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Quantification and characterization of energy flexibility in the residential building sector

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Abstract

Demand response can enable residential consumers to take advantage of control signals and/or financial incentives to adjust the use of their resources at strategic times. These resources usually refer to energy consumption, locally distributed electricity generation, and energy storage. The building structural mass has an inherent potential either to modify consumption or to be used as a storage medium. In this paper, the energy flexibility potential of a residential building thermal mass for the winter design day is investigated. Various active demand response strategies are assessed using two flexibility indicators: the storage efficiency and storage capacity. Using simulation, it is shown that the available capacity and efficiency associated with active demand response actions depend on thermostat setpoint modulation, demand response event duration, heating system rated power and current consumption.

Introduction

Demand Response (DR) is considered as one promising measure to enhance the penetration of renewable energy resources (RES) and reduce carbon emissions. However, electricity cannot yet be stored economically, so the supply of and demand for electricity must be maintained in balance in real time. In addition to this, demand levels also can change quite rapidly and unexpectedly causing mismatches in supply/demand balance, which can threaten the integrity of the grid (SEDC, 2015). To securely and efficiently tackle the aforementioned problems, more energy flexibility is needed to assist in the management of the electricity system.

Energy flexibility can be defined as the modification of generation injection and/or consumption patterns, on an individual or aggregated level, in reaction to an external signal (price signal/network tariff activation etc.) or in order to provide a service within the energy system or to benefit the grid. (CEER, 2018). Demand-side is referred either as dispatchable flexibility that can be traded on the different energy markets by an aggregator (explicit) or as the consumer's reaction to price signals (implicit) (SEDC, 2016). Regarding the energy flexibility of buildings, Jensen et al. (2017) define it as *“the ability to manage its demand and generation according to local climate conditions, user needs and grid requirements. Energy flexibility of buildings will thus allow for demand-side management/load control and thereby demand response based on the requirements of the surrounding grids and on the availability of RES, in order to minimize the CO2 emissions”*.

Buildings can be part of the solution in the evolving future smart grid, since they offer various storage potential options, either in their structural fabric (building envelopes) or by means of their HVAC systems (e.g., thermal storage tanks), electric vehicles, etc.. In addition, they can play a key role in the future smart grid as they account for approximately 40% of the global energy consumption (Byskov and Lindberg, 2017). By equipping buildings with ICT-based solutions, their energy efficiency and flexibility can be controlled. In this context, the energy flexibility of buildings should be defined and assessed to enable these smart capabilities. Such capabilities can effectively contribute to more comfortable buildings tailored to the needs of the user and the utility with lower environmental footprint (Verbeke et al., 2018).

Despite the various approaches over time regarding energy flexibility indicators, to date, there are no common definitions and methodologies for assessing energy flexibility. This is because energy flexibility is not only the result of the available technologies in a building, but it greatly depends on how these technologies are controlled, their interaction with the utility, the occupants and other boundary conditions (Finck et al., 2018). The resulting time-varying flexibility profiles should be available to communicate and interpret between different stakeholders of the energy system (e.g. energy system designers and operators, aggregators and governments) (Jensen et al., 2017).

DR strategies can provide additional flexibility to meet the requirements of the utility and/or aggregators. These expectations are accompanied by the need to determine not only the quantity of the load to be added or reduced but also the time and the duration at which the DR should be activated. In order for utilities/aggregators to be aware of the above-mentioned characteristics, suitable control strategies are needed to adapt the building electrical demand to render the DR idea feasible for the energy business. These control strategies must be able to dynamically control shiftable building without severely affecting occupant comfort (Christiantoni et al., 2016).

To exploit the energy flexibility potential of buildings, their structural thermal mass can be used as thermal storage capacity. The thermal mass of buildings is a readily available energy storage medium which can be used with few

additional investments, mainly by means of more sophisticated heating system controllers. Such controllers, if integrated within a building energy management system, can utilise the energy flexibility of the structural thermal mass, by responding to an external signal (Foteinaki et al., 2018). The energy flexibility potential depends on various factors such as the functional typology (commercial, residential building, etc.), the properties of the thermal envelope and the installed HVAC systems, as well as the building type (Reynders et al. 2017; Le Dréau and Heiselberg, 2016).

Unlike electric energy storage, the energy flexibility potential of the structural thermal mass is not constant but varies with the boundary conditions and use of the heating system. Specifically, the heat that can be stored or curtailed in the building fabric depends on various parameters such as the building thermal properties as well as occupant behaviour and climatic conditions. Consequently, energy flexibility is time-variant, and this attribute is also depicted in the definitions and the associated equations.

Background

The energy flexibility potential of the structural thermal mass of residential buildings has been thoroughly investigated in the literature. Specifically, Alibabaei et al. (2017) and Rodríguez et al. (2018) investigate the flexibility potential of the thermal mass by developing specific case studies of price-based control schemes. Foteinaki et al. (2018) and Le Dreau et al. (2016) assess the energy flexibility potential of residential buildings by using different energy flexibility indicators and by implementing DR actions with specific starting points and durations. A similar methodology is obtained by Reynders et al. (2016) but only for upward flexibility events. Finally, Reynders et al. (2013) couple the DR actions to investigate the energy flexibility potential of a residential building with the locally produced solar power.

Research Aim

The cited studies investigate the energy flexibility potential of the residential buildings thermal mass either by implementing DR actions at specific starting times or by developing control schemes for specific case studies. The main contribution of this paper is the evaluation of the energy flexibility potential through the daily energy flexibility profile of the structural thermal mass of a smart-grid ready residential building. The flexibility profiles are obtained for the available storage capacity as well as the associated storage efficiency for both upward and downward flexibility actions. This methodology is applied for various DR actions using suitable flexibility indicators. Special emphasis is put on the effect of rebound effects and boundary conditions. The obtained results indicate that the energy flexibility profile depends on thermostat setpoint modulation, demand response event duration, heating system rated power and the building heating demand during normal operation. Moreover, the daily profiles of storage capacity for various thermostat temperature setpoint modulations appear to exhibit a consistent trend, constrained by the heating system power limits.

Methodology

DR Events

In this section, the methodology followed to evaluate the energy flexibility potential associated with the building thermal mass is described. The reference case utilises a winter design day with a constant internal setpoint temperature of 20°C. The DR events are carried out as modulations of the living room thermostat temperature setpoint. These temperature changes can charge/discharge the thermal mass in case of a temperature setpoint increase/decrease. To evaluate these events, the difference \dot{Q}_{diff} between the modulated \dot{Q}_{mod} and the reference \dot{Q}_{ref} electrical demand is considered, as described in equation (1):

$$\dot{Q}_{diff} = \dot{Q}_{mod} - \dot{Q}_{ref} \quad (1)$$

The temperature setpoint changes could be necessitated by different levels of RES production availability: e.g., a downward/upward flexibility strategy corresponds to a high/low-level availability of RES generation. To assess the performance of these modulations, various DR actions (indoor temperature setpoint changes) are implemented considering different starting times and durations (L_{DR}). Specifically, twelve independent two-hour and six four-hour DR events are considered for the heating design day. Thus, the starting times of the two-hour DR strategies are 0000 hr, 0200 hr, etc., while the four-hour DR strategies starting times are 0000 hr, 0400 hr, etc. These simulations will result in the formulation of the energy flexibility profiles. Two major modulations were tested as follows:

Downward flexibility: In this case, the living room thermostat setpoint is decreased by 1-3°C, which subsequently decreases the GSHP power consumption. In this case, heat is curtailed during the modulation period and it is restored later, in order for the building to return to the state before the DR action. As illustrated in Figure 1, the green area corresponds to the energy reduction during the DR event, while the red area corresponds to the rebound effect, i.e., the energy consumption required to restore the previous setpoint conditions.

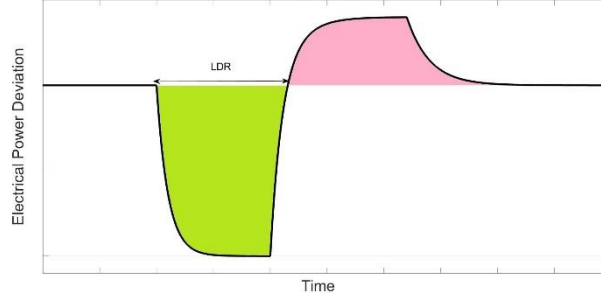


Figure 1: Energy reduction (DR action) / Energy Increase (Rebound).

Upward flexibility: In this case, the thermostat setpoint is increased by 1-3°C, and heat is stored passively in the building fabric by the increase of thermostat setpoint. Examining Figure 2, the red area corresponds to the energy used during the DR event, while the green area corresponds to the energy decrease (inverse rebound) related to this event.

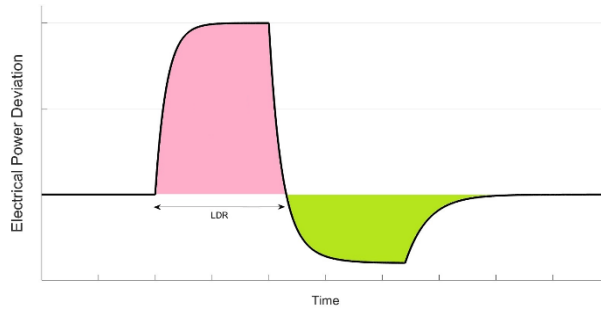


Figure 2: Energy Increase (DR action) / Energy Decrease (Inverse Rebound) .

Energy Flexibility Indicators

Flexibility indicators are useful to building owners and aggregators to exploit the available energy flexibility that the building can provide. In the literature, there is an abundance of methodologies to determine energy flexibility performance indicators (Finck et al., 2018). The flexibility indicators used in this study are the available structural storage capacity (C_{ADR}) and the storage efficiency (η). According to Reynders et al. (2017), “the available capacity for active demand response (C_{ADR}) is defined as the amount of energy that can be added to the storage system, without jeopardizing comfort, in the time-frame of an ADR-event and given the dynamic boundary conditions”. The C_{ADR} is given by equation (2). To account for both upward and downward flexibility, the absolute value of the \dot{Q}_{diff} is considered.

$$C_{ADR} = \int_0^{LDR} \left| \dot{Q}_{diff} \right| dt \quad (2)$$

To account for the energy savings (Figure 4) and the rebound effect (Figure 5) in upward and downward flexibility, respectively, equation (3) is used. The infinity symbol in the integral is interpreted as the time when the \dot{Q}_{diff} term becomes insignificant.

$$C' = \int_{LDR}^{\infty} \left| \dot{Q}_{diff} \right| dt \quad (3)$$

Regarding storage efficiency, it is defined as “the fraction of the heat that is stored during the ADR event that can be used subsequently to reduce the heating power needed to maintain thermal comfort”. In this study, the flexibility indicators as suggested by Kathirgamanathan et al. (2018) and Reynders et al. (2017) are used. Thus, the storage efficiency is given by different formulas for downward (equation (4)) and upward flexibility (equation (5)) as:

$$\eta_{DF} = 1 - \frac{\int_{LDR}^{\infty} \dot{Q}_{diff} dt}{\int_0^{LDR} \left| \dot{Q}_{diff} \right| dt} = 1 - \frac{C'}{C_{ADR}} \quad (4)$$

$$\eta_{UF} = 1 - \frac{\int_0^{LDR} \dot{Q}_{diff} dt}{\int_0^{LDR} \left| \dot{Q}_{diff} \right| dt} = \frac{C'}{C_{ADR}} \quad (5)$$

In this study, consecutive and independent DR events are imposed to create a daily flexibility profile; the later can be used to select the most suitable DR strategy in terms of requested energy (to be curtailed or postponed) and energy cost associated with the DR action. The methodological steps of this study are summarised in Figure 3.

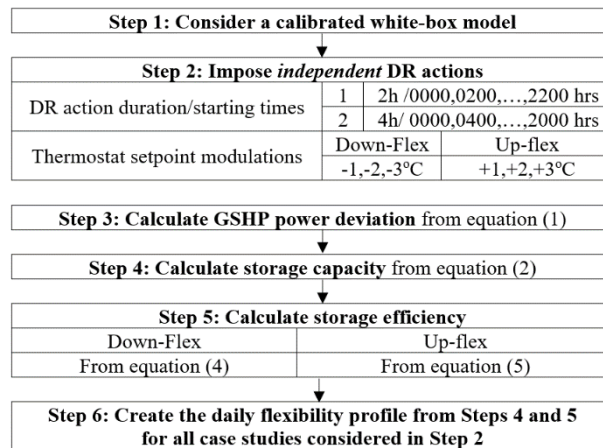


Figure 3: Methodology diagram.

Building Model

The selected testbed is a single-storey detached house located in eastern Ireland. This dwelling represents 40% of the Irish building stock and is the most common single building category (Pallonetto et al., 2016). A picture of the building and the modelled geometry are shown in Figure 4. It was constructed in 1973 with increased thickness of insulation materials in its opaque elements compared to the contemporary standards.



Figure 4: 3D rendering and picture of testbed house (Pallonetto et al., 2016).

As a result of its construction (two-leaf concrete wall with cavity insulation), it exhibits significant passive thermal energy storage capacity. The total surface area of the exterior walls is 187 m², excluding associated windows and doors. A slate roof has a surface area of 279 m². The roof does not have insulation, while the ceiling is covered with acoustic tiles to ensure both acoustic and thermal insulation. On top of the acoustic tiles, a 200 mm layer of fibreglass ensures high thermal resistance due to its low thermal conductivity (0.04 W/mK). The floor area is 208 m², and the overall window to wall ratio is 15%, with a 22% and 10% ratio on the south and north facades, respectively.

As illustrated in Figure 5, the house is comprised of twelve rooms and an unused attic space at roof level. Two temperature sensors were installed, one in the main living area and one in the corridor. The building walls, roof, windows, and floor have U-values of 0.21, 0.21, 1.7, and 0.21 W/m²K, respectively.

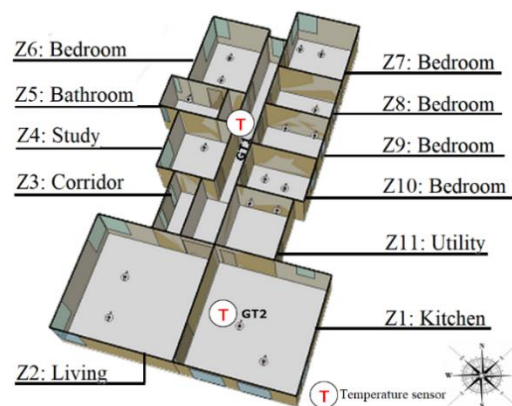


Figure 5: Representation of the building with the ground floor thermal zones and orientation and temperature sensors (Pallonetto et al., 2016).

The space heating system is a 12 kW (thermal output) ground source heat pump (GSHP). For the provision of thermal energy storage, the heat pump was equipped with a hot water storage tank of 0.8 m³. The system is illustrated in Figure 6.

The white-box model used to develop and analyse the DR control algorithms was created using EnergyPlus V. 8.9 and calibrated using monitored data from the building (Pallonetto et al., 2016).

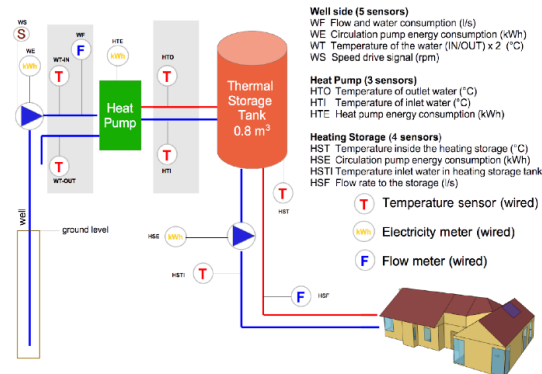


Figure 6: Heat system design and sensor metering (Pallonetto et al. 2016).

Boundary Conditions

The energy flexibility analysis in the current study is focused on the living room of the residential building testbed, considering a constant thermostat setpoint of 20°C. According to ASHRAE 2004b Standard 55 (2004), there is a maximum change in operative temperature allowed during a period, in order that the thermostat setpoint changes remain within the acceptable limits. Table 1 summarises DR durations and temperature restrictions applied in this study. For each DR action, the resulting operative temperature change is also tested to ensure that the thermal comfort is maintained. The upper limit of the integral in equation (4) changes, depending on the difference between modulated \dot{Q}_{mod} and \dot{Q}_{ref} (stable time).

Results

Reference Case

In this section, the weather profile (ambient temperature and global solar irradiance) of the simulation day and the day after (Figure 7a), the total internal gains (Figure 7b) and associated GSHP power consumption (Figure 7c) under normal operation are presented. As seen in Figure 6c, the GSHP power decreases between 1800 and 2200 hrs. During this period, the ambient temperature decreases by 0.5°C while the solar irradiance remains zero. This happens because during that period the indoor air temperature increases due to the internal heat gains which include heat emitted from lighting, equipment, and occupants. These internal gains depend on the occupancy schedules over the simulation period.

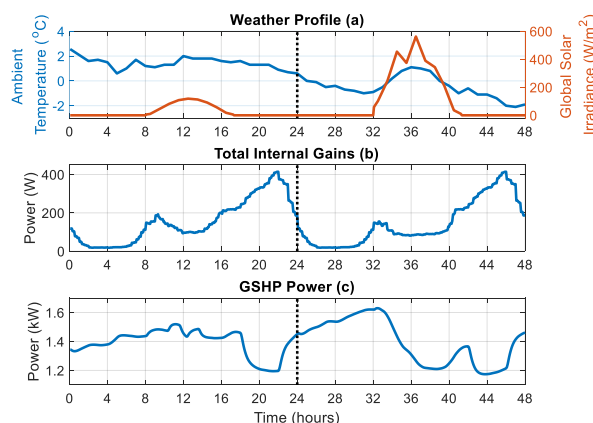


Figure 7: (a) Ambient temperature and global solar irradiance; (b) total internal gains; (c) GSHP power in the reference case.

Downward Flexibility

The GSHP electrical power deviation for a thermostat setpoint change of -1°C, -2°C, and -3°C between 0600 and 0800 hrs is presented in Figure 8a and the change in the room operative temperature is illustrated in Figure 8b. Similar figures can be obtained for all the twelve two-hour DR events. This scenario is indicative and is selected to assess the applied methodology and the impact of different thermostat setpoint reductions on occupant comfort. The area between the time

axis and the negative part of each curve equals C_{ADR} and the area between the time axis and the positive part of each curve equals C' . Furthermore, as shown in Figure 8b, the operative temperature change is within acceptable limits ($\Delta T < 2.8^\circ\text{C}$) as summarised in Table 1.

Table 1: Limits on temperature drifts and ramps.

Time Period	2 h	4 h
Max. Operative Temperature Change Allowed	2.8°C	3.3°C

The GSHP power for thermostat setpoint decreases of 1°C , 2°C , and 3°C between 0800 and 1000 hrs as well as 2000 and 2200 hrs are presented in Figure 9a and the electrical power deviation is illustrated in Figure 9b. It can be observed that the higher the heating demand the higher the energy curtailment potential.

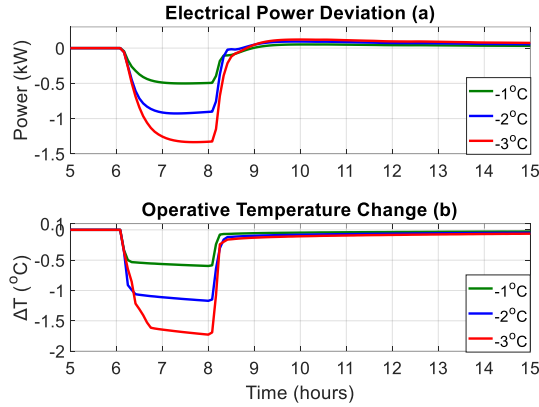


Figure 8: 2-hour down-flex DR action for temperature setpoint reductions of 1, 2 and 3°C , 0600-0800 hr: (a) GSHP power deviation; (b) operative temperature.

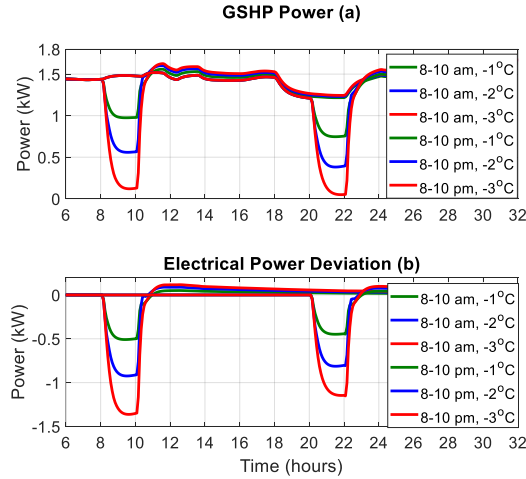


Figure 9: (a) GSHP power and (b) GSHP power deviation in down-flex between 0800-1000 and 2000-2200 hrs.

The storage capacity and the storage efficiency for each of the twelve two-hour DR events are illustrated in Figures 10a and 10b, respectively. C_{ADR} is observed to follow a specific trend. Specifically, the storage capacity for a -2°C setpoint change is on average 77% higher than the storage capacity for a -1°C setpoint change. Likewise, the storage capacity for a -3°C setpoint change is on average 152% higher than the storage capacity for a -1°C setpoint change. It can be also seen that the available storage capacity is decreased between 1800 and 2200 hrs; in fact, the higher the temperature setpoint change, the more the storage capacity decreases. This is due to the heating consumption decrease during that period, and the resulting flexibility margin reduction (Figure 7c). The storage efficiency for a thermostat setpoint change of -1°C is greater since the rebound effects resulting from thermostat setpoint changes of -2°C and -3°C are more significant. Because of the reduced GSHP power during 1800 and 2200 hrs, the associated DR actions result in less significant rebound effects; thus, the storage efficiency for the DR events between 1800 and 2000 hrs as well as 2000 and 2200 hrs is greater.

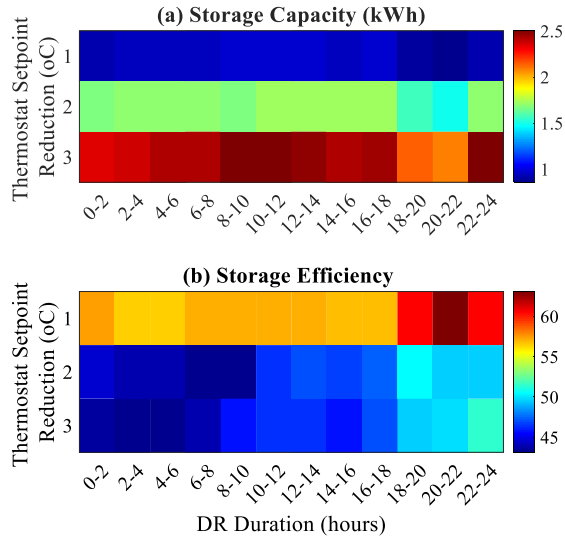


Figure 10: Down-flex DR action for temperature setpoint reductions of 1, 2 and 3°C, 2 hours DR actions: (a) storage capacity; (b) storage efficiency.

In Figure 11, the maximum operative temperature changes during the pertinent DR events are illustrated. It is evident that maximum operative temperature changes are within acceptable limits for all temperature setpoint changes considered. This is due to the high thermal mass of the building envelope.

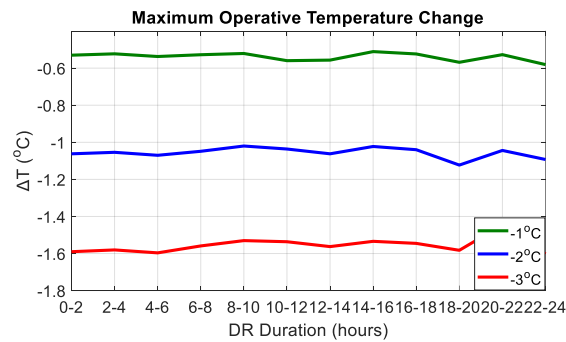


Figure 11: Maximum operative temperature decreases for two-hour DR down-flex actions.

The electrical power deviation for a four-hour DR action between 0800 and 1200 hrs is presented in Figure 12a and the change in the room operative temperature is illustrated in Figure 12b. As with the two-hour DR actions, 1°C, 2°C, and 3°C setpoint changes are evaluated. Similar figures can be obtained for all the six four-hour DR events. As shown in Figure 12b, the operative temperature change lies in acceptable limits ($\Delta T < 3.3^\circ\text{C}$) as per Table 1.

The storage capacity and the storage efficiency for all six four-hour DR events are illustrated in Figures 13a and 13b, respectively. The storage capacity over all DR events for all thermostat setpoint modulations (-1°C, -2°C, -3°C) appears to exhibit a consistent trend. The storage capacity associated with the -2°C and -3°C setpoint changes are on average 83% and 163% higher than the storage capacity for the -1°C setpoint change, respectively. The storage efficiency for a thermostat setpoint decrease of -1°C is constantly greater than the rest of the cases (thermostat setpoint decreases of -2°C and -3°C). This is due to the significant rebound effects which accompany the thermostat setpoint decreases of -2°C and -3°C.

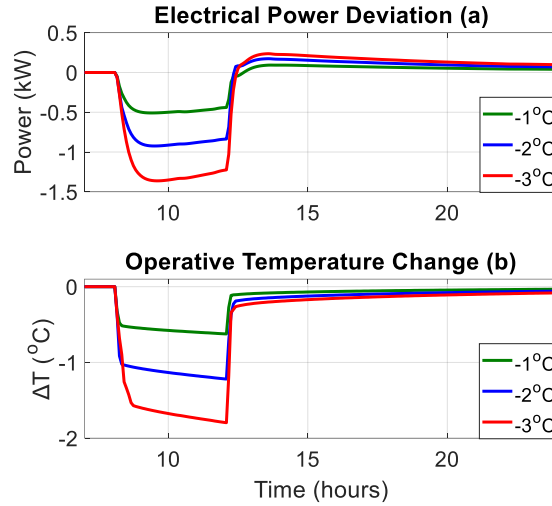


Figure 12: 4-hour down-flex DR action for temperature setpoint reductions of 1, 2 and 3°C, 0800-1200 hr: (a) GSHP power deviation; (b) operative temperature.

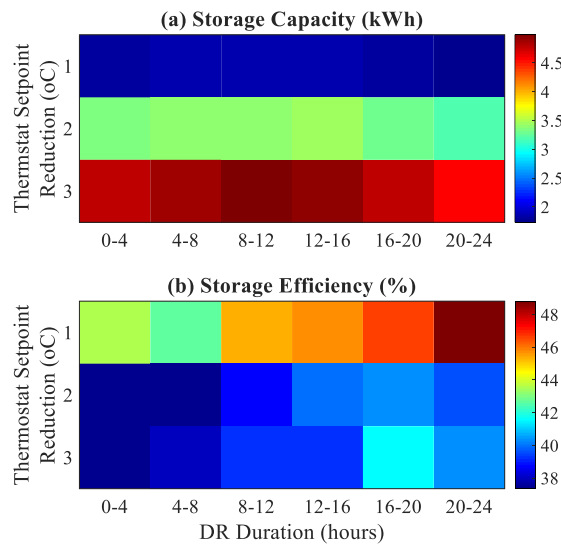


Figure 13: Down-flex DR action for temperature setpoint reductions of 1, 2 and 3°C, 4 hours DR actions: (a) storage capacity; (b) storage efficiency.

By comparing the storage efficiencies of the Figures 10b and 13b, it is shown that the efficiencies of the four-hour DR events are significantly lower than those of the two-hour DR events. This is due to the significant rebound effects resulting in from longer DR modulations, as well as greater associated energy losses from the building envelope. In addition, the operative temperature for all temperature setpoint modulations lie in acceptable limits changing by 0.5°C to 1.9°C.

Upward Flexibility

The GSHP power consumption and electrical power baseline deviation are presented in Figures 14a and 14b, respectively. Both DR events are independent and are for thermostat setpoint increases of 1°C, 2°C, and 3°C between 0800 and 1000 hrs and 2000-2200 hrs. The area between the time axis and the positive y-axis equals C_{ADR} and the area between the time axis and the negative y-axis equals C' . It can be observed that the GSHP power demand is 2.1 kW. Thus, the greater the heating power difference during the DR event with the maximum GSHP power level, the greater the energy flexibility potential. Regarding the 0800-1000 hr DR event, temperature setpoint increases of two or more degrees result in similar power deviations, because the maximum GSHP power has been reached. On the contrary, during the 2000-2200 hr DR event, the GSHP power does not reach its maximum value and the heating power can increase even with a thermostat setpoint increase of 3°C.

From the above analysis, it is evident that the energy flexibility potential strongly depends on the GSHP characteristics and the potential of reducing its peak power demand. This is because energy flexibility in each case depends on the allowable power deviation. The power deviation depends on the difference between the current power consumption and

the maximum GSHP power. Therefore, if the current power is already close to the maximum, the margin of energy flexibility is reduced.

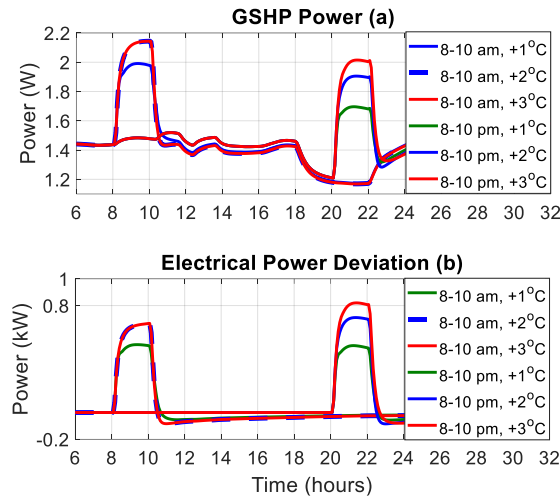


Figure 14: (a) GSHP power deviation and (b) GSHP power in up-flex between 0800-1000 and 0800-1000 hrs.

For the scenario in Figure 14, the room air temperature and operative temperature change are illustrated in Figures 15a and 15b, respectively. It is evident that in all cases, the room temperature does not reach the pertinent setpoint and the resulting operative temperature change lies in acceptable limits.

The storage capacity and the storage efficiency for all twelve two-hour DR events are illustrated in Figures 16a and 16b, respectively. Even though the storage capacity for DR events of 1°C and 2°C of temperature increase is the same before 1800 hr, a differentiation is noticed between 1800 and 2200 hrs. This is due to the GSHP decreased consumption during this four-hour period which allows for a further power increase. Finally, there is not any evident pattern between the storage capacity curves (as noticed in downward flexibility) due to the upper power limit of the GSHP.

Because of the different definition of storage efficiency in upward flexibility, the storage efficiency for a thermostat setpoint decrease of 1°C is constantly lower than the rest of the cases (thermostat setpoint decreases of 2°C and 3°C). The storage efficiency is proportional to the energy savings and the latter are greater during thermostat setpoint decreases of -2°C and -3°C (inverse rebound).

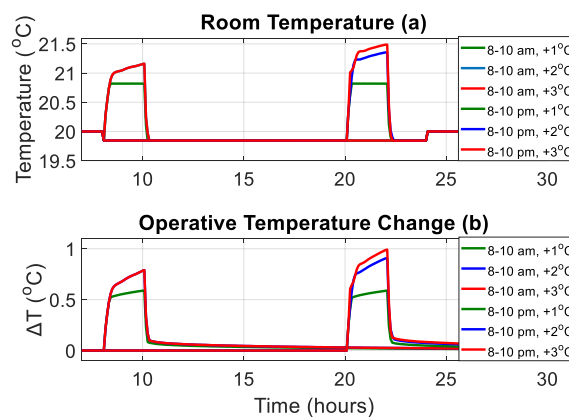


Figure 15: DR up-flex 0800-1000 and 2000-2200 hrs (a) operative temperature; (b) operative temperature change.

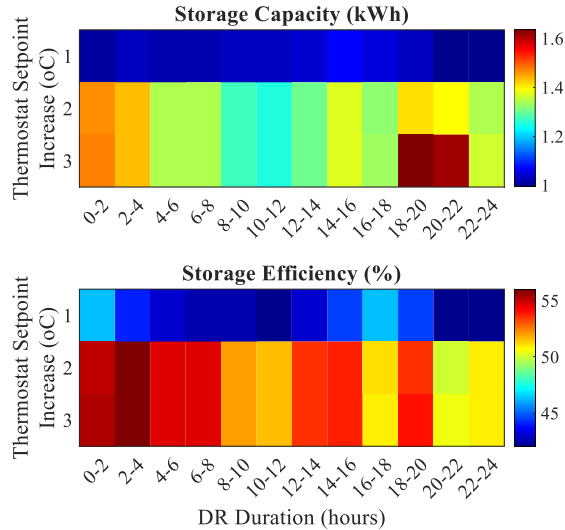


Figure 16: Up-flex DR action for temperature setpoint increases of 1, 2 and 3°C, 2 hours DR actions: (a) storage capacity; (b) storage efficiency.

The storage capacity and the storage efficiency for all six four-hour DR events are illustrated in Figures 17a and 17b, respectively. As is the case with two-hour DR events, storage capacity curves for temperature increases of 2°C and 3°C coincide before 1600 hr and differentiate afterwards due to the GSHP power decrease. The storage capacities of all four-hour DR events are approximately equal to the storage capacities of the corresponding two-hour events, as in downward flexibility. By comparing the storage efficiencies of the Figures 16b and 17b, the efficiencies of the four-hour DR events are significantly higher than those of the two-hour DR events. This is due to the significant energy savings resulting in from longer DR actions (rebound effect). From simulations, the maximum operative temperature change during the four-hour DR events is 1°C.

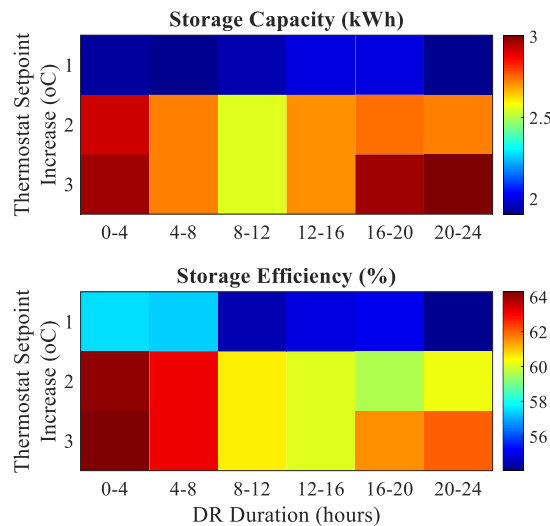


Figure 17: Up-flex DR action for temperature setpoint increases of 1, 2 and 3°C, 4 hours DR actions: (a) storage capacity; (b) storage efficiency.

Conclusions and future work

In this work, the energy flexibility potential of the structural thermal storage capacity of a dwelling has been investigated using various DR strategies. A methodology has been presented to quantify and characterise the energy flexibility provided by a residential building through suitable energy flexibility indicators and various DR modulations.

These indicators provide a quantification framework for assessing the flexibility potential of a dwelling over a 24h scenario. By using these indicators, stakeholders gain insight into not only the energy amount that can be shifted but also the energy cost (i.e. energy losses) associated with the activation of the structural thermal storage of the building. The aggregation of all the results associated with the considered case studies leads to the daily mapping of energy flexibility. This mapping can be of benefit to aggregators for optimising the portfolio of buildings with which to contract.

In downward flexibility, the storage capacity associated with the -2°C and -3°C setpoint changes is on average 77/83% and 152/163% higher than the storage capacity for the -1°C setpoint change, respectively for two-hour/four-hour DR actions. In addition, smaller temperature modulations and shorter DR events prove to be more efficient because of associated minor rebound effects. In contrast to this, in upward flexibility, greater changes in the room temperature setpoint and longer DR events are more efficient, as a result of the increased inverse rebounds. Finally, the energy flexibility margin is reduced when the current GSHP power is already close to the maximum. Thus, the available storage capacity of the building strongly depends on the difference between the heating system under normal operation and the GSHP power limitations. Specifically, the higher/lower the heating system power consumption, the greater the energy flexibility potential in downward/upward flexibility events.

The quantification and characterisation of the energy flexibility provided by the dwelling thermal mass depend on the heating system. Due to the presence of an integrated thermal storage system with the GSHP, the energy flexibility potential of the building could be also assessed by modulating the water tank temperature. In addition, the usage of phase change materials for passive thermal storage as well as the reduction of the rebound effects could be investigated. This methodology can also be extended to include other energy components of the residential testbed building.

In the current work, the demand response characteristics of the structural thermal storage were investigated by using suitable flexibility indicators. To evaluate the suitability and performance of these indicators, the proposed methodology was applied to a white box model developed on EnergyPlus. Nevertheless, wide-scale flexibility assessment by using building simulation tools was found to be impractical due to occupant behaviour variability, the detailed and often inaccessible information about the building geometry and thermal parameters, etc. Considering the large number of sites involved, the practical evaluation of energy flexibility would require the extension of the considered case-specific approach to a generic methodology. This methodology will aim to characterise and quantify energy flexibility by using data-driven methods, as described thoroughly in (Bampoulas et al. 2019).

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