SIMULATION AND ANALYSIS OF DEMAND SIDE MANAGEMENT EFFECTS ON OPERATING BEHAVIOUR AND EFFICIENCY OF HEAT PUMP SYSTEMS

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Abstract:
Increasing variable renewable electricity generation in Germany challenges the German electricity supply in terms of mismatch between supply and demand as well as grid capacity. Increasing the flexibility of electricity demand is a suitable measure to provide reliable future energy supply. Within the scope of Demand Side Management (DSM) heat pumps are able to contribute in terms of demand flexibility (Nabe, Hasche et al. 2011). Currently over 500,000 electrical compression heat pumps (HP) provide a potential for DSM in Germany with a positive market trend (Gorris, Stawiarski et al. 2011). Whereas static load shedding for heat pumps is state-of-the-art, concepts for dynamic load shifting still need to be developed. This simulation study has been performed to examine the impact of a smart heat pump control in a single family house regarding efficiency and potential for operating time optimization. To adapt the operating time the set temperature for both of the implemented buffer storages (room heating and domestic water heating) is raised. The smart control is influenced by a residual load based external signal. Grid stability and grid capacity are not focused within the present study.

Key Words: Demand Side Management · heat pumps · load shifting · smart grid · thermal energy storage

1 INTRODUCTION

The climate protection goals of the German government have led to a rapid increase of wind and solar electricity generation. In July 2013 34,600 MW installed solar power and 30,500 MW installed wind power have been connected to the German power grid (Burger 2014). During peak times in 2013 power production reached 23,100 MW (solar) and 23,300 MW (wind) (ibd.). Peak consumption in Germany typically leads to loads above 70,000 MW, whereas electricity consumption averages around 50,000 MW (ENTSOE 2013). These numbers illustrate the increasingly high impact of renewable electricity generation on the overall electricity generation in Germany. On the one hand existing grid capacity has been temporarily exhausted; on the other hand a low trading price of electricity has led to a rather paradoxical market situation (Mayer, Kreifels et al. 2013).
Solar and wind electricity output varies throughout the year. During monthly periods overall solar and wind power production complement each other, whereas daily and hourly electricity generation is highly intermittent, depending on weather conditions and the time of day. Solar power is produced only during the daytime (with cloudless sky having a maximum at noon), whereas wind power is not dependent on the time of day.
Different measures are able to compensate intermittent electricity generation. Better adjustability of conventional energy production, an increased flexibility of electricity demand and the expansion of storage capacity are suitable measures to provide the basis for the integration of renewable energy generation while having a reliable energy supply. Electrical driven heat pump systems facilitate increased demand flexibility since thermal storage

capacity, like building mass or buffer storages in the hydraulic system, provide the ability to shift operating time. In Germany over 450,000 heat pumps with an electrical capacity of 1,700 MW have been installed until 2011 (BDH, BWP et al. 2012). It is expected that in the year 2020 a total of 1.2 million heat pumps with an electrical capacity of 3,600 MW will be installed (ibd.). A study by the Federal Ministry of Economics and Technology (Nabe, Hasche et al. 2011) has recognized a significant Demand Side Management (DSM) potential of heat pump systems (HPS). Along with further potential analysis there is a need for research and development regarding communication, market models and the impact of DSM on HPS (ibd.).

2 GOALS OF THE STUDY AND CONCEPTIONAL FRAMEWORK

The present paper focuses on the evaluation of effects caused by DSM-measures in a typical German combination of an air-to-water heat pump system installed in a new single family house with low heating energy demand. An external signal provokes shifting heat pump operation to periods of electricity production by intermittent renewables. Between operating periods of the heat pump thermal storage is needed. There are two different approaches to store thermal energy. As mentioned in (Hong, Johnstone et al. 2012) one solution consists in activating thermal storage capacity in the masses of the building. In the second approach, which is applied in the present study, the capacity of the buffer storage for room heating and of the buffer storage for heating the domestic water is exploited by applying higher storage temperatures corresponding to a given DSM-signal. The required increase of the sink temperature in the heat pump system inevitably reduces the heat pump's efficiency and increases the storage losses. Based on simulations of different scenarios (in terms of control and components sizing) over the period of a year the additional electricity consumption is calculated and compared to the achieved load shifting. The examination of the introduced exemplary heat pump system does not consider issues concerning the electric grid. The control of several HPS connected to one branch in the electric grid is evaluated in (Toersche, Bakker et al. 2012) and (Tanaka, Yoza et al. 2012). The impact of DSM controlled heat pumps installed in an area where the buildings (102 households) are only supplied by electricity is put in concrete terms by (Nykamp, Molderink et al. 2012). The simulation shows that grid costs would increase up to 70 % with an inappropriate control (synchronized reaction to price signals) due to resulting extra costs on the grid side for additional and stronger dimensioned assets and decrease by 10 % with an optimal integration of heat pumps.

3 MODEL DESCRIPTION

3.1 Heat Pump System

In Figure 1 the scheme of the examined HPS is given and Table 1 summarizes the key parameters. The basic model connects an ambient air-to-water heat pump, an electrical back-up heater and two parallel installed buffer storages – one for room heating (BS-H) and one for domestic water heating (BS-D). Domestic water is heated up by using a fresh-water station connected to BS-D. Room heating is realized by using an underfloor heating connected via a mixing type circuit to BS-H.
The single family house (SFH) is a RC (resistances and capacities) model based on (Norm DIN EN ISO 13790:2008). It is parameterized according to the SFH60 IEA test reference building (Streicher and Heimrath 2003). The floor heating model is based on a validated thermo-active building component (TABS) model (Koschenz 2000) and is parameterized according to (Norm DIN EN 1264-3:2009). For both storages a 5-zone buffer storage model is used and the parameters affecting the specific storage losses are parameterized with field

test measurement data of a buffer storage with a volume of 1 m³. The model of the fresh-water station consists of a simple (constant effectiveness) heat-exchanger model and a pump by which the daily course of the energetic domestic hot water demand is realized in accordance to (Norm DIN EN 16147:2011) (profiles S, M and L).

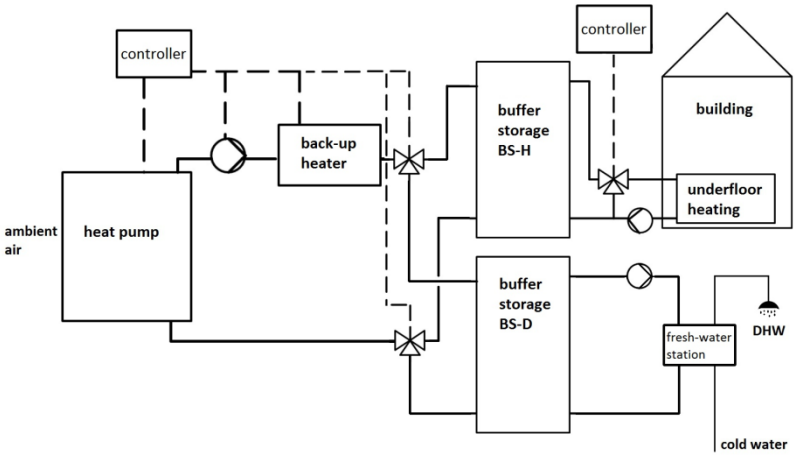


Figure 1: Hydraulic scheme of the simulated heat pump system

The heat pump quasi steady state performance map model is based on the Yearly Utilization Model describing the heating power and the COP related to the temperature of the sink circuit and the ambient temperature (Afjei 1989); (Haller, Bertram et al. 2012). It is parameterized with characteristic curves from manufactures measured under European standard EN 14511 test conditions (Norm EN 14511-2:2012). Additionally, dynamic behavior is considered in simplified terms by thermal mass of the condenser and the evaporator. The simple electrical back-up heater model with an efficiency of $\eta = 0.98$ is implemented in the heat pump flow line to the buffer storages. The heat pump and electrical back-up heater work in parallel as soon as the ambient temperature drops below -6 °C. The electric back-up heater is stepped up in three stages related to the ambient temperatures. The capacity of the heat pump is determined according to the heating demand at bivalence temperature and the heating power needed for domestic water heating. As climate region Potsdam is chosen. Potsdam is the reference city in German standards in terms of climate data. In the study the weather data is retrieved from the German Weather Service (data set TRY zone 4) (DWD 2010).

Table 1: Key parameters of the simulated standard model

Key parameter	Value	Unit
Heat pump: heating power	5.4	kW
Heat pump: COP	3.7	-
Room temperature set point	20	°C
Room heating demand	51.3	kWh/(m²*a)
Domestic hot water demand	5.1 (13.1)	kWh/d (kWh/(m²*a))
Back-up heater: electrical power	3 * 670 = 2010	W
Back-up heater: efficiency	98	%
Heated area	140	m²
Heating period	October 1 – May 31	-
Buffer storage (room heating)	0.5	m³
Buffer storage (domestic water heating)	0.3	m³
Note: The heating power of the HP is given according to EN 14511 at 2 °C ambient temperature, 35 °C flow temperature from the HP and 5 K temperature spread in the condenser.		

3.2 Control Strategy

Two control systems are separately regulating the floor heating and the heat pump operation. In the heating circuit a three-way valve mixes water from the buffer storage and floor heating return to keep the average room temperature permanently at 20 °C. The second controller regulates the heat pump and the electrical back-up heater. The temperature at the bottom of the buffer storage BS-H (hereafter referred to as buffer storage temperature) is controlled according to a heating curve (cf. Figure 2). The hysteresis is set to +/- 2 K. The set value for the temperature at the bottom of the buffer storage BS-D is fixed to 53 °C with a hysteresis of +/- 3 K.
In order to store heat for the purpose of DSM the storage capacity should be enlarged. Therefore the respective set value of both of the storages is raised - if requested. The degree of the temperature raise depends on the DSM-signal. In the following chapter the DSM-signal in general and the linkage to the temperature raise is introduced.

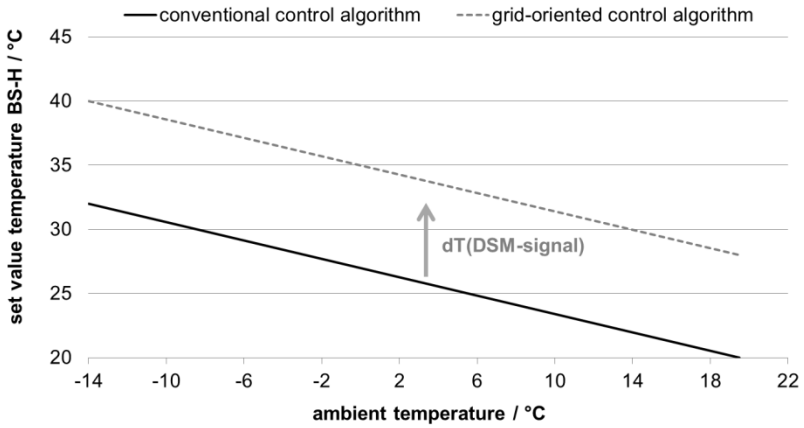


Figure 2: Adaption of the heating curve to support heat storage during low DSM-signal values

3.3 Residual Load and DSM-signal

In Germany no DSM-signal for enabling demand side management with heat pumps in residual buildings has been established. Hence, a DSM-signal is generated for the use in this study – developed on the basis of the DSM-signal applied in the previous study (Miara, Leitner et al. 2013). The DSM-signal is based on the residual load (RL), which is defined as the load minus the electricity generated by intermittent renewable energies. Thus, it represents the remaining load which has to be covered by conventional power plants or non-fluctuating renewable energies. The general goal is to balance the RL in order to enable the increase of the renewable energy share and decrease the continuously provided capacity of conventional power plants. The residual load for 2012 is retrieved from the EEX transparency platform (Transparency 2013). For the RL 2023 the same grid load as in 2012 is considered, however upscaled electricity generation is integrated according to scenario B2023 in (Feix 2013): capacities of 49,300 MW for wind on shore and 14,100 MW for wind off shore as well as 61,300 MW for PV.
The DSM-signal is generated on a daily basis. The method of determination takes three aspects into consideration:

- daily course of RL (residual load curve daily normalized between +/- 0.5 (DNRL))
- daily bandwidth of RL in relation to all other days (normalized daily bandwidth of RL (F1))

- level of RL in relation to yearly course (normalized daily average value of RL (F2))

The daily (d) factors F1 and F2 of one day (i) both for 2012 and for 2023 are calculated based on the course of the RL in 2023. This approach accounts for the fact that in 2023 the need of DSM measures is higher than in 2012.

(1)

(2)

The DSM-signal is calculated in each time step (j) by multiplying the normalized (N) arithmetic average value (F3) of the factors F1 and F2 of the day (i) by the value of DNRL in the specific time step (j). This means that the daily level of the RL in the course of the year has the same impact as the daily bandwidth of the RL.

(3)

Figure 3 displays the average daily course of the DSM-signal and the bandwidth for 2012 and for 2023. Periods with negative values imply beneficial operating time and obversely periods with positive values adverse operating times. In 2012 negative values occur primarily during the night between 22:00 and 05:00 because the RL is still mainly influenced by the load curve and less by the intermittent renewable energies. The DSM-signal reaches maximal value once during morning hours and second during evening hours. The influence of photovoltaic electricity generation decreases the average DSM-signal slightly below zero during late noontime. Compared to 2023 the bandwidths of 2012 are significantly smaller. This is a consequence of the chosen approach for determining the DSM-signal which reflects the increase of intermittent renewable energies from 2012 to 2023. Not only the bandwidth but also the shape of the average daily course of the DSM-signal change from 2012 to 2023. The average DSM-signal reaches its daily minimum at noontime due to the increased influence of photovoltaic energy generation. Consequently, besides the night-time a second period arises when the heat pump can contribute to adapt electricity demand to electricity production by extending the operating time in these periods.

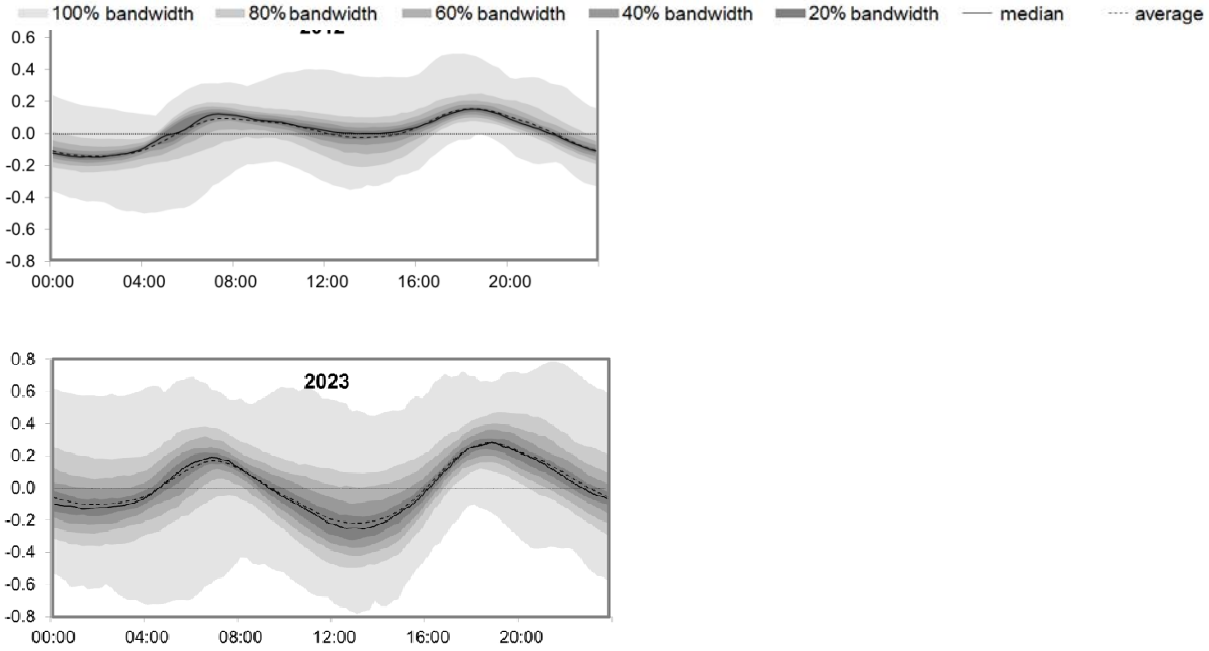


Figure 3: Average and bandwidth of the DSM-signal as a function of the daytime for 2012 and 2023

The assignment of the DSM-signal to the smart control strategy is displayed in Figure 4. While the DSM-signal is positive the conventional control algorithm is applied whereas a grid oriented control algorithm is applied when the DSM-signal is negative. In the grid oriented control algorithm the set points for the storages are raised by a value being inversely proportional to the DSM-signal. The raise of the set point of BS-H and BS-D differ. Due to the fact that the set point for BS-D is higher than the one for BS-H in the conventional control, the maximal raise for BS-D is less since the maximal operating temperature of the heat pump is limited. In the figure referred to, the DSM-signal of 2012 (dark line) and 2023 (grey line) are sorted by the value in ascending order. As previously mentioned the DSM-signal covers a wider range of values in 2023 as in 2012. Consequently the raise of the set value is less in 2012 than in 2023 and accordingly the load shifting potential is less due to lower available storage capacity. Considering 98 % of the time period when grid oriented control algorithm is applied in the year 2012 the raise of the BS-H set value (BS-D set value) amount up to 10 K (4 K) whereas in the year 2023 up to 19 K (6 K) are realigned.

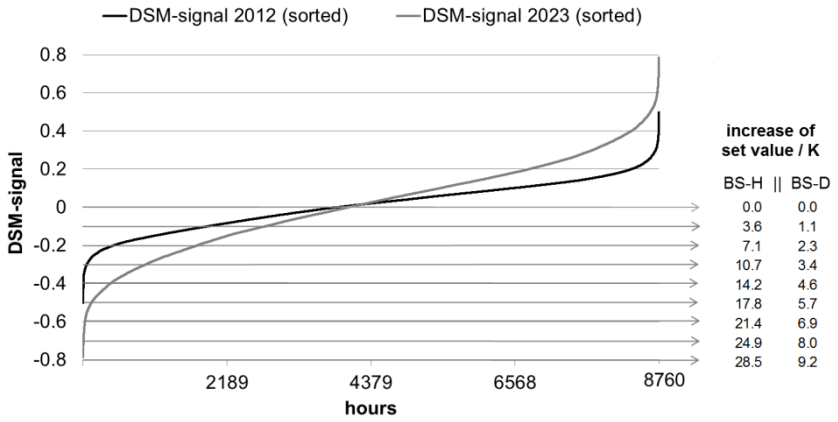


Figure 4: Sorted annual course of the DSM-signal in 2012 and 2023 and allocation of the rise of the set point temperature

4 ANALYSIS APPROACH

Six different control respectively system scenarios are presented, being simulated for both 2012 and 2023. Initially a basis scenario with conventional control and standard sized components is given. In four of the five smart controlled scenarios the smart control is applied to both storages as described in chapter 3. These scenarios differ in terms of the size of BS-H and size of the heat pump. In the fifth scenario the raise of the set point is realized only for BS-H; BS-D is controlled conventionally. Table 2 summaries the key figures of all of the scenarios and introduces the denominations used in chapter 5. The denomination describes the type of control strategy, the year of the residual load, the nominal thermal heat pump capacity and the buffer storage size.

Table 2: Descriptions and denominations of all the simulated scenarios

Scenario	Control	Heating power	Buffer storage	Residual load
C_2012_5.4_0.5	conventional	5.4	0.5	2012
S-H_2012_5.4_0.5	smart	5.4	0.5	2012
S-HD_2012_5.4_0.5	smart	5.4	0.5	2012
S-HD_2012_5.4_2.0	smart	5.4	2.0	2012
S-HD_2012_10.8_0.5	smart	10.8	0.5	2012
S-HD_2012_10.8_2.0	smart	10.8	2.0	2012

C_2023_5.4_0.5	conventional	5.4	0.5	2023
S-H_2023_5.4_0.5	smart	5.4	0.5	2023
S-HD_2023_5.4_0.5	smart	5.4	0.5	2023
S-HD_2023_5.4_2.0	smart	5.4	2.0	2023
S-HD_2023_10.8_0.5	smart	10.8	0.5	2023
S-HD_2023_10.8_2.0	smart	10.8	2.0	2023
Note: S-H: rise of set point only regarding the buffer storage for room heating (BS-H) S-HD: rise of set point regarding both buffer storages				

The load shifting potential depends on the one hand on the heating power of the heat pump and the current heating demand and, on the other hand, on the available storage capacity, which is determined by the storage volume and the overheating temperature difference. The buffer storage volume required to enable load shifting for at least six hours as a function of heating power and overheating temperature difference is shown in Figure 5. For the simulated HPS with an average heat demand of approximately 3 kW and an overheating temperature difference of 10 K, a 1.6 m³ buffer storage volume is needed. A typical single family house HPS is not equipped with such a storage volume. Therefore for BS-H an ordinary buffer storage size of 0.5 m³ and a large scaled one with 2 m³ are chosen for simulation. The sizing of BS-D is adjusted to the maximum daily heating demand for the domestic water heating and typical DHW storage sizes.

heating power / kW

temperature difference / K	2.0	2.5	**3.0**	3.5	4.0	5.0	6.0	7.0	8.0	9.0
5	2.5	3.1	3.8	4.4	5.0	6.3	7.5	8.8	10.0	11.3
6	2.0	2.5	3.0	3.5	3.9	4.9	5.9	6.9	7.9	8.9
7	1.6	2.0	2.4	2.8	3.3	4.1	4.9	5.7	6.5	7.3
8	1.4	1.7	2.1	2.4	2.8	3.5	4.2	4.8	5.5	6.2
10	1.1	1.3	**1.6**	1.9	2.1	2.7	3.2	3.7	4.3	4.8
12	0.9	1.1	1.3	1.5	1.7	2.2	2.6	3.0	3.5	3.9
14	0.7	0.9	1.1	1.3	1.5	1.8	2.2	2.6	2.9	3.3
16	0.6	0.8	0.9	1.1	1.3	1.6	1.9	2.2	2.5	2.8
18	0.6	0.7	0.8	1.0	1.1	1.4	1.7	1.9	2.2	2.5
20	0.5	0.6	0.7	0.9	1.0	1.2	1.5	1.7	2.0	2.2

minimal buffer storage volume / m³

Figure 5: Required buffer storage volume as a function of the heating power demand and the overheating temperature difference in the buffer storage

Another limiting factor for the ability of a HPS to realize load shifting is the heat pump capacity. At low ambient temperatures the load shifting potential is limited because long operating hours are required to cover the load. For raising ambient temperature the load shifting potential increases due to decreasing heating load on the one hand and increasing heat pump capacity on the other hand. In this study, two heat pump designs are considered. For the standard design the heat pump capacity is chosen according to the heating demand for room heating and domestic hot water at the design point (cf. chapter 3.1). Additionally a double sized heat pump (hereafter referred to as large HP) is considered in some of the simulation scenarios. This enables not only more flexible operating hours on days with high heating demand but also reduces the operating time required for heating up the storage. Hence short periods with beneficial DSM-signal could be used to a greater extend.

5 SIMULATION RESULTS

5.1 Operating Times for Conventional HPS

In order to explain the influence of smart control on load shifting the operating time of a conventional controlled heat pump (C_5.4_0.5) and the course of residual loads in the power grid are examined. Figure 6 displays the average DSM-signal (c.f. chapter 3.3) for 2012 and 2023 as well as the frequency of the operation in the course of the day. The solid black line represents the operation for both operating modes – room heating and DHW - together and the solid grey line the operation for room heating mode only.
The amount of operating during DHW mode seems to be quite high in respect to the fact that the annual heating energy demand for room heating is four times as much as for DHW. This effect is caused by two reasons. On the one hand the period under consideration comprises a whole year and therefore includes periods without room heating demand. On the other hand the heating power of the heat pump is smaller for higher heat sink operating temperatures as it occurs during DHW mode needing longer operating time to generate the same amount of heat.
In the course of the day, the time periods with high frequency of heat pump operation and low frequency of room heating mode occurring at the same time are conspicuous. This characteristic is caused by the priority of the DHW mode. The comparison to the course of the average DSM-signal reveals that the operation periods of the conventional controlled heat pump are unfavourable from the DSM's point of view. In particular, the high frequencies of operation during the morning and evening have a negative effect. On the other hand the - albeit smaller - peak of the DHW mode at midday coincides with a minimum of the DSM-signal caused by the PV generation in particular in 2023.

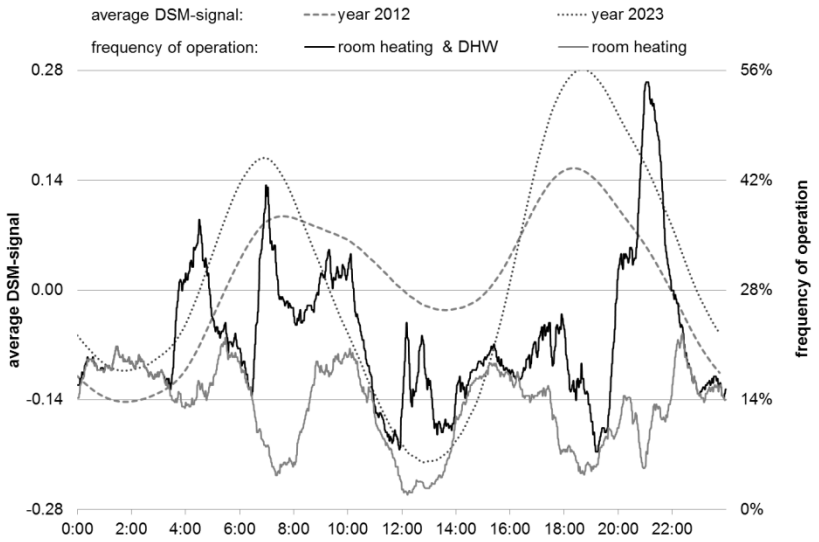


Figure 6: Frequency of operation for a conventional controlled heat pump (C_5.4_0.5) and average DSM-signals for 2012 and 2023 in the course of the day

5.2 Load Shifting Potential and System Efficiency in 2012

The main results of the different scenarios are displayed by the optimization of the operating time on one hand and the concomitant increase of the electric energy demand on the other hand. The increase of the electric consumption is engendered by both the decrease of the heat pump's efficiency and the increased storage losses. Figure 7 shows the yearly electric energy consumption of each scenario (cf. Table 2), subdivided by different DSM-signal level

ranges in which the electricity is consumed (from 1 (very beneficial) to 8 (adverse)). The hatched sections (1 to 4) designate the energy used during time periods having a beneficial DSM-signal (<0). Due to the characteristic of the DSM-signal (cf. Figure 6) in the year 2012 the section 2 and 7 are attained very rarely and the sections 1 and 8 never. The allocation of the energy to the different sections illustrates – as mentioned in chapter 5.1– that the distribution of the operating time in case of the conventional control is adverse in tendency. No more than 40 % of the total electric energy consumption is needed while the DSM-signal is negative. Within this beneficial period the signal predominantly amounts to more than -0.2 (34 % of the total electric energy is consumed in this period) and only rarely to less (6 % of the total electric energy is consumed in this period).

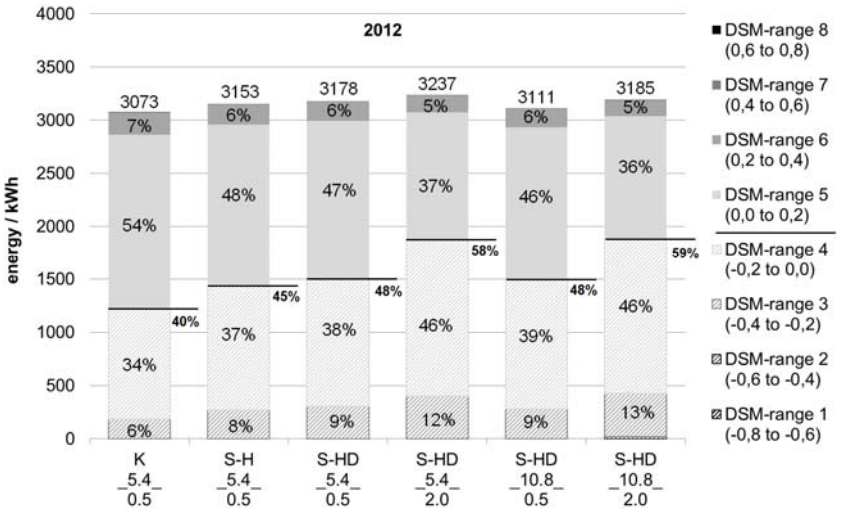


Figure 7: Electricity consumption (total value and allocation to the different DSM-signal sections) of the scenarios for the year 2012

The scenarios with smart control realize the desired load shifting to the beneficial sections as demonstrated in Figure 7. The goal of load shifting is achieved in different degrees. Even if the dimensioning of the system is not changed, a positive effect is arising due to the smart control. 45 % of the energy is consumed during beneficial time periods in the scenario S-H_2012_5.4_0.5, where only BS-H is included in the smart control and 48 % if additionally BS-D is used for load shifting (S-HD_2012_5.4_0.5). A significant increase of load shifting is achieved by enlarging the size of storage. The larger buffer storage BS-H (2 m³) extends the operating time during time periods with negative DSM-signal to 58 % (S-HD_2012_5.4_2.0). The installation of a larger heat pump is barely expedient. The load shifting is similar to the one with the standard heat pump if the standard storage size of 0.5 m³ is chosen and only little enlarged if a 2 m³ buffer storage is used. These results reveal that for the conditions considered in these scenarios not the operating time needed to heat up the buffer storage (induced by the heating power) is the limiting factor for the feasible load shifting but the available storage capacity, which is made up of the size of the storages and the defined temperature raise (cf. Figure 4). Increasing the storage capacity, the heating power gains influence on the obtainable load shifting.

Demand side management measures lead in all scenarios to positive effects but also to higher electricity consumption. Figure 8 displays the relative increase of electricity consumption for all scenarios in relation to the electricity consumption of the conventional system. The increase of the electric consumption is caused by the decrease of the HP's efficiency (due to higher operating temperatures on the heat sink side) and the increase of storage heat losses (higher temperatures in the buffer storage and bigger buffer storage as

the case may be). Table 3 summaries the SPF of the heat pump and the storage losses coming along with the respective scenario.

Table 3: Heat losses of the storages BS-H and BS-D as well as the SPF (annual value) and the E1 value (degree of exploiting the optimum) of the scenarios in 2012

Scenario	Storage loss BS-H [kWh/a]	Storage loss BS-D [kWh/a]	SPF	E1
C_2012_5.4_0.5	137	833	3.24	-
S-H_2012_5.4_0.5	193	833	3.18	13%
S-HD_2012_5.4_0.5	193	847	3.16	19%
S-HD_2012_5.4_2.0	435	847	3.19	42%
S-HD_2012_10.8_0.5	222	848	3.22	13%
S-HD_2012_10.8_2.0	491	847	3.24	33%

Note: Both of the storages are situated outside the thermal envelope of the building at a temperature being equal to the room temperature. The seasonal performance factor (SPF) includes the components of the heat pump system as specified in EN 14511 for the measurement of the COP and the back-up heater.

In order to describe the benefit (load shifting) so that it can be compared with the effort (increased electric consumption) the characteristic parameter K1 is defined (Equation 4). It indicates at which level of the DSM-signal the electricity is consumed in average. The lower the value of K1, the more beneficial is the realized load shifting.

(4)

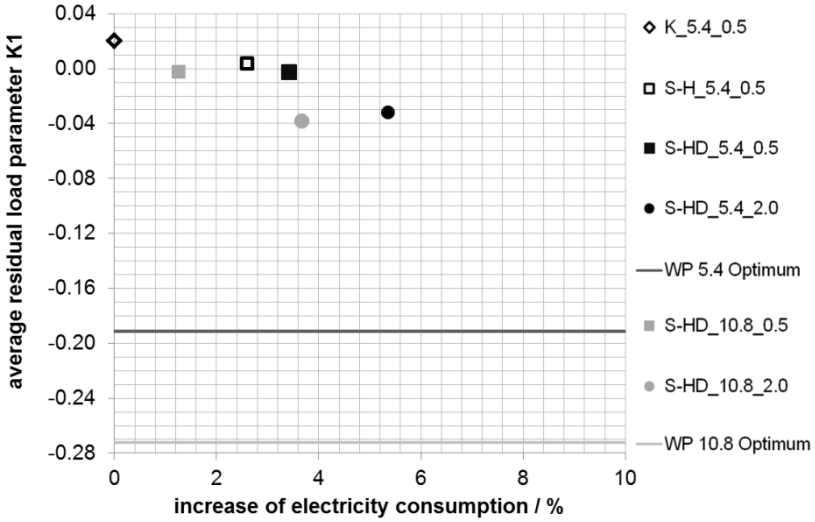


Figure 8: Benefit (average residual load parameter K1) and effort (increase of electricity consumption) based on simulation results for the year 2012

Figure 8 shows the parameter K1 (y-axis) and the percentage increase of the electric consumption compared to the conventional scenario (x-axis) for each of the scenarios. The value of the parameter K1 for the conventional scenario C_2012_5.4_0.5, hereafter referred to as conventional K1 value, is 0.02. The horizontal lines given in this figure display the lowest theoretically attainable K1 value, hereafter referred to as optimal K1 value. This value

is determined by an optimal distribution of the heat pump's daily operating time to the beneficial time periods. The optimal K1 value is mainly influenced by the daily operating time (and therefore by the heating power of the heat pump) and by the daily course of the DSM-signal. The lowest theoretical attainable value of K1 reaches -0.19 (light grey line) when the standard heat pump (5.4 kW) is installed. The heat pump system with the double sized heat pump has the potential to reach a minimum K1 value of -0.27 (dark grey line).

The K1 value for the simulated scenarios ranges between the conventional value and the optimal value. The degree of exploiting the optimum is characterized by the relative difference between the simulated K1 value and the optimal K1 value, here expressed as parameter E1. Equation (5) gives the calculation of E1, wherein $K1_{conventionel}$ is the K1 value for the conventional scenario.

$$E1 = \frac{K1_{conventionel} - K1}{K1_{conventionel} - K1_{optimal}} \quad (5)$$

Table 3 summaries the E1 values of the simulated scenarios. Applying a smart control to the BS-H of the standard sized HPS the associated optimal K1 value is exploited by 13 %. The additional electricity consumption of 2.6 % results from an increase of the storage losses of the BS-H by 41 % as well as on the decrease of the HP efficiency by 1.9%. Including not only the BS-H but also the BS-D to the smart control the E1 value is enhanced to 19 %. Considerably higher enhancement in terms of load shifting could be achieved by the system using the large BS-H. In that way the scenario S-HD_2012_5.4_2.0 exploits the optimal K1 value by 42 % causing an increase of the electricity consumption of 5.3 %. As mentioned before, doubling the heating power of the heat pump without scaling up the buffer storage volume (S-HD_2012_10.8_0.5) does not further extent the operating time of the heat pump in beneficial time periods compared to S-HD_2012_5.4_0.5. However, the increase of the electricity consumption is lower in comparison with the other smart scenarios amounting to no more than 1.3 %. This is due to the fact, that the back-up heater is not used and therefore the increased storage losses and decreased HP efficiency are compensated partly. The scenario using a double sized heat pump and a quadrupled BS-H realize the lowest value for K1 but the associated optimum is only exploited by 33 %. The increase of the electricity consumption (3.7 %) is mainly due the increase of the storage losses by 259 %.

5.3 Load Shifting Potential and System Efficiency in 2023

To evaluate the effects of load shifting in times of high renewable electricity generation, each scenario is simulated with the DSM-signal based on the residual load of 2023. To discuss the differences of the results for 2012 and 2023, identical graphics as in the previous section are used.

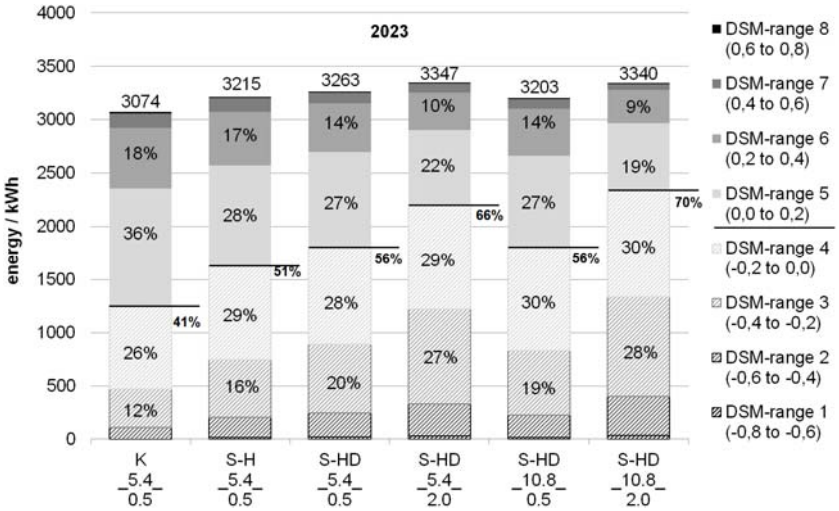


Figure 9: Electricity consumption (total value and allocation to the different DSM-signal sections) of the scenarios for the year 2023

Using the conventional controlled HPS in 2012 and 2023 a similar share of the total electric energy consumption is consumed during time periods having a beneficial DSM-signal (40 %, 41 % respectively). However, due to the larger amplitude of the DSM-signal (cf. chapter 3.3) electric energy is now also consumed in the sections 1 and 8. In all of the smart controlled scenarios load shifting towards the beneficial time periods could be achieved to a larger extent.

Table 4: Heat losses of the storages BS-H and BS-D as well as the SPF (annual value) and the E1 value (degree of exploiting the optimum) of the scenarios in 2023

Scenario	Storage loss BS-H [kWh/a]	Storage loss BS-D [kWh/a]	SPF	E1
C_2012_5.4_0.5	137	833	3.24	-
S-H_2012_5.4_0.5	258	833	3.14	21%
S-HD_2012_5.4_0.5	257	864	3.11	33%
S-HD_2012_5.4_2.0	607	864	3.14	57%
S-HD_2012_10.8_0.5	289	865	3.16	24%
S-HD_2012_10.8_2.0	686	865	3.16	50%

Note: Both of the storages are situated outside the thermal envelope of the building at a temperature being equal to the room temperature. The seasonal performance factor (SPF) includes the components of the heat pump system as specified in EN 14511 for the measurement of the COP and the back-up heater.

The combined depiction of the benefit (in terms of K1) and the effort (percentage increase of the electric consumption) is given in Figure 10. Compared to 2012 the better K1 value for all of the smart control scenarios goes along with increased electric energy consumption. The conventional K1 value is slightly higher than in 2012 and the changed DSM-signal results in lower optimal K1 values. For the standard sized HP, K1 optimum amounts to -0.19 and for the large sized HP to -0.27. All of the scenarios exploit the optimal K1 value to a larger extent. In the scenario where the smart control is only applied to BS-H an E1 value of already 21 % is realized (2012: 13 %) and with the additional use of BS-D an E1 value of 33 % (2012: 19 %). The increase of the electric consumption compared to the conventional scenario accounts for 4.6 % (S-H_2012_5.4_0.5) and to 6.1 % (S-HD_2012_5.4_0.5); in comparison 2012: 2.6 % and 3.4 %. Increasing the volume of BS-H to 2 m³ (S-H_2012_5.4_0.5) the most

favorable value for E1 is achieved (57 %). However the electric consumption is increased by 8.9 %. In comparison to 2012 the use of a larger HP could be advantageous for DSM if also a larger BS-H is applied. No enhancement of K1 is achieved by only using the standard BS-H. This demonstrates that the storage capacity is enlarged so much (due to the higher overheating temperature differences in 2023), that the standard sized HP is not always able to heat up the storage by the respectively permitted temperature difference. Sometimes the HP would need a longer time than the beneficial DSM-signal lasts. Therefore the feasible storage capacity could not be exploited on each day. Whereas a better K1 value (more load shifting) could be realized with the larger HP, the E1 (exploitation of the associated optimum) is minor compared to the standard heat pump; the electric energy consumption is similar.

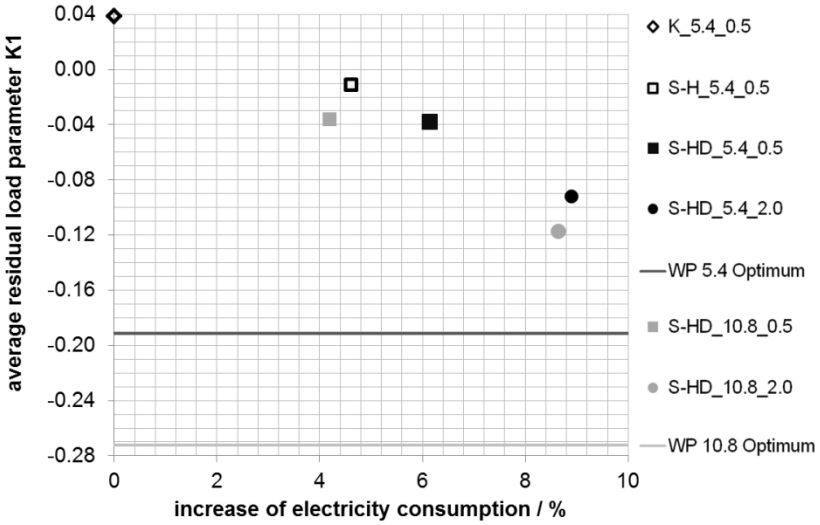


Figure 10: Benefit (average residual load parameter K1) and effort (increase of electricity consumption) based on simulation results for the year 2023

6 SUMMARY AND CONCLUSION

A typical ambient air-to-water heat pump system in a single-family house has been examined concerning the impact of demand side management providing control. On the one hand the load shifting potential and the load shifting realized within the different system scenarios has been evaluated and on the other hand the efficiency changes of the heat pump system has been considered. The increase of the electric energy consumption in the smart controlled scenarios compared to the standard scenario is caused by the decreasing HP efficiency and the increasing storage losses. Both are a result of the fact that load shifting is realized by increasing the set value of the temperature in the buffer storages (one for room heating and one for domestic water heating). The simulated scenarios differ from each other in terms of control strategies (conventional control and smart control), dimensioning of the buffer storage and the heat pump and of the DSM-signal. For the year 2012 and 2023 a DSM-signal is generated based on the residual load. The amplitude of the DSM-signal differs and is greater in 2023 than in 2012. Since the degree of raising the storage's set value is chosen to be proportional to the DSM-signal the enabled storage capacity is larger in 2023 and therefore the load-shifting potential is higher.

The results reveal that the chosen control strategy of increasing the temperature set value brings about an optimization of the HP operating time from the DSM's point of view. The theoretical load shifting potential of the considered standard sized HP systems could be exploited by 19 % in the year 2012 and by 33 % in the year 2023 using the smart control

without changing the dimensioning of the system's components. Enlarging the buffer storage for room heating from 0.5 m³ to 2.0 m³ boosts the load shifting further to 42 % and 57 % respectively. Doubling the heat pump capacity does have a positive effect on load shifting only when the capacity of the standard sized heat pump is too low - and therefore the required operating time too long - to heat up the buffer storage BS-H as much as a current positive DSM-signal could make available. In the considered scenarios this case occurs in 2023 regarding the system where a large buffer storage is implemented. Here the load shifting could be increased to some degree. In the other scenarios a larger heat pump entails nearly no benefit for the DSM.
The electric energy consumption in all smart controlled scenarios is higher than in the conventional controlled scenarios. It increases as the load shifting extents due to higher operating temperatures on the heat sink side. Only in the scenarios where the larger heat pump is implemented the electric energy consumption increases to a lower extend because the back-up heater is not in use. The increase of the electric consumption amounts to 8.9 % at the most. Considering both of the aspects that reduce the system's efficiency separately: the efficiency of the heat pump decreases by 4 % at the most and the storage losses (considering both storages together) increase by 60 % at the most.
It may be concluded that a heat pump system will pay for its "smartness" with additional energy costs when no special tariffs with lower energy prices could be used and with higher investment costs as the case may be. To make load shifting interesting for the end-user the additional expense has to be considered when developing new market models regarding the use of heat pumps in the context of DSM.

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