Aggregating the Flexibility of Heat Pumps and Thermal Storage Systems in Austria

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Abstract: This study analyses the challenges of aggregating the flexibility of heat pumps in Austria. Flexibility can be provided by shifting electrical load to other points in time with the use of thermal storage systems. At first the potential and typical combinations of heat pumps, buildings and thermal storage systems are described. Afterwards different operation strategies and applications in smart-grid context are discussed. To make optimal bids to the market a model is necessary that explains the thermal and electrical dynamics of the system. Therefore a thermal model is combined with an electricity market model. Load shifts can reduce the operational costs of heat pumps around 8-14 %, but can negatively affect their efficiency. At last a technical concept is discussed which allows the exchange of signals between aggregator and pool participants.

1 INTRODUCTION

At every time step electric demand and supply must match each other to guarantee a stable and secure provision of electricity. If deviations between demand and supply occur, flexible loads or generators are necessary, that can alter their momentary electrical consumption or production pattern to bring the system back in balance. Historically this flexibility was usually provided by large scale generators or loads in the MW-range. With a higher share of Renewable Energy Systems (RES) the demand for flexible units is rising. The residential sector theoretically possesses a huge potential for flexibilization of the electric demand side. This study focuses on analyzing the challenges of using thermostatically controlled loads (TCL), like heat-pumps in combination with thermal storage systems, to support smart grids. Water storage tanks for warm water and space heating purposes as well as the thermal storage ability of the buildings, where the heat pump is operated, are further considered. The operation of TCLs can be modified as long as devices stay in a defined operational area and user-defined comfort restrictions are met. The load shifting potential of a single residential heat pump and storage unit is rather low, being in the kW-range. By combining the flexibility of many devices however, the resulting flexibility pool is capable of shifting a considerable amount of electrical load. This is usually realized by an aggregator: *"Aggregator means a legal entity which is responsible for the operation of a number of demand facilities by means of demand aggregation"* (Entso-e, Glossary). Demand aggregation refers to *"a set of demand facilities which can be operated as a single facility for the purpose of offering one or more demand side response services"* (Entso-e, Glossary). Demand side response (DR) services are the objective for the aggregation of demand side facilities. There must be certain incentives (e. g. monetary) to offer those DR services. Ideally a pool of heat pumps is capable of switching its electrical load to other points in time without any drawbacks for the customers. The flexibility resulting from those load shifts can be marketed at electricity markets or used to actively support the electric grid. To exploit that flexibility however, a pooling concept must be developed including the analysis of the existing heat-pump, storage system and building landscape, potential operation strategies for the pool and a technical concept to enable signals between an aggregator and the single heat pump.

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2 AGGREGATION

Around 100.000 – 150.000 heat pumps are used for space heating (SH) in Austria at the moment. Another 50.000 heat pumps are installed to provide domestic hot water (DHW). Heat pumps for SH are responsible for the major part of newly installed devices over the last years. In the year 2012 alone, around 13.600 heat pumps for SH were sold with an expected minimum growth rate of 5 % (Gaehmi, S., 2013; Moser et al., 2014; Biermeyer et. al, 2013). The exact load shifting potential is hard to determine and depends on several aspects like season, time of day, ambient temperature and user-specific behavior. In winter for example the potential for load shifts of heat pumps used for SH is expected to be significantly higher than in summer. If also cooling applications are realized by heat pumps, then the potential in summer can be increased. Also the time of day is an important factor. Gaehmi indicates that the load reduction potential is highest between 6-8 am and 4-6 pm while at other times it is zero if the heat pumps must run at full load. Additionally Gaehmi estimates the load shifting potential for 1000 households around 1.3 MW. These values are still to be closer investigated and strongly depend on the specific combination of building, heat pump and thermal storage system. As a consequence also the different technical characteristics of the devices forming the flexibility pool are of high interest for an aggregator. Therefore a market study of typical building and heating system combinations in Austria was conducted. To reduce complexity, typical combinations were summarized to homogenous groups. An excerpt of these typologies is exemplarily shown in Table 1 with building types on the horizontal axis and heating system related parameters on the vertical axis. Additionally also passive houses, pure DHW heat pumps and large scale heat pumps for district heating are considered. With more pool customers, organizational as well as technical efforts are higher. Large scale heat pumps (around 0.25 MW) are expected to be more favourable in terms of aggregation. Both transaction costs and costs for the information and communication technologies (ICT) infrastructure are declining with fewer pool participants.

The load shifting potential of TCLs can be used for various applications in smart-grid context ranging from local voltage control in distribution grids, increasing the share of RES in the power system, to participating on electricity markets (Koch S., Andersson G., 2009a).

Using price spreads on wholesale markets by shifting electric load to low price periods can significantly reduce operation costs of heat pumps, as was shown for the Swiss market (Pfaffen, D., Werlen, K., 2013). Furthermore on the EPEX spot contracts of market participants have to match the actual schedules. Eventual deviations have to be compensated by the responsible market participant. So the flexibility of heat pumps can also be used to reduce those deviations. Additionally the flexibility to momentarily adapt the electricity consumption pattern enables to participate on balancing markets, where the provision of balancing energy to maintain frequency stability is compensated by the Transmission System Operator (TSO) (von Roon et al., 2014). Positive balancing energy can be provided by decreasing the electric consumption of the heat pumps, while negative balancing power is delivered by increasing their consumption. Different balancing products exist. In Austria secondary balancing energy usually features higher revenues but also poses higher technical requirements than tertiary balancing energy. The added value of the pool operation must provide incentives for both, aggregator and pool participant. Reducing the costs on energy-bill level can motivate participants to join the pool. In addition to monetary incentives, also non-monetary incentives provide interesting opportunities. While aggregators can eventually profit from higher customer loyalty and an innovative image, pooling participants might be inclined to support smart-grid issues. As a pooling concept requires an appropriate ICT solution, there might also be positive effects for participants like a

Table 1: Excerpt of collected typologies of buildings, heat pumps and thermal storage systems in Austria.

	New building	**Existing building**	**Renovated building**
Space heating [kWh/(m²*a)]	45 [~35 °C]	100 [~55 °C]	70 [~45 °C]
Heated area [m²]	140	120	120
Therm./el. capacity [kW]	5 / 1.5	12 / 4	7 / 2.7
Capacity control	on/off	on/off	variable
Heat source	air	ground	air
Heat sink	water	water	water
Heat distribution	floor heating	radiator	radiator
SH storage [l]	300	500	500
DHW storage [l]	300	300	300

monitoring system suggesting eventual cost savings or higher usability by intelligent control systems via smart-phone applications.

3 MODELLING

Thermal models are necessary to describe the dynamics of the heating system, make optimal bids to the market and operate the heat pump pool in real-time. As the aggregation involves a high number of different typologies, the models should be inexpensive and applicable to a large number of different thermal systems. (Jungwirth, 2014) The thermal behaviour of TCLs is often expressed by state-space models (Pfaffen, D., Werlen, K., 2013; Koch S., Andersson G., 2009a). Alternative approaches model the thermal storage potential of TCLs as battery storage systems (Khan S. et al., 2016; Hao H. et al., 2015). For every typology evaluated in the market study, a state-space model is developed describing the thermal dynamics of the system (Figure 1) and enabling the implementation into a control system. It describes the changes of the temperatures in the thermal storage for space heating T_{sh} , domestic hot water T_{dhw} , and room temperature T_r in response to model inputs. The model inputs consist of the electrical consumption of heat pump P_{el} , outdoor temperature T_{amb} , heat losses in the building and the storage systems $\dot{Q}_{trans}$, internal gains $\dot{Q}_{int.gains}$ and a DHW profile. Pool operation aims at gaining synergy effects compared to separate operation. This can be achieved by reducing the operation costs of the pool on wholesale markets and by additionally gaining revenues with balancing market participation. In both cases, a schedule has to be sent to the pool participants, to adhere to contracts made on electricity markets. Because of the complexity of the matter, this schedule should be determined by an optimization model. Here, mixed-integer linear programming techniques were applied. The focus lies on minimizing operation costs on wholesale markets. Load shifting is incentivized by sending different price signals to the heat pump pool (Figure 2). Flat and high-low price signals serve as reference cases with none or restricted incentives for load shifts. A dynamic price signal, coupled to the EPEX spot day-ahead, highlights the optimized operation using flexibility via load shifts. The price signals are scaled to allow for better comparison between each other (Fischer D. et al. 2014). A simulation is conducted for 1000 units of every topology (except large-scale heat pumps).

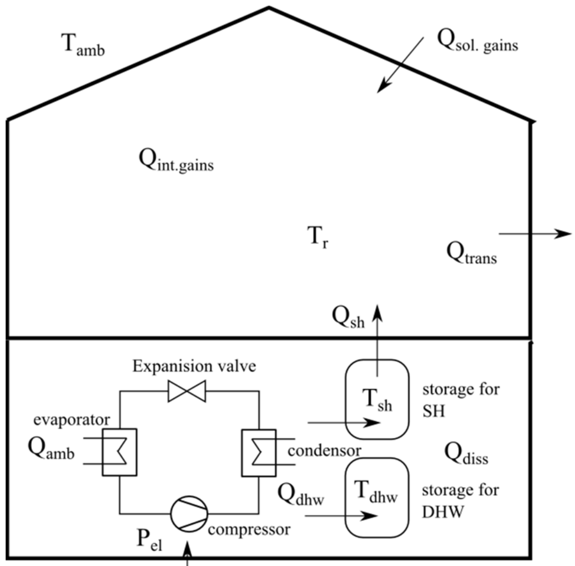

Figure 1: Basic scheme of thermal model.

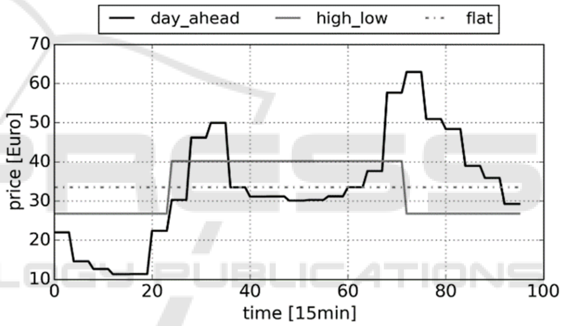

Figure 2: Price signals sent to heat pump pool to incentivize load shifts.

Table 2 shows the operational costs under different price signals for the year 2014. Under the here considered assumptions, allowing load shifts, the operational costs for the heat pump pool can be reduced around 8-14 % depending on the specific reference case. The major part of load shifts is happening during the heating period. The load shifting potential in summer is lower because only DHW is required.

Table 2: Operational costs and savings under different price signals for the year 2014.

	Flat	High-low	Day-ahead
Costs [€]	2.764.870	2.590.735	2.375.584
Savings [€]	- -	174.135 -	389.286 215.151
Savings [%]	- -	6,3 -	14,1 8,3

Load shifts use the possibility to temporarily overheat the temperature in the thermal storage systems (Figure 3). In times of low market prices the heat pumps are switched on and eventual excess heat is stored in the thermal storage systems. The maximum allowed temperature is set to 65 °C for SH and DHW storage systems whereas the minimum temperature is given by the specific heating system set points in Table 1. Room temperatures must stay between the interval 20-23 °C to fulfill user-specific comfort requests. Overheating the SH and DHW storage is preferred in contrast to the room temperature due to the higher storage capacity of water compared to air. The coefficient of performance (COP) is modelled as a function of the temperature difference between source and sink temperature (Fischer et al., 2014). Figure 4 shows the COP of the corresponding system with and without load shifts. It can be seen that due to load shifts the COP of the considered heat pumps is significantly declining. This effect is more prominent during the heating period where the major part of load shifts is happening. For the here considered case, the costs resulting from efficiency reduction are in the same scale like the potential gains of table 2.

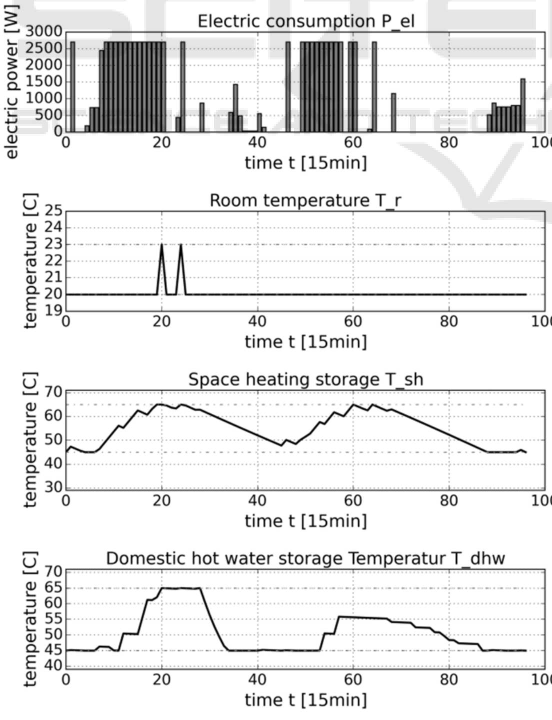

Figure 3: Temperatures in thermal storage systems due to load shifts for a winter day (Case: Renovated Building).

4 TECHNICAL CONCEPT

To control a high number of different demand facilities a suitable technical concept is necessary enabling the exchange of signals and data between the single pooling unit and the aggregator. The implemented technical concept should be cheap, secure and in line with certain grid codes to provide reliable ancillary services. The requirements for the ICT infrastructure depend on the chosen operation strategy. While the optimization of the heat pump schedule is less complex, the participation on balancing markets must be in line with the requirements of the TSO.

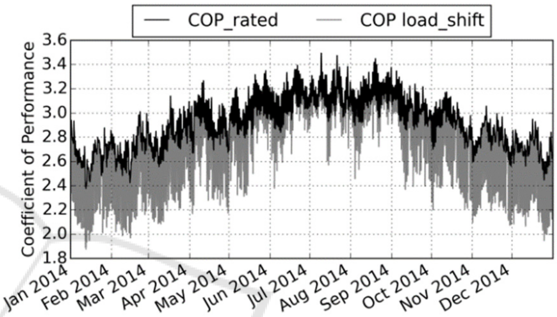

Figure 4: Coefficient of Performance without (COP_rated) and with overheating (COP load_shift) of temperature in thermal storage (Case: Renovated Building).

In case of a balancing energy call, the devices must be able to track a signal of the Austrian Power Grid (APG) to provide ancillary service. In case of tertiary reserve an electronic communication device is necessary to offer the minimum bid size of 5 MW in line with IEC 60870-5-101. A point-to-point fixed line connection like SDH or PDH and a serial interface V.24 / V.28 not longer than 15 m should be used. The components must guarantee a time for data exchange of a maximum of 5 s and an availability of 95%. Every 2 seconds measured data has to be sent to the APG. Also during the times no balancing energy is called, data exchange must be ensured. The actual electrical consumption as well as the operating point must be sent to the APG (Austrian Power Grid, 2014). An analysis of the different control concepts of heat pumps showed three types of possible implementations: External ripple control signal (ERCS): Via a potential-free contact demand devices can be externally switched-off. This is already used by utilities offering special tariff programmes. Interruptible tariffs e. g., are usually less expensive than normal ones, allowing an utility to actively switch heat pumps off for a given time, e. g. three times a day for two hours (in Austria and Germany). ERCS are also used to manage high/low tariffs where electricity consumed at night is less expensive than during the day. This concept is proved, already implemented and often existing infrastructure can be used. On the other hand, those external switching orders could result in a higher wear of the heat pumps, because ERCS are mandatory switching orders not considering the heat pump control and operation strategy. EEBus on the other hand is a protocol connecting IP-based devices of utilities and distribution service operators (DSOs) with the not yet IP-based devices of end customers. For smart control of end user devices the KNX and ZigBee standards can be used (Koch S. et al., 2009b). EEBus offers a framework to flexibly control end-user devices in a household from external IP-based systems. Typically the devices are connected to a Home Energy Management System. Compared to other communication technologies this is rather expensive and should already be considered in the construction phase of new buildings. To subsequently implement this concept for pooling concepts is rather inappropriate. In Germany exists a standard called Smart-Grid-ready (SG-ready) label supported by the German heat pump association. It is a label specifically designed for heat pumps and is already implemented in around 370 heat pump models of 19 different manufacturers. The SG-ready label defines the operation of heat pumps according to four operation modes (Bundesverband Wärmepumpe e. V., 2013, 2015). **Mode 1:** The heat pump is switched off for a maximum of two hours. This includes the already implemented functionality of interruptible tariffs via ERCS. **Mode 2:** Here the heat pump is operated in energy efficient operation mode according to the local controller taking into consideration the maximal switching time of two hours by guaranteeing a certain level of the thermal storage system. **Mode 3:** A switching recommendation is sent to the heat pump to alter its electrical consumption pattern by modifying the set-point of the room and/or thermal storage temperature. It is not an explicit switching order but a recommendation. **Mode 4:** The last operation mode is defined as a compulsory switching order. Two different mechanisms can be chosen. Either the compressor of the heat pump (optionally also an electric heating back-up device) can be directly switched on or the set-point temperature can be modified. The main difference to mode 3 is the fact that the signal is compulsory. Compulsory signals must be adhered to (mode 1 and 4) and intervene to some degree into the local heat pump controller. Switching recommendations leave the control to the local heat pump controller and only provide recommendations to alter the consumption pattern of the heat pump (mode 2 and 3). Regarding mode 4 it must be considered that directly controlling the compressor might result in a higher wear of the heat pump and its components while the control via temperature set-points is more favourable from technical view but leaves the exact operation to the local controller and therefore provides not full control of the heat pump consumption (Bundesverband Wärmepumpe e. V., 2013).Of the above mentioned control mechanisms the SG-ready label is assumed to be the most favourable because it is already implemented in many heat pumps and provides defined operation strategies enabling the external control of the single heat pump operation. Moreover it includes the functionality of ERCS and is considerably cheaper to implement than the EEBus. The technical concept must guarantee the conversion of external switching orders in real-time. This signal S_{aggr} is sent by an aggregator resulting from the participation on the specific electricity markets. The aggregated consumption of the pool P_{pool} should match the signal S_{aggr}. If $S_{aggr} < P_{pool}$ devices must be switched off until the signal matches the consumption of the heat pumps. If $S_{aggr} > P_{pool}$ additional devices must be switched on. In this context adequate sequencing algorithms are necessary respecting the actual operational condition of the single devices. It is favourable to switch those devices which will be switched in any case in future due to their normal operation mode. Alternatively a defined temperature distance to the upper or lower temperature limit can be used as a sequencing criterion (Hao et al., 2015; Khan, S., 2016). A smart box installed at households receives the schedule and sends adequate orders to the heat pump corresponding to the SG-ready operation modes 1-4. The local controller of the heat pump executes the schedule if possible and sends a feedback of power P_{el} and temperatures T_r , T_{sh}, T_{dhw} to the aggregator. The smart box is basically a communication device and the link between heat pump and aggregator. The smart box can be used to subsequently integrate other residential devices capable of load shifting.

5 CONCLUSIONS

With the use of load shifts the operational costs of a heat pumps pool can be reduced. In this context it is important to consider potential efficiency losses caused by overheating the thermal system. To approximate the flexibility, models are necessary that describe the dynamics of the interaction between electrical and thermal variables. These models should be inexpensive and applicable to a high number of different building types. The thermal model here applied will be further developed by including four layers to consider the temperature distribution inside the storage. Additionally also the efficiency will be considered in more detail. At the moment a black box building model is developed and will be validated by a more concise Dymola model and measured data of residential buildings. The market model will be extended to also evaluate the participation on balancing markets considering the probability a bid is accepted and the probability of balancing energy calls. At last a technical concept must be developed that guarantees a secure exchange of information and signals. The SG-ready standard is a promising control concept to externally control residential heat pumps. The concepts discussed are planned to be verified in a subsequent demonstration project.

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