Flexibility Quantification for Building Energy Systems with Heat Pumps

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Abstract

Building energy systems (BES) are meant to become a potential flexibility resource for the electrical energy system in the future. In literature, different approaches for flexibility quantification are presented. Each of these approaches either uses specific input data (like price signals), simplifications in the calculation (e.g. constant COP of heat pumps(HP)) and/or does not account for the aggregation of flexibility. To identify the characteristic behavior of the HP systems, building performance simulations in Modelica are performed in this paper. The power flexibility is mostly influenced by the HP size and the domestic hot water (DHW) share. However, the energy flexibility is influenced by thermal energy storage (TES) size, minimum supply temperature and the ratio of TES losses to DHW demand. It can be concluded that the proposed method can be used to compare BES flexibility to other flexibility options on an aggregated level.

Introduction

In recent years, the installation and operation of power generators based on renewable energy sources (RES) has increased. Especially wind and photovoltaics (PV) have an intermittent and partially uncertain nature. This faces the electrical energy system with challenges to ensure high supply quality. To deal with the intermittency, sources of flexibility on different time scales are necessary (Makarov et al., 2012). Different measures for flexibility provision are possible. This ranges from classical electrical storage systems (e.g. batteries) to ramping capabilities of conventional power plants.

As the flexibility sources vary in their properties, it is necessary to quantify flexibility to achieve a comparability of the variety of flexibility options. Generally, different performance indicators for flexibility description are necessary (Lund et al., 2015). This includes power and energy flexibility indicators as well as the ramping capability. Here, a generalized framework from the electrical side is presented by (Ulbig and Andersson, 2015). The framework allows the aggregation of different flexibility options in terms of ramping capability, power and energy. Most of the flexibility options come with non-avoidable energy losses that need to be taken into account. This is the energetical cost for the integration of higher amounts of RES. Therefore, the analysis of losses should be included in a holistic evaluation of flexibility options.

Besides the changes in the electricity sector, a transition to a more sustainable energy system is also meant to develop in the building sector. Nonetheless, the building sector uses 34 % of the final energy in Germany (Ziesing et al., 2013). A high share of this energy consumption belongs to the heating sector. Therefore, the idea of integrating RES systems into the built environment via demand side management (DSM) has gained attention in recent years. Different studies show the opportunity to balance intermittent renewable energy generation with the controlled operation of e.g. heat pumps (HP) (Arteconi et al., 2013) (Müller et al., 2015). As this type of flexibility competes with other flexibility options, it is necessary to develop methodologies to quantify the maximum flexibility potential that can be achieved by building energy systems (BES). This is especially relevant since the flexibility provision of BES needs to take the coupling of electricity and heat into account. Consequently, further restrictions compared to electricity-only systems need to be considered.

Some quantification methods are already published in literature (e.g. (Reynders, 2015)(de Coninck and Helsen, 2016) (Le Dréau and Heiselberg, 2016)). In general, these methods are not developed to aggregate flexibility on a higher level. However, this is necessary for the electrical energy system as single buildings can only contribute with a limited amount of flexibility. Furthermore, the flexibility quantification in some of the recent works relies on the provision of outer signals like prices. Additionally, the proposed methods for flexibility quantification on the BES side often simplify the influence of heat generator characteristics on the flexibility that can be provided. Especially for HP, the operation in a flexible environment influences the coefficient of performance (COP) and thus also the available power flexibility. Three major influencing factors on the power characteristics can be identified:

- Thermal energy storage (TES) heat losses

- Changing source temperatures, especially in case of an air-source HP
- Increasing sink temperatures during the TES charging process

In literature, a method for flexibility quantification on an aggregated level was proposed (MacDougall et al., 2013). Here, a constant TES capacity and a constant COP for HP systems are assumed. In another work, the flexibility aggregation of a HP pool is presented (Fischer et al., 2016). This study bases on the reaction on HP systems on different trigger signals. The resulting flexibility is therefore not a general measure for flexibility. A method for temporal, power and energy flexibility quantification and the aggregation potential of flexibility is shown by (Stinner et al., 2016). However, the COP of HP systems was kept constant in their case study.

The following work will extend the proposed methods of (Stinner et al., 2016) to evaluate the flexibility of HP systems. It is only used for the quantification of flexibility for BES with technical TES. The use of building thermal mass is out of scope of this study. Firstly, we will introduce the general methodology of flexibility quantification. Afterwards, the usage of building performance simulation (BPS) and the used models in Modelica are presented. In the case study, we perform a parameter variation to present several different influencing factors on both power and energy flexibility. Additionally, the potential losses of flexibility provision and the aggregation of flexibility indicators on a higher level are addressed.

Methodology

Flexibility calculation

The flexibility calculation is based on the methodology described in (Stinner et al., 2016). In general, two types of flexibility are analyzed. This is the forced and the delayed flexibility (Six et al., 2011) (Nuytten et al., 2013). Herein, temporal, power and energy flexibility can be calculated as it is shown for a charging and discharging process in figure 1. In the top figure, the reference operation and the flexible operation are shown. Reference operation can be any type of operation that is normally used to satisfy the heat demand of the building. Both operation profiles refer to electrical power values. The negative sign implicates the operation of a HP according to (Stinner et al., 2016). As we can see from the top figure, the electrical power is at its maximum absolute value during forced operation (time intervals from t_1 to t_2 and from t_3 to t_4). For illustration reasons, the maximum power is set to constant in this example. However, the maximum power curve is potentially not constant due to changing environmental conditions (source/sink temperatures).

In the middle of figure 1, the relative storage content is shown. The forced temporal flexibility determines the time the HP needs to charge the TES completely

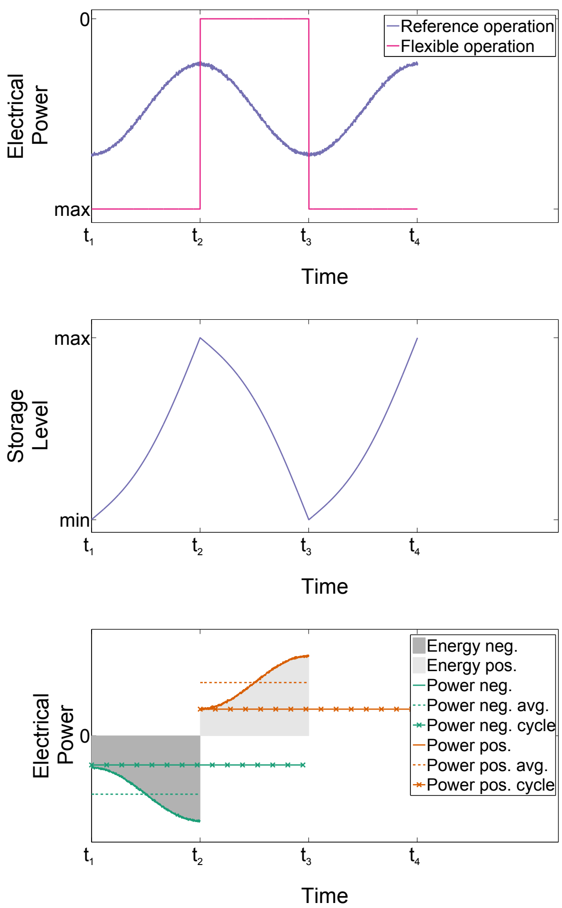

Figure 1: General principle of the different flexibility indicators.

from a discharged state at the beginning. Accordingly, the delayed temporal flexibility (time interval from t_2 to t_3) is the time the TES can supply the building with heat until the storage is completely discharged. During this time period, the electrical power of the HP is at the minimum.

In the lower part of the figure, different power and energy flexibility indicators are illustrated. Generally, the positive and negative power curves are derived from the difference of flexible and reference operation. For HP systems, forced flexibility is corresponding to negative flexibility and delayed flexibility is equivalent to positive flexibility. The integral below these power curves results in the energy flexibility that is available in the respective direction per cycle. It can be directly assigned to the corresponding starting point of the interval.

For the power flexibility curves, the interpretation of the results is more complicated. The shown calculation in the lower part of figure 1 can be performed starting at each time step t around the year. When analyzing seasonal fluctuations, the visual analysis of thousands of these curves is impossible. To get a good overview over the flexibility in a seasonal context, the average of the power flexibility is calculated and assigned to the start point of the interval. This is point t_1 and t_3 for the forced flexibility intervals in figure 1 and t_2 for the delayed flexibility interval. Additionally, the cycle power flexibility is calculated taking also the opposite part of operation into account. The cycle power flexibility is the average power flexibility that can be delivered in one direction (positive or negative) when considering that the TES needs to be recovered before it can be used again in the same direction. For forced power flexibility, it is exemplarily calculated as the average flexibility between t_1 and t_3 which includes one charging and one subsequent discharging process. The full negative energy flexibility in this period is divided by the time period between t_1 and t_3. Compared with this, the cycle power flexibility for the positive direction is exemplarily calculated in figure 1 with the time period between t_2 and t_4. Here, the positive energy flexibility is divided by the whole period of discharging and recharging. This flexibility indicator is especially important if the relation of forced and delayed temporal flexibility changes during the year. Thus, the time to recover the storage level in both directions needs to be taken into account. Detailed formulas and explanations of the single flexibility indicators can be found in (Stinner et al., 2016).

The efficiency of flexibility provision can be determined by the relative deviation of the negative to the subsequent positive energy flexibility. The building heat supply is the same for reference and flexible operation and the storage content is the same before forced and after delayed operation. Thus, if the electrical energy consumption during forced flexibility operation is higher than the savings in the following negative energy flexibility, it can be directly related to electrical losses.

Modelling

The BPS used in this study is performed in Modelica. Here, the building physics can be coupled to heat generators, TES systems and heat distribution. As the goal of this study is the flexibility quantification for BES on an aggregated level, the computational effort needs to be reduced. Thus, the building physics are modelled with a low order model in this work (Lauster et al., 2014). All building parts are represented with a limited amount of capacities and resistances. These parameters can be directly calculated from the building geometry (including sizes and material properties) with the parameterization tool *TEASER* (Remmen et al., 2016).

Besides the building physics, the technical equipment is modelled with the library *FastHVAC* (Stinner et al., 2015). This library includes models for HP, TES and radiators for heat distribution. All models do not include pressure-based information which reduces the computational effort as there is no hydraulic coupling. The nominal heating power of the HP ($\dot{Q}_{\mathrm{HP,nom}}$) is the maximum thermal power that is kept constant for all operation points. The COP of the HP is calculated based on the source temperature and the resulting supply temperature of the heating system:

$$\mathrm{COP} = \xi \cdot \frac{T_{\mathrm{sink}}}{T_{\mathrm{sink}} - T_{\mathrm{source}}} \tag{1}$$

The quality grade ξ describes the ratio of real HP systems in comparison to an ideal Carnot cycle (Zogg, 2009). Additionally, the source temperature T_{source} and the sink temperature T_{sink} are used for the COP calculation. Only air-source HP systems are considered in this work which results in the outdoor air temperature as source temperature. In equation 1, the sink temperature is equivalent to the HP supply temperature. The supply temperature increases during a charging process due to the rising temperature in the TES. As the flexibility calculation itself is performed in a post-processing step, a relation of TES content and supply temperature is calculated for all charging processes. In this work, the maximum thermal power output is assumed to be constant. Hence, the maximum electrical power at each point in time only depends on the COP.

A central element for the flexibility calculation is the TES. Its model is a one-dimensional discretization which is described in detail in (Huchtemann, 2015). From the storage model, the dynamic storage capacity can be obtained as described in (Stinner et al., 2015)(Stinner et al., 2016). Firstly, the TES energy content at each point in time is calculated (Dincer, 2002)(Rosen and Hamzeh, 2006):

$$Q(t) = \sum_{i=1}^{n} \rho \cdot c_P \cdot \frac{V_{\text{TES}}}{n}(T_i(t) - T_{\text{ref}}) \qquad (2)$$

In this equation, the density ρ and the specific heat capacity c_P are assumed constant. $\frac{V_{\text{TES}}}{n}$ describes the layer volume and $T_i(t)$ is the temperature of layer i. The reference temperature T_{ref} can be chosen freely as the energy content is normalized with the minimum storage content around the year. Afterwards, the difference in the energy content during one storage cycle (charging and discharging) is calculated. This is assigned to the temporal midpoint of the storage cycle. Between these points, the dynamic storage capacity is interpolated.

Besides the models for building physics and technical equipment, different input data sets are necessary. Firstly, weather data from test reference years is used as input for the heat demand and COP calculation (Deutscher Wetterdienst DWD, 2011). Secondly, user behavior profiles (especially DHW profiles) are necessary. These profiles are generated randomly to prevent the system from interacting with the same heat demand profile for different variations (Schiefelbein et al., 2014)(Schiefelbein et al., 2015).

Relative characteristics

To compare the flexibility indicators for BES with different heat demand, several flexibility indicators and parameters need to be expressed as relative figures. Firstly, the dimensionless capacity of a HP (α_{th} is expressed as follows:

$$\alpha_{\text{th}} = \frac{\dot{Q}_{\text{HP,nom}}}{\dot{Q}_{\text{building,nom}}} \qquad (3)$$

$\dot{Q}_{\text{building,nom}}$ is the maximum average thermal demand per hour, considering both the space heating and DHW demand. Additionally, in design phase, the relative thermal power related to space heating $\alpha_{\text{th,SH}}$ is used:

$$\alpha_{\text{th,SH}} = \frac{\dot{Q}_{\text{HP,nom}}}{\dot{Q}_{\text{SH,nom}}} \qquad (4)$$

Here, $\dot{Q}_{\text{SH,nom}}$ represents the maximum thermal demand for space heating per hour.

Furthermore, the TES volume can be expressed relatively to the heat demand.

$$\nu_{\text{th}} = \frac{V_{\text{TES}} \cdot n_{\text{days}}}{Q_{\text{SH}} + Q_{\text{DHW}}} \qquad (5)$$

Here, the TES volume V_{TES} is calculated relative to the daily heat demand consisting of space heating and DHW demand. Comparable to the HP capacity, the TES volume is only related to the demand for space heating in the design phase:

$$\nu_{\text{SH}} = \frac{V_{\text{TES}} \cdot n_{\text{days}}}{Q_{\text{SH}}} \qquad (6)$$

All flexibility indicators can also be scaled to make them comparable to each other. The power flexibility indicators are related to the maximum power in the heat demand (space heating + DHW):

$$\alpha_{\text{el}} = \frac{\pi_{\text{flex}}}{\dot{Q}_{\text{building,nom}}} \qquad (7)$$

π_{flex} is a placeholder for all power flexibility indicators (average/cycle and positive/negative). Consequently, the energy flexibility is related to the daily heat demand of the building (space heating + DHW):

$$\beta_{\text{el}} = \frac{\epsilon_{\text{flex}} \cdot n_{\text{days}}}{Q_{\text{SH}} + Q_{\text{DHW}}} \qquad (8)$$

Again, ϵ_{flex} can be replaced by any energy flexibility indicator.

If the TES capacity in terms of energy is addressed, it can also be related to the daily heat demand of the building:

$$\beta_{\text{th}} = \frac{Q_{\text{stor,avg}} \cdot n_{\text{days}}}{Q_{\text{SH}} + Q_{\text{DHW}}} \qquad (9)$$

Case study

Description

In the following, we will analyze a detailed case study with a parameter variation. Two different building types are analyzed. This includes a single family dwelling (SFD) and a multi family dwelling (MFD) with eight apartments. Both building types are calculated with three different insulation standards to generate different seasonal characteristics of the heat demand profiles. DHW profiles are generated according to German statistics about the persons living in single apartments (Federal Statistical Office, 2012). For each building type (SFD and MFD), three types of DHW profiles are generated. The first profile corresponds to 25 liters per day and person, while the second and third profiles corresponds to 37.5 and 50 liters per day and person, respectively. As the necessary DHW temperature is a crucial point that influences the amount of flexibility for HP systems, the influence is investigated with the variation in the minimum storage temperature at the top of the storage between 45 °C and 60 °C. Weather data is used from German test reference years for the region 5 (Essen/Germany) (Deutscher Wetterdienst DWD, 2011). Both the TES and heat generator size are varied. For the TES size, the relative volume ν_{SH} is set to 0.02, 0.08 and 0.14 $\frac{m^3}{kWh}$. The HP is sized to the maximum space heating demand per hour with factors $\alpha_{\text{th,SH}}$ of 2 and 4 to investigate the influence of the heat generator size on the flexibility indicators. In total, we generate 216 variations that are analyzed in detail in the following.

Results

Power flexibility

Figure 2 shows the positive and negative average power flexibility for three of the 216 variations. For

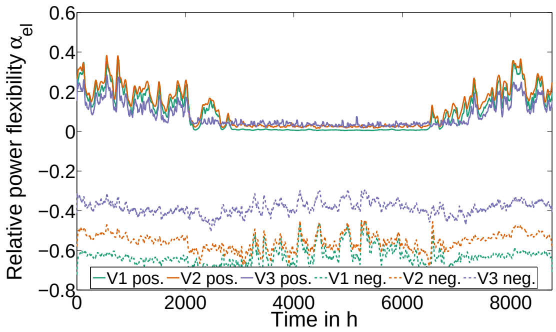

Figure 2: Three different variations of relative power flexibility.

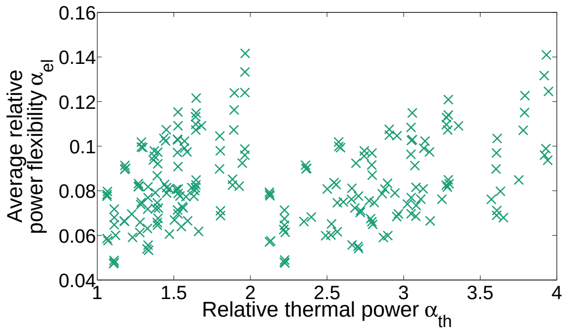

Figure 4: Influence of the relative thermal power on the average positive power flexibility.

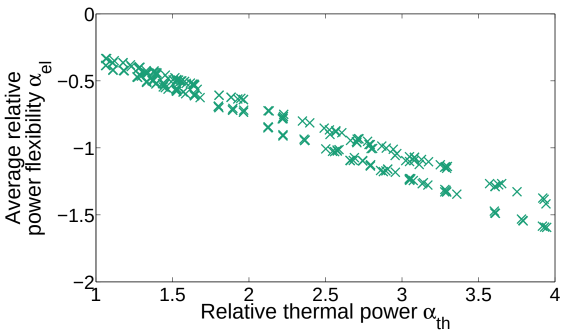

Figure 3: Influence of the relative thermal power on the average negative power flexibility.

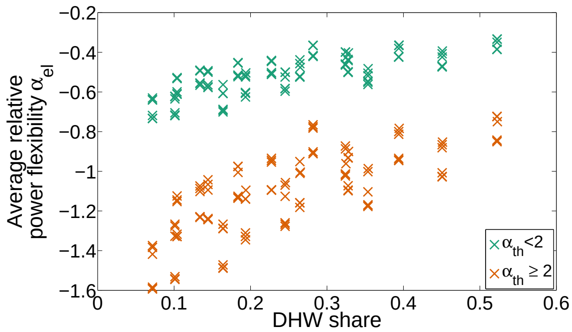

Figure 5: Influence of the DHW share and the minimum temperature on the average negative power flexibility.

the power flexibility of HP systems, various types of characteristics can be observed in the different variations. Three main aspects are shown in this figure. Firstly, the negative power flexibility level is higher than the positive power flexibility level. Secondly, the level of the power flexibility profile differs from variation to variation (especially for negative power flexibility). Thirdly, the seasonal fluctuations in power flexibility between summer and winter is differently distinct (especially for positive power flexibility).
These three effects are further analyzed for all variations in the following. The average of the negative power flexibility curves in figure 2 is calculated for all variations and compared to the relative thermal power of the HP in figure 3. As we can see, there is a strong linear relation between the negative power flexibility and the heat generator size which is expectable as a higher thermal power of the HP corresponds to a higher surplus electrical power during operation compared to the reference case.
However, for the positive power flexibility, the HP size has no observable influence on the power flexibility as it is shown in figure 4.
In addition to the HP size, the share of DHW at the total heat demand has a noticeable influence on the average power flexibility. For negative power flexibility, it is shown in figure 5. With increasing DHW share, the average power flexibility is decreasing. As figure 5 shows, relative thermal power has still a superior influence on the average negative power flexibility.
For positive flexibility, the influence of the DHW share is also noticeable as shown in figure 6. With increasing DHW share, the relative power flexibility is decreasing. This is caused by the fact that the ratio of average heat demand power and maximum heat demand power is decreasing with high DHW shares. As the positive power flexibility is coupled to the heat demand curve, this relation needs to be taken into account. Additionally, the positive power flexibility is higher with a minimum temperature of 60 °C compared to variations with a minimum temperature of 45 °C. This results from a lower COP and thus higher electrical power when generating the same amount of heat.
As shown in figure 2, differences in the deviation between summer and winter can be observed especially for positive power flexibility. Figure 7 demonstrates that this is mostly due to the DHW share. The higher the DHW share, the lower is the ratio between summer and winter flexibility. This is caused by the low seasonal dependency of DHW demand compared to space heating demand. The positive power flexibility depends directly on the heat demand. Hence, the reduced seasonal variation in heat demand with higher DHW share directly translates to reduced seasonal variations in power flexibility. The ratio between win-

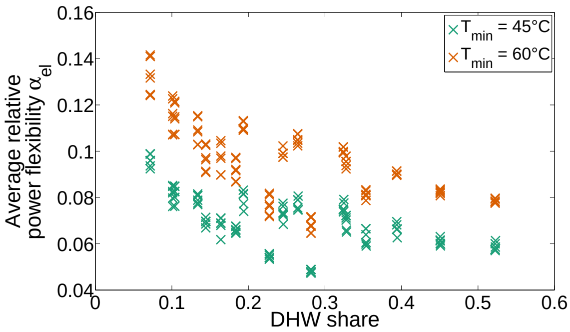

Figure 6: Influence of the DHW share and the minimum temperature on the average positive power flexibility.

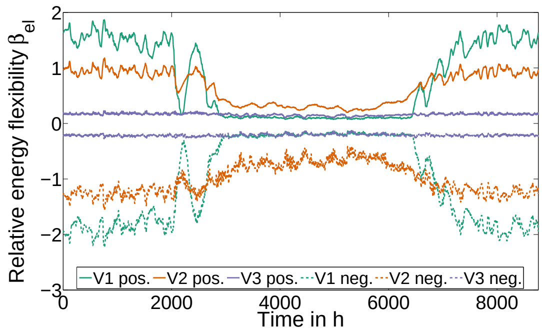

Figure 8: Energy flexibility per cycle for three different variations.

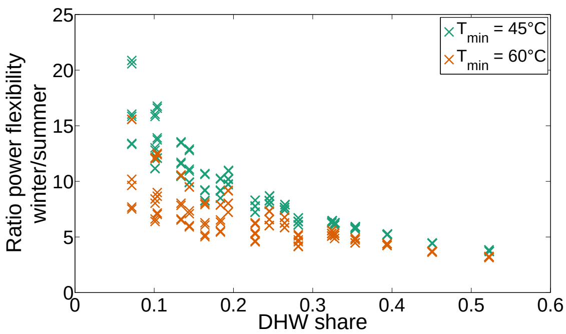

Figure 7: Influence of the DHW share on the ratio between winter and summer positive power flexibility.

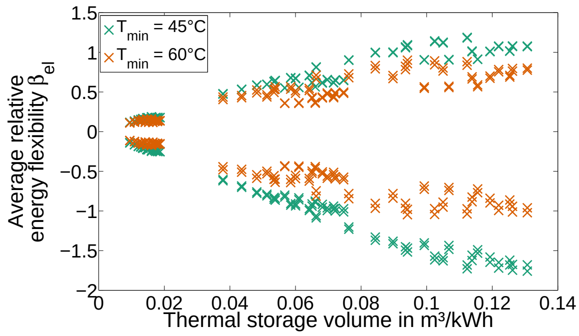

Figure 9: Influence of the storage volume on the positive and negative energy flexibility per cycle.

ter and summer is lower for systems with a high minimum temperature compared to the variations with lower minimum temperatures. This can be explained by the lower ratio of the COP from winter to summer in case of a higher sink temperature.

For negative power flexibility, the deviations between winter and summer are much lower and no clear influencing factor can be found. Thus, the values are not shown here.

Energy flexibility

Additionally to power flexibility, energy flexibility and thus storage capacity plays a major role when analyzing flexibility indicators of BES. Figure 8 shows the energy flexibility per cycle for three variations. Similarly to the power flexibility, different characteristics in the energy flexibility curves can be observed. Firstly, the level of relative energy flexibility is different for all shown variations (both positive and negative energy flexibility). Secondly, the variation in energy flexibility between summer and winter is noticeably different for all variations. Thirdly, negative energy flexibility values are higher than positive energy flexibility values.

Analyzing the general level of energy flexibility, we can see a clear relation of the relative TES volume and the negative energy flexibility as figure 9 shows. Additionally, the minimum supply temperature plays a major role. When analyzing systems with a minimum supply temperature of 60 °C, the negative energy flexibility is noticeably lower than for systems with a minimum supply temperature of 45 °C. For the positive energy flexibility, a similar influence on a slightly lower level can be observed. Both the storage volume and the difference of maximum temperature and minimum supply temperature influence the TES capacity. Thus, it is obvious that these two factors influence the energy flexibility both during charging (negative) and discharging (positive) the TES.

In figure 8, the difference of energy flexibility during the seasons is different for all variations. This is mostly due to the dynamic storage capacity that can be extracted from the BPS. It is shown for the same three variations in figure 10. We can observe a high ratio between storage capacity in winter and summer for variation 1, while it is rather low for variation 2 and near one for variation 3. Variation 3 even shows a slightly higher thermal storage capacity in summer. In the following, we will analyze the reasons for this noticeably different behavior.

In general, there are two major influencing factors on the ratio between winter and summer storage capacity and thus flexibility. These are shown in figure 11. One major influence is the ratio of TES losses to the DHW demand. Only the TES losses that are necessary to provide the flexibility are taken into account. First, it needs to be mentioned that the return tem-

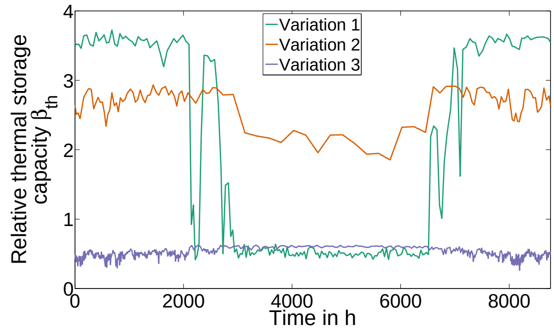

Figure 10: Dynamic thermal storage capacity for three variations.

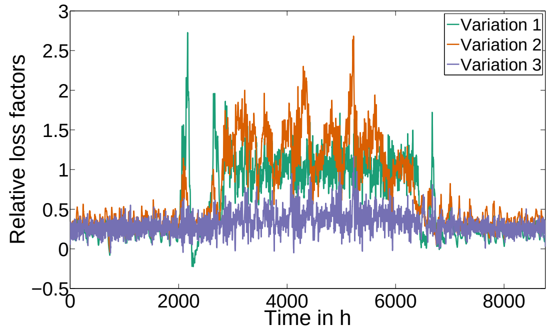

Figure 12: Maximum losses per cycle for three variations.

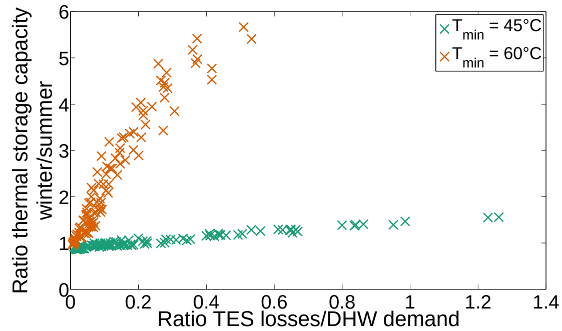

Figure 11: Influence of the ratio of TES losses to DHW demand on the ratio between winter and summer storage capacity.

perature of the DHW cycle is quite low with 15 °C. When discharging the TES with this temperature, a lower energy content and thus a deeper discharge is possible. If the TES losses dominate the discharging of the TES, the return temperature of the DHW cycle does not play a major role. In this case, the whole TES is mostly cooling down caused by losses. This cool-down process leads to a more uniform temperature distribution in the TES compared to a discharging process driven by the heat demand. As figure 11 shows, the minimum supply temperature plays a major role for this effect. When analyzing systems with a minimum supply temperature of 60 °C, the ratio between winter and summer storage capacity strongly increases with dominating TES losses. The reason for this is the short period of time that is necessary to reach the minimum supply temperature of 60 °C. In this time, the TES cannot be discharged enough with the low return temperature of the DHW cycle. However, with a minimum supply temperature of 45 °C, a much slighter increase in the ratio between winter and summer storage capacity can be observed. Even for higher ratios of TES losses to DHW demand the DHW cycle can still discharge the storage with the low return temperature.

Electrical losses

When analyzing the energy flexibility of different variations, we can observe higher absolute values for negative energy flexibility than for positive energy flexibility in figure 8. This discrepancy is caused by the unavoidable losses during the charging process of the TES. The losses differ from variation to variation as figure 12 shows. At a few points in time, even negative values for losses can be observed. This is reasonable as the reference operation was not planned according to an optimized operation in terms of energy efficiency. Thus, in times the flexibility would be used in a favorable time period with high outdoor air temperatures and replaces the electricity consumption in a much less favorable time period, even negative losses can be calculated. Additionally, the losses during summer time are noticeably larger than during winter time. This can mainly be explained by the lower heat demand in summer. This extends the periods of discharging and generally the TES losses are more dominant. For summer times, the values lie above 1 which means that the double amount of energy would be necessary if this flexibility is used. The losses are always related to a full cycle of charging and discharging the TES. If a lower share of the TES was used, the losses would also be reduced.

As figure 12 shows, the level of losses is different for the three variations. Here, a distinction between summer and winter times needs to be made. The losses in summer highly depend on the ratio of TES losses to the DHW demand as figure 13 shows. This is reasonable as the TES losses can directly be considered as an additional heat demand that needs to be covered. Again, only the TES losses related to flexibility are considered as only these cause the flexibility losses.

For winter times, the TES losses are compared to the total heat demand. As shown before, the losses rise with an increasing share of TES losses compared to the heat demand which is presented in figure 14.

Aggregation

The aggregation of flexibility values is an important point as single buildings can only contribute with a

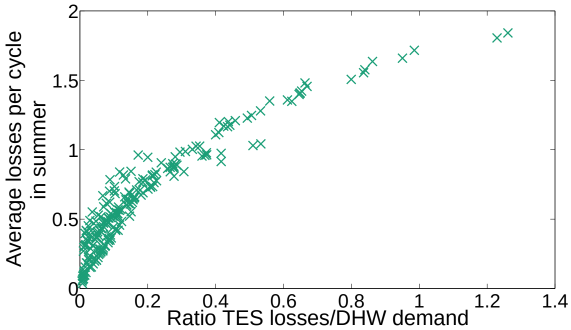

Figure 13: Influence of the ratio of TES losses to DHW demand on the losses in winter.

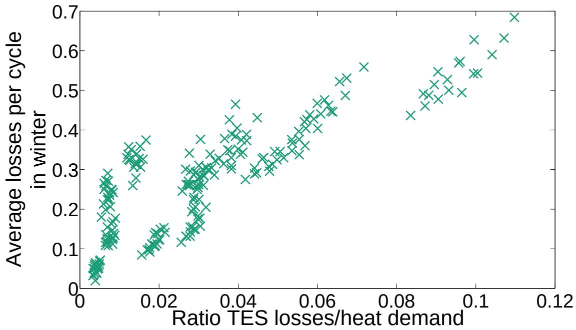

Figure 14: Influence of the ratio of TES losses to heat demand on the losses in winter.

minor amount of power and energy. In this work, all proposed flexibility indicators can be added up to get the aggregated flexibility of a city district, a region or the whole country. Figure 15 shows the absolute values for average power flexibility and energy flexibility per cycle. Three different curves are shown for each direction and flexibility indicator. Variation 1 offers a high power flexibility especially for the negative direction. However, the energy flexibility of this variation is rather limited both for positive and negative direction. In contrast, variation 2 offers a lower amount of power flexibility, but a noticeably higher amount of energy flexibility. When aggregating the flexibility of these two BES, the new aggregated system shows both the high power flexibility of variation 1 and the high energy flexibility of variation 2. This procedure can be repeated for an unlimited number of BES on the desired level.

Discussion

With the case study, several different influencing factors on power and energy flexibility of BES could be identified. In general, both the level of power and energy flexibility and the seasonal fluctuations vary noticeably for different analyzed variations. The HP thermal power is found to be the main influencing factor on the negative power flexibility. This is not surprising as the thermal power is directly related to electrical power via the COP. Nonetheless, the re-

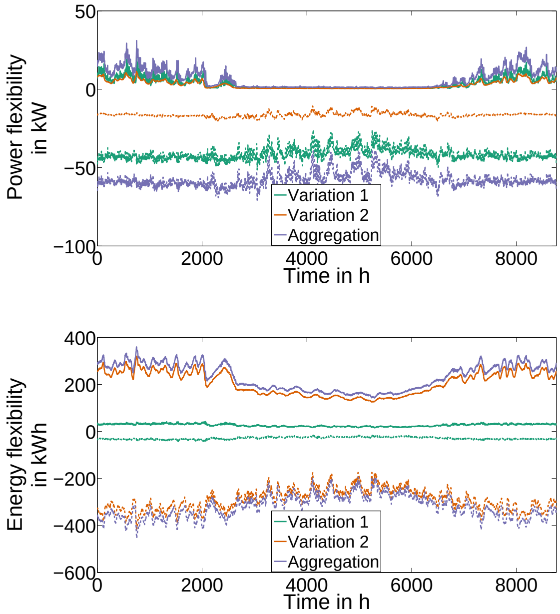

Figure 15: Aggregation of power and energy flexibility for two types of BES.

lation between thermal capacity and negative power flexibility can be quantified. For energy flexibility, the TES size is the major influencing factor on the average level of flexibility that can be provided. That holds both for positive and negative energy flexibility. Additionally, the minimum supply temperature for the BES plays a major role. The higher the minimum supply temperature is, the lower is the capacity as the temperature lift in the storage is more restricted.

Seasonal fluctuations in the different flexibility indicators are directly related to the DHW demand of the BES. For power flexibility, the DHW share plays a major role as it influences the seasonal fluctuations for positive and negative power flexibility. The higher the DHW share at the total heat demand is, the lower are the seasonal variations in the reference operation. Therefore, both the positive and the negative power flexibility have lower seasonal fluctuations. Regarding energy flexibility, the ratio of TES losses to DHW demand is an important input factor. With higher TES losses compared to the DHW demand, the TES discharging process is dominated by the losses and therefore a deep discharge is not possible. This influences directly the dynamic storage capacity and therefore positive as well as negative energy flexibility.

Especially the influencing factors on the dynamic storage capacity show the importance of BPS in the context of flexibility quantification. The seasonal variations can hardly be covered by methods that do not use BPS. Additionally, the relation of actual storage content and HP flow temperature is carried out from the BPS. This allows to analyze the influence of the COP on flexibility indicators in detail. Several different input factors directly influence the flexibility options of a BES. Not all of them are directly obvious, as the example of the dynamic storage capacity calculation shows.

In this work, the calculation of losses due to flexibility provision is introduced. Generally, the values for losses are very high as shown in figures 12,13 and 14. Especially during summer, the losses reach values that are above 1 which means that more than double the energy would be used if this flexbility option is considered. Here, the ratio of TES losses to the DHW demand plays an important role. The losses that are expressed in this work seem very high compared to publications where the operation of HP systems is adapted to e.g. dynamic price signals. The reason for this is that the full usage of flexibility is assumed. Thus, the shown values are the maximum losses that can occur. In real applications, a user of this flexibility might not utilize the full flexibility. Then, the lower values found in other publications will be reached. However, the analysis and comparison of the loss factors for different BES is important. It can demonstrate potential barriers for further flexibility usage as these losses are related to cost in the end. Especially configurations with generally high loss factors should potentially not be considered for flexibility provision.

Finally, the aggregation of flexibility indicators is addressed. A combination of one system with high power flexibility and another system with high energy flexibility is demonstrated. This can result in an aggregated system that unifies the positive properties from both systems. However, it can be observed that the positive power flexibility is hardly influenced by design parameters like the HP thermal power. Thus, it depends mostly on the time-resolved heat demand of the building. When aggregating the flexibility to a higher level, this strong relation to the heat demand remains even if the power in absolute numbers increases. Therefore, it can be beneficial if the scalable negative power flexibility of HP systems is accompanied with other flexibility options that can more easily provide higher amounts of positive power flexibility, e.g. combined heat and power (CHP) plants. The positive power flexibility of CHP plants can be directly influenced by the CHP size as shown in (Stinner et al., 2016).

Conclusion

This paper has shown a methodology to analyze the operational flexibility of BES with HP systems. The core for flexibility quantification is the usage of BPS which helps to analyze seasonal fluctuations in operational flexibility. Especially power and energy flexibility are analyzed in detail. Additionally, the losses of flexibility provision and the aggregation potential are addressed. Several influencing factors on the flexibility could be identified. Here, the HP capacity and the DHW share influence the level and the seasonal variation of power flexibility. The TES volume, the minimum supply temperature and the ratio of TES losses to DHW demand influence the level and seasonal variation of energy flexibility.

With the presented approach, it is possible to compare the flexibility of BES on an aggregated level to other flexibility options like battery storages. Here, the seasonal dependency of flexibility provision for the BES needs to be taken into account. Additionally, the restricted provision of positive power flexibility of HP systems is a crucial point.

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