Flexibility of heat pump pools: The use of SG-Ready from an aggregator's perspective

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Abstract

In this work the response of a heat pump pool towards direct load control signals sent by an aggregator is analysed and a characteristic response is presented. The signals differ by type, duration and frequency. The used signals are based on the SG-Ready definition. It is essential to understand the reaction of heat pump pools towards direct load control signals in order to use their flexibility. A simulation experiment is used to identify the response of a heat pump pool towards single and repeated SG-ready signals of different duration sent by an aggregator. The used pool consists of 284 heat pump systems connected to thermal energy storages each. Building type and size, as well as heat pump system sizing are chosen to reflect conditions representative for Germany and randomised to reflect diversity of buildings, sizing and control parameters.
It is shown that most energy can be shifted for repeated signals applied for a duration between 15 minutes to 60 minutes. In this case losses reach up to 17% of the invested energy. The use of the back-up heater increases flexibility significantly but can lead to losses up to 70% of the invested energy, especially for long signal durations. It should be highlighted that the different SG-ready options lead to different shifting potential and different efficiencies. Furthermore the influence of season on heat pump flexibility is studied.

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1. Using the flexibility of heat pumps for business

Heat pumps (HP) are an efficient technology to convert electricity into heat and are increasingly used for residential heat supply. Today 7.5 million HP units are installed and operated in the European Union and over the recent years about 800.000 new units have been installed yearly [1][2]. HPs are considered by many energy system modellers to be an important technology to manage the transition towards a renewable energy system [3]. Two developments promote HPs. First, the conversion efficiency from electricity to heat of commercially available HP units is constantly improving. Thus, HPs are progressively reducing the primary energy factor of heat generation. The second development is the target to de-carbonise the power sector [4], leading to lower specific CO_2-emissions for electricity used by heat pumps. The combination of those two points will lead to reduced CO_2-emissions per kWh heat generated by HPs. Flexibility on the demand side will play an important role for the integration of high shares of intermittent renewable electricity sources into the grid. It is widely accepted that HPs connected to thermal storage can be used for load-shifting applications and provide flexibility on the demand side [5].

However, in daily practice flexibility of HPs is barely used. A reason is surely that single HP units only offer limited capacity. Pooling of units is required to fulfil minimum requirements for market participation and allow for economies of scale. Hence, the technological approach used for integrating HPs must be cost efficient, reliable and simple enough to be deployed to a large number of units. Aggregators are seen as potential players that pool large number of HPs, to operate on markets or provide services to other actors in the power sector. For such aggregators the question of how to control and operate a pool of residential HPs arises and finding an answer to this question is supported by the insights presented in this study.

1.1. Approaches to use heat pump flexibility

The target of aggregator level controls is to modify HP operation in order to fulfil a certain goal in the context of the electric system. Generally, decentralised and centralised control approaches are used. In a decentralised approach, the field device receives information (usually electricity prices) and optimises its operation according to the price. In a centralised approach, operational planning is done in a single place and operational decisions are transmitted to the field devices. The centralised control of remote devices is referred to as direct load control (DLC).

[6] found that heat customers prefer direct load control (embedded in a flat rate tariff) over time variable prices as a way to influence electricity consumption of electric heating systems. [7] concludes that from a system perspective centralised optimisation together with DLC yields better performance results compared to decentralised optimisation. The authors also highlight the importance to take into account the field response towards a price signal, when using decentralised optimisation. A central question for DLC is which information is available as feedback for the aggregator to do operational decisions. This information could range from only metered power up to storage sensor values or customer feedback [8].

Based on [9]–[11], three main steps included in the control of a pool of thermal units are summarised: 1) A reference trajectory is generated (usually by buying energy based on a prediction). 2) System state of each participating device is collected. 3) An algorithm is used to generate a control signal sent to the individual devices based on their system state and the current situation in the power system.

In the past the available direct control options for heat pumps have been switching the devices off or on. To extend these options the SG-Ready interface has been developed and has been deployed to heat pumps over the recent years. It provides a standardised, low complexity access to the heat pump units and offers the possibility to trigger four different operation states of the heat pumps. These are “Switch off”, “Normal operation”, “Recommended on”, “Forced on”. Consequently, SG-Ready increases the option space for direct load control, which is addressed in this work.

1.2. Added value of this work

Most of the previous work focuses on the design of control algorithms or evaluating the use of HPs in special cases. This work takes one step back and asks three fundamental questions: “What happens if a DLC signal is sent to a pool of HPs?”, “How does HP flexibility change over the course of the year?” and “Does the flexibility depend on the signal sent?”. These questions often seem to be too trivial to be considered or are neglected by previous work, but they build the foundation for designing controls and understanding the behaviour of a HP pool. Furthermore, as SG-Ready offers new opportunities for DLC, a particular focus is put on these.

The presented results will give aggregators important insights into the operation of a pool of HPs by answering the following crucial questions:

- What type of signal should be sent?
- For how long should the signal be active?
- How often should it be sent?
- How many units should receive the signal?
- What additional costs would be generated at the end-customer’s site?

In this study, a further step towards designing adapted DLC strategies for HP pools is taken. This is done by first developing a generic pool model, as presented in detail in [12] and explained briefly in Section 2 in this study. By characterising the response of a HP pool to trigger signals, as done in Section 3.3, useful insights are provided for control system engineers for developing DLC approaches suitable for their needs.

Moreover, the effect of the different SG-Ready signals on the HP pool flexibility is investigated and presented. The results depicted in Section 3 clearly indicate the need to take into account different signal types. Another central question addressed in this study is the influence of repeated activation of HP pools triggered by an aggregator. Here, the impacts on the used flexibility parameters shiftable energy and annual load shifting efficiency are depicted as well. Furthermore, Section 3 indicates that certain repetition patterns are advantageous when it comes to the task to shift as much energy as possible, but also the repeated triggering comes at a price and has a strong dependency on the month.

2. Methodology

To analyse the impact of different DLC signals, based on SG-Ready, on a pool of residential heat pumps a model has been developed. The target of model development was to be able to simulate a large number of buildings, respecting their diversity while still keeping modelling effort and computational requirements low. A stochastic bottom up approach has been chosen and is explained and validated in [12]. The main parts are briefly introduced in the following.

2.1. Pool model

The pool model is a combination of single building unit models. Each building consists of a heat pump, a back-up heater and two thermal storage tanks for hot water and space heat. The thermal energy demand is provided by this system. Using a full stochastic bottom-up approach, sizing and energy demand of each building is different from the others, and the diversity in the demand profiles is properly respected. The heat distribution system used in each building is assigned based on the building energy standard. Different heat distribution technologies are reflected by different ambient temperature dependent heating curves.

2.2. DHW and space heating demand

A combination of a physical model with a behavioural model is used to calculated energy demand for space heating (SH) and domestic hot water (DHW) and electricity demand. The model is presented in validated in [13]. Activity data provided in [14] is used to derive probability distributions for the frequency, start and duration of occupant activity. This is used to determine the times and amounts of DHW consumption, SH set-points and internal gains in the building. The heat demand for SH is calculated using a 5R1C building model, based on the simplified hourly method. This model is combined with the model for occupant behaviour and is calibrated using a set of standardised buildings taken from [15], of which selected parameters are randomised to generate diversity in heat load profiles.

2.3. Heat generation

Ground-sourced HPs (GSHP) and air-sourced HPs (ASHP) are modelled with respect to their efficiency (COP) and thermal capacity $\dot{Q}_{HP}$ at a given temperature of the heat source T_{source} and the sink T_{sink} as shown in the equations (1) and (2). The coefficients a_i in (1) and (2) are obtained by using a least square fit on HP data from manufacturers [16]. The heat production from the electric back-up heater $\dot{Q}_{BH}$ is modelled using equation (3) where the conversion efficiency η is set to 0.99 and P_{el} represents the electric power of the back-up heater. The electric back-up heater is used together with the heat pump if the HP capacity is not sufficient to provide enough heat, or if activated externally.

$$\mathbf{COP} = \mathbf{a_0} + \mathbf{a_1} * (\mathbf{T_{sink}} - \mathbf{T_{source}}) + \mathbf{a_2} * (\mathbf{T_{sink}} - \mathbf{T_{source}})^2 \qquad [-] \qquad (1)$$

$$\dot{\mathbf{Q}}_{\mathbf{HP}} = \mathbf{a_0} + \mathbf{a_1} * \mathbf{T_{source}} \qquad [\mathrm{W}] \qquad (2)$$

$$\dot{\mathbf{Q}}_{\mathbf{BH}} = \boldsymbol{\eta} * \mathbf{P_{el}} \qquad [\mathrm{W}] \qquad (3)$$

For the operation of the HPs, minimum run- and pause times are implemented. These are 6 minutes minimum on-time and 3 minutes minimum off-time. These short periods were chosen in order to enable the analysis of the response of the HPs to short-term signals.

2.4. Storage

The thermal storage is modelled as mixing tank. The temperature in the tank is assumed to be homogeneous. In order to calculate the temperature changes in the DHW and SH storages, an energy balance is used with respect to heat production by the HP and the electric back-up heater, heat demand for DHW and SH, as well as storage losses. A two-point controller is used to keep the storage temperatures within the allowed temperature band (hysteresis) around the set point.

2.5. System sizing and randomisation

Sizing for HP, storage and backup heater is based on recommendations from manufacturers [16]–[18]. The sizing procedures have been adjusted by introducing randomization parameters for HP efficiency, which lead to under-/over- sizing of the HPs and the storages. Measured values of a field test [19] are used to calibrate the model to correctly account for a variation of annual operation hours and HP switching cycles per day. Figure 1 shows the randomisation procedure, which is fully explained in [12].

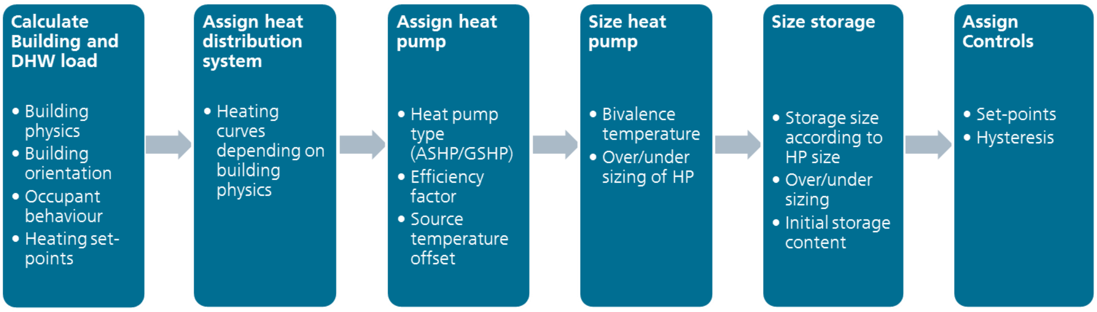

Fig. 1. Steps for system sizing and randomisation.

2.6. Implementation of direct load controls via SG-Ready

In order to offer the use of the HP flexibility, the SG-Ready label is issued from the German Heat Pump Association. It requires that four different operation states of the HP can be triggered via two zero voltage contacts. The detailed prerequisites for the implementation of the signals can be found in [20]. The four operation states mandatory are called: “Switch off”, “Normal operation”, “Recommended on” and “Forced on”. The details of implementation are not strictly specified in the document and are implemented differently depending on the HP manufacturer. Table 1 summarises the SG-Ready regulations and their implementation in the simulation study.

Table 1. SG-Ready according to the specifications and the implemented system response in the simulation.

	Corresponding name in this study	**SG-Ready recommendation** [20]	**Implementation in simulation**	**SH storage set temperatures in simulation***	**DHW storage set temperatures in simulation**
Off (1)	Off	HP is switched off. This mode might be realised as fixed times for a maximum of 2 hours.	HP is switched off.	[HC, HC+5°C]	[45.0°C, 52.5°C]
Normal (2)	Normal	HP operates in normal energy efficient mode.	HP operates with normal set-points.	[HC, HC+5°C]	[45.0°C, 52.5°C]
Recommended on (3)	On	HP is operating in an enhanced heating mode. The switch on has to be seen as a recommendation.	HP is switched on, hystereses are increased.	[HC+5°C, HC+10°C]	[50.0°C, 57.5°C]
Forced on (4a)	Superheat (HP)	HP has to switch on.	HP is switched on, temperatures increased to max.	[55°C, 60°C]	[52.5°C, 60.0°C]
Forced on with BH (4b)	Superheat (BH+HP)	HP and back-up heater have to switch on. Optional is the increase of the storage temperatures.	HP and back-up heater are switched on, temperatures increased to max.	[55°C, 60°C]	[52.5°C, 60°C]

*HC = Set temperature according to ambient temperature dependent heating curve

2.7. Set-up of the simulation study

The target of the simulation study is to explore the general characteristics of a heat pump pool and to evaluate its flexibility when using SG-Ready for DLC. For this purpose, a one year simulation of a pool consisting of 284 residential heat pumps is conducted. A simulation time step of 1 minute and test reference climate data (TRY2010) for Potsdam is used.

The pool is constituted to 88% of single family houses and to 12% of terraced houses. 80% of the buildings show a specific annual space heating demand between 50 and 80 kWh/(m^{2}a). The remaining buildings' demand is between 100 and 240 kWh/(m^{2}a) . 75% of the heat pumps are air sourced and 25% are ground sourced.

In a first experiment, the SG-Ready signals explained in Table 1 are sent to the pool for different time intervals (1 min, 15 min, 60 min, 360 min). The signals are sent every 19 hours, to cover different hours of the day and year, while enabling a regeneration of the pool in-between two signals.

In a second experiment the signals are sent repeatedly over a period of 12 hours, to investigate the effects of long time intermittent operation. During the 12 hours each signal (1 min, 15 min, 60 min, 360 min) is followed by a pause of the same duration. The 12 hours testing are followed by 7 hours without a signal. Then, after these 19 hours in total, the procedure is repeated.

The investigated scenarios are shown in Figure 2. The total number of simulation runs performed is 2840.

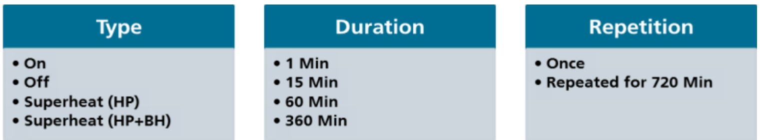

Fig. 2. Composition of trigger signals for the different simulated scenarios.

3. Results

This section presents the results for the simulation of a pool consisting of 284 HP units with a time resolution of 1 minute, for the different scenarios described in Section 2.7.

3.1. Response to a single signal

The operation of the HP pool with DLC signals is compared to an undisturbed operation – the business as usual case (see the case "normal" for the SG-Ready signal in Table 1). In this case the heat pumps are operated to keep the storage temperatures within the defined bounds. The point of interest is the deviation in electricity consumption when a DLC signal is applied to the normal operation. Figure 3 shows the differences in electricity consumption between normal and triggered operation for the whole pool, on an exemplary day in winter for a 15 min and a 360 min signal applied at 12:00 o'clock. The figure presents the difference in electricity consumption of the four SG-Ready signals to the normal operation. Signals causing an activation of the HP ("On", "Superheat" (HP) and "Superheat (HP+BH)") lead to an increase of electricity consumption, followed by a decrease in consumption (regeneration) when the signal is over. The "Off" signal leads to a reduced demand followed by an increased demand. For the 15 min signals presented in Figure 3, there is no difference visible between the "On" and the "Superheat (HP)" signal. This indicates that the time span is too short to superheat the storage. When the signal is applied for 360 min (see Figure 3) the differences between the different SG-Ready options become visible. After approximately 30 min the electricity consumption of the "On"-case drops. During this phase, an increasing number of HP systems have charged their storages and switch off. The systems commanded to superheat are still charging during this time. 2 hours after activation, systems commanded to superheat have charged and enter a steady state phase. The controllers are still operated with increased hysteresis values until the signal ends. As a result the storage is warmer than during normal operation, leading to thermal losses and decreased COP values. This explains the increased electricity demand during that period. Furthermore, it can be seen that electricity consumption increases significantly when using the back-up heater. For the "Superheat (HP+BH)" and the "On" case and the 360 min signal duration the time when the storages are charged completely is clearly visible by a decline in electricity consumption. In the cases when the HP is switched off, the electricity consumption of the pool oscillates until it has settled. Figure 3 depicts that the majority of HPs is only switched off for a duration of 15 min although the signal duration is 360 min. This behaviour is caused by the depletion of the storage and the consequent need for heating the storage in order not to violate thermal comfort.

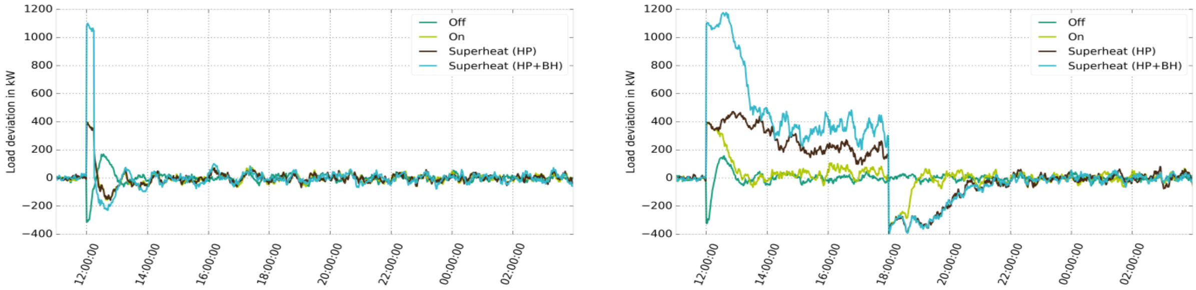

Fig. 3. Exemplary response of the heat pump pool to a 15 Minutes signal (left) and a 360 Minutes signal (right).

3.2. Response to repeated signals

In a second experiment, as described in Section 2.7, the signals are sent repeatedly over a period of 12 hours, to test the ability of the pool to provide constant services over a longer period. Figure 4 presents an exemplary result for the different signals repeated every 15 min (left part) and 60 min (right part). The figure shows that the HP pool is reacting to each signal repetition sent. After 12 hours of intermittent activation, a cumulated regeneration can be observed. Between single repetitions of the signals, the pool is already regenerating partly as seen in Figure 4. Nevertheless, the regeneration period after the signals is affected by the repetition of the signals as a comparison between Figure 3 and Figure 4 reveals. This comparison shows that the regeneration period is extended for a repeated signal with a duration of 15 min. The peak in the power deviation due to a trigger signal is changing throughout the signal repetitions. The magnitude and trend of this peak is depending on the thermal load. In times of high thermal loads, the peaks stay on a high level with a constantly long charging phase, as seen in Figure 4. In cases of changing thermal load, the peaks in the power are changing according to the thermal demand of the houses. Hence, for oscillating thermal load during the course of the signal repetitions, the peaks in power deviation oscillate as well. By summing up the power deviation observed over time, the energy deviation from normal operation is yielded. This energy yield by triggering during each repetition is dependent on the thermal load as well as the efficiency of the HP pool. The efficiency is affected negatively by increasing storage temperatures as it becomes more visible for times of lower thermal load and is further explained in Section 3.5.

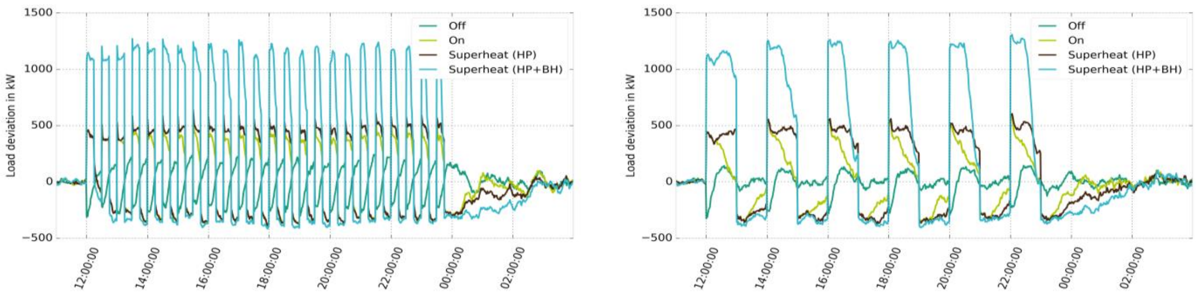

Fig. 4. Exemplary response of the heat pump pool to a repeated 15 Minutes signal (left) and a repeated 60 Minutes signal (right).

3.3. Characteristic response

The observed responses, as shown in Figure 3 and Figure 4, are similar in shape during the course of the year. Based on these observations, a characteristic response of a triggered HP pool has been identified and is shown in Figure 5.

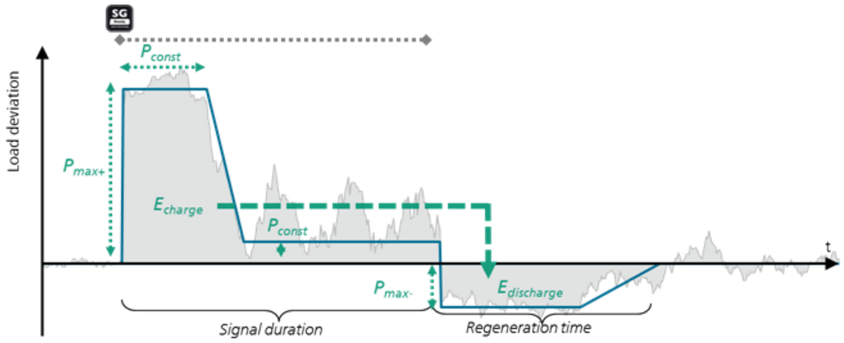

Fig. 5. Typical characteristic response of the pool and key parameters for flexibility determination.

Three main phases defining the chronological characteristics are observed:

1. Charging phase: During this time the activated systems are charging the storage. A clear increase in electricity consumption heading to a maximum can be observed.
2. Steady state phase: After a transition period, during which an increasing number of HP systems have charged the storage completely, the pool enters a steady state period. During this time the systems are operated with increased storage temperatures, leading to additional losses due to reduced HP efficiency and heat losses of the storage.
3. Discharging/regeneration phase: After the activation signal has ended, the storages are discharged until reaching their normal set-point temperatures. During this period the electricity consumption in the pool is lower than in normal operation as heat is taken from the thermal storage. After a while the pool is fully regenerated and back to normal operation.

The different phases describe the typical response. They may differ in length and magnitude for individual responses throughout the year. Figure 5 shows the response for activation signals, the “Off” signal follows the same pattern but with inverse signs, excluding the steady state phase.

The observed response shown in Figure 5 is used for defining four key parameters describing the flexibility of the HP pool:

- **E_{charge} (shiftable energy):** This energy is used to charge the storages and keep them at temperature. It is the sum of all deviations during the presence of a load shift signal. It is referred to as “usable energy” as well.
- **$E_{discharge}$:** This energy represents the “saved” energy when shifting loads. It is the sum of all deviations between the end of a signal and the beginning of the next triggering cycle.
- **E_{loss}:** The difference between invested energy (E_{charge}) and saved energy ($E_{discharge}$).
- **Load shifting efficiency:** The absolute of the ratio of $E_{discharge}$ to E_{charge}.

3.4. Shifted energy and efficiency over the course of the year for single signals

A central question is the availability of HPs for load shifting over the course of the year. In order to assess the flexibility of the HP pool, the annual load shifting efficiency and the shiftable energy are analysed. Figure 6 shows the monthly average of shiftable energy per cycle for the different signal durations (see Section 2.7). It can be seen that the average shiftable energy varies strongly throughout the year. In summer, the potential for load shifting is almost negligible compared to winter, as in summer only DHW is needed and the heating buffer tank is not used. For the cases with the highest storage hystereses (“Superheat (HP)” and “Superheat (HP+BH)”) the annual variation has the strongest severity. The effect of superheating the storage with only the HP becomes visible for activations lasting more than 15 min. In general, increased signal durations allow shifting higher loads but are more dependent on the month (e.g. increasing the signal duration from 15 min to 60 min increases the shiftable energy by a factor of around 2 for the “On” signal in November). For durations below 360 min, the shifting potential remains almost constant during winter and increases slightly during changing seasons and drops during summer (compared to January for a duration of 60 min, the “Superheat (HP)” signal yields 1.33 times the amount of shiftable energy in March, but only 0.46 times the amount in June). The usage of the back-up heater almost doubles the shiftable energy during the cold months. In changing seasons, superheating the storages over a longer period yields lower amounts of shiftable energy, since the demand for SH is decreased.

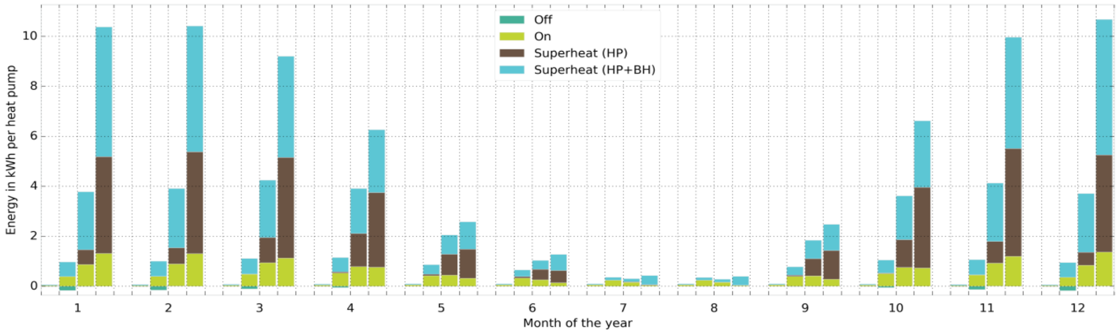

Fig. 6. Shiftable energy for single signals (monthly average). Values are per heat pump unit and the test cycle of 19 hours. The groups per month represent the signal durations in ascending order (1 min, 15 min, 60 min, 360 min).

For the flexibility assessment of a HP pool, the annual load shifting efficiency is important in order to save costs and CO_2-emissions. The left part of Figure 8 shows the annual efficiencies of the different signals. Here, the annual load shifting efficiency is calculated by dividing all negative energy by all positive energy over the course of the year and taking the absolute of the result. For durations of 1 min, the efficiency of all signals is over 0.96 and for 15 min the efficiency of the “On” and the “Superheat (HP)” signal are approximately 0.97. When signals last for 60 min, the efficiency is affected by the effect of storage superheating which leads to a decreased efficiency of the “Superheat (HP)” signal down to 0.84. When the signal is applied for 360 min, efficiency values for all signals drop significantly. The reason is that the storage is kept at a high temperature during most of the activation phase, leading to additional storage losses and losses due to operating the HP at low COP values, referred to as “steady state phase” (see Section 3.3). The usage of the back-up heater leads to losses in all cases reaching up to 70% of the activated energy. With increasing signal duration, the usage of the back-up heater subsequently decreases the annual load shifting efficiency (from 0.96 for 1 min down to 0.3 for 360 min). Figure 8 depicts, that the efficiencies for cases without using the back-up heater initiate their main decrease when the signal duration is extended from 15 min to 60 min. Consequently, for signals sent once, a signal duration from 15 min to 60 min is preferable in order to shift as much energy with a high efficiency.

3.5. Shifted energy and efficiency over the course of the year for repeated signals

Regarding the flexibility of the pool when signals are sent repeatedly, a strong dependency of the shiftable energy on the thermal load is observed. Figure 7 presents the variation throughout the year for each signal duration when the signals are repeated over a period of 12 hours as described in Section 2.7. The values given in Figure 7 represent the average shiftable energy per cycle during a certain month, shown for each signal duration. As explained in Section 2.7, there is no difference in triggering the pool between repeating the signal with a duration of 360 minutes and the unrepeated signal with the same duration. Despite the fact, that the total period of pool triggering is equal for all signal durations (see Section 2.7) Moreover, the duration of each trigger repetition is influencing the shiftable energy, although all signal durations have the same ratio of triggered times over untriggered times (see Section 2.7). Repeating a 15 min signal over the course of 12 hours yields the highest amount of shiftable energy. A comparison between Figure 6 and Figure 7 shows, that the repetition of signals yields significantly higher amounts of shiftable energy (for a repetition of a 15 min “Superheat (HP+BH)” signal in February, there is an increase of around factor 20). Moreover, repeating the signals reduces the influences of signal duration and thermal load on the shiftable energy. When comparing between repeated and non-repeated signals, it is remarkable, that the repeated “Off” signal shifts considerably higher amounts of energy during winter. For “Off” signals, the effect of increasing the amount of shiftable energy due to the repetition of signals is the strongest.

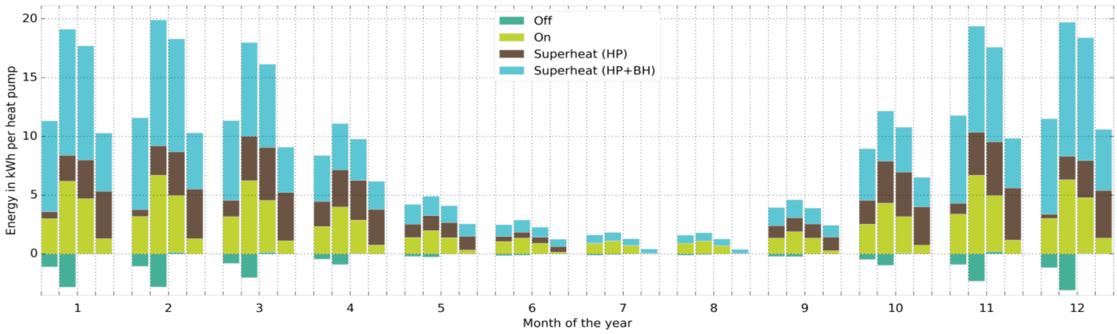

Fig. 7. Shiftable energy for repeated signals (monthly average). Values are per heat pump unit and the test cycle of 19 hours. The groups per month represent the signal durations in ascending order (1 min, 15 min, 60 min, 360 min).

Another important aspect for the assessment of the HP flexibility towards repeated triggering is the efficiency. The right part of Figure 8 presents the annual load shifting efficiency calculated with the same methodic as in Section 3.4. Compared to the unrepeated triggering of the HP pool, the efficiencies are lower and drop down to 30% in some cases. Thus, the efficiency for repeated superheating without back-up heater is only around 70% of the one for single signals for a signal duration of 15 min. The drop in efficiency is the highest for signals lasting for only 1 min, since the continual on- and off- switching shifts the storage temperatures subsequently to a higher level. Moreover, the relatively low efficiencies of signals with a duration of 1 min respectively 15 min are caused by the minimal run- and pause- times of the heat pumps. This causes that some of the HPs cannot follow the signal in every repetition. As a consequence, the operation of the HP pool is “clocked” for short repeated signals, operating at the limits of minimum run- and pause-times. For repeated signals, signal durations of 60 min yield the highest load shifting efficiencies. Hence, the optimum signal duration for repeated triggering is between 15 min and 60 min, when taking the amount of shiftable energy (see Figure 7) and its efficiency (see Figure 8 right) into consideration. The use of the back-up heater is accompanied by losses in annual load shifting efficiency between 30% and 45% regardless the signal duration.

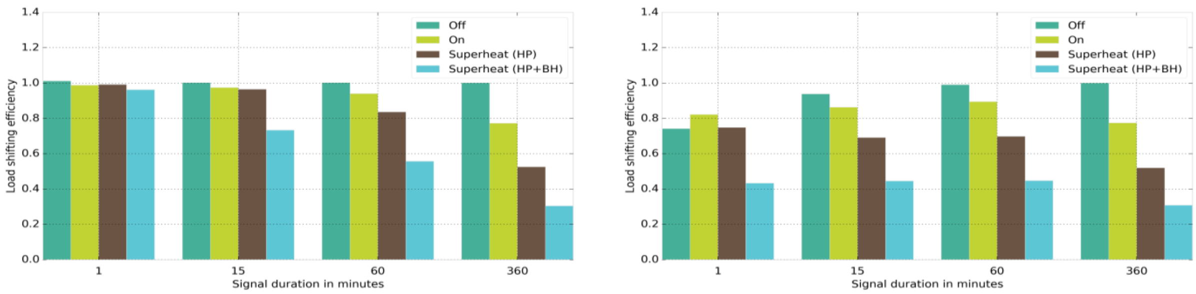

Fig. 8. Annual load shifting efficiency for unrepeated signals (left) and repeated signals (right).

4. Conclusion

HPs are a key technology for energy efficient heat supply. HP systems designed with thermal storage capacity, as it is the case in Germany, can be used to provide flexibility to the energy system. Since individual units’ electricity consumption is relatively small, pooling of a large number of HPs is required in order to actively participate in electricity markets or to provide services to the grid. Managing a pool of HPs requires fundamental knowledge about available power and energy as well as the response expected when controlled externally. A simulation study using a pool of 284 HPs was conducted to examine these points. The SG-ready interface, which is implemented in over 900* market available HPs in Germany, was used for direct load control (DLC).

*https://www.waermepumpe.de/fileadmin/user_upload/waermepumpe/02_Waermepumpe/Qualitaetssicherung/SG_Ready/Modellliste_SG_Ready__Stand_03.06.2016_.pdf

It was found that HPs sized according to today's procedures offer an electric shifting potential between -0.18 and 10.68 kWh per heat pump and load shift cycle. The availability of HPs for load shifting has a strong seasonal dependency, showing negligible shifting potential during summer compared to winter and changing season. An analysis of signal length leads to the conclusion that shifting intervals of between 15 min to 60 min are best suitable for HPs with respect to shiftable energy. For these signal durations, losses remain under 17% when not using the back-up heater. An analysis of the characteristic response showed further that shifting energy over a long period leads to losses up to 70%, depending on the SG-Ready signal used. The repeated application of trigger signals over a period of 12 hours leads to an increase in the amount of shiftable energy accompanied by a decrease in the annual load shifting efficiency by -15.6% on average.

At first glance using the back-up heater for load shifting seems an attractive option from the power system's point of view, as it yields high power and high shiftable energies, particularly for long activation times. However, using the back-up heater creates losses going up to 70% of the invested energy, generating additional costs.

A study of the characteristic response leads to the conclusion that achieving a constant increase in energy consumption over a period longer than 1-2 hours needs tailored control strategies, as the response towards an activation signal leads to a peak followed by a steady decline and a consecutive steady state phase. Furthermore, the regeneration period after an activation signal has to be considered, especially for the case of repeated triggering.

The SG-Ready interface allows more options for using the HP's flexibility than previously possible by just switching it off. This study shows, that the established control signals of SG-Ready offer a wide range of possibilities for DLC conducted by a pool aggregator and therefore are well suited to ease the integration of renewable energies into the grid.

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References

[1] M. Miara, D. Günther, Z. L. Leitner, and J. Wapler, "Simulation of an Air-to-Water Heat Pump System to Evaluate the Impact of Demand-Side-Management Measures on Efficiency and Load-Shifting Potential," *Energy Technol.*, vol. 2, pp. 90–99, 2014.

[2] T. Nowak and P. Westring, "European Heat Pump Market and Statistics Report 2015," Brussels, 2015.

[3] H.-M. Henning and A. Palzer, "Energiesystem Deutschland 2050," Freiburg, 2013.

[4] IPCC, "COP21-Annex," *FCCC/CP*, vol. L.9, pp. 21–32, 2015.

[5] D. Fischer and H. Madani, "On heat pumps in smart grids: A review," *Renew. Sustain. Energy Rev.*, vol. under re, 2016.

[6] M. J. Fell, D. Shipworth, G. M. Huebner, and C. A. Elwell, "Public acceptability of domestic demand-side response in Great Britain: The role of automation and direct load control," *Energy Res. Soc. Sci.*, vol. 9, pp. 72–84, 2015.

[7] D. Patteeuw, G. P. Henze, and L. Helsen, "Comparison of load shifting incentives for low-energy buildings with heat pumps to attain grid flexibility benefits," *Appl. Energy*, vol. 167, pp. 80–92, 2016.

[8] T. S. Pedersen, P. Andersen, K. M. Nielsen, H. L. Starmose, and P. D. Pedersen, "Using heat pump energy storages in the power grid," in *Proceedings of the IEEE International Conference on Control Applications*, 2011, pp. 1106–1111.

[9] H. Hao, B. M. Sanandaji, K. Poolla, and T. L. Vincent, "Aggregate Flexibility of Thermostatically Controlled Loads," 2015.

[10] B. Biegel, P. Andersen, T. S. Pedersen, K. M. Nielsen, J. Stoustrup, and L. H. Hansen, "Smart grid dispatch strategy for ON/OFF demand-side devices," in *Control Conference (ECC), 2013 European*, 2013, pp. 2541–2548.

[11] T. S. Pedersen, K. M. Nielsen, and P. Andersen, "Maximizing storage flexibility in an aggregated heat pump portfolio," in *IEEE Conference on Control Applications*, 2014, pp. 286–291.

[12] D. Fischer, T. Wolf, J. Wapler, and R. Hollinger, "Model-based Flexibility Assessment of a Residential Heat Pump Pool," *Energy*, vol. submitted, 2016.

[13] D. Fischer, T. Wolf, J. Scherer, and B. Wille-Haussmann, "A stochastic bottom-up model for space heating and domestic hot water load profiles for German households," *Energy Build.*, vol. 124, pp. 120–128, 2016.

[14] Eurostat, "Harmonised European time use surveys: 2008 Guidelines," Eurostat, Luxembourg, 2009.

[15] TABULA, “Residential Building Typology for Germany,” 2016. [Online]. Available: www.episcope.eu/building-typology/country/de.html. [Accessed: 01-May-2016].

[16] Stiebel Eltron, “Planung und Installation: Wärmepumpen.” Holzminden, p. 460, 2013.

[17] Buderus, “Planungsunterlage Logatherm WPL,” Bosch Thermotechnik GmbH, Wezlar, 2012.

[18] Viessmann, “Planungsanleitung VITOCAL Luft/Wasser-Wärmepumpen.” Viessmann Deutschland GmbH, 2013.

[19] M. Miara, D. Guenther, R. Langner, S. Helmling, and J. Wapler, “„WP Monitor“ Feldmessung von Waermepumpenanlagen,” Freiburg, 2014.

[20] M. Koch, *Regularium für das Label „SG Ready“ für elektrische Heizungs- und Warmwasserwärmepumpen*. Berlin: Bundesverband Wärmepumpe e.V., 2013.