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Investigation of Thermal Storage Operation Strategies with Heat Pumps in German Multi Family Houses

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Abstract

The use of air source heat pumps is an efficient method to provide heat for space heating and domestic hot water in residential buildings, which cover roughly one third of the German domestic energy use. Capacity controlled heat pumps are gaining increased market share and provide high flexibility in operation. The possibility to use thermal storage to decouple thermal production and electric load from the heat pump can be used for operation strategies, hereby increasing the possibility to integrate electricity production from renewable energy sources. In the work presented, a range of operational strategies for capacity controlled heat pumps connected to a thermal storage in German multifamily houses are introduced and evaluated. The use cases include maximization of energy performance, cost minimization and utilization of on-site photovoltaic production. For optimal storage operation a model predictive control (MPC) approach using quadratic programming is presented together with simplified models of the multi-family house, a thermal storage and a capacity controlled air-to-water heat pump, the MPC creates a control signal to the heat pump. The resulting control signal is then applied to a detailed heat pump model to investigate the impact on the efficiency of the heat pump unit and thereby its electric energy consumption with different storage options. Results show that the MPC strategy is able to adapt to different objectives. One of the most important findings is that changing the objective towards a variable day-ahead-price-based operation leads to decreased heat pump efficiency but increases revenue. The sensitivity analysis towards storage size shows little influence in the range of sizes investigated.

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Table 1: Nomenclature

<u>Optimization Model</u>		<u>Abbreviations</u>	
A_d	System matrix, discrete time	$ASHP$	Air-Source-Heat-Pump
B_d	Inputs matrix, discrete time	COP	Coefficient of Performance
E_d	Disturbances matrix, discrete time	DHW	Domestic Hot Water
J	Objective function	HP	Heat Pump
N	Prediction horizon	HTG	Space Heating
Q	Optimization weight for states	$Share_{\{solar\}}$	Share of solar energy used
R	Quadratic Optimization weight for inputs	SPF	Seasonal Performance Factor
W	Optimization weight for states x inputs	STC	Solar Thermal Collector
k	Time (discrete)		
u	Input vector		
$u_{\{lb\}}, u_{\{ub\}}$	Upper, lower bounds of the input vector		
r	Linear optimization weight for inputs	<u>Physical Units</u>	
x	States vector	Q	Heat
$x_{\{lb\}}, x_{\{ub\}}$	Upper, lower bounds of the states vector	\dot{Q}	Heat flow
$x_{\{ref\}}$	Vector of set points	$P_{\{el\}}$	Electrical power
z	Disturbances vector	$W_{\{el\}}$	Electrical energy

1. Introduction

In the 27 EU member states, buildings consume 68% of the total final energy consumption where space heating is responsible for 70% of this share [1]. A similar trend is to be observed in other parts of the world. In Canada, the building sector consumes 50% of the electricity, 31% of final energy consumption, and contributes to approximately 17% of the GHG emissions [2]. In 2004, according to [3], buildings in the United States accounted for 39% of the total energy use, 12% of the total water consumption, 68% of the total electricity and 38% of the carbon dioxide emissions. Thus, the building sector represents globally an important potential for energy efficiency and GHG reduction. In this context, heating systems based on heat pumps have been identified as an important tool to improve both situations. On the one hand they can smooth the electricity production peaks caused by the introduction of renewable energies. On the other hand they can reduce the GHG emissions and final energy consumption in the building sector [4].

In this study, the potential applications of heat pumps in households connected to a thermal storage are analyzed as they hold a high impact on the overall energy system. The optimal operation and how the storage sizing influences the system performance are investigated.

The work is focused on Air-Source-Heat-Pumps (ASHP) due to the good availability of air as heat source in addition to the simplified system configuration and lower investment costs compared to a Ground-Source-Heat-Pump. In buildings equipped with heat pumps and thermal storage, heat production and usage can be decoupled by storing heat and thereby shifting the electricity demand. The optimal operation strategy depends on the system configuration and the tariff structure, described in Section 2. In Section 2.2 the optimal system operation is derived with help of an MPC approach and quadratic programming. In Section 3 the impact on the heat pump operation is evaluated by three key performance indicators; system efficiency, yearly energy costs and the time of operation during the day. The influence of storage size is analyzed in Section 3.4 and finally an overall conclusion is given in Section 4.

2. Methodology

In order to answer the questions raised in the beginning of this work, the following steps were taken:

1. A simplified model that captures the most important physical aspects of the technical components in Fig. 1 was created for each use case.
2. The optimal operation strategy for each use case is calculated, using a partly linearized formulation of the heat pump model.
3. The thermal operation strategy and resulting system temperatures found in step 2 are fed into a detailed heat pump model to calculate the efficiency and the electric energy flows.

2.1. System model and sizing

The aim of the system model is to capture the main physical aspects without being too specific in the characteristics of the thermal storage and the heat pump used. Thereby maintaining a robust result, which captures the general trend. The target application is a refurbished multi family house in Germany with a monovalent ASHP and a thermal storage for heating and domestic hot water (DHW). Depending on the investigated case a solar thermal collector (STC) and PV panels are added. A scheme of the system model can be seen in Fig. 1, where the regarded energy flows are shown. The most important characteristics are listed in Table 2. The heat pump is sized to serve the peak heat demand. The heat pump can draw water from two different layers to provide heat for space heating and DHW. The solar thermal collector is connected to provide energy for DHW. The minimum temperature in the storage is 50°C for the DHW layer. In the heating layer of the storage the minimum temperature is determined by a heating curve based on the three day average outdoor temperature. If this temperature lies above 15°C the heating is switched off.

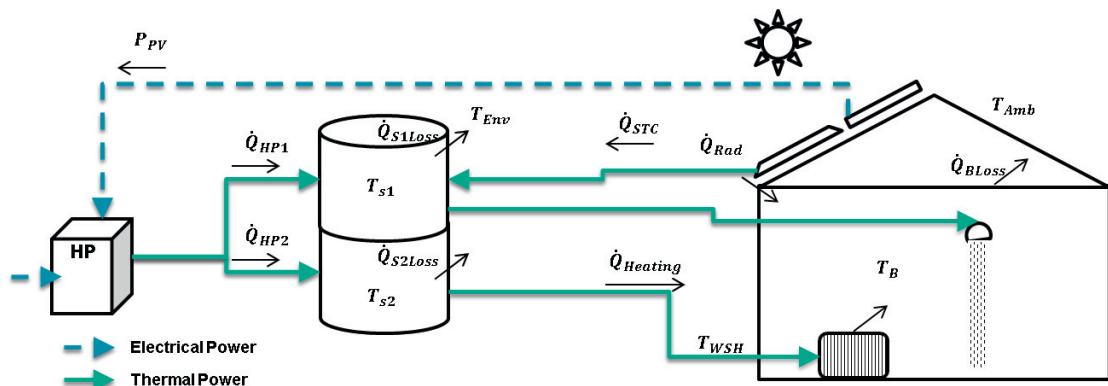


Fig. 1 Simplified Model of the system

2.1.1. Building model and DHW load

To derive the overall heating load of the system, the building was modeled in as a single zone building using TRNSYS Type 56 [5].

The DHW load is based on the model introduced by [6] and scaled to the 27 dwellers.

2.1.2. Storage Model

The thermal storage is modeled based on an energy balance including the enthalpy flows of the water, losses to the environment due to convective heat transfer and the change in storage temperature. This leads to a first order linear time invariant system.

Table 2: System characteristics

	Value	Unit
Location of building	Dusseldorf	-
Year used in simulation	2012	-
Building number of inhabitants	27	Persons
Living area	412	m ²
Annual heating demand	69	MWh/y
Annual DHW demand	18	MWh/y
Peak thermal demand (DHW+SH)	35	kW
Heating temperature at -10°C	55	°C
Min. DHW temperature	50	°C
Solar thermal collector type	Flat Plate	
Solar thermal collector area [7]	15	m ²
Photovoltaic system type	Monocrystalline	
Photovoltaic system size	10	kWp
U value of storage	1.26	W/m ² K
Temperature around the storage	20	°C
Maximum supply temperature of HP	65	°C
Electricity price (mean value)	30	ct/kWh
Feed-in tariff	13.4	ct/kWh

2.1.3. Solar energy resources

Photovoltaic electricity and solar thermal heat are the two renewable energy sources that are in the focus of this work. Photovoltaic electricity generation was taken from measurements of the location from panels with 35°C inclination and orientation southwards. Irradiation data measured in the same location was taken and feed into a solar thermal collector model used to determine the maximum possible heat it can provide. The model used for the solar thermal collector is described in detail in [8].

2.1.4. The heat pump model

In this work, the heat pump behavior is described by modeling its most important components. For the compressor, an performance map is used. The heat exchangers are modeled based on an energy balance. When assuming a constant heat transfer coefficient, the evaporation and condensing temperatures are merely dependent on the heat produced. The energy for inverter, fans and pumps is assumed constant when the heat pump is operating.

2.1.5. Resulting system model

The dynamics of the building and the storage are derived by performing an energy balance for each storage layer and the building. This leads to a model in discrete state space representation of the form:

$$x_{k+1} = A_d x_k + B_d u_k + E_d z_k \quad (1)$$

The states x of the model eq. (1) are the temperatures in each layer of the storage T_{Si} . The input u is the thermal energy produced by the heat pump for each layer $\dot{Q}_{HP,i}$, the heat supplied to the building $\dot{Q}_{HTG,in}$ and the energy from solar thermal collector \dot{Q}_{STC} that is used. The thermal losses of the storage are calculated assuming that the temperature of the room where it is installed is constant at 20°C. The disturbances z are the DHW as well as the heating demands ($\dot{Q}_{DHW(k)}$, $\dot{Q}_{HTG(k)}$) described in Section 2.1.1. *Optimal Control*

To derive the optimal operation schedule for the system, a model predictive control strategy based on quadratic programming was implemented. The objective function (2) used for the controls, aims to keep the temperature in the building at the desired value and minimize the electricity bill at the same time. In this work a deviation in building temperature is heavily penalized, thereby not using the building as storage. This is done to be able to focus the results on the thermal storage.

$$\text{mit } J = \sum_{k=0}^{N-1} (\text{Temperature error})^2 + (\text{Electricity bill}) \quad (2)$$

The electricity bill is the product of the electrical energy consumed and the tariff (Electricity bill = eCost · P_{el}). The electrical energy P_{el} consumption at a given time is derived using a first order Taylor expansion of Q_{HP}/COP around the optimal operation point. The heat pump model was discretized accordingly to account for the temperatures in the storage. The resulting optimization problem is formulated in (3).

$$\min_{J} J(x_0, u) = \frac{1}{2} \sum_{k=0}^{N-1} \left[\underbrace{(x_k - x_{ref_k})^T Q (x_k - x_{ref_k})}_{\text{Temperature error}} + \underbrace{r^T u_k}_{\text{Linear Cost}} + \underbrace{u_k^T R u_k}_{\text{Quadratic Cost}} + \underbrace{x_k^T W u_k}_{\text{Mixed Costs}} \right] \quad (3b)$$

$$\text{s.t. } x_k + 1 = A_d x_k + B_d u_k + E_d z_k, k = 0, \dots, N-1 \quad (3b)$$

$$u_{lb} \leq u_k \leq u_{ub}, \quad \forall k \in 0, \dots, N-1 \quad (3c)$$

$$x_{lb} \leq x_k \leq x_{ub}, \quad \forall k \in 1, \dots, N \quad (3d)$$

$$x_0 = x \quad (3e)$$

Where Q,R,W and r are matrices of adequate proportions which serve as optimization costs. The heat pump efficiency as well as the electricity tariff are embedded in this costs.

2.3. Testing scenarios

Thermal storage in combination with a heat pump system can be used to store heat and thereby decouple the electricity consumption for heat generation from the thermal energy demand of the building. Capacity controlled heat pumps can vary thermal output within a certain bandwidth to follow the demand, however the efficiency decreases when moving away from its designed operation point. In the most basic applications using a thermal storage, the operation of the heat pump system could be shifted towards its designed operation point thereby increasing the efficiency. From the power system point of view flexible prices can be introduced to motivate system controls to align electricity consumption with cheap heat production possibility. This is in contrast to the current state where German households see a constant electricity price throughout the year. Further, improved utilization of local on-site solar energy generation from PV or STC could also be achieved by altered storage operation. Motivated by these facts, two price scenarios, three system configurations and five different storage sizes were analyzed. The first price scenario uses a constant electricity price together with a feed-in-tariff. The second price scenario considers a day-ahead electricity tariff, which consists of 22 ct/kWh constant fees plus a variable share based on the EEX day-ahead-price (www.eex.com). The variable share is scaled such that the annual mean electricity price is the same as for the fixed price case. The three system configurations are as follows: First a baseline configuration conformed by a storage and an ASHP is investigated. Secondly PV panels are added to the baseline system in the "PV" system configuration. This system is extended with a solar thermal collector as the "PV+STC" system configuration (see visualization in Fig. 3). Each system configuration combined with a price scenario constitutes a use case and is depicted in blue. Each use case was tested with five different storage sizes shown in Fig. 2.

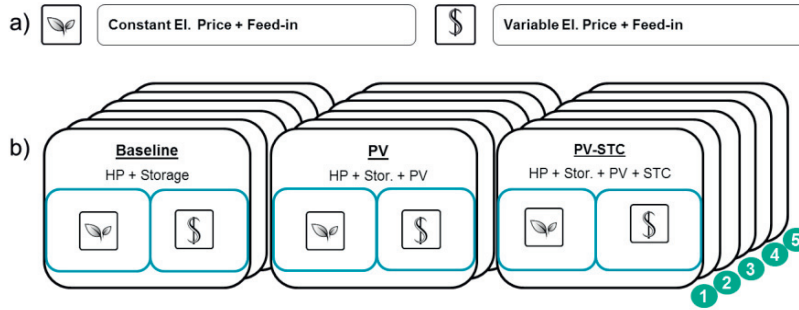


Fig. 3: a) Price scenarios b) Use cases: combination of a system configuration, a price scenario and a storage size.

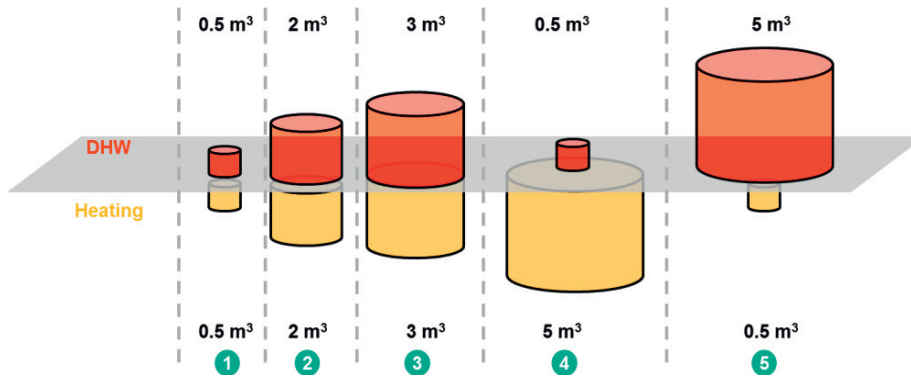


Fig. 2 Storage size options.

3. Results

The scenarios described in Section 2.3 were simulated for a period of 365 days with a time resolution of 15 minutes, a prediction horizon of 22 hours and a control horizon of 7 hours. To compare the results, the following key performance indicators (KPI) are introduced.

3.1. Key Performance Indicators

The seasonal performance factor (SPF) defined as the ratio between the thermal energy demand in the building for heating Q_{HTG} and DHW Q_{DHW} , and the electrical energy W_{el} needed for its generation:

$$SPF = \frac{Q_{HTG} + Q_{DHW}}{W_{el}} \tag{4}$$

The solar share is introduced to investigate the utilization of the on-site renewable heat generation, and is defined as the ratio of utilized solar energy ($Q_{STC} + Q_{HP,PV}$), to the total heat demand of the building ($Q_{HTG} + Q_{DHW}$). Notice that the utilized solar energy is the sum of solar heat generated from the collectors Q_{STC} and the heat generated by the HP using PV electricity $Q_{HP,PV}$:

$$Share_{solar} = \frac{Q_{STC} + Q_{HP,PV}}{Q_{HTG} + Q_{DHW}} \tag{5}$$

The annual energy costs is used as the third and last KPI.

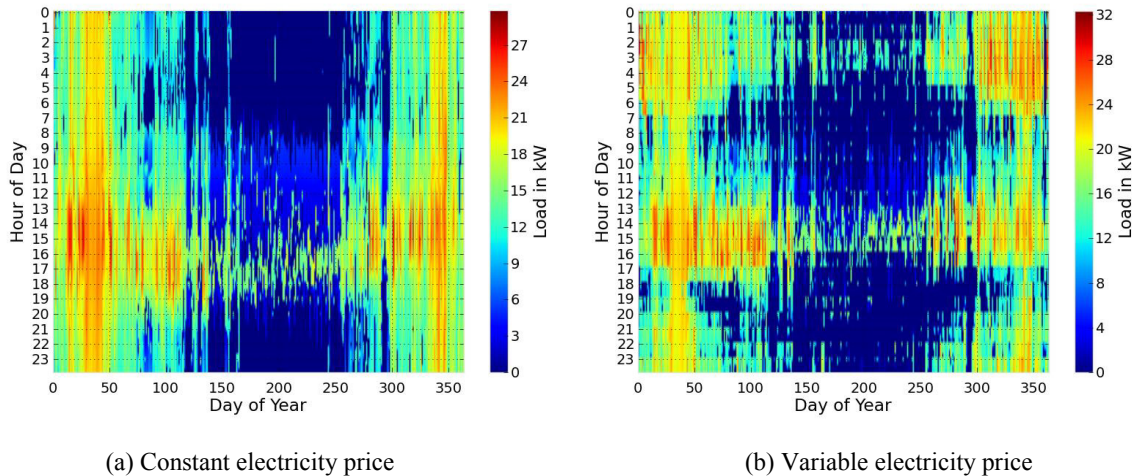


Fig. 4: Comparison of heat pump operation using different price schemes. The thermal load can be seen for each 15 min. of the year.

3.2. Impact of the price scenario

The results of the two price scenarios investigated are shown in Fig. 4. In the case of constant electricity price (left plot), the heat pump is mostly operated during the late morning and the afternoon when outdoor temperatures are favorable. However as the heating load is rather low at these hours, the heat production is used for charging the storage. Discharging of the storage occurs mostly in the late evening and night. In this case the efficiency of the heat pump is at its highest because it is operated at daytime when the temperature lift is at its lowest. However, in case of operation under flexible energy prices (right plot) the operation of heat pump (and the adjacent charging of the storage) is shifted towards night time. Together with the fact that the heat pump is operated at higher loads, this leads to a 5% reduction of the overall efficiency of the heat pump. For comparison, the second last line in Table 3 shows the main hours when the storage is charged for all the use cases.

3.3. Impact of the system configuration

The integration of photovoltaic energy leads to a change in operation of the heat pump in summer time towards hours with high irradiation and high outdoor temperatures. In order to incorporate most of the solar electricity available, the heat pump is operated with higher part load ratios, which leads to decreased efficiency, but also to decreased costs for the provided energy. Integrating heat from a solar collector increases the SPF and reduces operating hours of the heat pump during summer. Also the overall energy costs are reduced by using solar heat, because the ST heat is added at no cost and the sales of the generated PV electricity is increased since PV and STC are mostly operating at the same time. Adding a solar collector to the PV system leads to slightly higher solar shares.

3.4. Impact of storage size

For all use cases an increase of the storage size (storage option 1 to 2) has a positive - but small - effect on the key indicators shown in Table 3. However, further storage increase (from option 2 to 3) does not give any significant changes. It can also be seen that an increase of storage size increases the flexibility of operation. With the baseline system configuration, the largest heat storage for space heating demand (storage option 4) was the preferred solution both with constant and variable electricity prices. If solar resources are present a larger DWH storage is favorable, since DWH demand is also existing during summer when solar resources are mostly present. This leads to an increasing solar share with increasing DWH storage size. However, these positive effects are offset by additional storage losses (as seen in the results of storage size option 5).

Table 3: Comparison of simulation results of the use cases. Range reflecting different storage options.

	Baseline		PV		PV + STC	
	Const. Price	Var. Price	Const. Price	Var. Price	Const. Price	Var. Price
SPF System	3.2-3.3	3.2	3.2	3.1-3.2	3.4-3.5	3.3-3.4
SPF Heat Pump	3.3-3.5	3.3-3.4	3.2-3.4	3.2-3.4	3.2-3.3	3.1-3.2
Diff. in Money Spent	3.00%	1.00%	6.00%	4.00%	6.00%	4.00%
Solar Share	0	0	24%-28%	23%-27%	25%-30%	25%-29%
Storage Charging Hours	11 -19	12-17, 22-5	11-18	11-17, 22-5	10-18	10-17, 23-5
Best Storage Option	4	3	3	3	3	3

4. Conclusion

This paper investigates the effects of different price signals, system configurations and storage sizes on the operation of a thermal storage in combination with an ASHP. All use cases were simulated using an optimal control trajectory for the heat pump. For the investigated cases, adding a thermal storage offers the advantages of reacting to a price signal and thereby decreasing operation costs, compared to an operation without storage.

Adding on-site solar heat generation to the system, the hours of operation of the heat pump in summer was eliminated or shifted towards nighttime giving room for the heat generated by the STC during daytime. However adding solar electricity generation gives the opposite effect, as the heat pump would like to use the PV electricity generated at daytime for heat production. It was identified that increased storage size for space heating is favored over DWH if no solar resources are present. If solar resources are present a larger storage size for DHW increases the solar share, but has hardly any positive effect on the annual energy costs.

Increasing the storage size increases the heat pump efficiency, but also leads to additional losses of the system, and consequently the SPF and the annual energy costs is hardly improved. With increased storage size, a point is reached when the storage losses overcompensates the benefits of having additional flexibility for operation.

The work presented gives evidence that storage is favorable in terms of utilization of on-site solar energy generation. As storage sizing and operation are dependent on the system characteristics (Table 2) chosen, further work will entail detailed analysis of these input parameters for each use case. The effect of solar supported heating should also be investigated further.

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