

Thermal storage improves flexibility of residential heating systems for smart grids

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Abstract

Renewables energies such as photovoltaics are often available when there is little energy demand for space heating. One major strategy to enable this flexibility in heat pump operation is the short-term storage of thermal energy.

In our contribution, we explore the boundaries of flexibility achievable by the combination of heat pumps and thermal storage systems in residential heating. Flexibility is quantified based on the average fraction of hours per day with blocked heat pump and the costs for the consumed electricity on the German EPEX-Spot day-ahead market. The impact of different system designs (heating capacity of the heat pump and storage capacity), and control algorithms is examined with an experimentally verified model for the complete residential heating system. As an example for a typical old building in Switzerland, a single family house (SFH) with 100 kWh/m² annual heating energy consumption adopted from the IEA Annex task 44 is considered.

The integration of a thermal storage system together with scaling the heat pump power increases the flexibility (fraction of the day with blocked heat pump) by up to 43 %. Furthermore, the number of blocking periods longer than 12 hours increases by a factor up to 16. With the EPEX-Spot prices, the annual energy costs can be reduced by up to 28 %. In selected periods of the year, cost reductions of up to 30 % can be achieved with only 6 % reduction of efficiency. Future incentives for flexibility will help to increase the financial benefits, compensate for the costs of the required additional installations and thereby improve the integration of heat pumps into smart grids.

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1. Introduction

An extended integration of variable renewable energies such as wind power or solar energy intensifies the imbalance between electricity production and consumption if the current operation schemes are not adjusted. Due to the high energy demand for space heating (50 % in the European Union), the increasing distribution of heat pumps in Europe and the high efficiency of the latter, the heat pump technology is an optimal candidate for improving the balance between energy consumption and production. However, to decouple the provision of heat (consumption of electricity) from the heat demand of the building, heat has to be stored intermittently [1,2]. The storage capacity can be provided both by the building mass and the heating system as well as an additional thermal storage system.

An experimental verification of various configurations of buildings with different storage systems/sizes is prohibited by high costs and the high time demand for installation, monitoring and running the experiment.

Therefore, computer simulations of parts or the whole heating system and its control are a viable alternative. In many cases, the simulations enable predictions in faster than real time [3–5] (simulations for a full year with a one-minute resolution can be performed in less than a few hours). The simulation approaches can be split into two different categories: In a top-down approach, existing monitoring data of different configurations are analysed to predict the energy demand over multiple years [6,7]. In a bottom-up approach, simplified models for the individual components are connected to describe parts or the whole heating system [3,7,8]. Both public buildings [3] as well as multiple houses [9] are in the focus of modelling studies. Also for the control algorithm, both simple three point control algorithms as well as complex model predictive control algorithms [10] are investigated.

In this contribution, we explore the potential to improve the flexibility of a heat pump in a residential heating system by the integration of additional thermal storage system. The investigation is centred around a single family house (SFH100) with an annual heating energy demand of 100 kWh/m²/a [11], which is a typical example of a renovated old building in Switzerland. In Section 2, the definition of flexibility is reviewed altogether with the key features and investigation scope of the Matlab/Simulink model [12] for the residential heating system. In section 3, the results of the simulation study are presented, and a conclusion is drawn in Section 4.

2. Quantification of Flexibility and Modeling Methodology

2.1. Measures for flexibility

According to Eurelectric (Association of electricity industry in Europe), flexibility is the modification of generation injection and/or consumption patterns in reaction to an external signal (price signal and activation) [13]. In their list of quantifiers for flexibility, Eurelectric includes the price for the primary energy, the duration of the modification and the amount of the power modulation.

For a residential heating system, these three quantities have to be reinterpreted: As price signal, the price of the electricity at the German EPEX-Spot Day ahead market is considered. In contrast to the available pricing schemes for end users, this price model does not consider only a few discrete price levels, but offers traded prices with a binding to electricity demand and supply. As a second quantity, the share of the day during which the heat pump operation is certainly stopped (averaged over the heating period) is considered. This fraction quantifies which share of the day the heat pump can be employed for ancillary service provision, i.e. the contribution to the power modulation. As a third quantifier, the fraction of blocks with certainly stopped heat pump longer than 12 hours is calculated. This quantifier measures the potential of modifying the consumption pattern over a period of 12 hours, which exceeds the currently common horizon of 2 – 4 hours.

2.2. Modelling of components and system and parameter range under investigation

The impact of the different configurations is studied with a Matlab/Simulink model [12,14,15] extending the Carnot toolbox [16]. To simulate the dynamics of the building a three-parameter model is implemented [12] based on an energy balance [17]:

$$C \frac{d\vartheta}{dt} = g I(t) + \dot{Q}_{int} + \dot{Q}_H - H (\vartheta(t) - \vartheta_A(t)) \quad (1)$$

with the lumped heat capacity C , the conversion factor g for the solar intensity $I(t)$, $\vartheta(t)$, $\vartheta_A(t)$ the room and ambient temperature, \dot{Q}_H , \dot{Q}_{int} the heat flux due to the heating systems and internal appliances, respectively, and the heat transfer coefficient H through the envelope. In this contribution the parameters C , g , H are calculated for the reference single family house (SFH100) with an annual energy consumption of 100 kWh/m²/a as defined in the IEA Annex Task 44 [11,18]. The heating medium transfers heat to the room via radiators, which are modelled by an elementary heat transfer model.

The operation of the heat pump is modelled via performance curves (heat capacity generated and coefficient of performance for different ambient temperatures). These performance curves (displayed in Fig. 1) are derived from detailed models of the heat pump including optimum defrosting procedures [19,20]. Considered in this paper is a heat pump ZHI-14 from Emerson Climate Technologies, St. Louis, MO. The capacity generated by the heat pump is chosen conventionally: the thermal design power of 8091 W fulfils the heat demand (7337 W) of the building at the design temperature – 10 °C plus the demand for domestic hot water. To facilitate an operation of the heat

pump concentrated on few short time intervals, besides the conventionally selected heat pump also two models with 1.5 times and twice the power of the standard heat pump are considered.

As storage systems, water tanks of 1, 2, 4 and 8 m³ volume are considered. The volume is chosen similar to the size of a conventional oil storage tank such that the study also considers the cases where conventional oil burner-based system are replaced with a modern heat pump based heating solutions. In the presented model, the water tank is modelled with the corresponding model from the CARNOT toolbox using a node model for the storage [12].

The system configuration is implemented according to STASCH6 [21] employing the piping models as implemented in the CARNOT toolbox.

To control the heat pump, two different algorithms have been implemented. First, a conventional two-point controller where the heat pump is switched on or off whenever the inlet-temperature to the heat pump leaves a 5 K wide corridor around the set temperature. The set temperature of the heat pump-control is set according to the heating curve of the building minus the six-fold difference (i.e. the gain is 6) between actual room temperature and target room temperature (20 °C) (i.e. the set temperature is increased by 6 K in case the room temperature is 1 K below the target temperature). To exploit the benefits of an additional thermal storage system, a predictive control algorithm with a target on low energy costs is implemented. As mentioned in Section 2.1, the German EPEX-Spot day ahead market prices are considered here, which are at 23.00 on the evening prior the day of action. The availability of certain price information the day before yields a natural planning horizon of 24 hours. For this planning horizon, the operation times of the heat pump are selected such that the heat pump provides the required heat during the hours with the cheapest electricity. All simulations are performed for Zurich as the location in the year 2013. The climatic data are extracted from IDA-Web from MeteoSuisse, Zurich, Switzerland [22].

2.3. Verification of the model

Simulations are performed here to evade cost-intensive real-world experiments. Therefore, a direct verification of the whole system simulation is not possible due to the absence of reference data. To ascertain a high prediction quality of the model, each component model has been verified individually.

The building dynamics is compared to detailed simulations performed with the reference software IDA Indoor Climate and Energy framework (EQUA Simulation AB, Solna, Sweden). For both models (three parameters and IDA-ICE), eight physical parameters (heat load, solar gains, transmission and air flow losses, ground heat exchange, room, flow and return temperatures) are compared for simulations of Strasbourg for the norm year and for Zurich in the year 2013 are compared. The agreement between the simulations was very good [12], however, the three parameter models overestimated the heat consumption of the building slightly. The deviation can most likely be attributed to missing control of the radiator system.

The storage model is verified based on measurements of a 100 m³ storage tank in a district heating system in collaboration with Regiowerke Solothurn, Switzerland. If the simulations are corrected for an underestimated mass flow through the tank (the mass flow is overestimated as only measurements upstream a splitter serving three parallel tanks are available), the agreement on nine different levels within the storage tank is excellent [12].

The heat pump performance curves are derived from a detailed simulation software developed in-house [19]. As these models have been encompassingly verified experimentally, the performance curves represent the system behaviour reliably.

2.4. Optimisation in selected periods of the year

To push the limits of flexibility even further, a short period (21.3.2013 – 4.4.2013) has been investigated in more detail. The residential heating system is configured according to STASCH6, where the heat storage system is connected in parallel to the heat pump to enable an operation of the heating system where all heat is extracted from the heat storage system. The heat pump is selected conventionally, and a water tank with a volume of 2 m³ is included as thermal storage. The control algorithm has been manually fine-tuned for both high flexibility and efficiency.

3. Results of Simulation Study

3.1. Limits of flexibility (defined as fraction of the day with guaranteed non-operation of the heat pump)

In Fig. 1, the influence of different heat pump capacities as well as storage sizes on the flexibility (defined as the fraction of the day the heat pump is certainly not operational) is displayed. With the examined configurations, the

flexibility can be improved by up to 43 %. Furthermore, the results in Fig. 1 indicate that the capacity of the heat pump has a stronger impact on the flexibility as the size of the water tank. An increase of the heat pump capacity by 50 % and 100 % increases flexibility on average about by 10 % and 15 %, respectively. In contrast, the extension of the water tank from 1 m³ to 2, 4 and 8 m³ improves flexibility by around 3.8 %, 6.5 % and 7.5 % (the last value is calculated only for the cases with 1.5 times and twice the generated capacity of the heat pump).

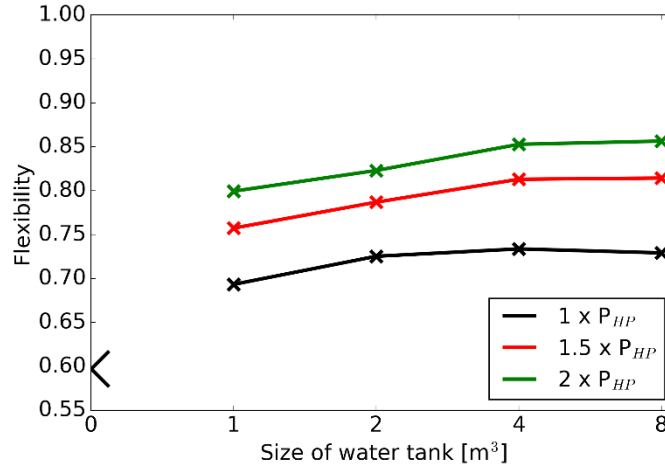


Fig. 1. Dependence of flexibility (fraction of the day with certainly blocked heat pump operation) on heat pump power (P_{HP}) and capacity of the storage system (size of the water tank). For all simulations, a prediction horizon of 24 hours in the predictive control algorithm has been employed.

The stronger contribution of the heat pump scaling to the flexibility as defined here was expected since high flexibility implies short operation times. As the same required energy has to be provided in shorter time, the appliance has a higher power. In consequence, high flexibility also implies higher peak power.

3.2. Focussing the operation times to facilitate grid management

Besides peak power, long period, where the heat pump is certainly switched off, are indicative of periods during which the power of the device can be called to balance production and consumption in the grid. In Fig. 2, the average duration of a period with certainly switched off heat pump is shown. In contrast to flexibility studied above, the average duration displays only a weak dependence on the power of the heat pump, whereas the influence of the size of the water tank is dominant. By the integration of the storage system, the average duration of the blocked heat pump periods can be increased by a factor of 11. Even the smallest storage causes an extension of the average duration by a factor of 7.2.

The contribution of the heat pump is predominately preventing a levelling of the influence of the storage size. With a conventionally selected heat pump the influence of the storage is already marginalised at a water tank size of 2 m³, whereas with double heat pump capacity even with 8 m³ water tank the average block size can be increased.

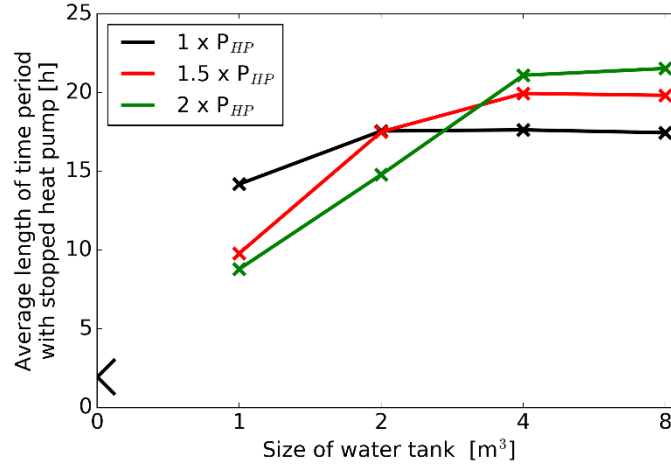


Fig. 2. Average length of the periods with stopped heat pump calculated for a residential heating system with the building type SFH100. Tested are three different heat pumps with scaled power (P_{HP}) and capacities of the thermal storage system. All simulations with storage system are performed with a predictive control algorithm with a horizon of 24 hours.

If the grid operator is interested in shifting the load from day to night or vice versa, the number of blocks longer than 12 hours is essential. In Fig. 3, the fraction of blocks with certainly stopped heat pump longer than 12 hours is displayed. The integration of a stronger heat pump and storage systems may increase the fraction of long blocks by a factor of up to 45. Even the integration of a small storage system with 1 m³ volume with conventionally selected heat pump, causes an increase by a factor of 19. The impact of heat pump capacity and storage size are similar to their effect on the average duration above: the size of the storage system has a stronger impact than the heat pump power. The latter predominately prevent an annihilation of the effect of the storage size.

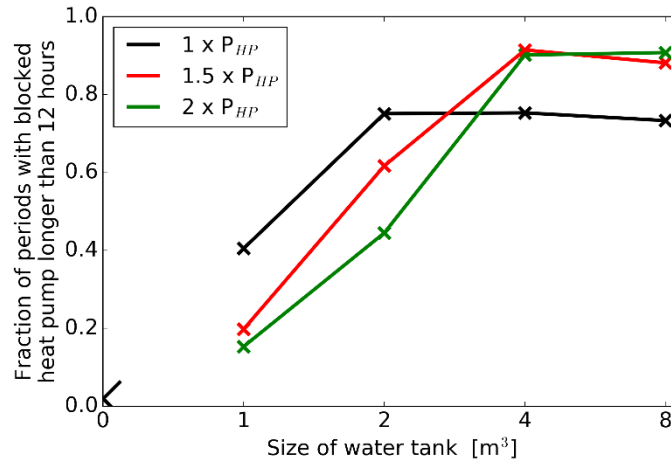


Fig. 3. Fraction of periods with stopped heat pump longer than 12 hours. The simulations are performed with the same parameters as Fig.1 and Fig. 2.

3.3. Cost reduction by storage integration

In Fig. 4, the influence of the different configurations and the action of the control algorithm on the primary energy costs is displayed. With large storage systems, a cost reduction of up to 20 % can be achieved. However, for small storage capacities, the electricity costs for a full year operation exceed even the costs of a conventionally (operated) system. More powerful heat pumps suffer from higher electricity costs due to shorter operation times, higher

storage medium temperature and, therefore, reduced efficiency of the heat pump. In larger storage systems, similar quantities of heat are stored with lower medium temperatures. Therefore, the heat pump can be operated with higher efficiency.

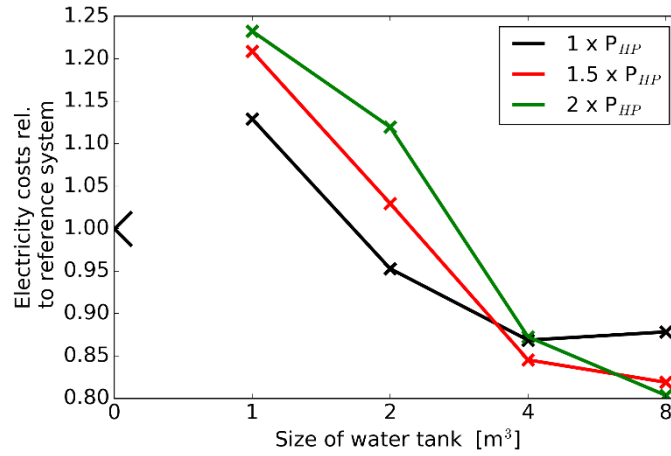
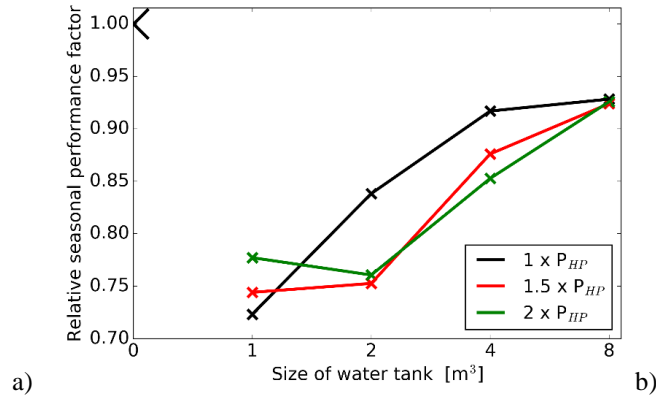


Fig. 4. Primary energy costs for full year heating operation relative to the respective value of the simulation with conventionally selected heat pump and two-point control algorithm. The simulations are performed with the same parameters as the previous Figures.

3.4. Drawbacks of flexibility providing operation mode

The elevated storage medium temperatures and the thermal losses of the storage system cause a reduction of the seasonal performance factor (SPF) as shown in Fig. 5. In particular, if a fixed prediction horizon of 24 hours is chosen, the reduction of the SPF (cf. Fig. 5.a) may be up to 28 %. However, if the prediction horizon is varied, the SPF is partially recovered and drops only by 12 % of the original value.

The general trend of the SPF on the variation of storage size and heat pump power is as expected: Large storage sizes enable lower storage medium temperatures, therefore, higher efficiency and, in consequence, higher SPF. For heat pumps with high capacity, the control algorithm compresses the running times of the heat pump and, thereby, causes higher storage medium temperatures yielding lower SPF.



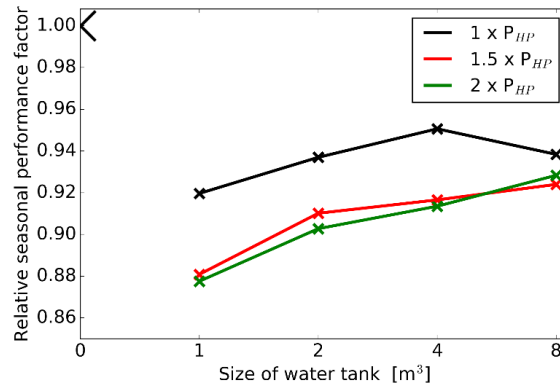


Fig. 5. Seasonal performance factor for different configurations of residential heating systems for the building SFH100. In the plot left (a), a fixed prediction horizon of the predictive control algorithm of 24 hours has been employed, whereas in the plot b) the optimum seasonal performance factor is determined among the solutions with prediction horizon 6, 12, 24 or 48 hours.

3.5. High flexibility with high efficiency (for a selected time periods)

In the previous sections, we focused on full year simulations and observed that increased flexibility and longer periods of blocked heat pump cause efficiency reductions. In this section, we concentrate on a fortnight in the second half of March 2013. The obtained results are summarised in Table 1. With the fine-tuned control algorithm, the number of hours per day with blocked heat pump can be increased by a factor of 2 – 3, the electricity costs be reduced by 36 % and the number of switching events of the heat pump reducing the life expectancy of the device by 80 %. These benefits can be achieved with a reduction of the efficiency by only 7.1 %. Remarkably, these results have been achieved with a conventionally selected heat pump and a storage system with mediocre storage capacity.

Table 1. Results of optimisation study for the inter season period of 21.3.2013 - 4.4.2013.

System / Operation mode	Hours blocked [h/d]	COP [%]	Relative Electricity costs [%]	Switching cycles [%]
No additional storage / 0 h blocked	0	100	97.3	100
No additional storage / 2 x 3 h blocked	2 x 3	97.9	100	78.7
Additional storage, predictive control	14 – 16	93.9	64.4	19.8

4. Conclusion

In this contribution, we investigated the potential of exploiting thermal storages for the provision of flexibility with heat pumps for the smart grid. Based on a simulation model of the whole residential heating system with experimentally verified components, the influence of additional thermal storages on the modulation strength of the heat pump, the duration of the modulation and the electricity costs is studied. As a typical example of the (Swiss) building park, a single family house with an annual energy consumption of 100 kWh/m²/a is considered.

The simulations indicate that the integration of an additional thermal storage may increase the flexibility (guaranteed off-time of the heat pump) by almost 50 %. With the same configuration, the average duration of these off-blocks can be increased by a factor of up to 45 and the costs can be reduced by up to 28 %. Although these large improvements require a unconventionally high powered heat pump and a large storage tank, even with a small tank of only 1000 litres and a predictive control algorithm, the flexibility can be substantially improved. For instance, the average off-time can be increased by a factor of almost 20.

The combined action of control algorithm, strong heat pump and large storage tank enable to save primary energy costs (assuming a demand-driven price structure). However, the potential of refinancing the additional investment for the house owner is very small if no further incentives are created by grid operators and electricity providers to foster flexibility provision with residential heat pumps.

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