Impact of different control strategies on the flexibility of power-to-heat-systems

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Abstract

Flexible electrical loads are essential to overcome the challenges caused by the increasing share of volatile renewable energy sources in the European power system. Especially power-to-heat-systems seem to be promising for providing required flexibilities. These flexibilities, however, heavily depend on the control strategies of the heating devices as well as the technical endowment and heat usage-patterns. This paper investigates the impact of three alternative control strategies for an electrical heating device coupled with a hot water tank on the temporal flexibilities of the system. Besides a conventional strategy (*Conventional Control*), we introduced three alternative strategies that aim to have the temperature of the hot water tank as close as possible to the upper thermal limit (*Small Upper Control*), to the lower thermal limit (*Small Lower Control*) or in the middle of these limits (*Middle Control*) in order to offer flexibilities within the technical limits. The results for a typical German single-family house show that there are significant differences in flexibility potentials between the strategies. Furthermore, outside temperatures and hot water tank volumes affect the resulting flexibilities of the control strategies differently.

1 Introduction

The share of renewable energy sources has increased strongly during the last years in Europe. While this reduces CO_2-emissions, crucial challenges arise, as the power output of renewable energy sources like wind and photovoltaic is volatile and cannot be controlled. Furthermore, the energy generation is shifting away from large central power plants to smaller decentral generation units. One way to cope with the fluctuating supply is to make the demand for electricity responsive to the supply aiming to ensure balance in the grid. This necessitates flexible electrical loads not only in industry, but also in the residential sector. Electrical heating devices in combination with storages can shift their time of operation and thus react to the current electricity supply without affecting user's habits. These so-called power-to-heat-systems can for example be heat pumps, electrical heating elements or electrical storage heaters. The thermal demand of buildings plays a significant role for reaching climate reduction targets. In 2016 space heating contributed 70 % of the end energy consumption in German households, while energy for domestic hot water contributed 14 % and electrical appliances 16 % [1]. Moreover, the number of heat pumps in Germany has almost doubled during the last 6 years [2]. Thus, the flexibilities of these systems in residential areas offer a promising option to react to the changing electricity supply. Existing hot water tanks or the thermal mass of the building itself can serve as the heat storage making it possible to exploit flexibilities only by investing in a control unit but without additional investments in storages. While in this study only space heating is considered the proposed model and control strategies can also be applied to domestic hot water heating.

Several different concepts for quantifying the flexibility of electrical heating devices coupled with thermal storages exist in literature. Reynders et al. [3], Oldewurtel et al. [4] and Yin et al. [5] define flexibility as the difference in power between a baseline power profile, generated by conventional control strategies, and an adjusted power profile. In [3] the temperature set point for the heating system is increased for limited periods resulting in altered power profiles. The differences between these profiles are calculated for different buildings of the Belgian residential building stock. Oldewurtel et al. [4] use a model predictive control algorithm to react to a varying price signal with flexible heat and cold generation. They calculate for every hour of the day the amount of power a typical Swiss office building can deviate from the baseline consumption. Yin et al. change the thermostat set points of commercial buildings in their simulations and use regression models to predict demand response potentials based on the hour of the day, set point changes and ambient air temperatures. Hurtado et al. [6] define five parameters to quantify demand flexibility of buildings based on structural thermal storage. The ramping rate measures how fast buildings can react to an up regulation (increasing power) or down regulation (decrease power) request. The power capacity and the energy capacity quantify how much power and energy can be delivered during the regulation request. The timespan until comfort levels of the building are violated after having received a regulation request (comfort capacity) and the timespan to restore the nominal comfort level (comfort recovery) are also taken into account.

Nuytten et al. [7] use the concept of delayed and forced flexibility of thermal heating systems to quantify the temporal flexibility of thermal energy storages for district heating. The delayed flexibility (negative flexibility) measures the maximal amount of time a thermal storage can be cooled down without violating the lower temperature limit of the storage whereas the forced flexibility (positive flexibility) quantifies the time a thermal storage can be heated up without violating the upper temperature limit. Figure 1 visualises these temporal flexibilities for a certain time of a day (4:50 AM). In the shown example, the delayed flexibility is 38 minutes and the forced flexibility 24 minutes because after these timespans the thermal limits would be reached. Six et al. [8] calculate the delayed and forced flexibility of a residential heat pump in combination with a hot water tank for one household. They alter the volume of the hot water tank and the difference between upper and lower thermal limit of the hot water tank to quantify the effects of these variations. Stinner et al. [9] also use the concept of delayed and forced flexibility together with a power and energy flexibility metric. They calculate these flexibility measures for a building and compare the flexibility of thermal energy storages with the ones of batteries.

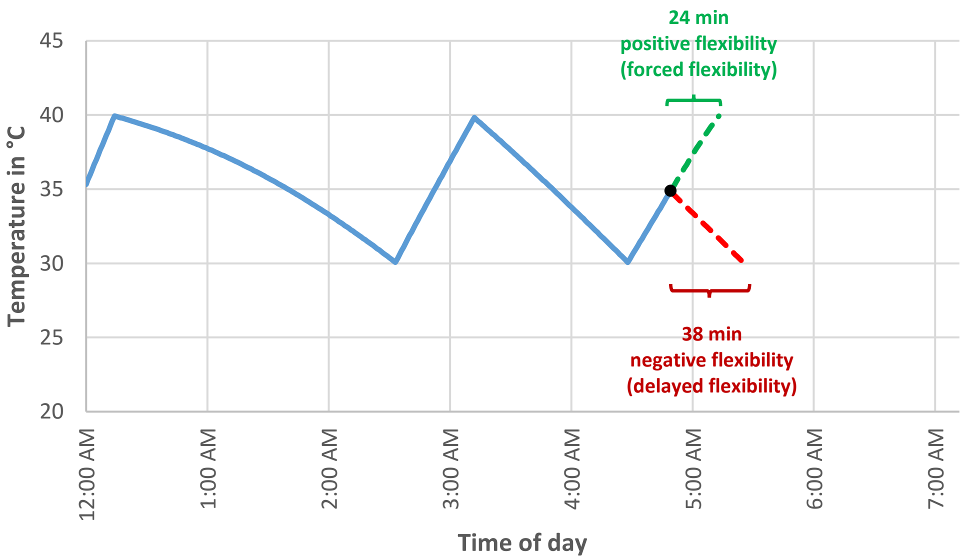

Figure 1: Visualisation of the temporal flexibilities for a hot water tank

We use the concept of delayed and forced flexibility for our analysis and denote them as positive and negative flexibility. These flexibilities are calculated for different control strategies of electrical heating devices coupled with a hot water tank. Furthermore, we investigate the impact of the outside temperature and the size of the hot water tank on these flexibilities.

The remainder of this paper is organized as follows: Chapter 2.1introduces the three alternative control strategies and in Chapter 2.2 our simulation model of the hot water tank is explained, which serves as the buffer storage for our analysis. Subsequently we describe the results in Chapter 3. This paper ends with a conclusion and an outlook in Chapter 4.

2 Control Strategies and simulation model of the hot water tank

2.1 Different Control Strategies

Currently, most often a conventional control strategy is used for heating devices in which the heating device starts to heat the hot water tank when the lower temperature limit is reached and terminates this heating process after the water reaches the predefined upper limit. In this study, we investigate the impact of three different control strategies (*Small Upper Control*, *Small Lower Control* and *Middle Control*) on the temporal load flexibility of a single building equipped with a heat pump and a hot water tank. In the *Small Upper Control* strategy, the temperature in the hot water tank is as close as possible to the upper thermal limit of the tank. The consideration of minimal running times and minimal standby times, both caused by technical limitations of the electric heating device, leads to a zig-zag line right below the upper thermal limit. The longer the two time limits are, the higher the amplitude. The *Small Lower Control* strategy is similar to the *Small Upper Control* strategy but in this case the temperature is as close as possible to the lower thermal limit. Hence, while the latter strategy is suitable for providing positive loads as flexibilities (e.g. positive control reserve), the former is suitable for negative loads (e.g. for avoiding grid overloads). The *Middle Control* strategy aims to have the temperature of the hot water tank around the middle of the upper and lower thermal limit in order to provide both flexibilities.

In Figure 2 the temperatures of the hot water tank for the *Small Upper Control* and the *Small Lower Control* strategy are illustrated during one day. In this exemplary case, the lower thermal limit of the hot water tank is 30 °C and the upper thermal limit is 40 °C respectively. As in [8] the temperature difference is assumed to be constant at 10 K. The initial and end temperature are set to 35 °C. The temperature of the *Small Lower Control* is always below the one of the *Small Upper Control*. The width of the temperature ranges of those two strategies are almost identical but their positions are shifted. If the temperature reaches a thermal limit, the heating device either starts (*Small Lower Control*) or stops heating (*Small Upper Control*). In both cases, the device has to proceed with its current mode until the minimal standby or running time has passed. The temperature ranges that those two strategies can use for providing flexibilities are between 5 °C and 10 ° C. Figure 3 shows the corresponding temperatures for the *Middle Control* and the conventional control strategy. The Middle Control provides a minimum temperature range for using flexibilities of about 3 °C and a maximum of about 7 °C whereas the ranges of the *Conventional Control* vary between 0 °C and 10 °C. It can be seen that these two strategies are similar to each other but the *Middle Control* has a reduced temperature amplitude.

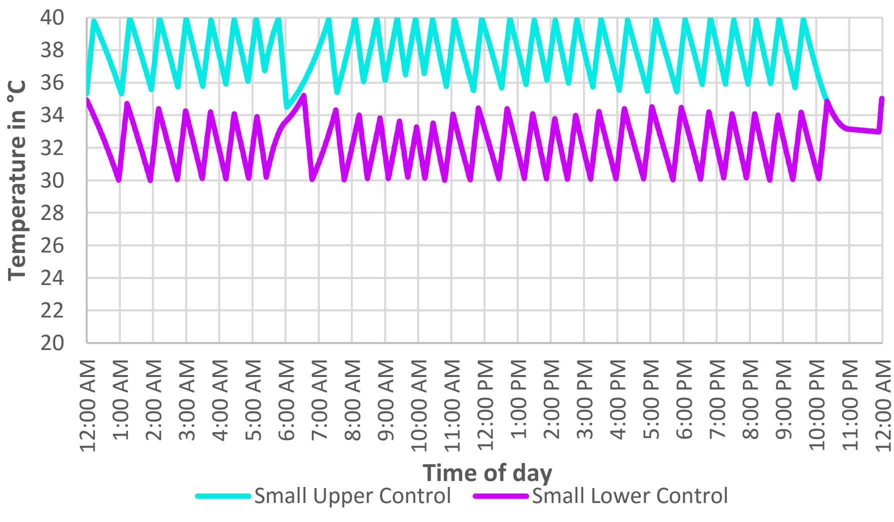

Figure 2: Temperatures of the hot water tank for the Small Upper Control and the Small Lower Control strategy

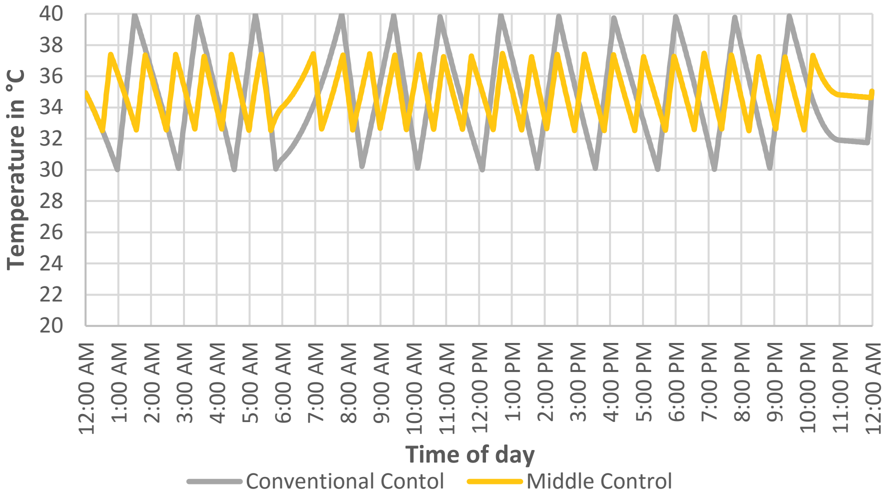

Figure 3: Temperatures of the hot water tank for the Conventional Control and the Middle Control strategy

Figure 4 depicts the positive flexibility for the *Small Upper Control* and the *Small Lower Control* during one day. These values, as well as the values for the negative flexibilities, are calculated by applying one control strategy for the whole day and deriving the resulting flexibilities for every timeslot. The application of the *Small Lower Control* leads to temperatures, which are always below the corresponding ones of the *Small Upper Control*. This results in higher positive flexibility values for the *Small Lower Control* as the timespan for heating up is increased when the temperature of the hot water tank is low. Between 5 a.m. and 6 a.m., both curves have a peak that is caused by a high heat demand during that time of the day. The negative flexibility of the *Conventional Control* and the *Middle Control* can be seen in Figure 5. The fluctuations of the *Middle Control* are generally smaller than the one of the *Conventional Control* and the negative flexibility is always greater than zero. In contrary to the positive flexibility the high heat demand during 5 a.m. and 6 a.m. results in relatively low values for the negative flexibility. As the temperature of the hot water tank at the end of the day has to be at a certain level (equal to the temperature at the beginning), the positive and negative flexibilities for all control strategies are converging towards zero.

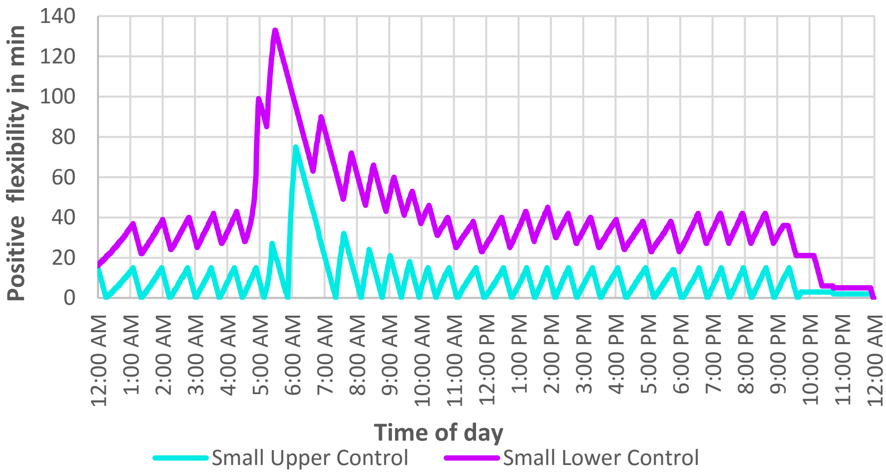

Figure 4: Positive flexibility for the Small Upper Control and the Small Lower Control strategy

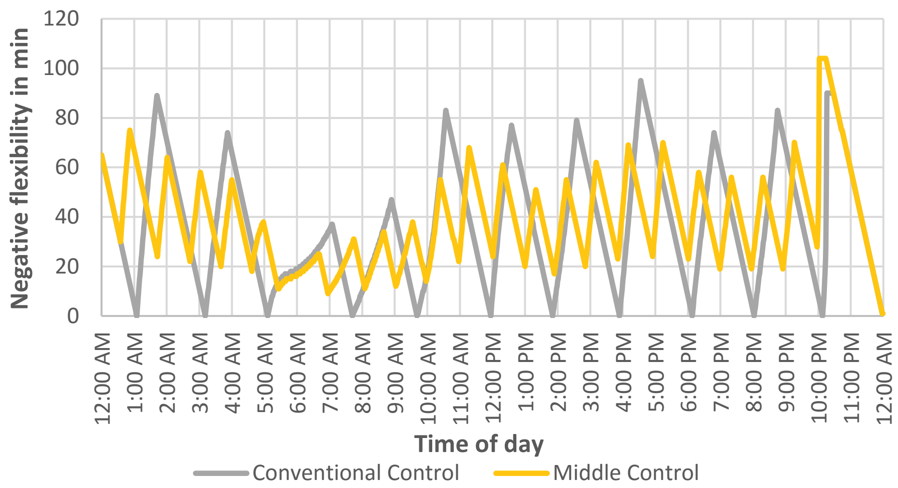

Figure 5: Negative flexibility for Conventional Control and Middle Control

2.2 Hot Water Tank

We choose a uniform temperature model for the hot water tank. This means that the temperature is homogeneous within the tank and there is no temperature stratification. To calculate the temperature changes we use an energetic difference equation (1) that is similar to the ones described in [10, 11].

$$T_{HWT}(t) = T_{HWT}(t-1) + \frac{Q_{Heating}(t) - Q_{Demand}(t) - Q_{Losses}}{V_{HWT} * \rho_{Water} * c_{Water}}, \forall t \in \{t_1, \dots, t_{end}\} \quad (1)$$

$$Q_{Heating}(t) = x(t) * P_{Electrical} * \Delta t * COP, \forall t \in \{t_0, \dots, t_{end}\} \quad (2)$$

$$T_{HWTmin} \leq T_{HWT}(t) \leq T_{HWTmax}, \forall t \in \{t_0, \dots, t_{end}\} \quad (3)$$

$$T_{HWT}(t_0) = T_{HWT}(t_{end}) \quad (4)$$

$T_{HWT}(t)$ is the temperature of the hot water tank at time t, V_{HWT} is the volume of the hot water tank, ρ_{Water} the density of water and c_{Water} its specific heat capacity. As seen in equation (2), the generated heat energy $Q_{Heating}(t)$ depends on the operation of the heat pump $x(t)$. Since the considered heat pump cannot be modulated arbitrarily between capacities, $x(t)$ is a binary variable that can only have the values 0 (indicating that the device is switched off) or 1 (indicating that the device is switched on) for every timeslot t. For calculating the generated heat energy, the constant electrical power $P_{Electrical}$ of the heat pump is multiplied by the constant COP (coefficient of performance) and the length of the timeslot Δt. For our calculations, we assume that the COP depends neither on the outside temperature nor on the temperature level of the hot water tank.

The generated heat energy increases the temperature of the hot water tank whereas the heat demand of the building $Q_{Demand}(t)$ and the constant losses Q_{Losses} of the tank decrease the temperature. The constraint in equation (3) ensures that the temperature of the hot water tank is newer below the lower temperature limit T_{HWTmin} and never higher than the upper temperature limit T_{HWTmax}. Whenever a thermal limit is reached, the heating device changes its operative mode to ensure that the limits are not violated. Due to the fact that the initial temperature level of the hot water tank significantly effects the temporal flexibilities we ensure that the temperature level $T_{HWT}(t_{end})$ of the last time slot t_{end} is equal to the initial temperature $T_{HWT}(t_0)$ level with equation (4). Thus, we eliminate biased values for the flexibilities occurring because of different temperature levels at the beginning and at the end of the day.

3 Results

A heat pump with an electrical power of 2500 W and a constant coefficient of performance of 4 is chosen for the analysis, which is in line with the analysis of Henning et al. [12]. The minimal running and standby times are set to 15 minutes. Although many heat pumps can have shorter minimal running and standby times, we choose this value to decrease the number of starts. We choose three different volumes for the hot water tank (300 litres, 400 litres, 500 litres) [8] and analyse their impact on the temporal flexibilities. The upper thermal limit is 40 °C and the lower limit is 30 °C. We assume the standing losses of the hot water tank to be constant at 75 W. The time resolution of the simulations is 1 minute. We use heat demand data generated by the tool *synPRO* [13] that has been developed by *Fraunhofer Institute for Solar Energy Systems (ISE)*. The resulting heat demand data was successfully validated against measured data of German single-family houses [13]. For our analysis, we choose a typical German single-family house with four inhabitants that was built after the year 2001 and whose energy efficiency level is high. The power of the heat pump was determined by scaling the heat demand of the building up to an outside temperature of -12° C. Since different weather conditions significantly affect the heat demand, we calculate the flexibilities for three days with different mean outside temperatures. A tool that requires the technical parameters and the heat demand profile of a day as inputs was implemented in Java to simulate and compare the different control strategies. As the flexibilities of each control strategy are converging towards zero at the end of the day, the last 30 minutes of the day were excluded for the following analysis.

Figure 6 illustrates boxplots for the positive flexibilities for the different control strategies and Figure 7 shows the corresponding negative flexibilities. For the calculation, we set the volume of the hot water tank to 300 litres and choose a day with an average outside temperature of 5 °C. The black line in the box is the median and the box spans the 25th and the 75th percentile. The median of the positive flexibilities for the *Small Lower Control* lies at 22 minutes and is more than three times higher than the median for the *Small Upper Control*. The values for the *Small Upper Control* range from 0 to 15 minutes whereas the maximal value for the *Small Lower Control* is 36 minutes and the minimal value is 10 minutes. The *Conventional Control* has the widest range of values, with the lowest being 0 and the highest being 36 minutes. Moreover, the *Conventional Control* yields the highest fluctuations. The median of the *Middle Control* and the *Conventional Control* are identical and approximately in the middle of the ones from the *Small Upper Control* and *Small Lower Control*. The *Middle Control* has a reduced range of values and a smaller standard deviation compared to the *Conventional Control*. By applying the *Small Lower Control* or the *Middle Control*, the positive flexibilities never reach zero meaning that there is always the possibility for the heating device to use electrical power to heat up the hot water tank.

The negative flexibilities are generally higher for this day compared to the positive flexibilities and the ranges of the values for all strategies are larger. The *Small Upper Control* has the highest median (48 minutes) and the *Small Lower Control* has the smallest one (16 minutes). As with the positive flexibilities, the *Conventional Control* and the *Middle Control* have the same median but the *Middle Control* has a smaller range and smaller fluctuations. The use of the *Small Upper Control* or the *Middle Control* never result in zero negative flexibility making it always possible to stop using electrical energy for a certain timespan when applying these strategies.

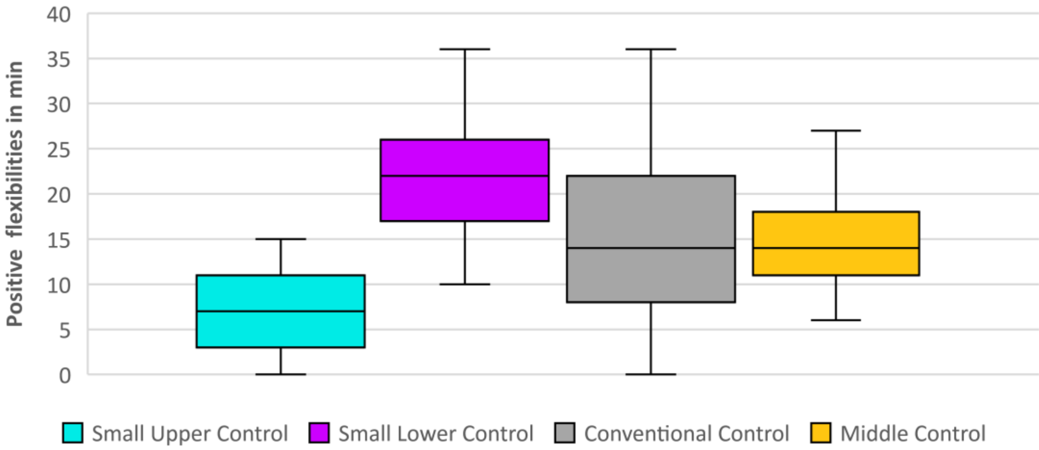

Figure 6: Boxplots for the positive flexibilities

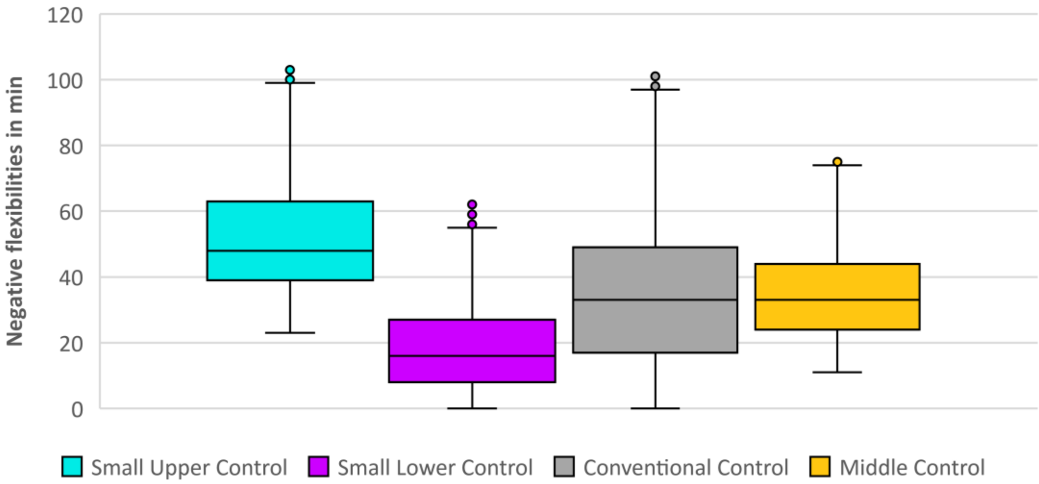

Figure 7: Boxplots for the negative flexibilities

The positive average flexibilities and the negative average flexibilities of three different days for a hot water tank with a volume of 300 litres are displayed in Figure 8 and Figure 9. The average positive flexibilities of all control strategies decrease with an increasing average outside temperature whereas the average negative flexibilities become higher. For the day with an average outside temperature of -5 °C, the average positive and negative flexibilities have similar magnitudes but for the other two days (with higher average temperatures), the negative flexibilities are generally higher. An increased outside temperature results in lower heat demand. Consequently, the hot water tank does not cool down as rapidly if the heating device is switched off leading to increased negative flexibilities. On the contrary, when the heat demand is relatively high the hot water tank can be heated up for a longer period without violating the upper thermal limit of the tank because of a reduced temperature increase. This results in higher values for the positive flexibilities. The average positive and negative flexibility of the *Conventional Control* and the *Middle Control* strategies are almost equal but the range and the standard deviation of the values for the *Middle Control* strategy is smaller.

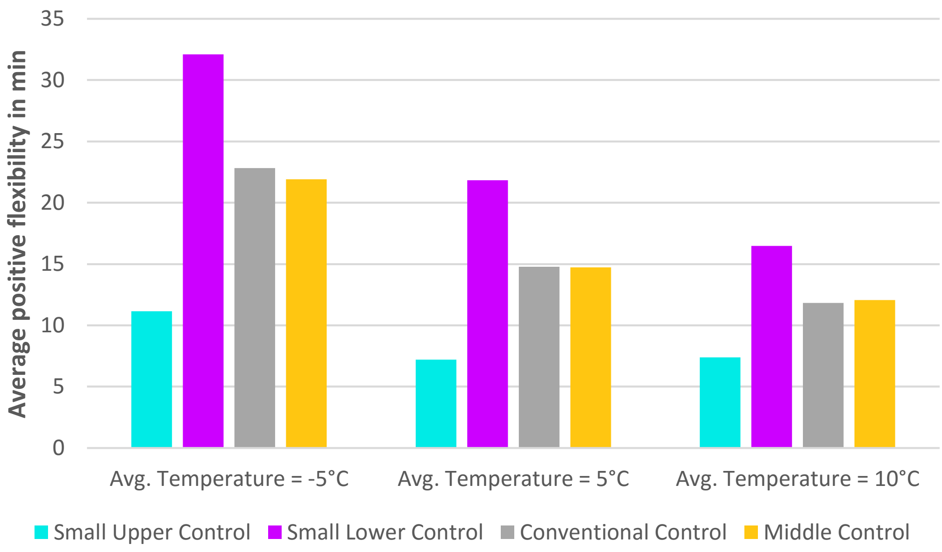

Figure 8: Average positive flexibilities for different days

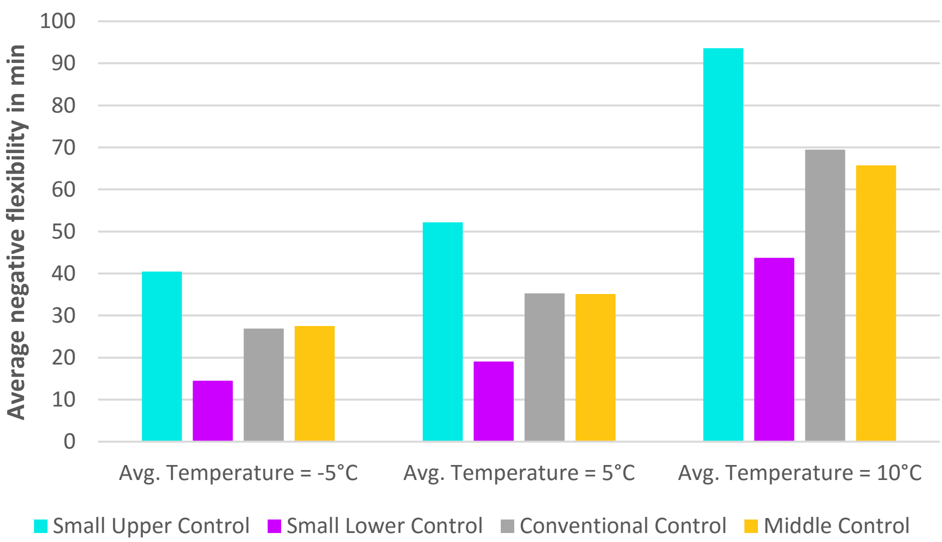

Figure 9: Average negative flexibilities for different days

Figure 10 and Figure 11 show the average positive and negative flexibilities of the control strategies for different hot water tank volumes. These values were calculated for the day with an average outside temperature of 5 °C. The volume of the hot water tank hardly effects the positive flexibilities of the *Small Upper Control* strategy whereas the positive flexibilities of the *Small Lower Control* strategy increase strongly when using a larger hot water tank. The negative flexibilities show the exact opposite results for those two strategies. Since the temperature in the tank is as close as possible to the upper thermal limit when applying the *Small Upper Control* strategy, an increased volume does not influence the maximal time for heating up the tank without violating the constraints. With a higher volume and the temperature being close to the upper limit, the time for switching off the heat pump and cooling down the tank is increased in a strong way. When the temperature of the hot water tank is as close as possible to the lower thermal limit (*Small Lower Control*) a higher volume significantly increases the time for heating up the tank as it can store more energy. However, the time for cooling down remains equal. The temperatures of the hot water tank when using the *Conventional Control* or the *Middle Control* strategy vary between the upper and the lower limit (the *Middle Control* has modified limits). Because of this, a larger volume increases both the positive and the negative flexibilities moderately for these two strategies.

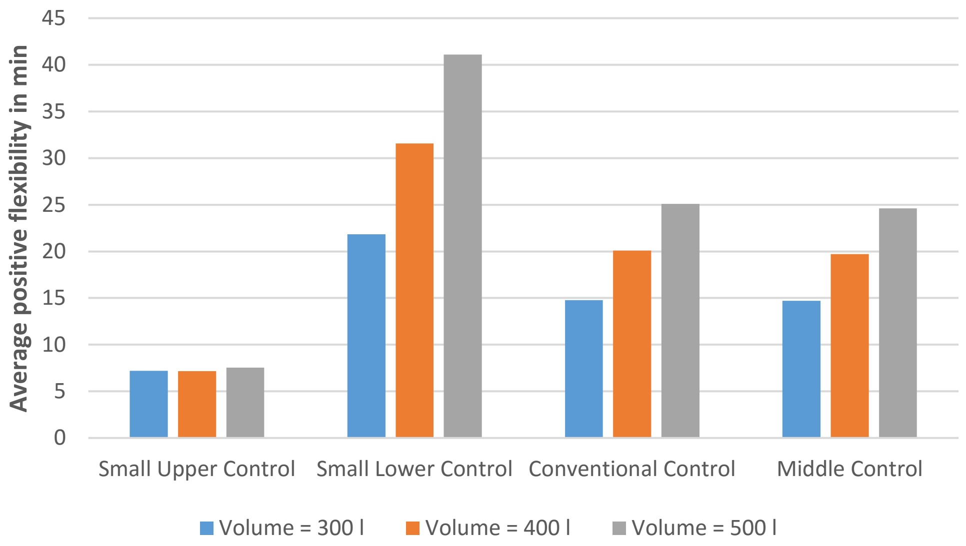

Figure 10: Average positive flexibilities for different volumes of the hot water tank

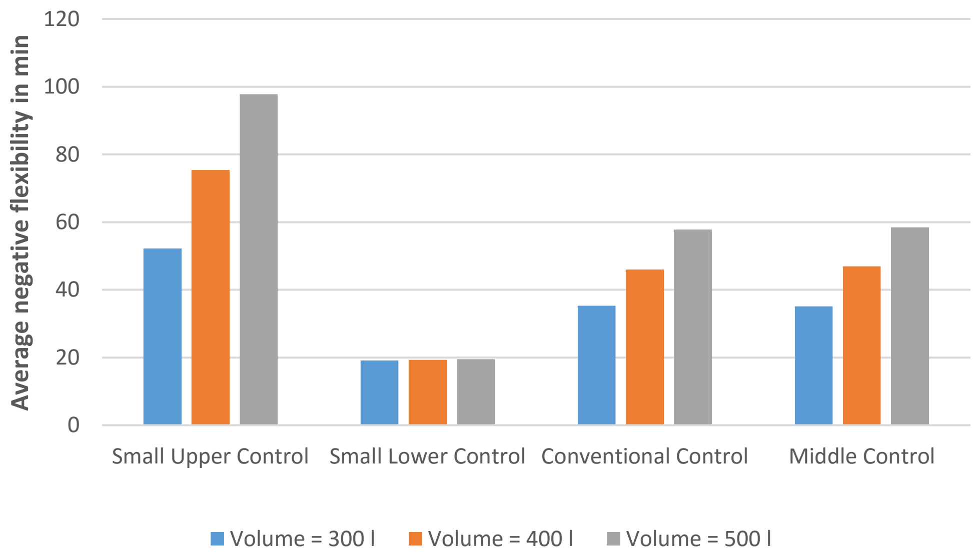

Figure 11: Average negative flexibilities for different volumes of the hot water tank

4 Conclusion and Outlook

In this study, we investigated the impact of four different control strategies (*Conventional Control*, *Small Upper Control*, *Small Lower Control*, *Middle Control*) for electrical heating devices coupled with a hot water tank on the temporal flexibilities of the system. We used a uniform temperature model for the hot water tank with no temperature stratification and an energetic difference equation to calculate the temperature changes of the tank. A typical German single-family house with a heat pump and a hot water tank was chosen for our analysis. For every timeslot of a day, we calculated the positive flexibility, quantifying the maximal timespan for heating up the hot water tank, and the negative flexibility, quantifying the maximal timespan for switching off the heating device without violating thermal constraints. The results show significant differences among the strategies. Not surprisingly, the *Small Upper Control* strategy leads to the highest average negative and to the lowest positive flexibility the application of the *Small Lower Control* strategy results in the highest average positive and the lowest negative flexibility. The average positive and negative flexibility for the

Middle Control and the *Conventional Control* strategy are almost equal whereas the *Middle Control* strategy yields decreased ranges and lower standard deviations for the values of the flexibilities.

For our analysis, we did not alter the strategy during the day to illustrate the differences between them. However, changing the strategies during a day can help reacting to intra-daily supply fluctuations. If high power output by the renewable energies is predicted for a certain time of the day, applying the *Small Lower Control* strategy before that period will result in high positive flexibilities of electrical heating systems. Central or decentral control units could exploit these flexibilities and increase the electrical load of the system during periods of high supply. If on the other hand very low generation by the renewable energies is forecasted, the use of the *Small Upper Control* beforehand will yield high negative flexibilities for the time when they are needed. In situations with rapidly changing demand or supply, it might be beneficial to apply the *Middle Control* strategy as it leads to nonzero positive and negative flexibilities that can contribute to balance demand and supply.

While this study merely considered one building for one day, future work can analyse the use of the described alternative control strategies for a residential area with different heating systems during longer periods. In this paper, we solely considered a hot water tank as the thermal buffer storage. However, underfloor heating systems serve as the buffer storage for the majority of heat pumps as they lead to higher efficiencies. The proposed model has to be slightly adjusted in order to make it applicable for underfloor heating systems. The energy demand for domestic hot water is playing an increasing role for buildings with a high energy efficiency standard. With decreasing demand for space heating, due to better insulation of the buildings, the share of energy needed for domestic hot water has heavily increased. Since heat pumps are primarily used for buildings with reduced demand for space heating, the combination of a buffer storage for space heating and for domestic hot water should be analysed. Moreover, the assumption of a constant efficiency for heat pumps is only justifiable for ground-source heat pumps. The *COP* of air-source heat pumps strongly depends on the outside temperature. This can be also taken into account in future work.

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