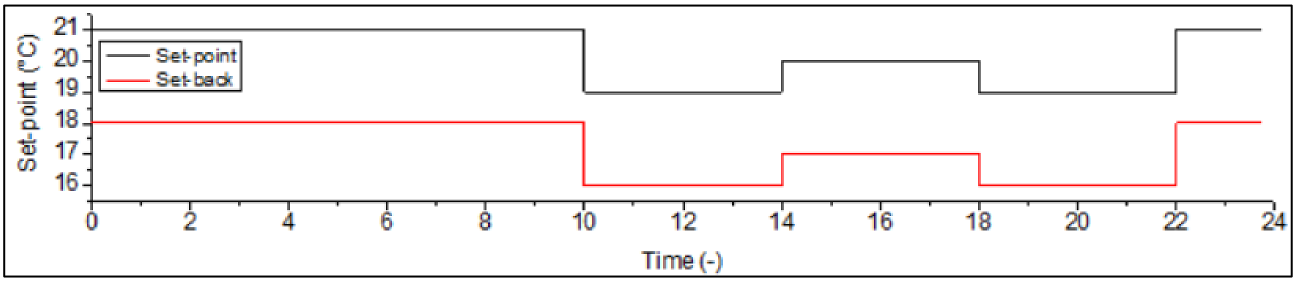

Figure 5: Control strategy example: temperature set-point for heating, at household level. Price penalty strategy.

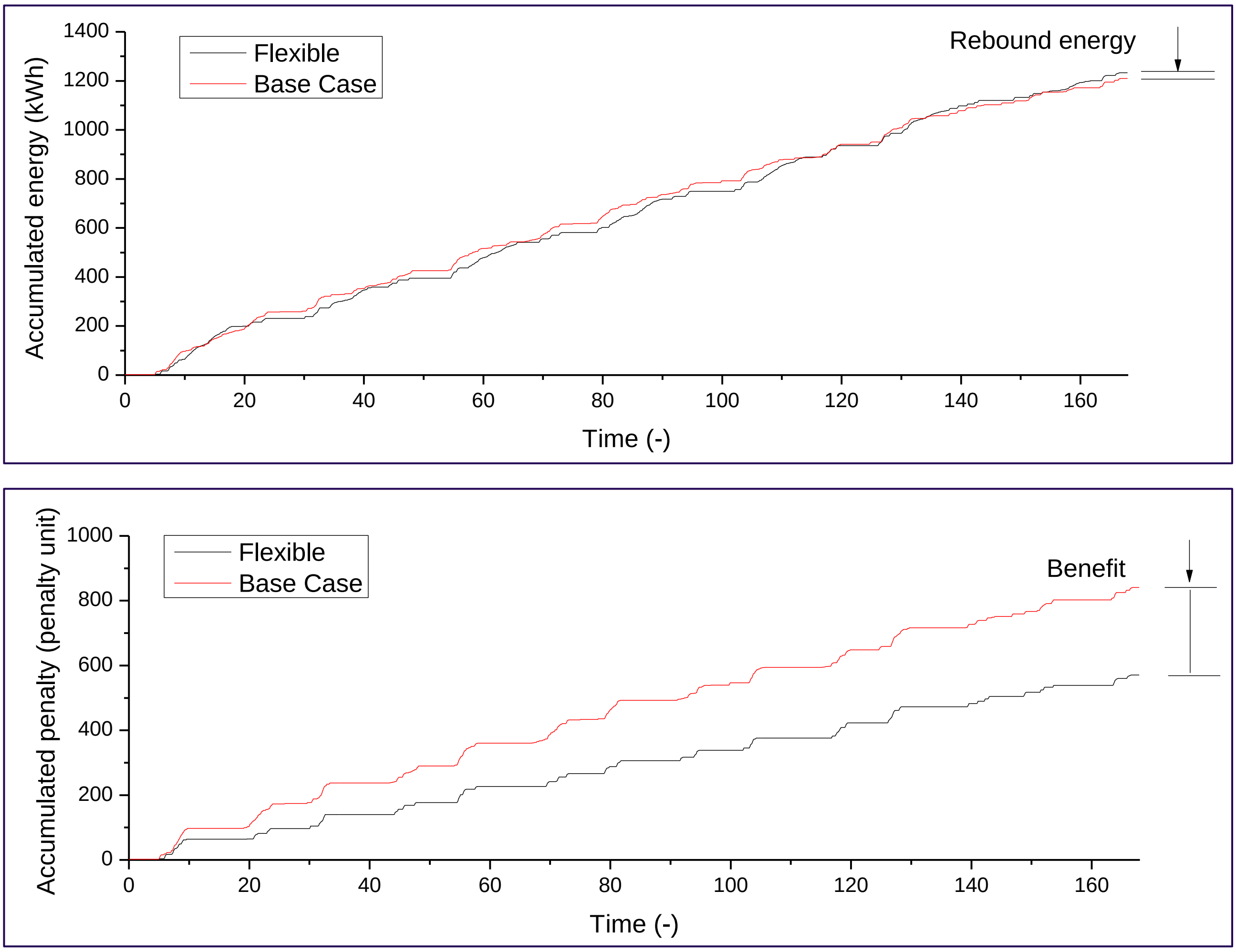

Figure 6: Accumulated energy (top) and accumulated penalty (bottom) of the base case and the flexible scenario.

6. Scenario definition

Scenarios Dutch demo case

For the Dutch demo case the following reference scenarios are defined, including varying occupant behavior:

Reference scenarios for space heating

- Main reference scenario (SP-20):
  - The heating setpoint is kept constant at 20°C.
  - The ventilation is dominantly provided by the exhaust fan (flow rate 37 dm^3/s = 0.81 ACH). Windows and grills remain closed.
  - Electricity use:
    - Household appliances: 2250 kWh/year
    - Lighting: 250 kWh/year
  - The temperature of the neighbouring apartments is assumed to be equal to the average temperature of the target apartment (adiabatic inner walls to neighbouring apartments).
- Alternative reference scenarios:
  - SP-20-lowapp: similar to SP-20, but the household appliances electricity use is reduced to 1500 kWh/year, and the contribution of lighting in the internal heat gain is neglected.
  - SP-20-lowNtemp: similar to SP-20, but the neighbors' temperature is reduced by 1°C.
  - SP-20-highvent: similar to SP-20, but the fan air flow rate is increased to 59 dm^3/s.

Reference scenarios for domestic hot water production

The heat pump is assumed to operate in the comfort mode with a constant temperature setpoint of 62°C. Two different reference scenarios are considered based on the daily demand for domestic hot water:

- Low domestic hot water use (CW1 according to NTA 8800 [4], 140 l/day at 40°C)
- High domestic hot water use (CW4 according to NTA 8800 [4], 302 l/day at 40°C)

ADR scenarios

For the Dutch demo case the following ADR scenarios are simulated for each of the above reference scenarios:

- The temperature setpoint for the space heating is increased by 1°C for either 4 or 6 hours during the day. The starting hour of the ADR events is systematically varied.
- The temperature setpoint for the space heating is decreased by 1°C for either 4 or 6 hours during the night. The starting hour of the ADR events is systematically varied.
- For the domestic hot water, the heat pump is prevented to operate during the ADR events. The ADRs start at 10 pm every day. The duration of the ADR is systematically varied.

Scenarios Spanish demo case

The flexibility scenarios carried out in the Spanish demo simulations include applying 2 different types of penalty signals: solar and price related (Figure 7). Both penalty signals are applied alternatively with different control strategies at household level (H) or building level (B). Both household and building level includes 4 modulations, which defined the set-points, set-backs and dead bands regarding to the control strategy (Appendix C – Spanish demo modulations). The different control strategies implemented together with the different penalty signals are described below and summarised as Table 2.

The intention of the solar penalty signal is to increase the solar hours' energy consumption in order to self-consume more energy, while the purpose of price penalty and control strategy is to shift the demand away from the high price periods to the lower price area, in order to reduce the energy costs and reduce the consumptions during the peak hours.

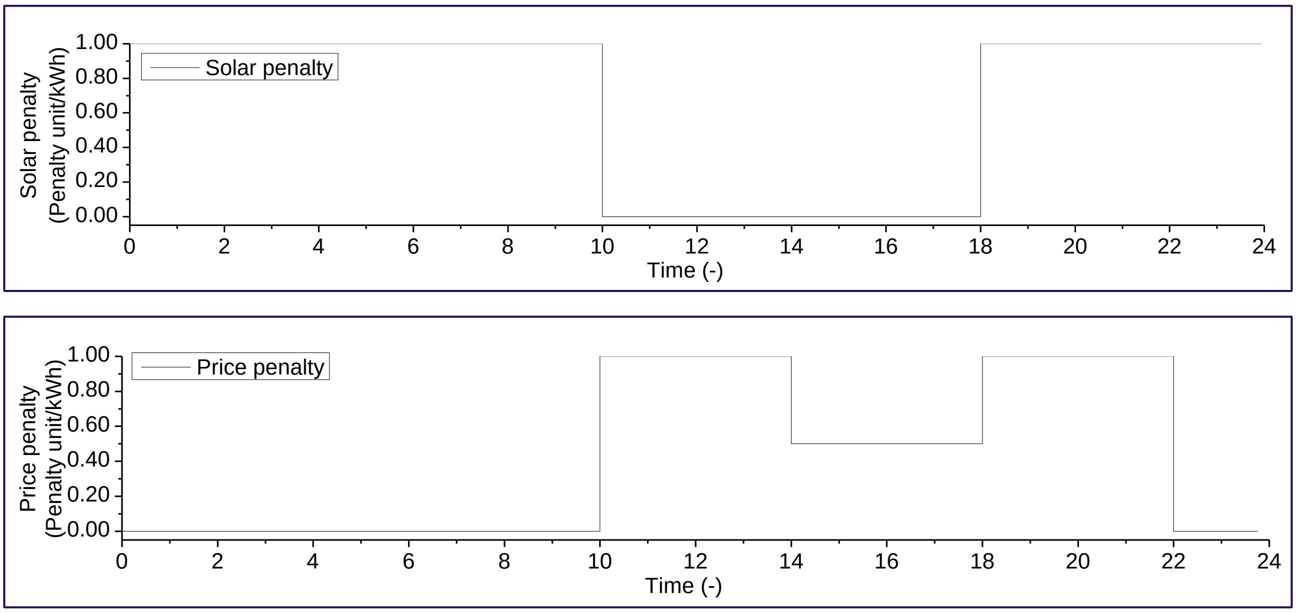

Figure 7: Simplified penalty signals of Spanish demo: solar penalty (top) and price penalty (bottom).

- HM1: Household level control strategy modulation 1. Household set-point temperatures are increased or decreased by 1°C.
- HM2: Household level control strategy modulation 2. Household set-point temperatures are increased or decreased by 2°C.
- HM3: Household level control strategy modulation 3. Household set-point temperatures are increased by 1°C.
- HM4: Household level control strategy modulation 4. Household set-point temperatures are increased by 2°C.
- BM1: Building level control strategy modulation 1. Heating and DHW heat pump and tank set-point temperatures are increased or decreased by 3°C.
- BM2: Building level control strategy modulation 2. Heating and DHW tank controller dead bands are amplified and shifted (Appendix C – Spanish demo modulations).
- BM3: Building level control strategy modulation 3. Heating and DHW heat pump and tank set-point temperatures are increased by 3°C.
- BM4: Building level control strategy modulation 4. Heating and DHW tank controller dead bands are shifted upwards 2°C and 3°C respectively.

Table 2: Flexibility scenarios of Spanish demo.

Level	Solar				Price	
Household	SHM1	SHM2	SHM3	SHM4	PHM1	PHM2
Building	SBM1	SBM2	SBM3	SBM4	PBM1	PBM2

*Example: SHM1 is household level, solar penalty, modulation 1.

7. Simulation results Dutch demo case

To assess the flexibility potential of the components in the Dutch Demo, dynamic simulations on 20-minute basis were performed with SirinE, a building simulator developed at TNO.

Results scenarios for shifting heating setpoint for space heating

To assess the flexibility potential of the heat pump in space heating, ADR events are created every day where the heating setpoint is shifted either up or down for a limited duration, l_{ADR}, starting from hour h_{ADR}. Figure 8 shows an example of an ADR event, where the setpoint is shifted by 1°C between 9 a.m. and 1 p.m.

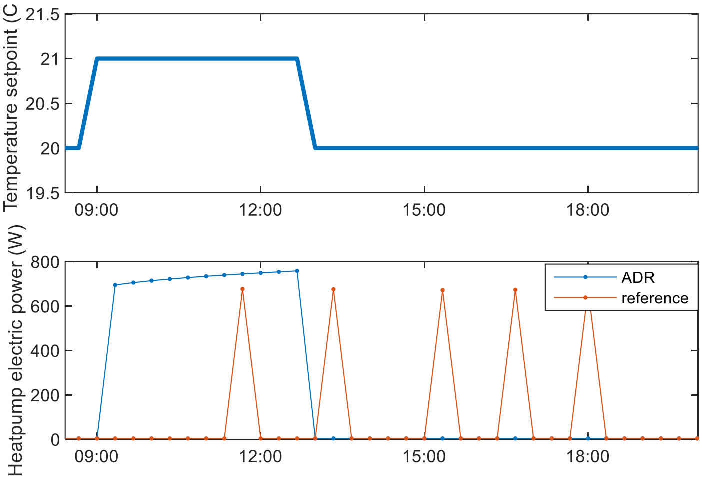

Figure 8: Example of an ADR event, where the setpoint is shifted by 1°C during 9 a.m. and 1 p.m (in the lower graph the separation between the successive points is 20 minutes).

Specifically, when calculating the supply cover factor, it is assumed that the generated solar energy is only used by the heat pump. In this way, the flexibility potential of the component can be quantified isolated from other use of solar power.

Upward flexibility: optimal strategy

Using the scenario SP-20 (see **Scenarios Dutch demo case**) as the reference, multiple ADR strategies were tested, were the setpoint was risen by 1°C either for 4 or 6 hours, each with 11 different choices for the starting hour during the day. The rationale behind choosing the ADR duration of 4 or 6 hours is related to our goal of increasing the consumption of the generated solar energy: we choose the ADR duration to be compatible with the typical duration of solar energy generation in winter period. Computational limitations prevent us to explore more ADR strategies. The resultant flexibility KPIs, calculated in the heating season, are shown in Figure 9 and Figure 10.

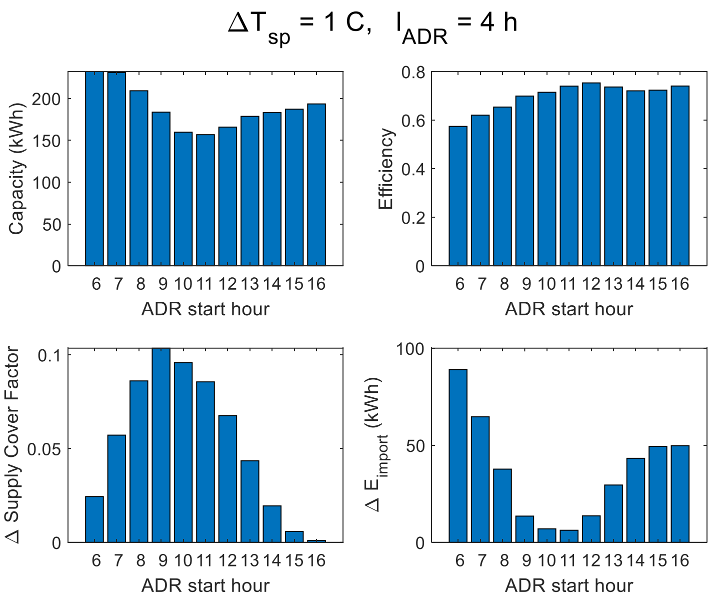

Figure 9: Flexibility KPIs calculated over the heating season, where the heating setpoint is shifted by 1°C for a period of 4 hours, with the ADR starting hour is varied during the day.

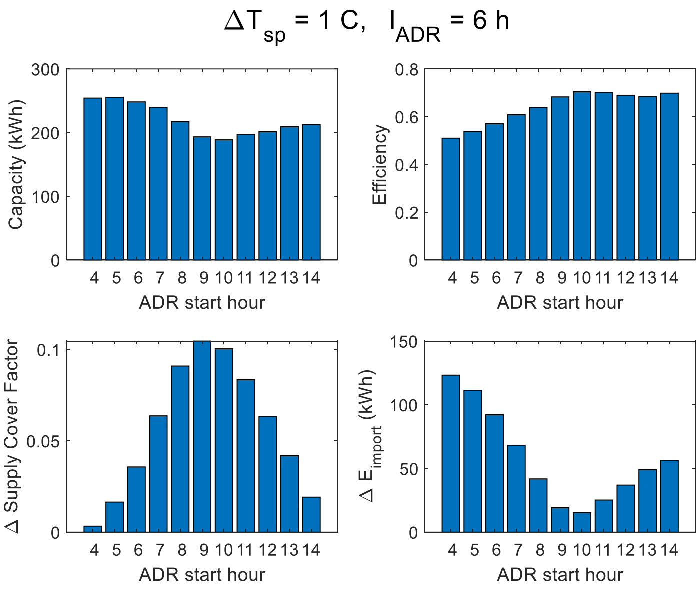

Figure 10: Flexibility KPIs calculated over the heating season, where the heating setpoint is shifted by 1°C for a period of 6 hours, with the ADR starting hour is varied during the day.

The hour of the day when the ADR events start affects all the flexibility KPIs. The storage capacity decreases by ~60-80 kWh (25-30%) in the middle of the day compared to the morning and afternoon hours. This is due to the higher solar gain and outdoor temperature during midday hours, that can cause the room temperature to exceed the ADR setpoint more frequently. The efficiency is less than 1.0, which is typical for upward flexibility due to the higher thermal losses when the setpoint is increased. In the morning hours the efficiency is lower, reflecting the fact that the thermal losses are higher when the outdoor temperature is low.

Specifically, both for $l_{ADR} = 4\ h$ and $l_{ADR} = 6\ h$, starting the ADR at 9 a.m. leads to the highest supply cover factor and consequently a lower import from the grid. Comparing these two strategies (Figure 11), it turns out that prolonging the ADR event from 4 to 6 hours slightly increases the capacity and decreases the efficiency (due to setpoint increase for a longer period), while the difference in the supply cover factor was negligible, leading to a larger import from the grid (Figure 11). It can therefore be concluded that, among the upward strategies tested, rising the setpoint by 1°C for four hours starting from 9 a.m. is most optimal for promoting the use of the generated solar power. Even with this optimal strategy, the total imported energy from the grid is increased by a small amount of ~ 10 kWh per year, which amounts to 2% increase compared to the reference scenario. This implies that on some of the days during the heating season the generated solar energy during the ADR period is not enough to fully cover the extra energy consumed by the heat pump. Therefore, applying an adaptive strategy (e.g. by using model predictive control) rather than a fixed strategy would be a more effective approach to reduce the imported electricity from the grid. This will be studied further in the subsequent work packages.

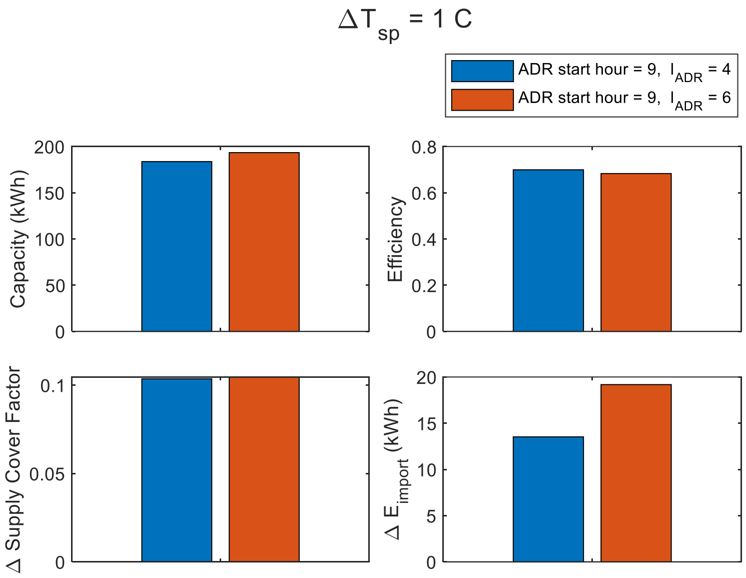

Figure 11: Comparison of the flexibility KPIs for two strategies that result in high supply cover factor when the setpoint is increased.

Upward flexibility: effect of the external conditions

To investigate the effect of external conditions on the energy flexibility resulted from the optimal strategy, the flexibility KPIs were calculated in successive periods of one week, changing the starting day of the week through each day of the year (e.g. the first period is 1-7 January, the second period is 2-8 January, etc.). Considerable day-to-day variations are evident in all the KPIs (Figure 12).There are distinct periods where the storage capacity is small. These generally correspond to the warmer periods where the space heating rarely occurs. In these periods the calculation of the storage efficiency becomes challenging due to its high sensitivity of the small changes in capacity and rebound. The data points with capacities smaller than 1 kWh were therefore excluded from the efficiency graph in Figure 12. For the remaining data points the storage efficiency is generally below one.

The optimal strategy increases the supply cover factor substantially in winter periods. The difference in the imported energy from the grid, ΔE_{import}, highly fluctuates. This is the result of varying capacity and efficiency on one hand, and the varying generated solar energy on the other hand. Occasionally ΔE_{import} takes negative values, but in total the optimal strategy leads to a higher import from the grid with respect to the reference scenario. This implies that a smart controller that uses an adaptive strategy instead of a fixed one would be able to better leverage the generated solar power and minimize the import from the grid.

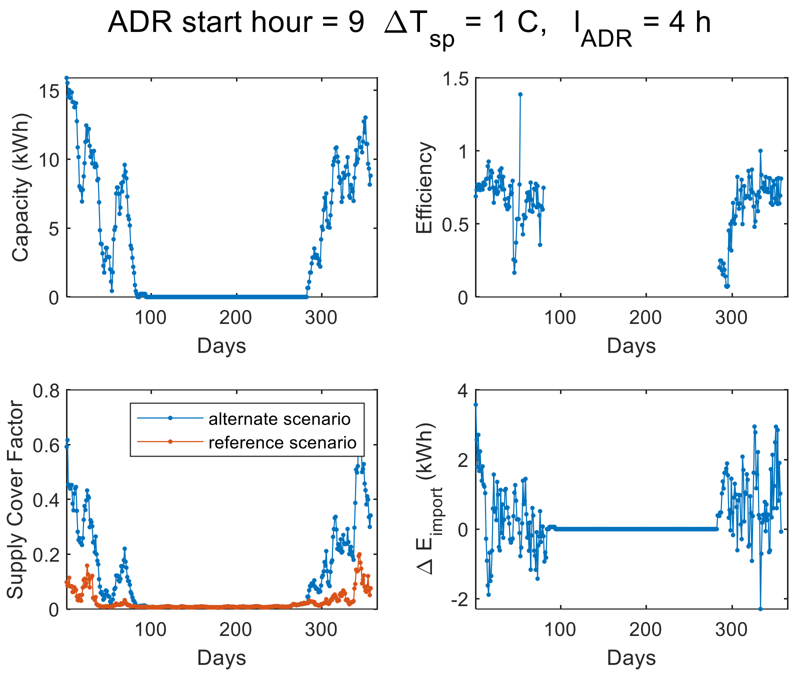

Figure 12: Flexibility KPIs for the optimal upward strategy calculated over successive periods of one week, where the starting day of the week is changed throughout the year.

Figure 13 shows the weekly values of capacity and efficiency vs. the weekly average outdoor temperature (points with capacities smaller than 1 kWh were excluded). At low average outdoor temperatures (between 0 and 4°C) the capacity increases by increasing the temperature. When the outdoor temperature is too cold there is a high chance that the heat pump is already on in the reference scenario during the ADR event. Then increasing the setpoint won't change the status of the heat pump. This is why the capacity is limited at low temperatures (between 0 and 2°C). On the other hand, the capacity decreases to zero when the outdoor temperature is too high, as there is the higher chance that the room temperature remains above the setpoint even when the setpoint is increased by 1°C. There is thus an intermediate range of temperatures (between 2 and 8°C) which leads to the highest flexibility capacity. The efficiency stays rather constant at low average outdoor temperatures but decreases to zero at higher temperatures. This can be understood considering that in these periods the room temperature is generally high, as is evident from the small values of storage capacity in these periods. In the situation that the room temperature in the reference scenario is already higher than the setpoint outside the ADR interval, the ADR event would not create any rebound, leading to zero efficiency.

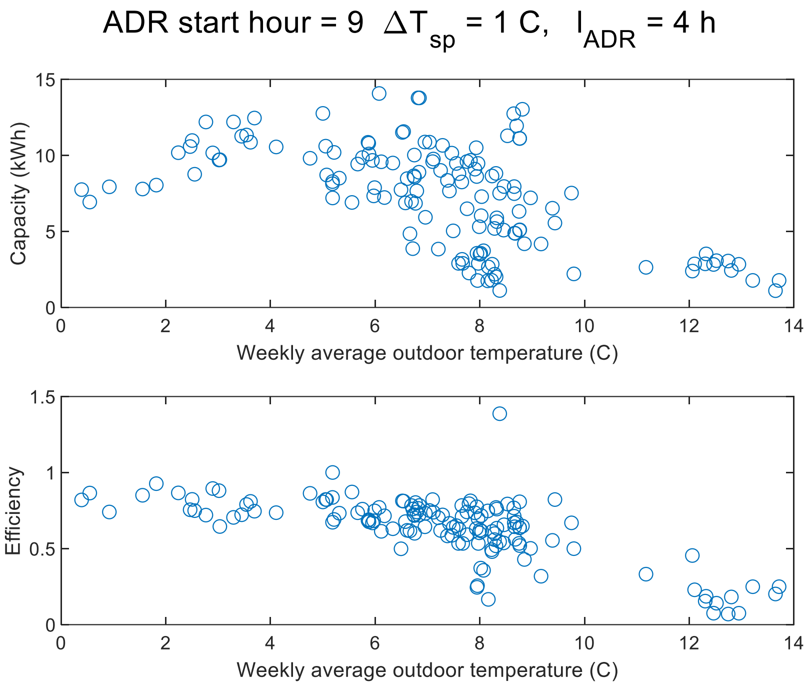

Figure 13: Weekly values of capacity and efficiency vs. the weekly average outdoor temperature (points with capacities smaller than 1 kWh are excluded).

Upward Flexibility: penalty function and flexibility index

Based on the optimal upward strategy that was found in the previous sections, a penalty function can be constructed to promote the use of generated solar energy. It is assumed that the penalty function is zero between 9 a.m. and 1 p.m. and one everywhere else (Figure 14).

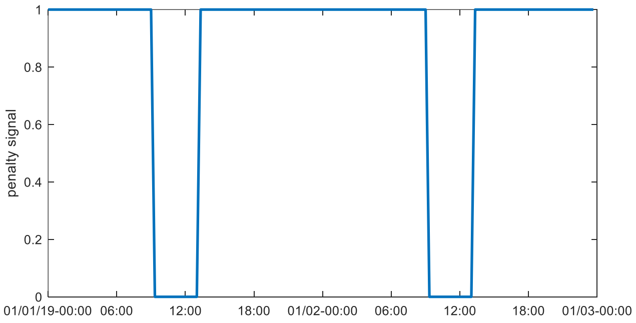

Figure 14: Penalty function constructed from the optimal upward strategy for 2 consecutive days.

Based on the penalty function in Figure 14 the flexibility index can be calculated. Figure 15 shows the flexibility index (as described in chapter 4) calculated over the successive weeks similar to Figure 12. It can be seen that the flexibility index remains positive during the entire heating season. Day-to-day variations are evident, which are caused by not only the magnitude of the rebound effect, but also by the accumulated penalty in the reference scenario. This is why the points with high flexibility index do not necessarily correspond to the points with highest capacity or efficiency. When calculated over the whole year, the optimal strategy has a flexibility index of about 0.27.

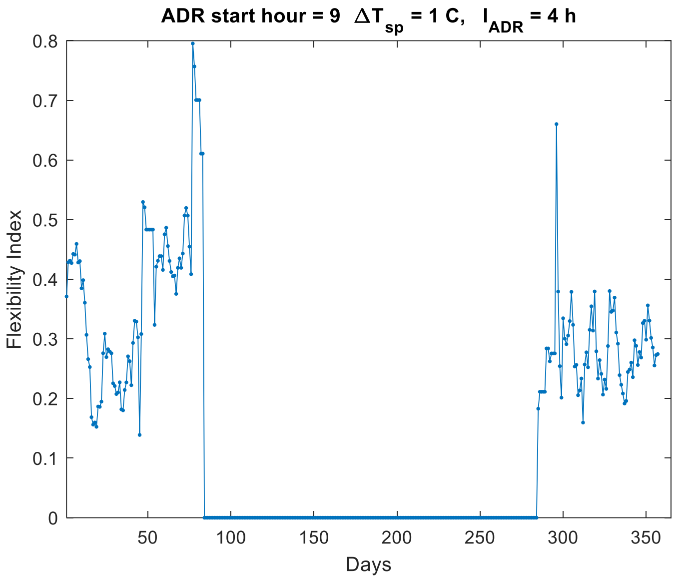

Figure 15: Flexibility index for the optimal upward strategy calculated over successive periods of one week, where the starting day of the week is changed throughout the year.

Upward Flexibility: effect of the occupants' behavior

Previous sections have focused on a single reference scenario, namely SP-20. In this section the effect of occupants' behavior is investigated by considering variations to this reference scenario, while the ADR strategy remains the same. The variations include decreasing the thermal gain from appliances and lighting (SP-20-lowapp), decreasing the temperature of the neighbors (SP-20-lowNtemp) and increasing the mechanical ventilation (SP-20-highvent). For details about the scenarios see chapter 4. All of these variations either increase the thermal losses or reduce the thermal gains. Figure 16 shows the flexibility KPIs, calculated in the heating season, for the optimal ADR strategy where the setpoint is risen by 1°C between 9 a.m. and 1 p.m.

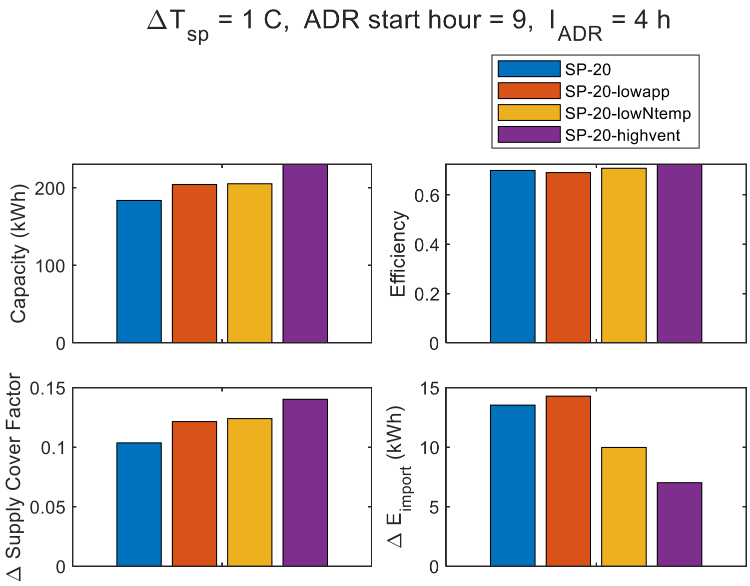

Figure 16: Flexibility KPIs, calculated over the heating season, for the optimal upward strategy and different reference scenarios.

All the variations to the reference scenario lead to higher storage capacities and higher supply cover factors to different degrees. The reason is increasing the thermal losses or decreasing the thermal gains reduces the indoor temperature, thereby increasing the storage capacity in the warmer days in the beginning/end of winter where there is more solar radiation (see Figure 17).

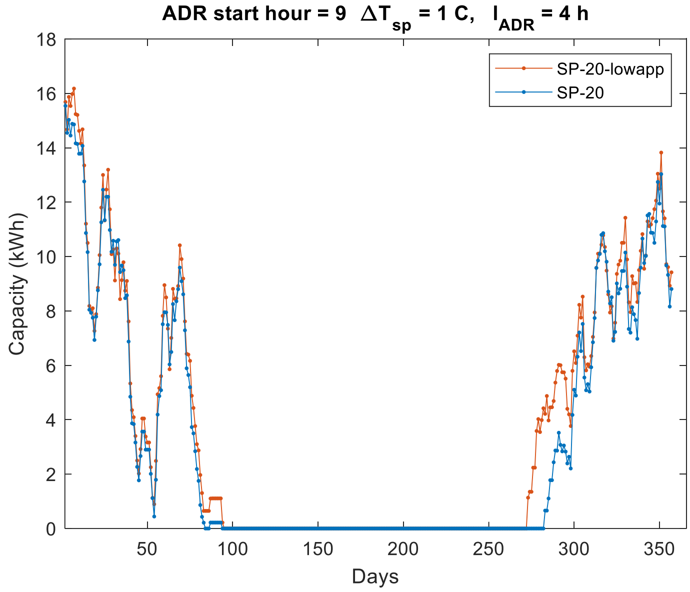

Figure 17: Storage capacity for the optimal upward strategy and two different reference scenarios calculated over successive periods of one week, where the starting day of the week is changed throughout the year.

Although the storage efficiency is not significantly affected, the change is nonmonotonic: compared to the SP-20 scenario, SP-20-lowapp has a lower efficiency, while the other two have higher efficiencies. This can be best understood by introducing the concept of normalized rebound. For a given period, the normalized rebound is defined by dividing the rebound in the period by the total storage capacity for the whole year,

$$E_{\text{rebound, norm}}^{\text{period}} = \frac{E_{\text{rebound}}^{\text{period}}}{C_{ADR}^{tot}}.$$

Figure 18 shows the values of the normalized rebound calculated in every week of the year for the optimal ADR strategy with three different reference scenarios regarding occupants' behavior. In each case, the total storage efficiency over the years can be calculated by summing the normalized rebounds of all weeks. It is clear from Figure 18 that, among the three reference scenarios shown, the normalized rebound for SP-20-highvent is lowest in cold winter periods and highest in warmer periods in the beginning/end of winter. This can be understood by considering that higher thermal losses on one hand lead to lower efficiencies in cold periods, and on the other hand increase the flexibility capacity in warmer periods. Both factors contribute to the total efficiency, and depending on which factor is stronger, increasing the thermal losses can either increase or decrease the efficiency. Accounting for the differences in the capacities, efficiencies and supply cover factors in various reference scenarios, the variations in ΔE_{import} can be explained. In case of SP-20-lowapp, the lower efficiency is responsible for the higher import from the grid. In case of SP-20-lowNtemp and SP-20-highvent, the higher supply cover factors and efficiencies both contribute to a lower import from the grid.

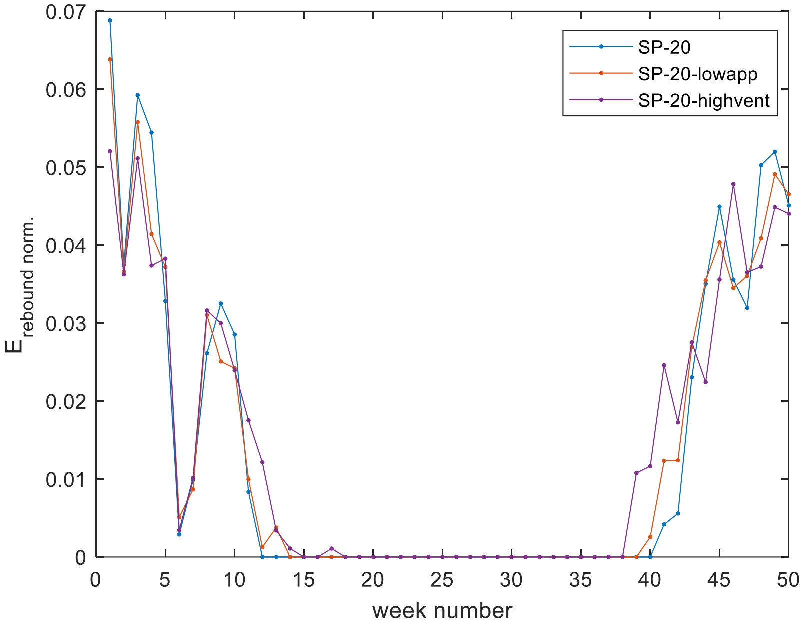

Figure 18: Normalized rebound calculated over each week of the year, for the optimal upward strategy and three different reference scenarios.

Downward flexibility: optimal strategy

The analysis was repeated for downward flexibility where the temperature setpoint is decreased by 1°C either for $l_{ADR} = 4\ h$ or $l_{ADR} = 6\ h$, every day at a specific hour. Figure 19 and Figure 20 show the resulted flexibility KPIs, calculated in the heating season based on the SP-20 reference scenario, where the starting hour of the ADR event changes from 8 p.m. to 6 a.m.

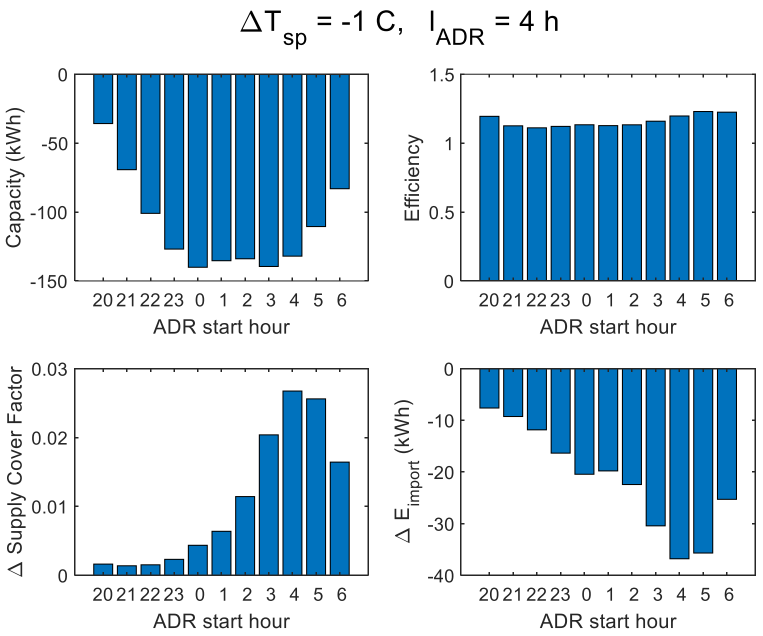

Figure 19: Flexibility KPIs calculated over the heating season, where the heating setpoint is shifted by -1°C for a period of 4 hours, with the ADR starting hour is varied during the evening and night.

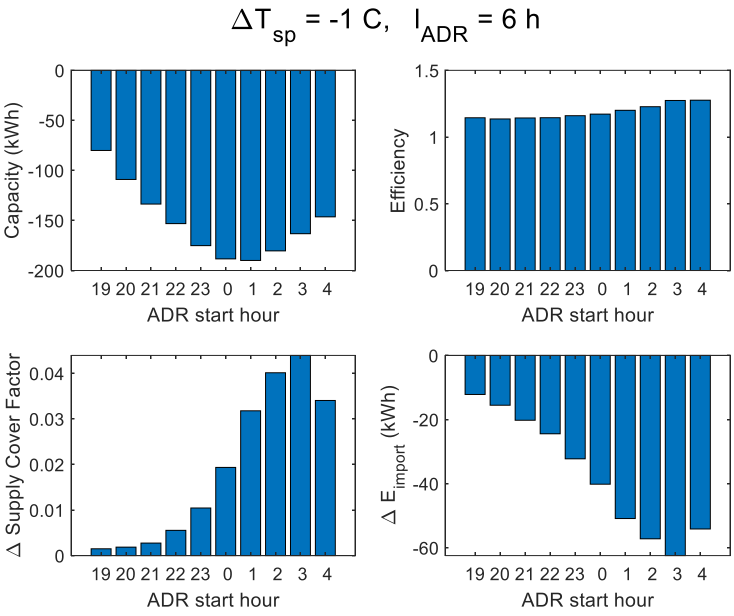

Figure 20: Flexibility KPIs calculated over the heating season, where the heating setpoint is shifted by -1°C for a period of 6 hours, with the ADR starting hour is varied during the evening and night.

As expected, downward flexibility leads to negative storage capacity. The capacity turned out to be lowest in the evening hours and highest around midnight and early morning hours. In SP-20 reference scenario, large thermal gains associated with lighting, combined with a larger people gain in the evening (2 occupants are present in the evening while there is one during the day), increases the room temperature and thus decreases the chance that the heat pump is on during the evening, leading to a low capacity in the evening. The high capacity around midnight indicates higher chance for the heat pump to be operational in these hours, compatible with the fact that these are most likely the coldest hours in a winter day. The efficiency is higher than one (based on the definition in Equation (3)), indicating that lowering the setpoint leads to less thermal losses. For $l_{ADR} = 4\ h$ the difference in the supply cover factor is highest when the ADR starts at 4 a.m. For $l_{ADR} = 6\ h$, the ADR, which increases the supply cover factor the most, starts at 3 a.m. In both cases the rebound effect is pushed to the hours after 8-9 a.m. This is compatible with the results of upward flexibility, which suggest that shifting the heat pump operation to the interval 9 a.m. to 1 p.m. leads to the highest consumption of the generated solar energy. In all strategies ΔE_{import} is negative (e.g. -37 kWh for $l_{ADR} = 4\ h$ starting at 4 a.m. and -63 kWh for $l_{ADR} = 6\ h$ starting at 3 a.m.). This is mainly due to the high storage efficiencies, which reduce the energy consumption of the heat pump (e.g. -26 kWh for $l_{ADR} = 4\ h$ starting at 4 a.m. and -45 kWh for $l_{ADR} = 6\ h$ starting at 3 a.m.), but is also affected by the increase in the amount of solar energy used (e.g. 11 kWh for $l_{ADR} = 4\ h$ starting at 4 a.m. and 18 kWh for $l_{ADR} = 6\ h$ starting at 3 a.m.).

Comparing the downward strategies with the highest increase in the supply cover factor (Figure 21), it turns out that choosing $l_{ADR} = 6\ h$ leads to almost two times larger increase in the supply cover factor, and consequently two times larger decrease in the imported energy, compared to $l_{ADR} = 4\ h$. It can be therefore concluded that, among the downward strategies tested, decreasing the setpoint by 1°C for six hours starting from 3 a.m. is most optimal for promoting the use of the generated solar power. Comparing the optimal downward strategy (Figure 21) with the optimal upward strategy (Figure 11) shows that the upward strategy is better to consume the generated solar energy on site, while the downward strategy is better when the import from the grid is to be reduced.

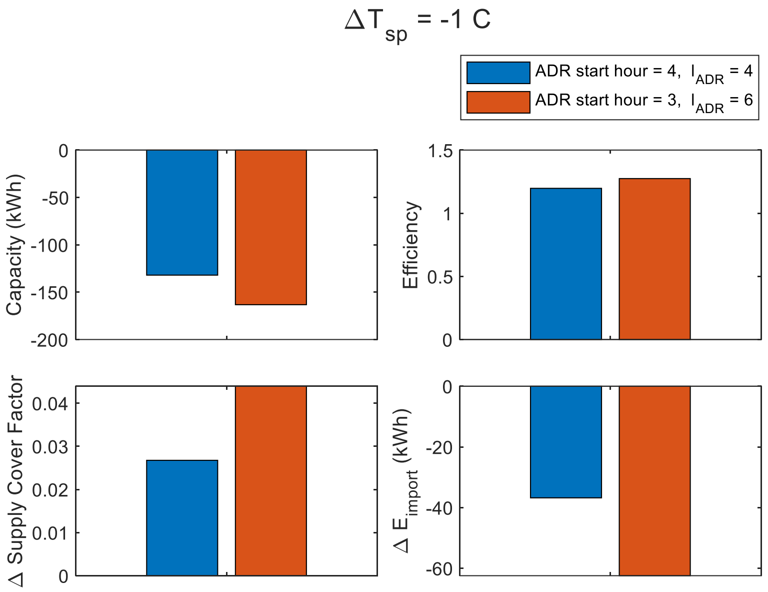

Figure 21: Comparison of the flexibility KPIs for two strategies that result in high supply cover factor when the setpoint is decreased.

Downward flexibility: effect of the external conditions

Figure 22 shows the Flexibility KPIs for the optimal downward strategy calculated over successive periods of one week, where the starting day of the week is changed throughout the year. Similar to the upward flexibility case, significant day-to-day variations are evident. The magnitude of the storage capacity is smaller in warmer periods. The storage efficiency remains higher than 1.0, and approaches 2.0 in the warmer periods with small capacity. The supply cover factor increases by more than 0.1 in the mid-winter periods. ΔE_{import} highly fluctuates but never becomes positive, since the storage efficiency is always greater than 1.0.

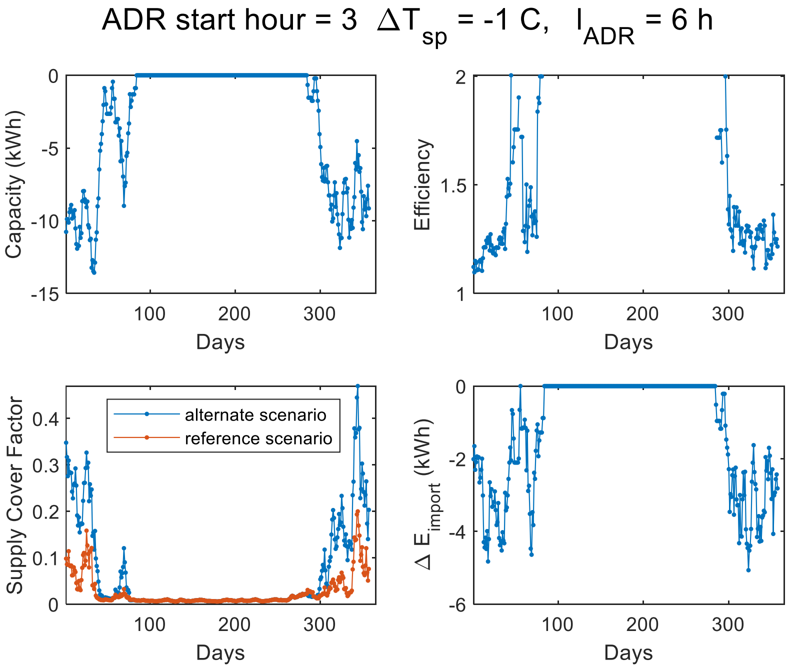

Figure 22: Flexibility KPIs for the optimal downward strategy calculated over successive periods of one week, where the starting day of the week is changed throughout the year.

Figure 23 shows the weekly values of capacity and efficiency for the optimal downward strategy versus the weekly average outdoor temperature (points with capacity magnitudes smaller than 1 kWh are excluded). The magnitude of the storage capacity is smaller at warmer periods. This is due to the fact that if in a certain time interval, the room temperature exceeds the setpoint in the reference scenario, inducing an ADR event in that interval by decreasing the setpoint offers no flexibility. The storage efficiency increases to 2.0 in the warmer periods, indicating that periods with small flexibility capacity produce even a smaller rebound effect. This can be understood considering that, for the optimal downward strategy, the temperature outside the ADR event, i.e. during the day hours, is typically higher than the temperature during the ADR event which covers the night and early morning hours. In the warmer periods, where the potential for downward flexibility is quite limited, it can easily happen that forcing the heat pump to be turned off momentarily by decreasing the setpoint during the ADR effect does not perturb the room temperature enough to produce a significant rebound effect, which leads to an efficiency close to 2.0.

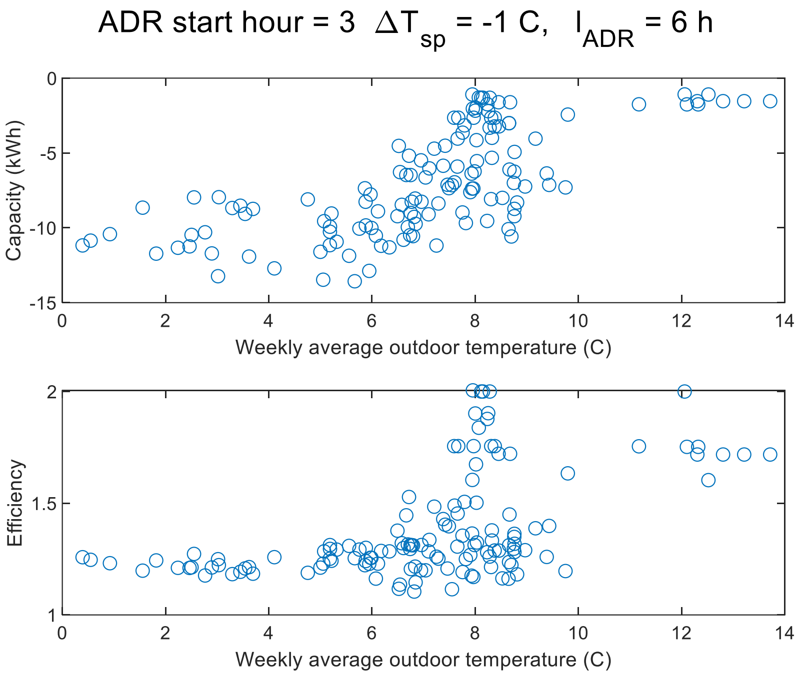

Figure 23: Weekly values of capacity and efficiency vs. the weekly average outdoor temperature (points with capacity magnitudes smaller than 1 kWh are excluded).

Downward flexibility: flexibility index

Figure 24 shows the flexibility index calculated over the successive weeks for the downward optimal strategy (solid curve, blue) with the penalty function shown in Figure 14. The flexibility index for the upward optimal strategy (Figure 15) is also shown for comparison (dashed curve, orange). Also, in the case of the downward strategy, the flexibility index remains positive during the entire heating season. The day-to-day variations of the flexibility index differs from the upward strategy, but their values are often close. When calculated over the heating season, the flexibility index for the downward strategy is 0.29, only 0.02 higher than the upward case.

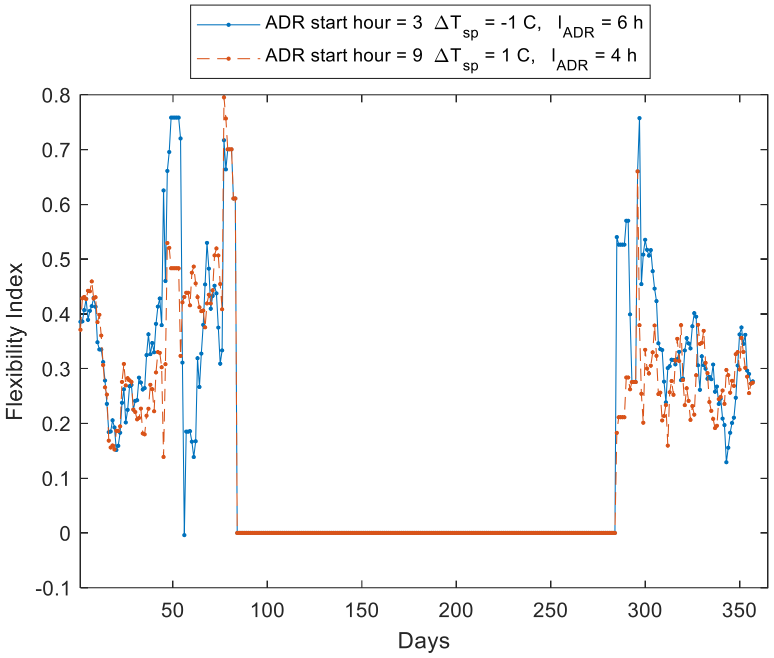

Figure 24: Flexibility index for the optimal downward (solid curve, blue) and upward (dashed curve, orange) strategies calculated over successive periods of one week, where the starting day of the week is changed throughout the year.

Downward Flexibility: effect of the occupants' behavior

Figure 25 shows the flexibility KPIs calculated in the heating season for the optimal downward strategy and 4 different reference scenarios regarding occupants' behavior (see chapter 4). Increasing the thermal losses or decreasing the thermal gains extends the heat pump operation to warmer periods with more solar radiation, and therefore increase both the storage capacity and the supply cover factor. It is therefore expected that both KPIs follow the same trend. The storage efficiency remains almost unaffected. The import from the grid shows a decreasing trend, consistent with the increase in the supply cover factor.

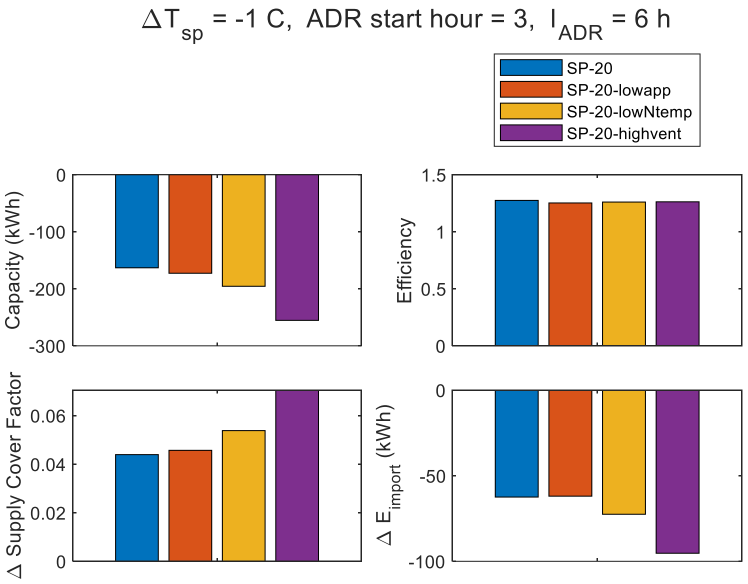

Figure 25: Flexibility KPIs, calculated over the heating season, for the optimal downward strategy and different reference scenarios.

Results scenarios for shifting heating setpoint for domestic hot water

To investigate the flexibility potential of the DHW tank, a reference scenario was considered where the tank operates in comfort mode with the setpoint at 62°C. In this case continuous availability of warm water is ensured. Since the tank has a limited thermal mass, and the heat pump has to operate for at least 20 minutes before it turns off, any operation of the heat pump heats up the water to a couple of degree above the set point. This offers a very limited potential for upward flexibility, as the maximum value for the set point is 65°C. Therefore, this chapter focuses on downward flexibility. To assess the maximum flexibility potential, the setpoint is decreased substantially during the ADR event to prevent any operation of the heat pump during the event. The tappings that occur during the ADR event drain the thermal energy stored in the hot water, thereby creating capacity for flexibility. As soon as the ADR event ends, the heat pump turns on to get the water temperature to 62°C, see Figure 26.

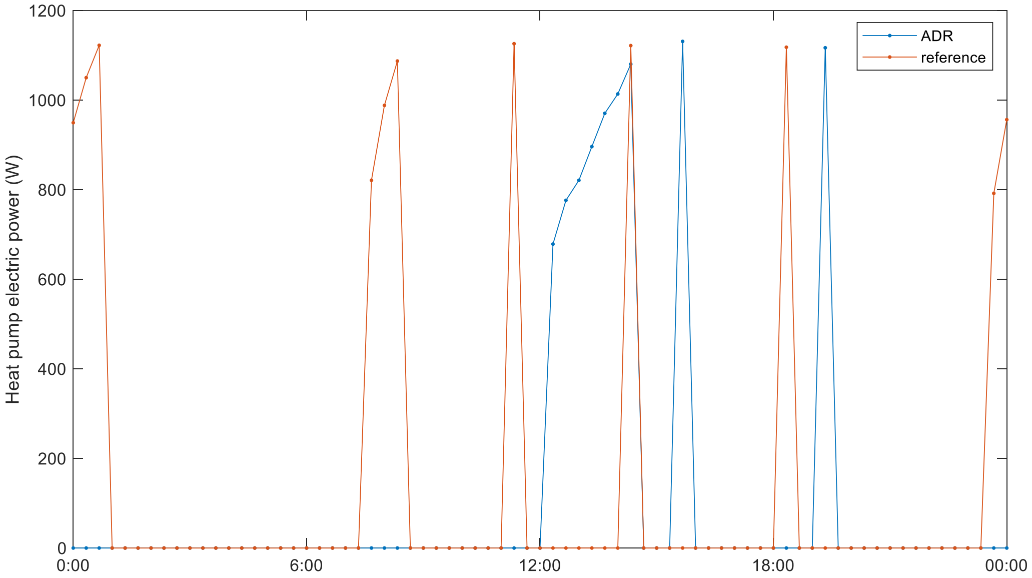

Figure 26: An example of an ADR event (blue), which starts at 22:00 and ends at 12. During the ADR the operation of the heat pump is prevented. In the reference scenario (orange) the heat pump operates in the comfort mode with the setpoint of 62°C (the time interval between the successive points is 20 minutes).

The flexibility potential of the DHW tank depends on the demand for the domestic hot water. Two typical profiles were considered according to NTA 8800 (see Section 6), indicating the DHW demand at 40°C during the day in intervals of 20 minutes, see Figure 27. CW4 has two major peaks in the morning and late in the evening. CW1 has a lower daily demand, as it has a lower peak in the evening and misses the morning peak. The analysis mainly focuses on CW4 profile, as it offers more flexibility potential. In the end of this chapter a comparison with CW1 is made.

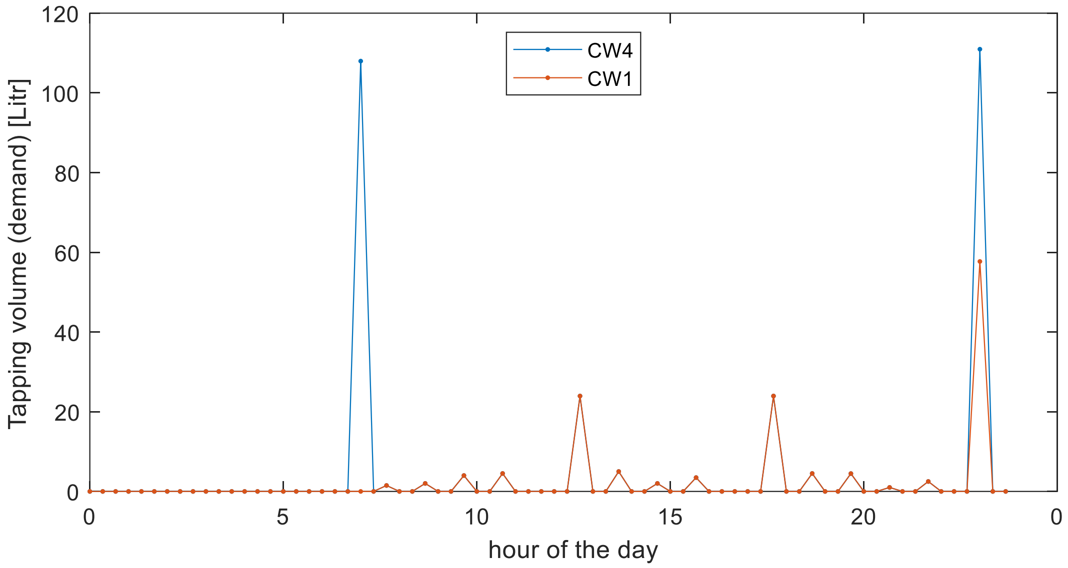

Figure 27: Two profiles for the DHW demand at 40°C (the time interval between the successive points is 20 minutes).

Downward flexibility: optimal strategies

Figure 28 and Figure 29 show the flexibility KPIs calculated for the CW4 profile during the heating season (October to April) and outside the heating season, respectively, with different ADR strategies. All the strategies start at 22.00, before the start of the evening peak in DHW demand (Figure 27). The duration of the ADR events varies between 11 and 17 hours. As expected, the storage capacity is negative and increases with increasing the ADR duration. The storage efficiency is higher than one based on the definition in Equation (3), reflecting lower thermal losses as well as a higher heat pump efficiency associated with lowering the water temperature. The optimal ADR strategy with the highest increase in the supply cover factor, and lowest import from the grid, starts at 22.00 and ends at 11.00 ($l_{ADR} = 13\ h$), although the strategy with $l_{ADR} = 12\ h$ has quite comparable KPI values.

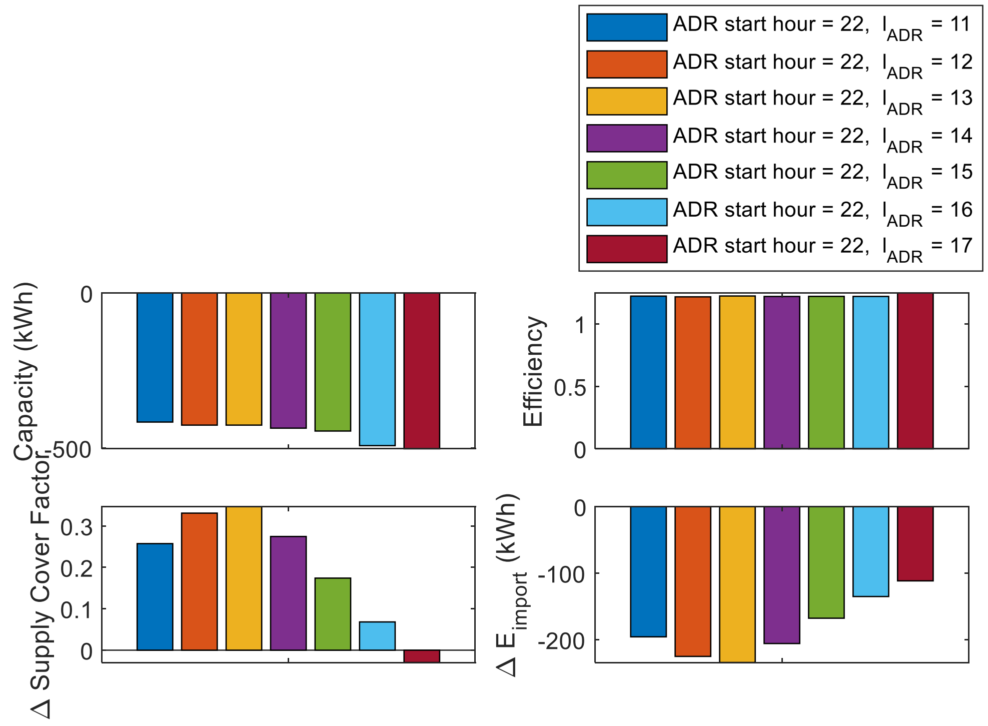

Figure 28: Flexibility KPIs calculated over the heating season for the CW4 profile and different ADR strategies. During the ADR events the heat pump operation is prevented.

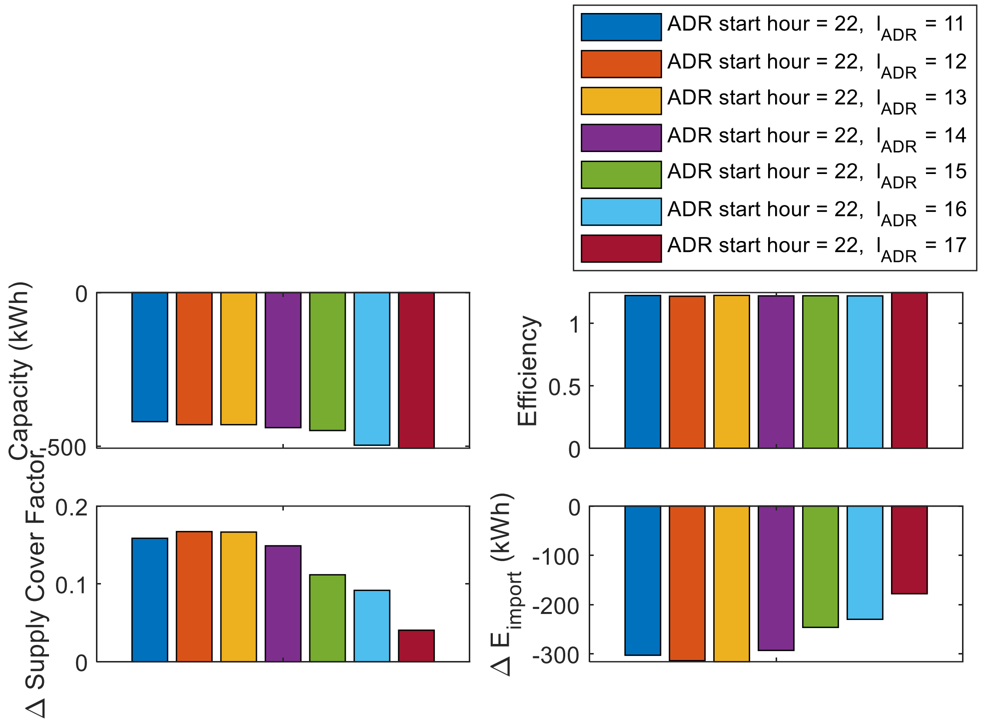

Figure 29: Flexibility KPIs calculated outside the heating season for the CW4 profile and different ADR strategies. During the ADR events the heat pump operation is prevented.

As a validation that the comfort level of the occupants is not violated, Figure 30 shows the DWH supply temperature (taken from the top of the tank) for the CW4 profile during a typical week when the optimal ADR strategy is adopted on daily basis. It can be seen that the minimal temperature reached at the end of the ADR event is above 42°C. Once the ADR event is over, the heat pump can switch on again, triggered by a temperature sensor in the vessel. In about 1.5 hours the complete vessel is again heated to 65°C**.** Therefore at each day the supply temperature decreases to 42°C before the heat pump is turned on at the end of the ADR event. This is close to the highest acceptable tolerance for the supply temperature. A more restricted tolerance can decrease the flexibility potential.

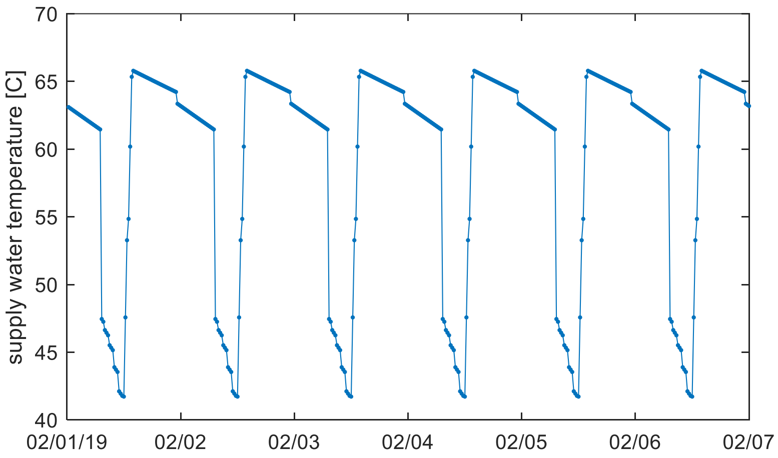

Figure 30: temporal variation of the DHW supply temperature in a typical week with CW4 profile.

Comparing Figure 28 with Figure 16 and Figure 25 shows that, with the CW4 profile, the optimal ADR strategy for DHW leads to a higher increase in the supply cover factor (and consequently higher decrease in the imported electricity) compared to the optimal strategies for space heating under all reference scenarios.

Downward flexibility: effect of the external conditions

Figure 31 shows the flexibility KPIs for the optimal downward strategy with the CW4 profile, calculated over successive periods of one week, where the starting day of the week is changed throughout the year (as similarly done in Figure 12Figure 22) . The storage capacity and efficiency show no variations. The supply cover factor is increased in all weeks and the imported electricity from the grid is always negative. In the summer period the increase in the supply cover factor is less, and the decrease in the imported energy is higher. Both these effects can be explained by the fact that more solar energy is generated during the summer than during the winter. Therefore, the import from the grid is reduced more in the summer because more solar energy is used, and the supply cover factor is also reduced because the generated solar energy is much larger than the amount used by the tank.

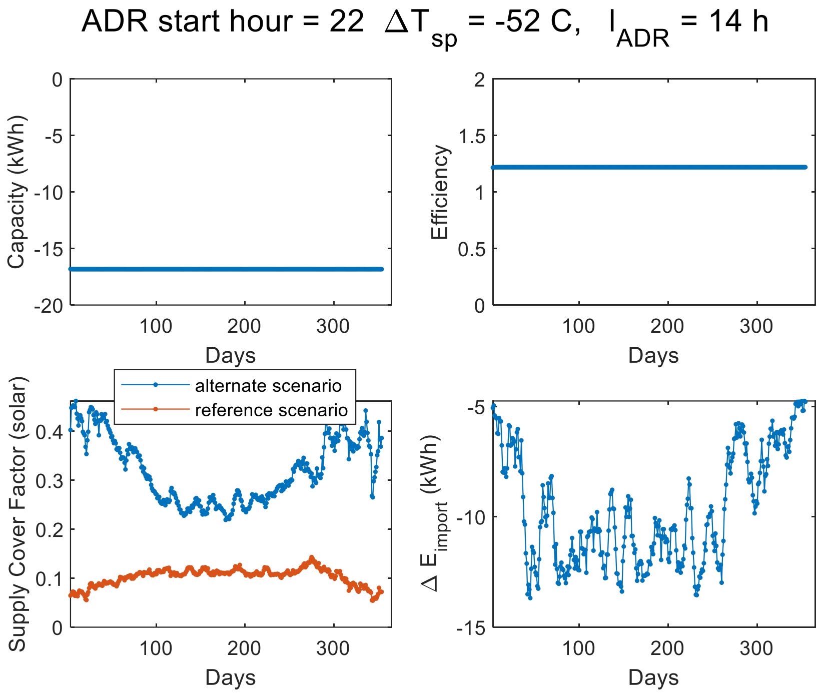

Figure 31: flexibility KPIs for the optimal downward strategy with the CW4 profile, calculated over successive periods of one week, where the starting day of the week is changed throughout the year.

Downward flexibility: effect of occupants' behavior (CW4 vs CW1)

Repeating the analysis for the CW1 profile leads to the same optimal ADR strategy. However, the provided flexibility is significantly decreased compared to the CW4 profile, as judged by all KPIs (Figure 32 and Figure 33). This is due to the lower evening peak as well as the absence of the morning peak in CW1 profile (Figure 27). In particular the storage efficiency is lower for CW1 as the water temperature reduces less during the ADR event. Compared to the optimal downward strategy for space heating (Figure 21), the CW1 profile leads to a similar decrease in the imported energy from the grid during the heating season.

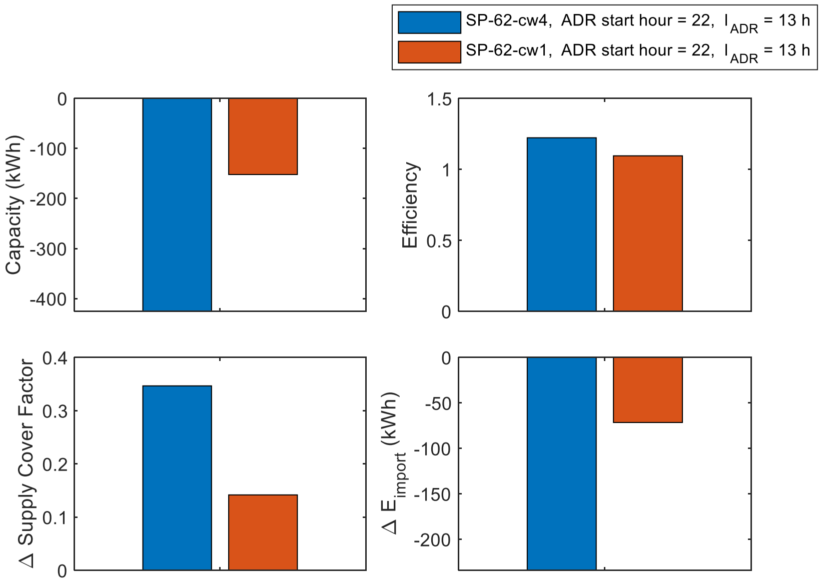

Figure 32: Flexibility KPIs over the heating season for CW1 profile (orange) compared to the CW4 profile (blue).

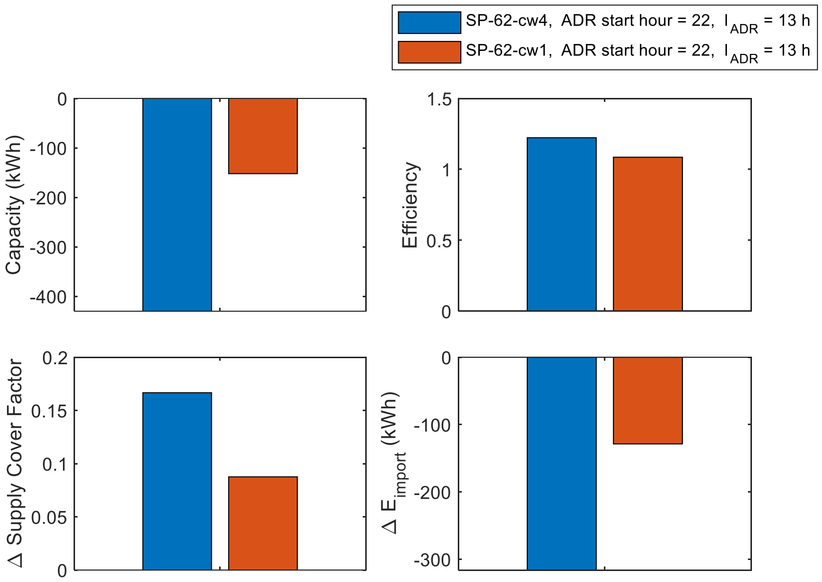

Figure 33: Flexibility KPIs outside the heating season for CW1 profile (orange) compared to the CW4 profile (blue).

Figure 34 and Figure 35 show the temporal variations of the control temperature (measured at 30 cm from the bottom of the tank) (top) and the heat pump operation (bottom) for the optimal ADR strategy, compared to the reference scenario, using CW1 and CW4 tapping profiles respectively. It can be seen that in both cases the operation of the heat pump is shifted to the hours around 12.00. However, for CW1 the control temperature decreases to 40°C at the end of the ADR event, while for CW4 the temperature can get as low as 14°C. This can explain the results shown in Figure 33, as the ADR strategy leads to a longer operation of the heat pump for the CW4 profile, resulting in a higher capacity and more increase in the supply cover factor compared to CW1. It should be noted that although the control temperature near the bottom of the tank can be as low as 14°C for the CW4 profile, the supplied DHW temperature, taken from the top of the tank, is still above 40°C which is within the comfort band (see Figure 30).

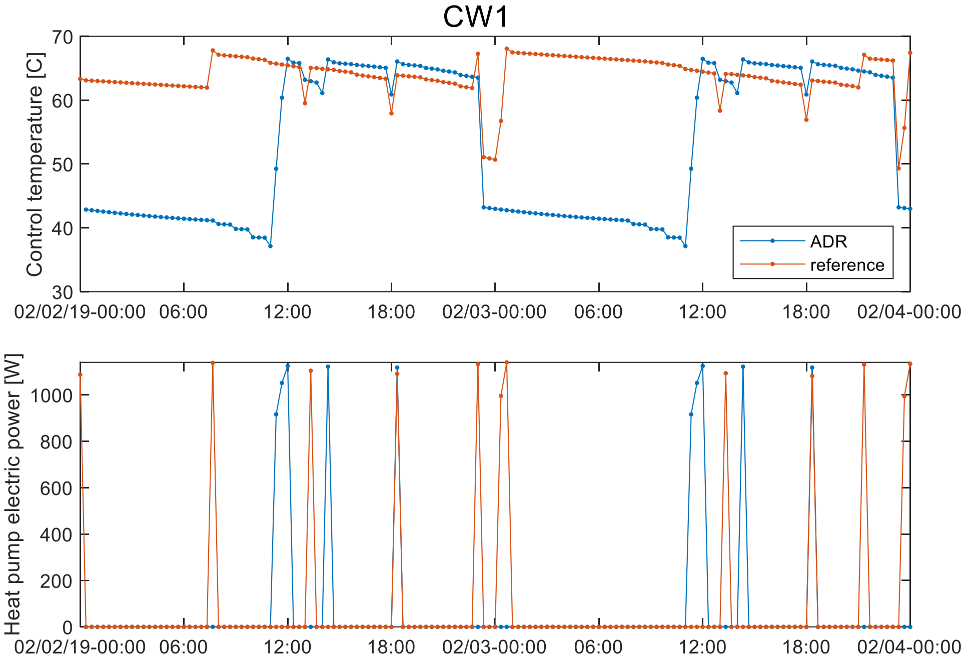

Figure 34: The temporal variations of the control temperature – measured at 30 cm from the bottom of the tank – (top) and the heat pump operation (bottom) for the optimal ADR strategy (blue), compared to the reference scenario (orange), using the CW1 profile.

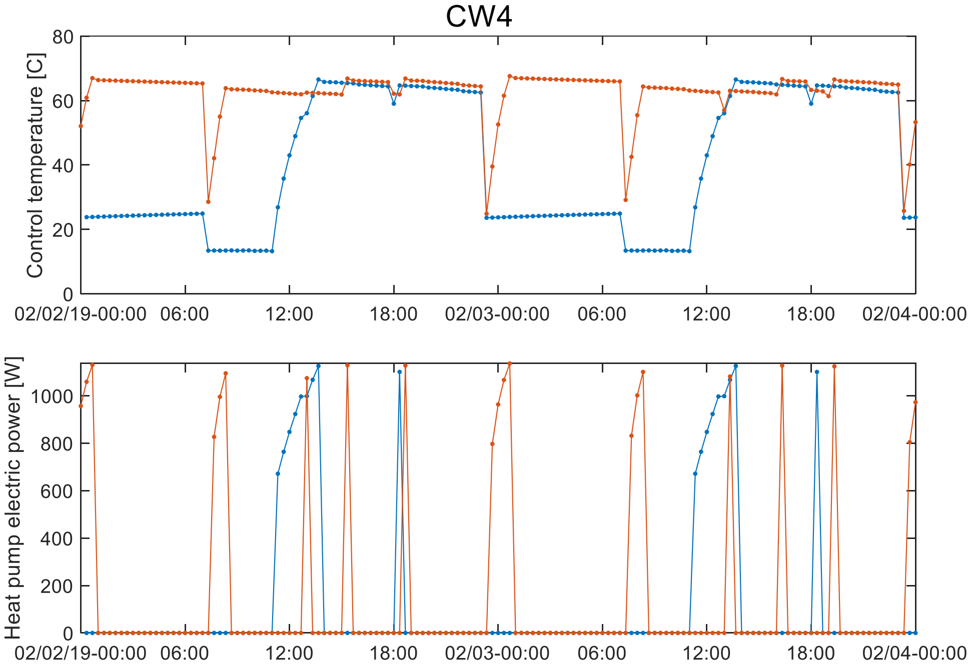

Figure 35: The temporal variations of the control temperature – measured at 30 cm from the bottom of the tank – (top) and the heat pump operation (bottom) for the optimal ADR strategy (blue), compared to the reference scenario (orange), using the CW4 profile.

Comparison of the flexibility potential of space heating with the flexibility potential of domestic hot water production

Figure 36 and Figure 37 show the yearly extra solar energy used and the yearly extra energy imported from the grid respectively, for all the optimal ADR strategies and boundary conditions analysed in this chapter. Various scenarios for space heating lead either to a small reduction of the imported energy (60-100 kWh) in the case of downward flexibility, or an increase up to 10kWh in the case of upwards flexibility, and a small increase of the utilisation of solar energy (15-50 kWh). Furthermore, the saving on imported energy in case of downward flexibility is for the larger part due to the decrease in heating demand as a result of the lower average indoor air temperature (45-70 kWh, data not shown). On the other hand, the DHW production offers a high flexibility potential. A significant increase in the solar energy self-usage (~170 kWh per year for the CW1 tapping profile and ~360 kWh per year for the CW4 tapping profile) is evident, which is primarily responsible for the reduction in the imported electricity from the grid (~200 kWh per year for the CW1 tapping profile and ~550 kWh per year for the CW4 tapping profile). It is clear that, in the case of the Dutch demo and on a yearly basis, production of domestic hot water has a significantly higher potential for usage of the generated solar energy and the reduction of the import from the grid than the space heating.

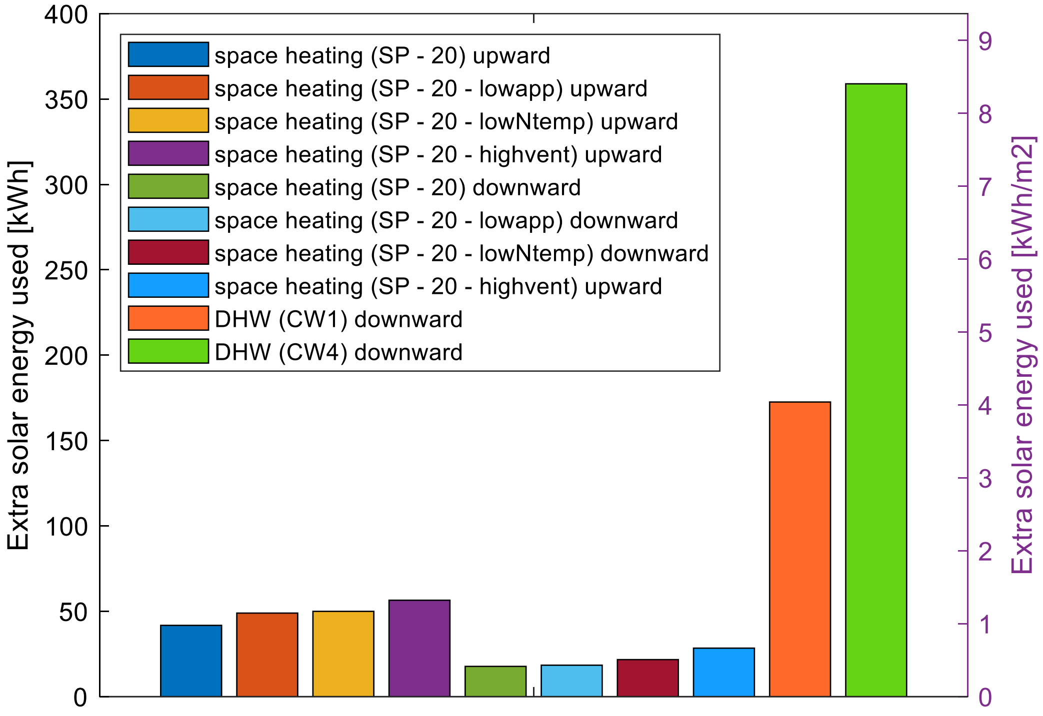

Figure 36: The yearly extra solar energy used for optimal ADR strategies for space heating and DHW production with different boundary conditions.

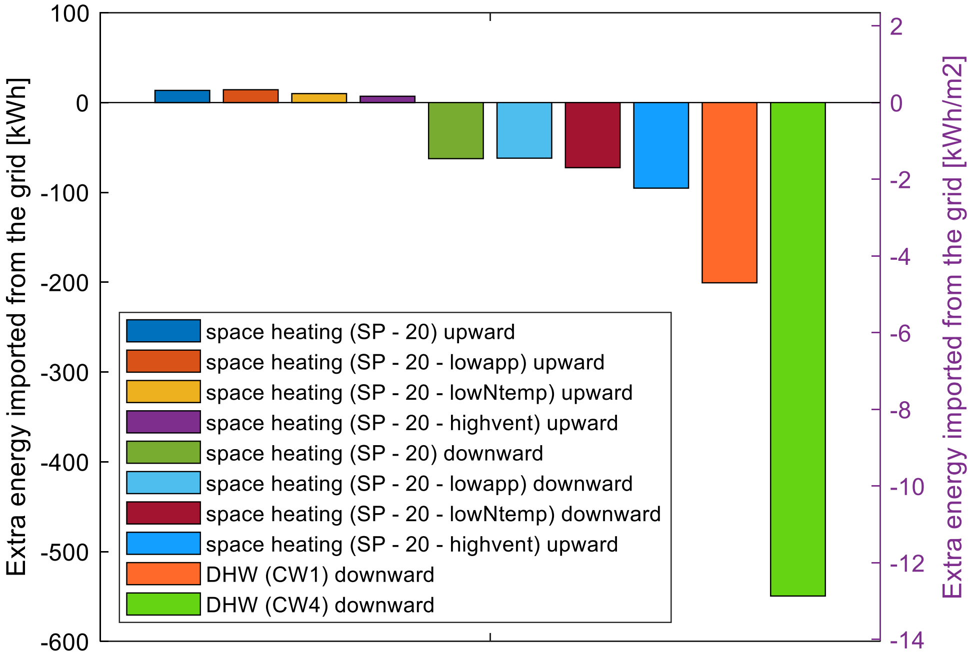

Figure 37: The yearly extra energy imported from the grid for optimal ADR strategies for space heating and DHW production with different boundary conditions.

8. Simulation results Spanish demo case

To assess the flexibility potential of the components in the Spanish demo, dynamic simulations with a simulation time stamp of 3 minutes to account for short-terms variations (e.g. short DHW tapping operations) are performed with TRNSYS.

Results scenarios for shifting Heating and DHW demand through a simplified solar penalty signal

Four scenarios are here compared: 2 of them have household control strategies (SHM1 and SHM2), and 2 the building level strategies (SBM1 and SBM2). The additional modulations M3 (SHM3, SBM3) and M4 (SHM4, SBM4) are being analyzed in further discussion. Modulations M1 and M2 introduce both up- and downwards flexibility, while M3 and M4 represent the case of a user who doesn't accept downward flexibility and therefore only upward flexibility is considered. In M1 and M3 the set-points are being varied in smaller amplitude and in M2 and M4 in greater amplitude. Household level modulations affect only heating demand as the room thermostat setpoints are being varied. Building level modulations keep all the room set-points on a standard level and the flexibility potential is reached while varying the set-points of tanks and heat pumps.

The flexibility potential is mainly analyzed through two indicators: flexibility index (indicating the flexibility potential in comparison to the base case), and efficiency of rebound energy (indicating the effect on increased/decreased energy consumption of the flexible case, in respect to the base case). Figure 38 represents the flexibility indexes of the four flexibility scenarios. The data is represented as 365 values, where the flexibility index of each day represents the ratio of accumulated penalties (of base case and flexible one) of 1 week. The energy consumption represented in all the figures is the heat pump electrical consumption.

When analyzing the flexibility indexes and rebound efficiencies, it has to be kept in mind that those values are relative, depending on the base case value. Therefore, the numerical value of flexibility index of summer is not comparable with the same value of winter, as the energy consumption is not the same. For example, if the flexibility index is 0.2 during winter, and also 0.2 during summer, but during winter the demand is 2 times higher than in the summer, it expresses that in both cases the flexible case accumulated penalties are of 80% of the base case ones, yet by the quantity, the reduction in accumulated penalties in the summer was twice less than in the winter. The same goes for rebound efficiency.

In household level scenarios the flexibility index is 0 during summer, as the control strategies of household level affect only heating demand (Figure 38 : 2 upper graphs). The differences between SHM1 and SHM2 modulation are that in the first scenario the household set-points are increased/decreased 1°C, while the SHM2 scenarios' 2°C. As observed from the figures, and as expected, greater amplitude in set-points allows to reach higher flexibility potential (the FI of SHM2 is higher than the one of SHM1).

On the same time, the control strategies of building level modulations are applied all through the year, which is why there is flexibility potential also during the summer (Figure 38 : 2 lower graphs). The difference between those 2 scenarios is that the first building level scenario (SBM1) forces bigger amplitude in set-points of heating/DHW tank, hence forcing the heat pump set-point to be lower during the penalty period. On the same time the second building level scenario (SBM2) introduces changes only in the tank controller dead-bands, resulting in smaller amplitude of set-points on penalty and non-penalty periods. Therefore, as expressed in Figure 38, the building scenario with greater amplitude in tank (and heat pump) setpoints (SBM1) is more flexible than the second building level one (SBM2), as the flexibility in index is lower.

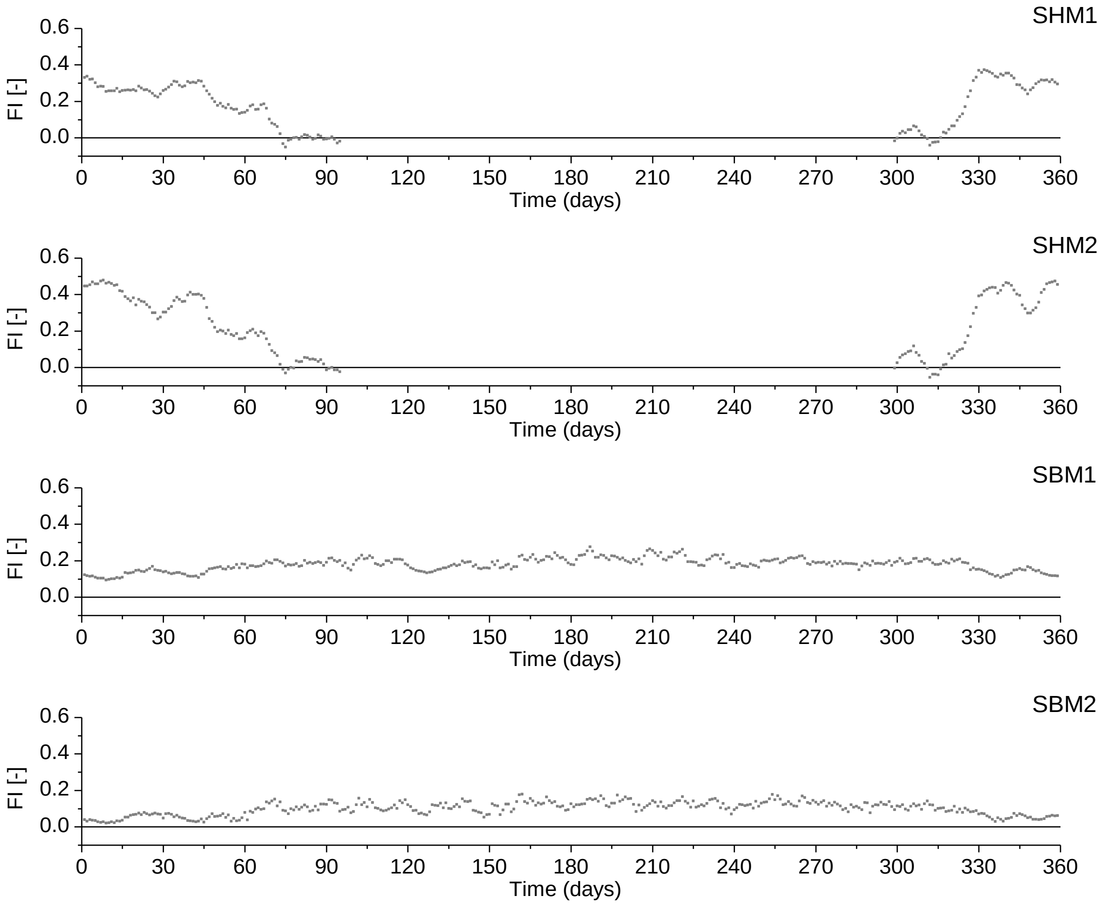

Figure 38: Weekly Flexibility Index (FI) for shifting Heating and DHW through a simplified solar penalty signal. SHM1: Modulation 1 at household level. SHM2: Modulation 2 at household level. SBM1: Modulation 1 at building level. SBM2: Modulation 2 at building level.

Rebound efficiency is the second indicator that describes the flexibility potential, being a complementary indicator for flexibility index. Flexibility index is indication only about the flexibility potential, while the rebound efficiency is giving an understanding of which is the difference in energy consumption for the reached flexibility. The rebound efficiency has both negative and positive values, being positive when the energy consumption of the flexible case is smaller than the base case one, and negative if opposite. The household level modulations (Figure 39: 2 upper graphs) indicate a clear tendency that during the colder winter months the rebound efficiency is positive (energy consumption of flexible case is lower than base case), as the flexibility control strategy tends to degrade thermal comfort for some hours due downwards flexibility although within an acceptable range for the users. During intermediate (spring/autumn) periods, when little heating is needed, yet the household set-points are still being modulated, the rebound efficiency is negative, and flexible case energy consumption is higher than the base case one. Second household level scenario (SHM2) observes greater amplitude in rebound efficiency than the first one (SHM1), due to the greater amplitude in set-points. The building level modulations both provide rebound efficiency values close to 0 all through the year, indicating similar energy consumption of flexible case and base case (SBM1 staying slightly positive: flexible case consumption lower than base case, and SBM2 slightly negative: flexible case consumption higher than base case). As the building level second modulation (SBM2) is giving the lowest flexibility indexes and on the same time consuming more energy than the base case, this strategy should be neglected. On the same time household level second modulation provides the highest flexibility indexes (in the winter months) and on the same time consumes less energy than the base case.

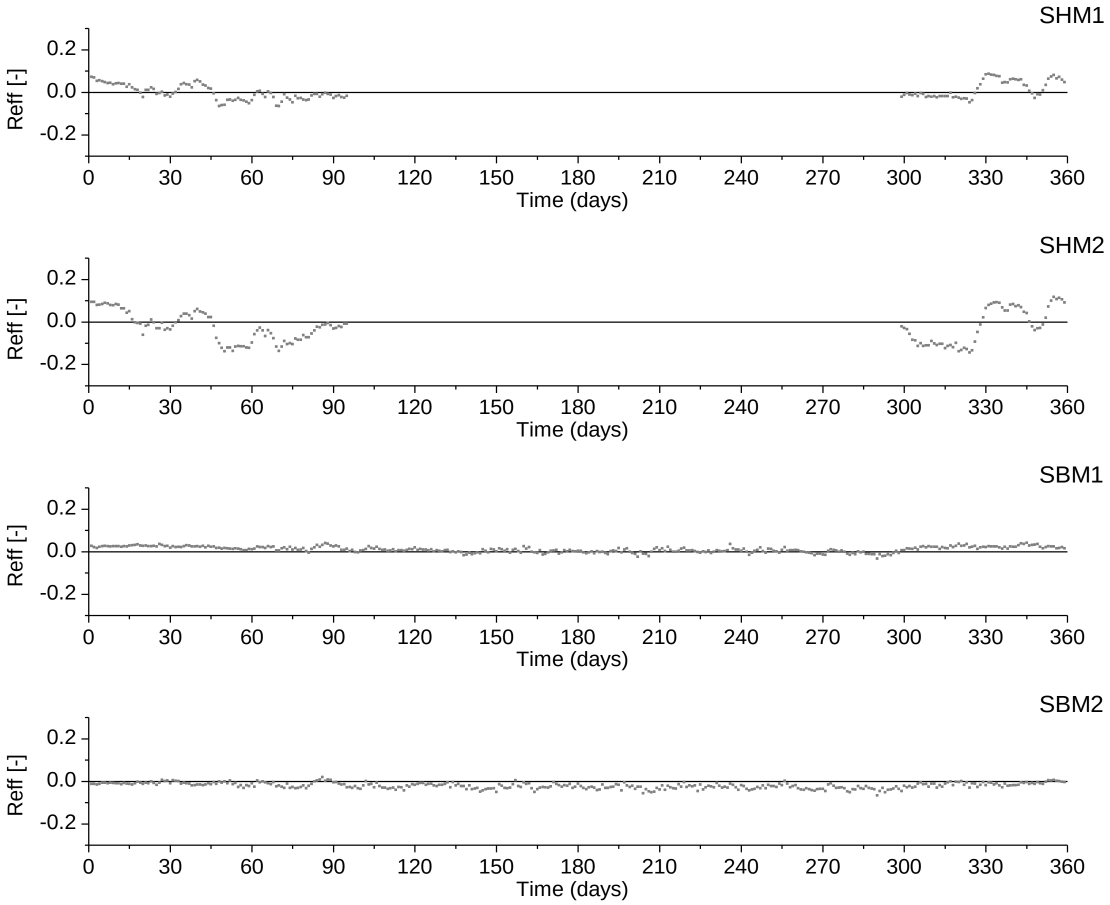

Figure 39: Weekly Efficiency of the Rebound energy (Reff) for shifting Heating and DHW through a simplified solar penalty signal. SHM1: Modulation 1 at household level. SHM2: Modulation 2 at household level. SBM1: Modulation 1 at building level. SBM2: Modulation 2 at building level.

The Figure 40 represents the relation between flexibility index and rebound efficiency, while providing ambient temperature on the color scale. In the household level scenarios (Figure 40: upper graphs), as the control strategy affected heating system, there is a clear tendency between the ambient temperature and flexibility potential. It can be observed that the colder the temperature, the higher the flexibility index, and on the same time the rebound efficiency is the biggest due to the decrease in set-points during the night (flexible case has much lower energy consumption than base case). The tendency becomes even clearer when the control strategy allows greater amplitude in heating household set-points (SHM2), reaching the highest flexibility indexes. The Figure 40 introduces also the modulation 3 and 4 scenarios, whose control strategy allowed only upward flexibility (meaning that during the non-solar hours the set-points are kept the same as base case, not being lowered). Having the control strategy that only increases the consumption during solar hours, it can be observed that the rebound efficiency stays negative in almost during all the year of all the modulation M3 and M4 scenarios (SHM3, SHM4).

On the same time, as the building level modulations result in lower flexibility potential and the energy consumption of base case and the flexible ones (SBM1 and SBM2) is rather the same: Reff=0, the temperature-tendency is not that observable. The higher is the ambient temperature, the higher the flexibility index, yet the rebound efficiency stays rather uninfluenced. The M3 and M4 (only upward flexibility) of building level provides generally lower flexibility indexes than the M1 and M2 (both upward and downward flexibility), as the non-solar period does not allow reduction in energy consumption in M3 and M4. This is also why the rebound efficiency of M3 and M4 is more negative (flexible case has more energy consumption than base case) than the M1 and M2.

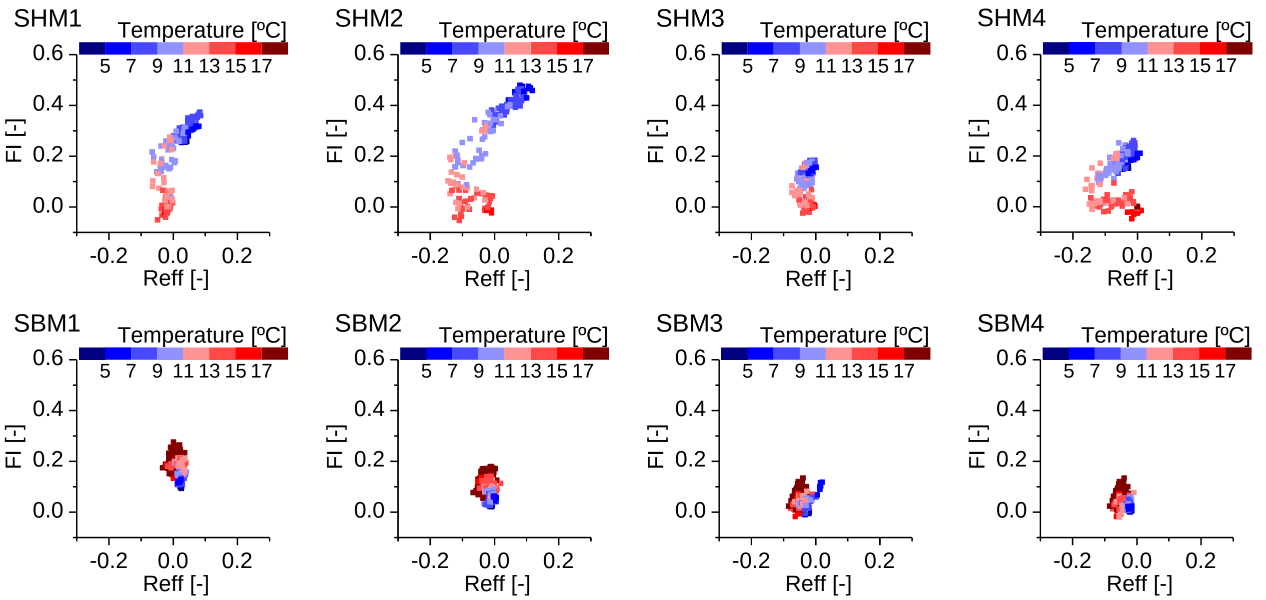

Figure 40: Relation between Flexibility Index (FI) and Efficiency of the Rebound energy (Reff) for shifting Heating and DHW through a simplified solar penalty signal. Colormap represents the ambient temperature. SHM1: Modulation 1 at household level. SHM2: Modulation 2 at household level. SHM3: Modulation 3 at household level. SHM4: Modulation 4 at household level. SBM1: Modulation 1 at building level. SBM2: Modulation 2 at building level. SBM3: Modulation 3 at building level. SBM4: Modulation 4 at building level.

The seasonal behavior of the flexibility scenarios is presented in Figure 41 as typical winter week, intermediate week and summer week profile. It is 15 minutes aggregated heat pump electrical consumption (kWh) profile of a day (daily average profile of a week), where the base case is presented with the bold black line, household scenarios with red and building scenarios with blue, and on the right axes is the solar penalty signal. In all three weeks (Figure 41) the effect of the set-point variation is observed right after the penalty signal drops from 1 to 0 at 10:00: the energy usage peaks, which is more evident at building level. In the winter profile and household scenarios (SHM1 and SHM2) it can be clearly stated that during the penalty period the energy consumption is strongly reduced (between 7:00 and 10:00), and once the penalty signal drops, the energy usage rises higher than the previous base case level. The intermediate and summer weeks provide smaller shifting in energy as the overall energy demand is much lower than during winter. It has to be stated that in the summer week only the building level scenarios' demand is shifted (blue), as the household level strategies are not affecting this week (shifting on DHW, not on heating).

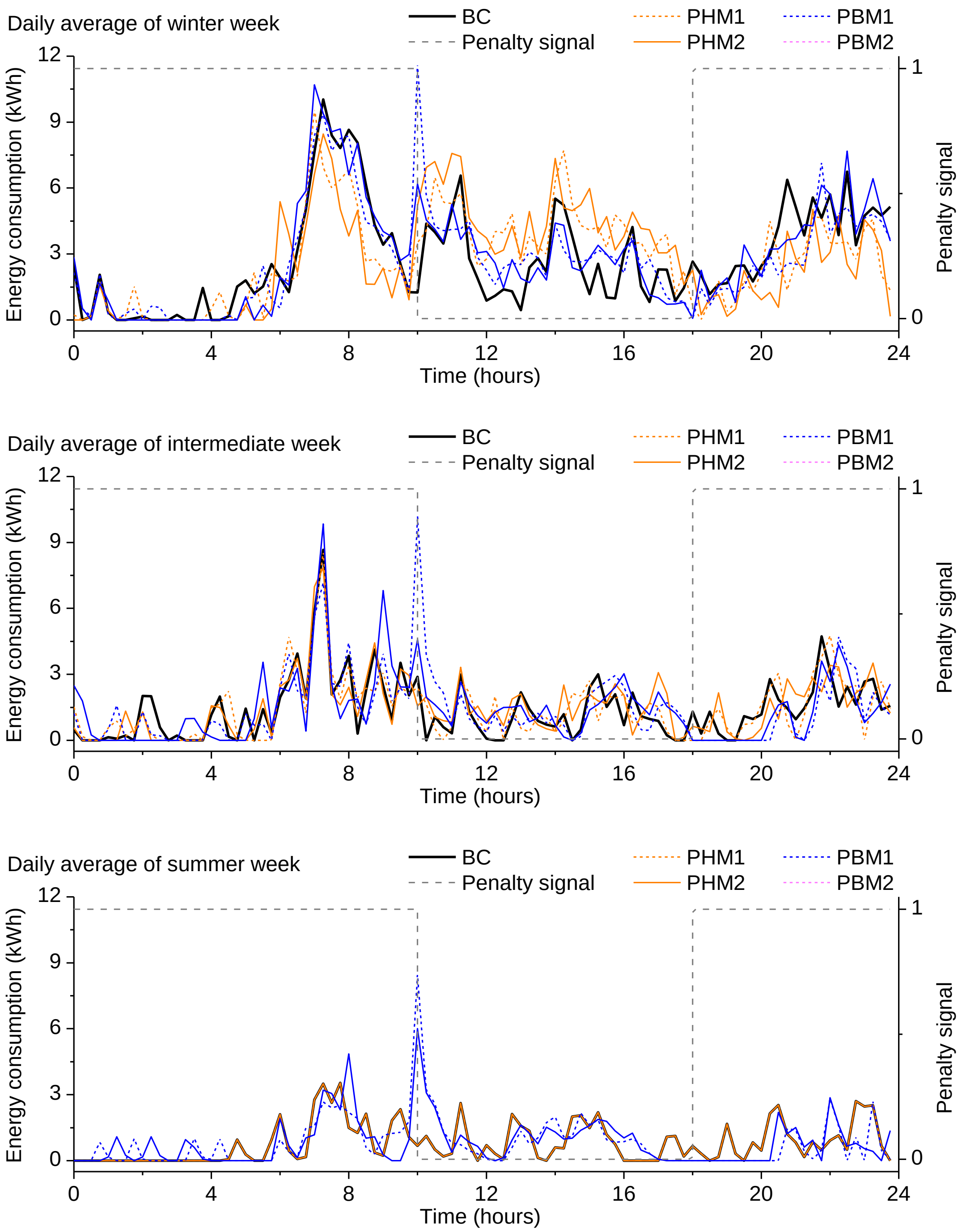

Figure 41: Energy consumption daily profile of a typical week in winter, intermediate and summer season for the base case (BC) and the flexibility strategies for shifting Heating and DHW through a simplified solar penalty signal. SHM1: Modulation 1 at household level. SHM2: Modulation 2 at household level. SBM1: Modulation 1 at building level. SBM2: Modulation 2 at building level.

As expected and presented in Table 3, the solar penalty signal scenarios result in higher supply cover factors (for example the winter supply cover factor of the base case is 0.47 and the solar scenarios vary between 0.57 and 0.67). One objective of the flexibility strategies is to observe a decrease in accumulated penalties while not increasing the energy consumption excessively. For example, when looking at the household level M1 (SHM1), in winter week the accumulated penalties have been reduced from 946.9 penalty units to 678.7 penalty units, and on the same time the total energy consumption (HP electrical consumption) has also been reduced from 270.83 to 266.23 kWh. In this case it could be stated that the flexibility index 0.28 is obtained solely due to the efficient control strategies that did not cause increase in energy consumption (comfort and discomfort are discussed in the next paragraph). On the same time, household modulation M4 observes also reduction in accumulated penalties (from 946.9 to 770.3 penalty units), yet the consumption is increased (from 270.83 to 283.39 kWh). The flexibility index is this case is 0.19, yet when comparing those 2 scenarios, it has to be kept in mind that to reach flexibility index 0.19 in SHM3 case energy consumption is increased, while SHM1 managed to reduce it.

Among other values of typical weeks, Table 3 presents the comfort indicators as percentage outside of comfort range (POR) of IEQ2 of adaptive comfort model. Mean POR represents the mean POR of all the zones of this specific typical week (whether winter, summer or intermediate week). The reason of presenting the comfort indicators, is to see how the flexibility strategies affect the user comfort. The thermal comfort of household level modulations is affected, and it results in greater percentage outside of comfort range (IEQ2) than the base case (for example in winter week base case the mean POR is 0.8%, while the household modulations reach to 1.4%) and the discomfort is mainly due to temperatures outside the upper range. This is caused by the downwards and upwards flexibility control strategy, which allows to lower and increase the set-points (1 and 2 degrees from the standard, respectively). On the same time, in building level modulations, the household thermostat set-points are kept on the standard level, and the flexibility potential is provided through the set-point changes of the tanks and heat-pumps. As the household set-point are kept the same, the comfort indicator (percentage outside of comfort range: POR of IEQ2), as expected, has similar values to the base case (Table 3). The base case average POR in the winter is 0.8% and the building level scenarios vary between 0.8% and 0.9%.

Comparing SHM1 and SHM2 (assuming that the users are willing to lower and increase the set-points during penalty period) with SHM3 and SHM4 (which represents the case of users who are not willing to accept reduction in thermal comfort due to lowering the set-point) is possible to observe that both strategies are able to guarantee high levels of comfort for the users, being the POR lower than 1.4% in average. The modulations M3 and M4 provides slightly higher values of POR (see Table 3) due to some specific zones in the attic floor that experienced overheating, but in general, the discomfort due to lower temperature is negligible.

Regarding comfort in the DHW production, it shall be noted that through all the flexibility scenarios the DHW load is fully covered.

Table 3: Key Performance Indicators of a typical week in winter, summer and intermediate season for the base case (BC) and the flexibility strategies for shifting Heating and DHW through a simplified solar penalty signal. SHM1: Modulation 1 at household level. SHM2: Modulation 2 at household level. SHM3: Modulation 3 at household level. SHM4: Modulation 4 at household level. SBM1: Modulation 1 at building level. SBM2: Modulation 2 at building level. SBM3: Modulation 3 at building level. SBM4: Modulation 4 at building level. POR (mean) refer to percentage outside of range of IEQ2 of all the zones (of the typical weeks).

KPIs	Week	Energy consum. [kWh]	Acc. penalty [Penalty unit]	FI [-]	Reff [-]	Peak export [kW]	Peak deliver [kW]	Supply cover factor [-]	Mean POR (IEQ_{II}) [%]	DHW cover. [%]
BC	W	270.8	946.9			26.6	-61.6	0.47	0.8	101.5
	S	77.4	258.8			31.9	-58.5	0.19	4.6	102.1
	I	134.1	507.4			33.5	-57.1	0.22	1.3	101.6
SHM1	W	266.2	678.7	0.28	0.02	25.5	-60.9	0.61	1.1	101.5
	S	77.4	258.8	0.00	0.00	33.5	-57.1	0.19	4.6	102.1
	I	138.6	504.2	0.01	-0.03	31.5	-58.7	0.24	1.5	101.6
SHM2	W	264.8	587.9	0.38	0.02	25.4	-60.1	0.67	0.9	101.5
	S	77.4	258.8	0.00	0.00	33.5	-57.1	0.19	4.6	102.1
	I	143.8	490.7	0.03	-0.07	30.6	-58.6	0.28	1.7	101.6
SHM3	W	277.5	814.8	0.14	-0.02	25.6	-61.2	0.58	1.0	101.5
	S	77.4	258.8	0.00	0.00	33.5	-57.1	0.19	4.6	102.1
	I	138.7	515.1	-0.02	-0.03	31.5	-58.5	0.23	1.5	101.6
SHM4	W	283.4	770.3	0.19	-0.05	25.2	-61.1	0.63	1.4	101.4
	S	77.4	258.8	0.00	0.00	33.5	-57.1	0.19	4.6	102.1
	I	145.9	516.0	-0.02	-0.09	30.6	-58.4	0.27	1.7	101.6
SBM1	W	264.8	827.7	0.13	0.02	24.0	-61.1	0.60	0.8	101.3
	S	77.4	203.1	0.22	0.00	33.5	-56.7	0.25	4.6	101.9
	I	134.6	419.5	0.17	0.00	31.3	-57.7	0.29	1.3	101.4
SBM2	W	274.5	922.1	0.03	-0.01	24.1	-61.1	0.59	0.8	101.6
	S	79.5	220.5	0.15	-0.03	33.5	-57.0	0.24	4.6	102.3
	I	136.9	452.5	0.11	-0.02	31.3	-58.4	0.28	1.3	101.7
SBM3	W	280.6	929.4	0.02	-0.04	24.0	-62.0	0.57	0.8	101.6
	S	81.6	240.1	0.07	-0.05	33.5	-56.7	0.24	4.6	102.3
	I	143.3	482.2	0.05	-0.07	31.4	-58.5	0.29	1.3	101.7
SBM4	W	277.1	930.3	0.02	-0.02	24.2	-61.9	0.57	0.9	101.6
	S	81.6	240.1	0.07	-0.05	33.5	-56.7	0.24	4.6	102.3
	I	142.7	482.9	0.05	-0.06	31.5	-58.5	0.28	1.3	101.7

Figure 42 represents the effect of rebound in energy consumption. The brown columns represent the energy that is consumed when the penalty signal is 1 (downward modulation) and blue columns represent the penalty signal 0 (upward modulation). All the values of Figure 42 are relative, expressed as a difference from the base case. The intention of the flexibility scenarios is to shift the consumption from high penalty period to low penalty periods. Figure 42 represents the energy consumptions of a winter week, an intermediate and summer week. The biggest effect of energy shifting can be observed from the winter figure, as this is the only one that includes heating demand, meaning that there is simply more demand that can possibly be shifted. In the winter week, all the flexibility scenarios increased the low penalty period consumption (blue), and household M2 scenario the most. Successfully also the high penalty period consumption is reduced in all the scenarios, and again the household M2 scenario the most. In general, the household scenarios allow much higher degree of energy shifting than the building level in winter, as the household scenarios directly affect the demand of the building.

During the intermediate week, the flexibility potential is higher when the control strategy is implemented at building level, mainly due to the lower heating demand of that period. In fact, scenarios SHM3 and SHM4 are worse that the base case, in terms of flexibility and energy consumption (FI and Reff are negative). However, the total amount of energy that is possible to shift from the higher period to the lower is slightly smaller than the winter week.

Analyzing the summer week, the building strategy is the only one that provides flexibility, with a flexibility index of 0.22 (SBM1), slightly higher than the winter one (SBM1, 0.13). However, analyzing the total amount of energy that is possible to shift from higher to lower periods, the highest potential is provided in winter.

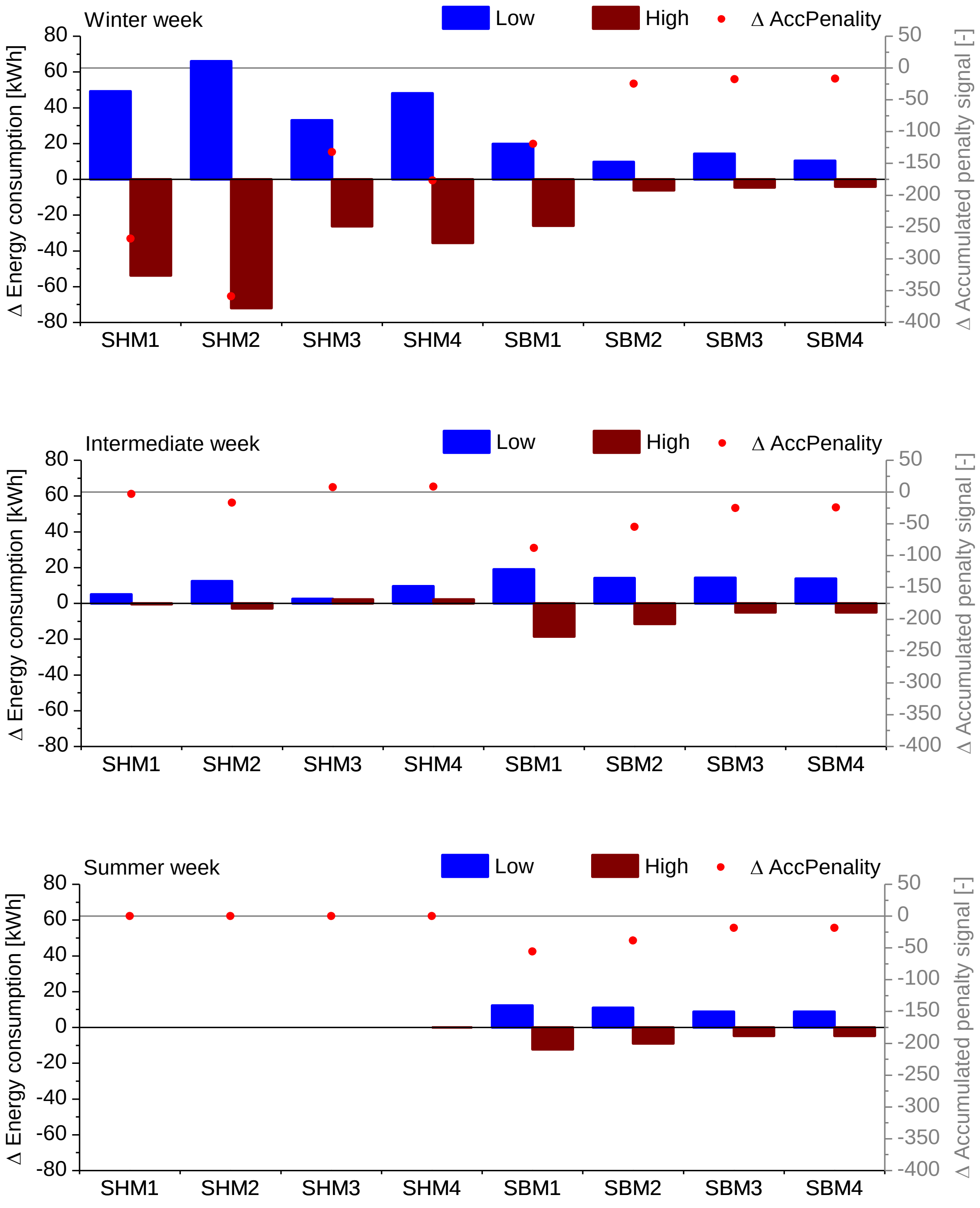

Figure 42: Variation of average daily energy consumption for solar penalty signal periods (low and high) and variation of weekly accumulated penalty (red dots) of a typical week in winter, intermediate and summer season comparing the base case and the flexibility strategies. SHM1: Modulation 1 at household level. SHM2: Modulation 2 at household level. SHM3: Modulation 3 at household level. SHM4: Modulation 4 at household level. SBM1: Modulation 1 at building level. SBM2: Modulation 2 at building level. SBM3: Modulation 3 at building level. SBM4: Modulation 4 at building level.

Results scenarios for shifting Heating and DHW through a price penalty signal

In following four scenarios of price-based control strategies are presented: 2 of the household modulations (PHM1, PHM2) and two of building level (PBM1, PBM2). The control strategies include 3 different levels (while solar strategy has only 2), meaning that during low energy price period the set-points are being set to the highest, on the high energy price period to the lowest, and on the intermediate period to the intermediate (standard) level. The price penalty signal that is introduced in the model is represented in Figure 7 and varies between 1, 0.5 and 0.

The household level modulations (PHM1, PHM2), as described in the solar penalty description, include household temperature set-points' (and set-backs') modification (of heating period) depending on the penalty signal (upward flexibility during lower price period, downward flexibility on higher price period and standard level during intermediate period). This results in higher set-points during the night and generally lower set-points during the day. The low penalty period (upward modulation) in case of price penalty signal is 12h, while in the solar penalty it is only 6h (Figure 7). While the household modulations provide rather similar flexibility indexes than the solar household scenarios, the building level modulations of price scenarios outperform the solar ones, reaching to higher flexibility indexes. This is caused by the longer energy shifting period (low penalty period from 22.00 till 10.00), while the storage tanks can be preheated.

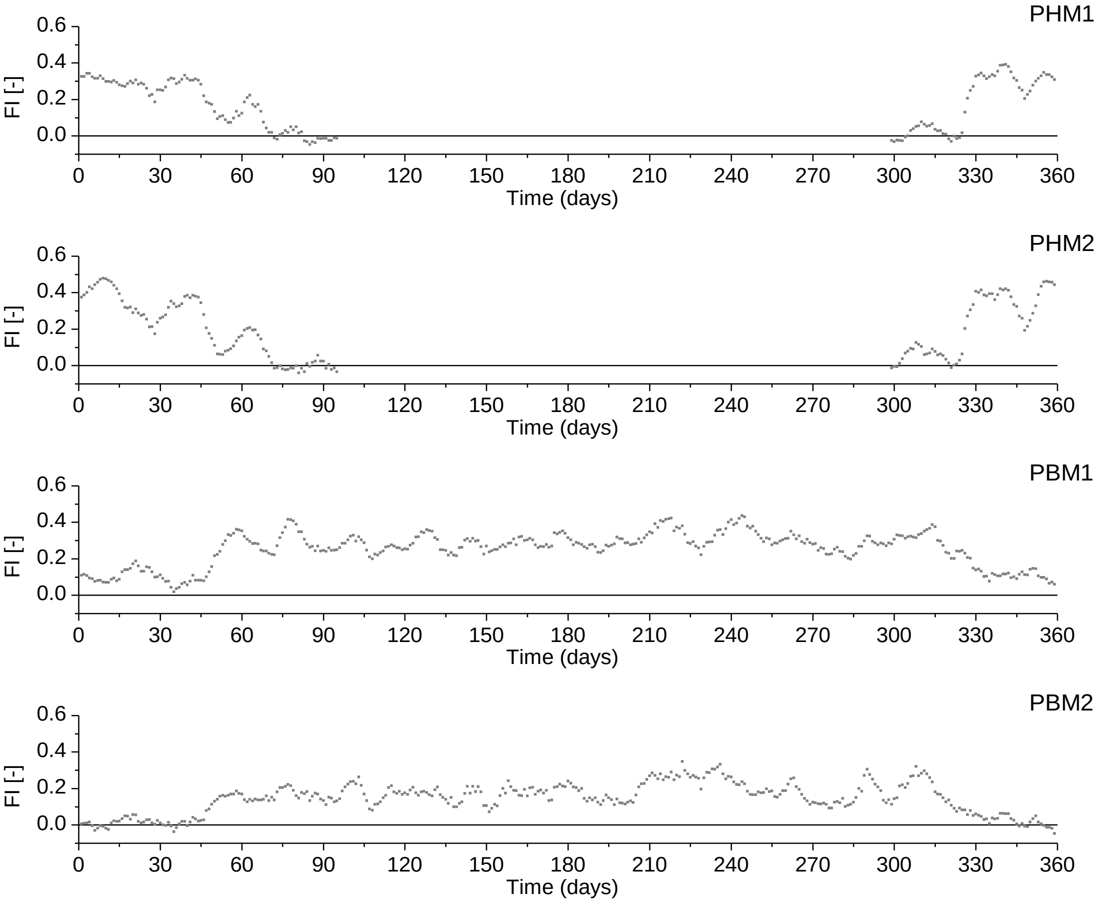

Figure 43: Weekly Flexibility Index (FI) for shifting Heating and DHW through a simplified price penalty signal. PHM1: Modulation 1 at household level. PHM2: Modulation 2 at household level. PBM1: Modulation 1 at building level. PBM2: Modulation 2 at building level.

The flexibility indexes have to be analysed in parallel with the rebound efficiency, to be sure that the flexibility potential is not obtained with increasing the low penalty consumption excessively. At household level, while the flexibility index is quite similar to the obtained flexibility in the solar penalty signal, the efficiency of the rebound energy is slightly worse, increasing the energy consumption for most of the winter weeks. Analysing the building level modulation PBM1, we can see that this scenario is providing the overall highest flexibility indexes (Figure 43), and when checking the rebound efficiency (Figure 44), it can be seen, that the flexible case rebound efficiency is almost zero all through the year, meaning that the energy consumption of the base case and flexible case is almost equal (flexible case consumes a bit more than base case, as the rebound efficiency is negative but higher than -0.1) and therefore the flexibility potential that is provided by this control strategy is obtained while not increasing considerably the overall energy usage of the building.

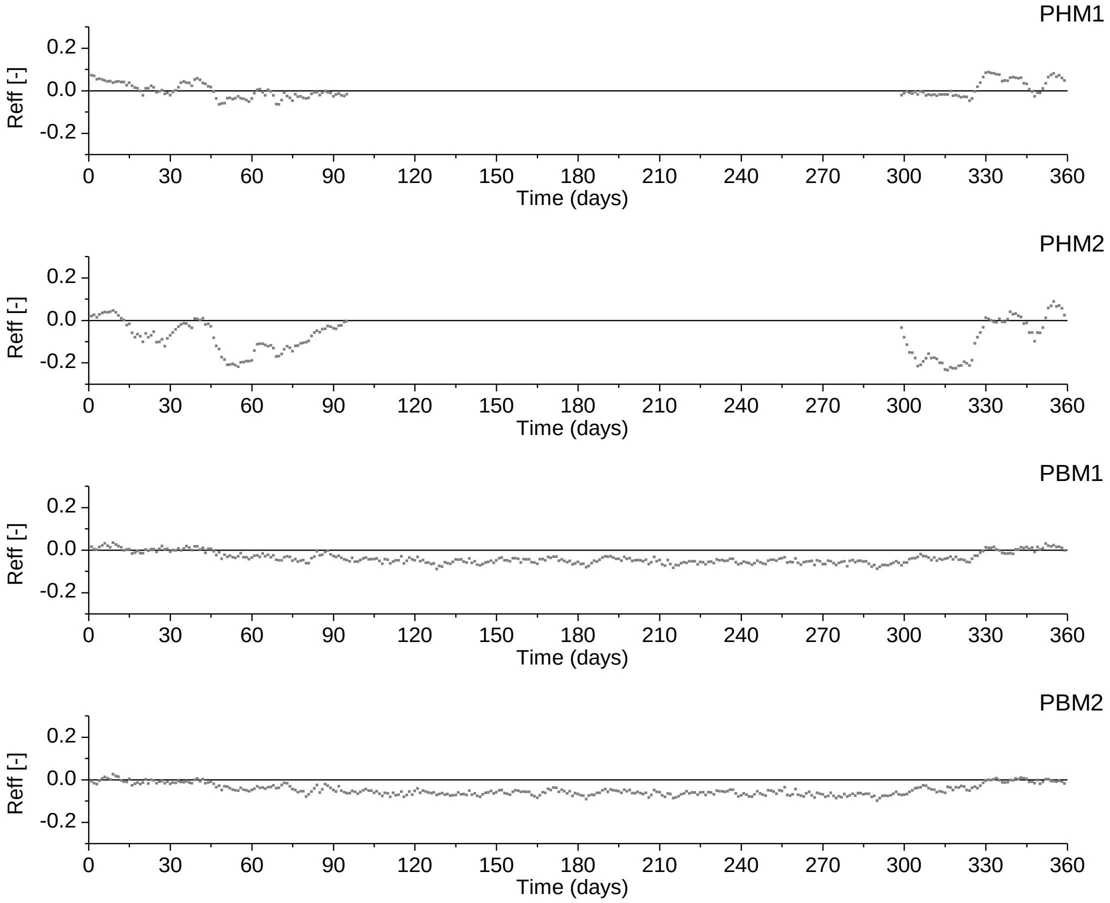

Figure 44: Weekly Efficiency of the Rebound energy (Reff) for shifting Heating and DHW through a simplified price penalty signal. PHM1: Modulation 1 at household level. PHM2: Modulation 2 at household level. PBM1: Modulation 1 at building level. PBM2: Modulation 2 at building level.

As well as the solar penalty scenarios, the price household level modulations (PHM1, PHM2) arrive to similar flexibility potential distribution in terms of ambient temperature: colder temperatures result in higher flexibility index, as the household level modulations are affecting only heating demand. The flexibility index is therefore higher when there is more demand that can possibly be shifted. The differences between solar and price control strategies become evident though in the building level scenarios: in price scenarios there is a clearer tendency between the correlation of ambient temperature and flexibility potential. The building control strategies (that affect tank and heat pump set-points) provide higher flexibility during warmer periods (and have higher consumption of energy), and lower temperatures result in lower flexibility indexes. The tendency of flexibility indexes and rebound efficiencies of building level scenarios are similar, yet the modulation PBM1, having greater amplitude in the tank and heat pump set-point differences, arrives to higher flexibility indexes.

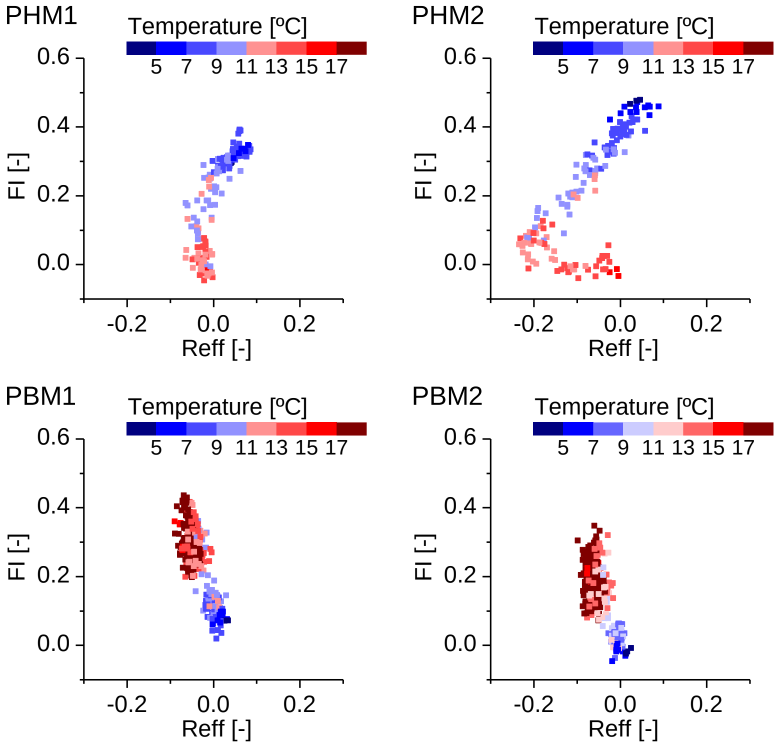

Figure 45: Relation between Flexibility Index (FI) and Efficiency of the Rebound energy (Reff) for shifting Heating and DHW through a simplified price penalty signal. Color map represents the ambient temperature. PHM1: Modulation 1 at household level. PHM2: Modulation 2 at household level. PBM1: Modulation 1 at building level. PBM2: Modulation 2 at building level.

Figure 46 represents the daily profile of the typical weeks (winter, intermediate and summer), providing the mean heat pump electricity consumption profile. The most illustrative is again the winter figure, as the energy consumption is the highest of those 3 weeks. Due to the variation of set-points, two great peaks can be observed: one at 14.00 when the penalty signal drops from 1 to 0.5, and second at 22.00 when penalty signal drops from 1 to 0. The intermediate and summer weeks express less energy shifting due to the generally lower energy consumption. The summer week household scenarios follow the base case energy consumption, as the flexibility strategies affect only heating demand.

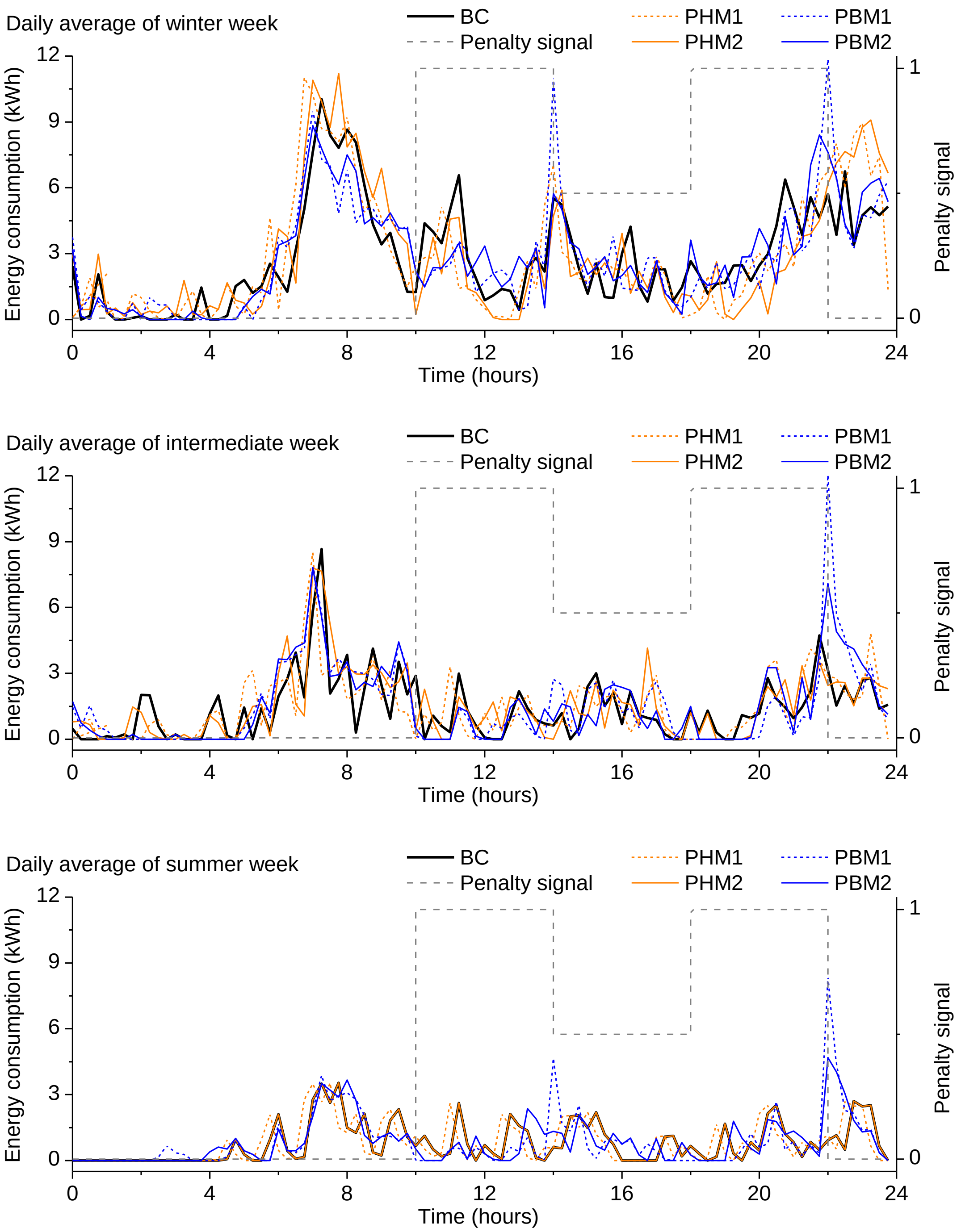

Figure 46: Energy consumption daily profile of a typical week in winter, intermediate and summer season for the base case (BC) and the flexibility strategies for shifting Heating and DHW through a simplified price penalty signal. PHM1: Modulation 1 at household level. PHM2: Modulation 2 at household level. PBM1: Modulation 1 at building level. PBM2: Modulation 2 at building level.

As the intention of the price control strategies is to shift the demand away from the high price periods (and reduce the consumptions during the peak hours), which on the same time coincide with solar hours, a reduction in supply cover factor is observed in household level price flexibility scenarios: for example, base case winter week supply cover factor is 0.47 and the household ones are PHM1: 0.41 and PHM2: 0.40. Yet building level supply cover factors are rather similar to the base case ones, meaning that the building control strategies of price did not affect the self-consumption drastically. As all the price control strategies introduced both upwards and downwards flexibility, the thermal comfort is lowered, reaching in household scenarios the winter mean POR percentages up to 1% (base case 0.8%). On the same time, as also in solar strategies, the building level scenarios even when having downwards flexibility, as the household level set-points are kept the same, don't suffer in worse thermal comfort. As well as in the solar scenarios, DHW coverage was not affected by the price flexibility strategies, resulting in full coverage. Almost all the price control strategies result in increased energy consumption, when comparing with the base case (Table 4).

Table 4: Key Performance Indicators of a typical week in winter, intermediate and summer season for the flexibility strategies for shifting Heating and DHW through a simplified price penalty signal. PHM1: Modulation 1 at household level. PHM2: Modulation 2 at household level. PBM1: Modulation 1 at building level. PBM2: Modulation 2 at building level. POR (mean) refer to mean percentage outside of range of IEQ2 of all the zones.

KPIs	Week	Energy consum. [kWh]	Acc. penalty [Penalty unit]	FI [-]	Reff [-]	Peak export [kW]	Peak deliver [kW]	Supply cover factor [-]	Mean POR (IEQ$_{II}$) [%]	DHW cover. [%]
BC	W	270.8	569.1			26.6	-61.6	0.47	0.8	101.5
	S	77.4	160.1			31.9	-58.5	0.19	4.6	102.1
	IM	134.1	232.2			33.5	-57.1	0.22	1.3	101.6
PHM1	W	274.6	407.9	0.28	-0.01	26.7	-62.0	0.41	0.8	101.4
	S	77.4	160.1	0.00	0.00	33.5	-57.1	0.19	4.6	102.1
	IM	141.0	228.4	0.02	-0.05	31.5	-59.3	0.22	1.6	101.6
PHM2	W	278.5	372.9	0.34	-0.03	26.7	-62.2	0.40	1.0	101.4
	S	77.4	160.1	0.00	0.00	33.5	-57.1	0.19	4.6	102.1
	IM	147.3	241.4	-0.04	-0.10	31.5	-59.6	0.24	1.7	101.6
PBM1	W	269.5	522.3	0.08	0.01	26.1	-61.5	0.51	0.9	101.4
	S	80.4	110.4	0.31	-0.04	33.5	-57.7	0.20	4.6	102.1
	IM	142.4	151.3	0.35	-0.06	31.5	-58.3	0.24	1.3	101.5
PBM2	W	273.4	554.8	0.03	-0.01	26.6	-60.8	0.47	0.9	101.5
	S	81.2	140.6	0.12	-0.05	33.5	-57.6	0.19	4.6	102.2
	IM	143.3	198.1	0.15	-0.07	31.5	-58.4	0.23	1.3	101.7

Figure 47 expresses the energy consumption of the 3 periods: high level (brown: penalty is 1), low level (blue: penalty is 0) and medium level (orange: penalty is 0.5). The intention is to increase the low and medium level consumption by shifting the energy away from high period. Consequently, it can be observed that in the household level modulations (PHM1, PHM2) the low-level consumption is increased, while the high period consumption is strongly reduced. Meanwhile, the building level modulation PBM1 of winter week results in similar low and medium period consumption, yet the high period consumption is reduced. As well as in the solar scenarios, the greatest energy shifting is observed in the winter week, due to the higher thermal demand that can be possible shifted. Figure 47 presents also the variation of the accumulated penalties comparing the base case with each scenario (on the right vertical axes, red dots). There is a clear relation between the quantity of energy that is shifted from high period to lower, with the variation of the accumulated penalty, as higher is the energy shifting, higher is the difference of the accumulated penalty.

Looking the variation between seasons of the building level strategies, the flexibility index increases with the ambient temperature (summer and intermediate weeks); however, the total amount of energy that can be shifted is reduced substantially (daily average consumption varies from 269.5 to 80.4 kWh in winter and summer, respectively for PBM1).

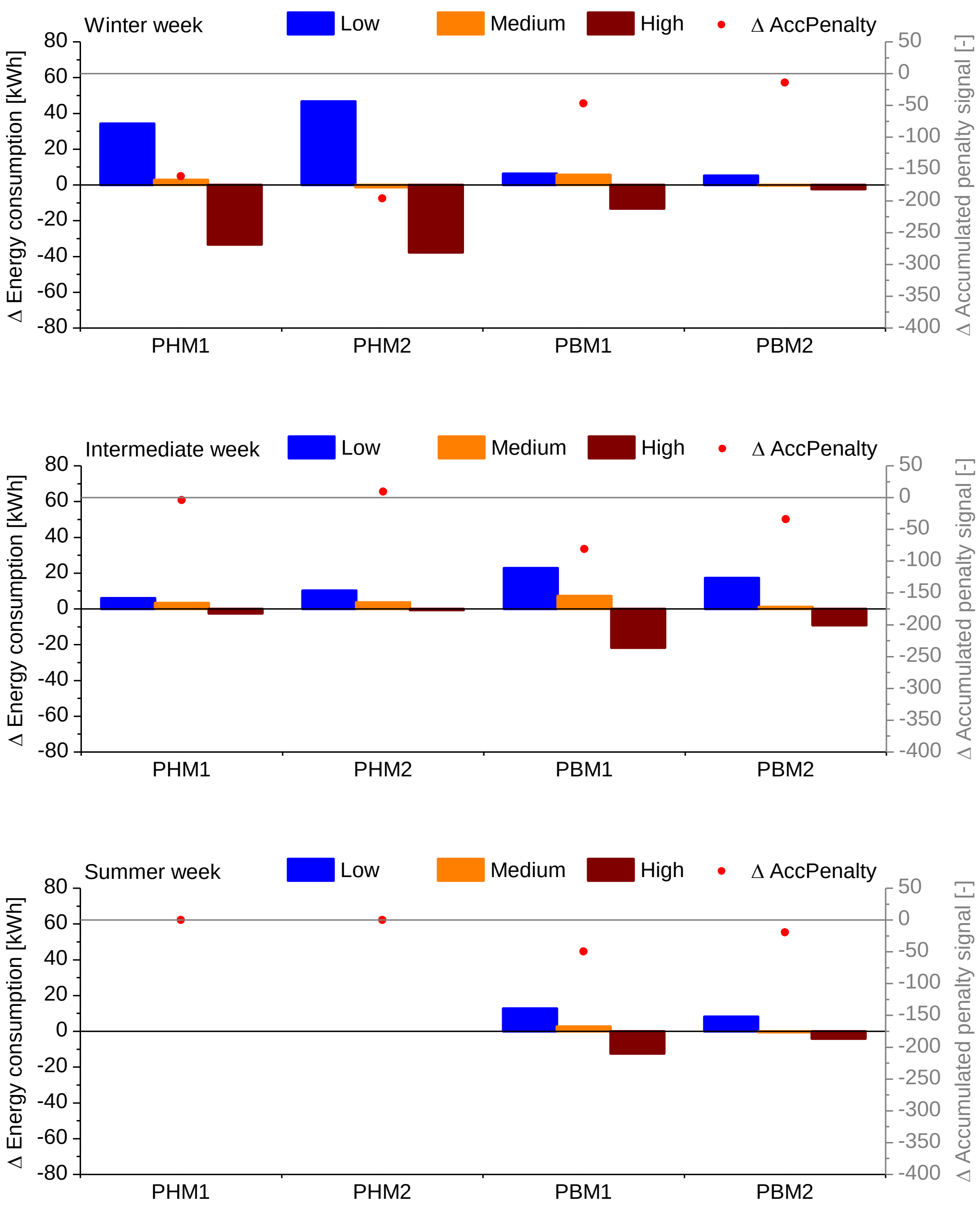

Figure 47: Variation of average daily energy consumption for price penalty signal periods (low, medium and high) and variation of weekly accumulated penalty (red dots) of a typical week in winter, intermediate and summer season comparing the base case and the flexibility strategies. PHM1: Modulation 1 at household level. PHM2: Modulation 2 at household level. PBM1: Modulation 1 at building level. PBM2: Modulation 2 at building level.

Comparison of the flexibility strategies: self-consumption and energy imported from the grid

Figure 48 represents the extra solar energy that is used in the flexibility scenarios of Spanish demo case. As expected, all scenarios with solar control strategies (SHM1…SBM4) result in increased extra solar energy consumption, as the control strategy introduces higher set-points during solar hours, and therefore increase the self-consumption. It is important to notice that the annual extra solar energy used is higher in building scenarios than in household. The main reason is related to the period of implementation of each strategy, the household control level acts only in winter months, and the building level strategy during the whole year. On the same time, price-based control strategy scenarios result in lower self-consumption: the household level scenarios (PHM1 and PHM2) result in lower solar energy consumption than the base case and the building level scenario in a slightly higher extra solar energy consumption, as price control strategy introduce higher set-points during lower price periods, which in general are the non-solar hours, as it is not the objective of the price penalty signal to increase self-consumption.

The annual extra import from the grid of Spanish demo case flexibility scenarios in presented in Figure 48. Negative values indicate that the flexibility scenario imports less energy from the grid, while positive values represent more annual energy imported from the grid. All price scenarios (PHM1…PBM2) show higher energy usage from the grid than the base case, as the consumption is shifted off the solar hours. On the same time, all building level solar scenarios together with the first two household level scenarios (SHM1 and SHM2: both upwards and downwards flexibility), result in less energy imported from the grid, due to the higher self-consumption The household solar scenarios that introduce only upwards flexibility (SHM3 and SHM4: only increased consumption during solar hours) result in more imported energy from the grid, comparing to the other household scenarios (SHM1, SHM2 which have both up- and downward flexibility strategy).

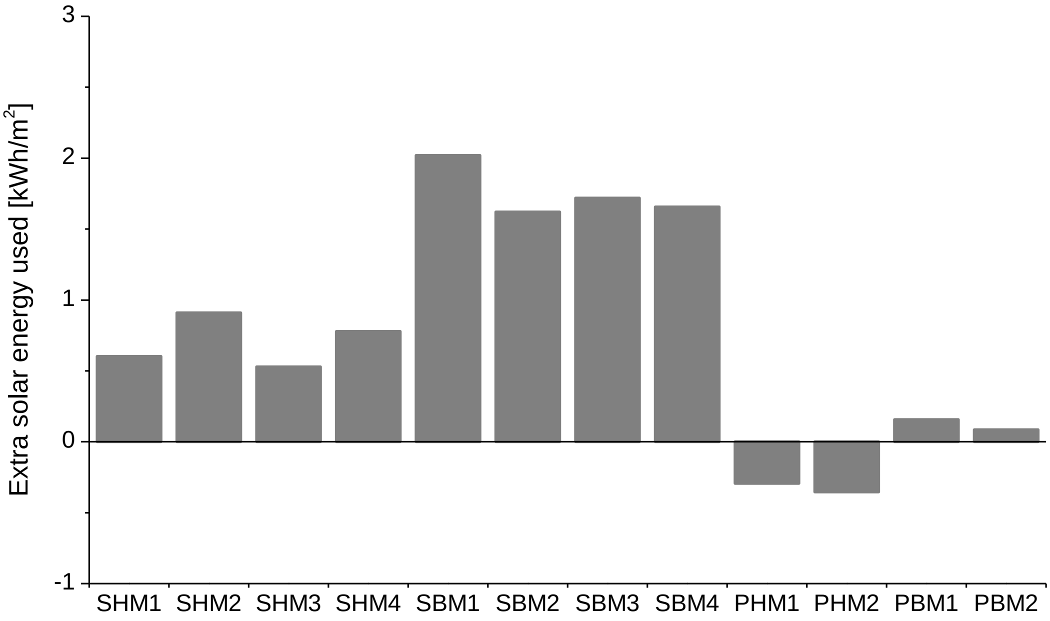

Figure 48: Annual extra solar energy used in different flexibility scenarios of Spanish demo case. Negative values: less solar energy used than in the base case; positive values: more solar energy used than in the base case.

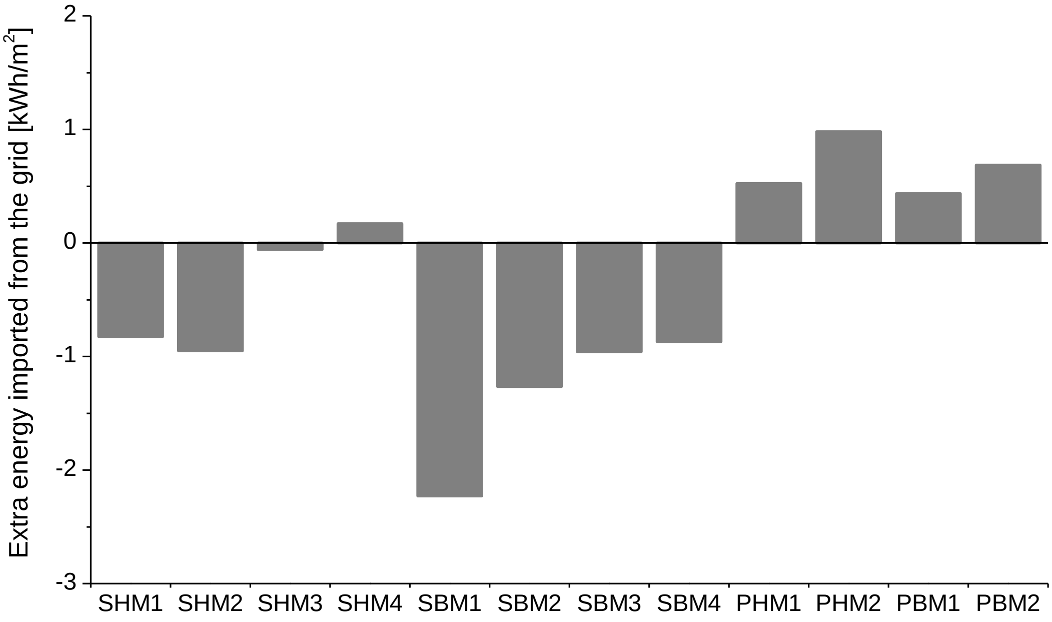

Figure 49: Annual extra energy imported from the grid in different flexibility scenarios of Spanish demo case. Negative values: less energy imported from the grid than the base case; positive values: more energy imported from the grid than the base case.

9. Conclusions and guidelines for energy flexibility

Insights from the Dutch demo case

The flexibility potential of the space heating is rather limited and leads to a small reduction of the imported energy (i.e. 60-100 kWh/year per apartment (10-17%)) or even an increase up to 10kWh/year per apartment (2%) in case of upwards flexibility and a small increase of the utilisation of solar energy (15-50 kWh/year per apartment). Furthermore, the saving on imported energy in case of downward flexibility is for the larger part (~70%) due to the decrease in heating demand as a results of the on average lower inside air temperature. Nevertheless, downward flexibility for heating is preferred over upward flexibility as it does not lead to an increased import from the grid. Since the amount CO_2 emission is directly proportional to the electricity delivered by the grid, the above-mentioned downward strategies result in 20-34 kg/year decrease in CO_2 emission per apartment, assuming a proportionality constant of 0.34 kg/kWh [4].

The flexibility potential was studied by increasing/decreasing the temperature setpoint by 1°C for a limited period on a daily basis, with respect to the reference value of 20°C. It turned out that increasing the setpoint during the day promotes the consumption of the self-generated solar energy. However, the amount of used solar energy is rather limited (~40-60 kWh/year per apartment, depending on the boundary conditions). At the same time this strategy leads to an overall, albeit minor, increase in the imported electricity from the grid (~10 kWh/year per apartment, ~2%). It should be noted that external conditions such as solar radiation and outdoor temperature can significantly affect both the consumption of the solar energy and the imported energy from the grid. Adopting a smart adaptive strategy, e.g. resulting from MPC, instead of a fixed daily strategy, is expected to utilize the flexibility potential more efficiently, resulting in a reduction in imported electricity. On the other hand, reducing the heating temperature setpoint during the night, always leads to less import from the grid although rather limited (~60-100 kWh/year per apartment depending on the boundary conditions, i.e. 10-17%). This is due to the combined contribution of lower thermal loss, increased consumption of solar energy and higher heat pump efficiency. However, the extra solar energy used is quite limited (~20-30 kWh extra yearly consumption per apartment, depending on the boundary conditions). Boundary conditions including the occupants' behaviour affect the flexibility potential of the space heating in the upward case as well as the downward case: more thermal losses (e.g. higher ventilation) or less thermal gains (e.g. less use of appliances) both extend the heating season thereby increasing the storage capacity and the consumption of the solar energy.

The domestic hot water production offers a significant potential for downward flexibility, provided that the operation of the heat pump is prevented during the evening and early morning hours. Depending on the demand, the extra usage of the solar energy can be as large as 360 kWh, leading to a 550 kWh/year (~50%) reduction in the imported energy per apartment equivalent to a reduction of 190 kg/year in the CO_2 emission per apartment. However, the flexibility capacity is affected by the demand profile and comfort restrictions: a narrower comfort band will decrease the flexibility capacity.

The flexibility potential of domestic hot water production was studied by preventing the heat pump to operate starting from late evening to early morning hours. The resulting increase in the consumption of solar energy and decrease in the electricity import from the grid strongly depends on the DHW demand: a high demand in late evening and / or early morning will create capacity for flexibility and promote extra consumption of solar energy. The two tapping profiles considered in this report lead to a significant increase in the solar energy consumption (~170 kWh/year per apartment for the CW1 tapping profile and ~360 kWh/year per apartment for the CW4 tapping profile), which is primarily responsible for the reduction in the imported electricity from the grid: ~200 kWh/year per apartment (~35%) for the CW1 tapping profile and ~550 kWh/year per apartment (~50%) for the CW4 tapping profile. The rest of the reduction in imported electricity is due to the lower heat losses of the buffer and the higher efficiency of the heat pump due to the on average lower water temperature of the buffer.

In general, for the Dutch demo, domestic hot water offers more flexibility potential then space heating in well insulated dwellings, but user behaviour, comfort level and dimensioning of installations and dwellings has a huge impact on both. The limited flexibility potential of space heating is on one hand due to the tight comfort boundaries in this study that were considered for the space heating and, on the other hand, due to the limited flexibility potential of the space heating in the colder months of the year when the solar radiation is typically low. It should however be noted that, besides the DHW demand, occupant comfort can also significantly affect the flexibility potential. Less strict comfort bounds, for instance plus or minus 2°C, will naturally lead to higher consumption of solar energy.

Insights from the Spanish demo case

Several strategies have been tested to evaluate the flexibility potential for shifting heating and DHW: two different simplified penalty signals (solar and price) and two different control levels (at household or at building level). The main difference between the solar and the price penalty signal is that the solar penalty signal incentivises the energy consumption during solar hours and discourages the consumption during night hours, with the main objective to increase self-consumption; however, the price penalty signal implements the opposite strategy, discouraging the consumption during day-hours (two periods: medium and high price) and encouraging it at night (price valley period), and in that case the objective is to reduce the consumptions during the peak hours. The control strategy at household level is based on changing the heating setpoints (DHW is not affected), and the building level strategy modifies the setpoint of the centralized heating water tank and DHW tank.

Analysing the solar penalty signal and comparing both, household and building level implementation, the flexibility potential provided by the household level regulation is higher than the building level during winter period (a Flexibility Index up to 0.5 and 0.3, respectively). As soon as the outside temperature increases, the heating demand is lower and therefore the flexibility potential of the household level is reduced up to zero in summer. Nevertheless, the building level strategy allows to have almost constant flexibility potential over the year. On the one hand, the household level strategy presents a stronger relationship with the outside temperature: lower outside temperatures result in higher flexibility index and higher efficiency of rebound energy (flexibility strategy consumes less energy than the reference case). On the other hand, the building strategy results in lower flexibility potential, but almost constant over the year and with low values of efficiency of rebound energy (Reff close to zero).

For each strategy, different levels of modulation have been tested: M1 upwards and downwards with lower amplitude, M2 upwards and downward with higher amplitude, M3 upwards with lower amplitude and M4 upwards with higher amplitude. Comparing M1 and M2 at household level, the higher modulation (M2) is the one with better flexibility potential. At building level, the differences are lower, being a better strategy M1. Modulations M3 and M4 want to represent a reduced user acceptance, in comparison to M1 and M2, whose occupants do not agree in reducing the comfort levels and do not allow downwards flexibility (reduce the heating and DHW setpoint). A lower user acceptance results in lower flexibility potentials in the household level modulation, going from FI of 0.5 in M2 to 0.3 in M4. At building level, the effect is also observed, but with lower impact (from FI of 0.3 to 0.15).

Analysing the price penalty signal scenarios, some important differences can be observed in comparison to the solar penalty signal. In general, the efficiency of rebound energy is negative in all the scenarios, meaning that all the flexibility strategies consume more energy than the reference case, but this does not happen with the solar penalty signal. One possible reason could be that the upward activation in the price penalty signal is done at night hours, and the outside temperature provide the most unfavourable conditions (lower temperature, higher thermal losses and/or less COP of the Heat Pump). Despite of this, the flexibility potential at household level achieves similar values than the solar penalty signal (up to 0.5 in M2); and higher values at building level, arriving up to 0.4 in M1. Additionally, when the control is implemented at building level a clear dependency between the FI and the outside temperature has been appeared: at higher outside temperature, higher FI are obtained.

In general, the supply cover factor is increased in the solar penalty signal scenarios thanks to the heating and DHW shifting from night hours to solar hours. In addition to this, all scenarios (solar and price signal) have been able to move the delivered energy from the high penalty periods. However, the peak power values have not been reduced, only appearing at different time of the day.

In conclusion, the building is able to provide flexibility following different penalty signals and under different control strategies. The building results in reasonable flexibility potentials that vary from 15% to 50% depending on the outdoor conditions and the control strategy implemented. Further work is necessary to evaluate the possibility to combine different strategies at the same time (household and building level) or investigate which penalty signal is more appropriate for the building in terms of energy cost.

In summary, some conclusions can be extracted for zero energy buildings in the Mediterranean climate provided by centralized heating and DHW systems:

- A control strategy implemented at household level, changing the heating setpoint temperature, is recommended during winter periods, providing a high flexibility potential especially with upward and downward modulation of 2°C. The FI is about 0.4 for a winter week and the supply cover factor has increased from 0.5 to 0.7, in comparison to the reference case.
- A control strategy implemented at building level, changing the heating water tank and DHW water tank setpoints, is recommended in intermediate and summer periods, especially with upward and downward modulation of 3°C. The FI is around 0.2, however, it is impact on the supply cover factor is limited (increasing around 0.1, in comparison to the reference case).
- If the user acceptance is limited and does not allow downward flexibility at household level, the flexibility potential is reduced substantially, from 0.4 to 0.2 in a winter week.
- The control strategy at building level allows to implement upward and downward modulation without to jeopardize the user comfort, as the control strategy has a very low impact on the user comfort (households setpoints are not changing during the modulations).
- If the modulation at household level follows a solar penalty signal (increase the consumption during solar hours, and reduce at night) the efficiency of rebound energy is positive for the colder weeks, meaning that the flexibility strategy consumes less energy than the reference case. However, if the modulation follows a price penalty signal with an opposite pattern (reduce the consumption during day hours, and increase at night) all the flexibility scenarios consume more energy than the reference case, resulting in negative values of efficiency of rebound energy.
- If the building follows a solar penalty signal (increase the consumption during day-hours) the FI is around 0.2 for a summer week. However, if the strategy is based on a price penalty signal, the FI increases up to 0.4 in summer periods. The efficiency of the rebound energy is in both cases between 0.0 and -0.1, which means that the flexibility scenario consumes slightly more energy than the reference case.

Generic guidelines for energy flexibility of multi storey apartment buildings

The flexibility potential of a component is strongly dependent on the design of the system, occupant's behaviour, the comfort constraints, the penalty signal and control algorithms used. The space heating can provide more flexibility in the heating season if the heating system includes a storage as in the case of the Spanish demo with centralized heating. If the goal is to shift the energy consumption to the night hours, the flexibility control strategy may lead to a higher total energy consumption if the thermal losses to the outside environment are substantial, which however corresponds to overall lower CO_2 emissions. The domestic hot water production offers flexibility throughout the whole year, although its flexibility capacity can be limited by the actual DHW demand, by the capacity of the tank and by the comfort restriction. Energy flexibility for appliances is determined by the use in time. Using appliances when there is on-site solar energy generation will lead to an increase of the use of solar energy provided by the PV panels and decrease of the imported energy in the same amount.

Based on the analysis of the flexibility potential of the Dutch and Spanish demo we can derive the following guidelines:

For space heating:

- Downward flexibility in a good insulated building saves more energy than upward flexibility because of lower energy demand and reduced heat losses due to the on average lower setpoint for space heating.
- If the user acceptance is limited and does not allow downward flexibility (i.e., reducing the room setpoint), the flexibility potential of the downward strategy is reduced substantially.
- Even with floor heating, the flexibility potential in space heating is limited in good insulated buildings, due to the narrow comfort band width.
- The flexibility potential can be increased by using a tank; controlling the tank temperature has less impact on the user comfort than using the thermal mass of the building.

For domestic hot water:

- A tank using a large water temperature range will result in a large available flexibility.
- The size of the tank has a significant influence on the flexibility. The capacity should at least be in the order of the daily DHW demand.
- Downward flexibility during the night saves energy because of increased use of solar energy during the day and reduced heat losses.
- In case of a heat pump upward flexibility is limited, because of reduced efficiency of the heat pump and increased heat losses.
- Using a separate legionella control (once a week) a higher temperature range is allowed leading to a higher downward flexibility (low temperature heat exchanger/substation is an alternative to avoid legionella problems and increases the overall system efficiency).

The insights derived from the flexibility analysis in the two demos were formulated in terms of guidelines for flexibility, and will be taken into account in designing smart control systems in work package 4 – Flexibility measures in different climate zones and markets.

10. References

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Appendix A – Inventory of the operational range and constraints of all active components in the Dutch demo case

Heat pump for space heating

Control input	Input range	Input & output constraints	Remarks
Setpoint room temperature	Variable	Heat pump (HP) cannot modulate; Minimal switch off time? Minimal switch on time?	Manual control by user. Floor heating and warming the DHW tank with heat pump are mutually exclusive Max 0.8 kW, max current 8.3 A.
Weather compensation Temperature Tmax	Variable depending on outside temperature example: 25°C at 25°C outside temperature	Max temperature 45°C can be reached by the HP, automatic switch off	May be used to control HP switching times (HP is on/off). Outlet CV Temperature
Weather compensation Temperature Tmin	Variable depending on outside temperature example: 45°C at -10°C outside temperature		May be used to control HP switching times (HP is on/off)

Heat pump for domestic hot water production

Control input	Input range	Input & output constraints	Remarks
Setpoint DHW tank comfort mode [°C] + dead band	Variable	HP either heats water or heats building Max 58°C can be reached by the heat pump. The mode is selected by the user at the heat pump itself. Minimum 40°C Minimum 55°C (regulations)	May be used to force tap water heating. Heats water if the high tank temperature is below setpoint, continuously over the day. Domestic hot water is dominant over space heating. It takes 1-2 hours to heat the vessel depending on the temperature in the vessel.
Setpoint DHW tank eco mode	Variable	Max 58°C can be reached by the heat pump. The mode is selected by the user at the heat pump itself.	Heats the DHW tank once daily till setpoint reached (fixed time). In both comfort and eco mode there is once a week legionella protection at 62°C.
[°C] + dead band	On/off		not available

Appendix B – Inventory of the operational range and constraints of all active components in the Spanish demo case

Heat pump (building level)

Control input	Input range	Input & output constraints	Remarks
Heat pump (HP) supply temperature	Variable, depending on outside temperature. It is linked to the heating and DHW tank set-point temperatures.	The HP supply temperature will be controlled indirectly based on the heating and DHW water tank temperature.	DHW demand is prioritized over heating demand. Therefore, the HP supply temperature is: - If there is DHW demand: HP supply temperature = DHW tank set-point temperature + 5°C - If there is no DHW demand, winter: HP supply temperature = heating tank set-point temperature + 5°C

Heating water tank (building level)

Control input	Input range
Heating tank set-point temperature	Variable depending on outside temperature: Heating curve [30…37] + 5°C

Domestic Hot Water tank (building level)

Control input	Input range
Set-point DHW tank temperature	60 ± 3°C

Thermostat (household level)

Control input	Input range	Remarks
Room thermostat set-point and set-back temperatures	Winter: Set-point 21 ± 0.5°C Set-back: 18 ± 0.5°C	Set-point room thermostat is defined based on the occupancy and day/night hours: - If there is occupancy and day hours → Set-point temperature - If there is not occupancy and night hours → set-back temperature

Appendix C – Spanish demo modulations

Household level Modulations (heating)

	Modulation 1		Modulation 2		Modulation 3		Modulation 4	
Penalty signal	Heating set-point	Heating set-back	Heating set-point	Heating set-back	Heating set-point	Heating set-back	Heating set-point	Heating set-back
1	20	17	19	16	21	18	21	18
0.5	21	18	21	18	-	-	-	-
0	22	19	23	20	22	19	23	20

Building level Modulation 1 (heating and DHW)

	Heating			DHW		
Penalty signal	Heat pump set-point	Tank set-point	Household HX set-point	Heat pump set-point	Tank set-point	Household HX set-point
1	HC *+ 7	HC + 2	HC	62	57	45
0.5	HC + 10	HC + 5	HC	65	60	45
0	HC + 10	HC + 8	HC	65	63	45

Heating tank controller dead bands +/-2°C and DHW tank ones +/-3°C. *HC: heating curve

Building level Modulation 2 (heating and DHW)

	Heating				DHW			
Penalty signal	Heat pump set-point	Tank set-point	Dead band	Household HX set-point	Heat pump set-point	Tank set-point	Dead band	Household HX set-point
1	HC + 10	HC + 5	+4, -2	HC*	62	57	+5, -3	45
0.5	HC + 10	HC + 5	+/-2	HC	65	60	+/-3	45
0	HC + 10	HC + 5	0/-4	HC	65	63	0/-6	45

Building level Modulation 3 (heating and DHW)

	Heating			DHW		
Penalty signal	Heat pump set-point	Tank set-point	Household HX set-point	Heat pump set-point	Tank set-point	Household HX set-point
1	HC **+ 7	HC + 2	HC	62	57	45
0	HC + 10	HC + 8	HC	65	63	45

Heating tank controller dead bands +/-2°C and DHW tank ones +/-3°C.

Building level Modulation 4 (heating and DHW)

	Heating				DHW			
Penalty signal	Heat pump set-point	Tank set-point	Dead band	Household HX set-point	Heat pump set-point	Tank set-point	Dead band	Household HX set-point
1	HC + 10	HC + 5	+4, -2	HC*	62	57	+5, -3	45
0	HC + 10	HC + 5	0/-4	HC	65	63	0/-6	45

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DTU
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SIR
SALZBURGER INSTITUT FÜR RAUMORDNUNG & WOHNEN

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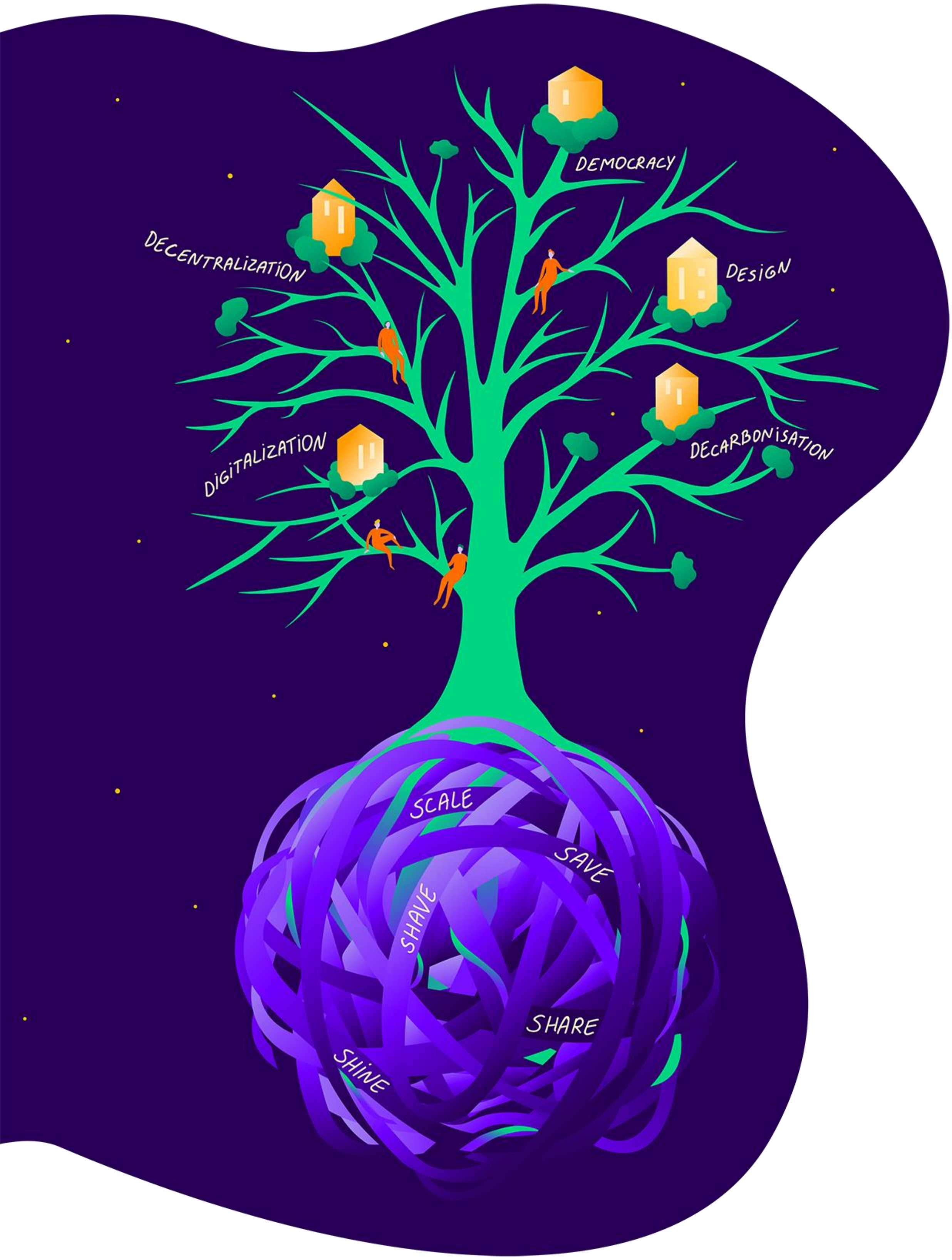
DEMOCRACY
DECENTRALIZATION
DESIGN
DIGITALIZATION
DECARBONISATION
SCALE
SAVE
SHAVE
SHARE
SHINE