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Impact of PV and variable prices on optimal system sizing for heat pumps and thermal storage

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ABSTRACT

Heat pump (HP) units coupled to thermal storage offer flexibility in operation and hence the possibility to shift electric load. This can be used to increase PV self-consumption or optimise operation under variable electricity prices. A key question is if new sizing procedures for heat pumps, electric boilers and thermal storages are needed when heat pumps operate in a more dynamic environment, or if sizing is still determined by the thermal demand and thus sizing procedures are already well known. This is answered using structural optimisation based on mixed integer linear programming. The optimal system size of a HP, an electric back-up heater and thermal storage are calculated for 37 scenarios to investigate the impact of on-site PV, variable electricity price, space heat demand and domestic hot water demand. The results are compared to today's established sizing procedures for Germany. Results show that the thermal load profile has the strongest influence on system sizing. In most of the scenarios investigated, the established sizing procedures are sufficient. Only large PV sizes, or highly fluctuating electricity prices, create a need for lager storage. However, allowing the storage to be overheated by 10 K, the need for a larger storage only occurs in the extreme scenarios.

1. Introduction

Increased generation of electricity from intermittent renewable energy sources increases the need for flexibility on the demand side. This is needed to allow stable operation of the power system [1,2]. It has been widely accepted that heat pumps coupled to thermal storage can provide flexibility to the power system [3–5]. For such a case variable electricity prices can be used as a way to influence heat pump operation [6–8]. Further, heat pumps (HP) can be used to increase the use of electricity from photovoltaic plants (PV) on a building level [9–11]. In many countries the cost for on-site generated PV electricity is below the electricity price, and self-consumption of PV electricity is economically attractive. Today, most HP manufacturers offer control schemes to align heat generation with available PV electricity.

Thus variable electricity prices and PV self-consumption will change the way HPs are used. As a consequence, the sizing procedures of the heat pump unit, the electric back-up heater and thermal storage might need to be adjusted. The aim of this study is to find the optimal system configuration and operation which minimizes the costs over a lifetime of 20 years, using structural optimisation.

A central question of this study is whether operation under variable electricity prices or PV requires different system sizing compared to what is seen today? This essentially boils down to the question if larger storages for heat pump systems are required in the future. Further, the role of the electric back-up heater is questioned. If there is no need for changed sizing procedures it can be concluded that the current system sizing procedures and hence, what is installed in the field today, is already prepared to a large extend for the increased flexibility demanded by the changes in the electric energy system.

It is assumed that thermal energy storage will play a central role for the heat pump's ability to respond to the needs of the power system [3]. This is good news as at least in Germany installing thermal storage is common practice. As a consequence the focus of this study is on storage tanks. The use of the building's thermal inertia is not part of this study, but is reflected in the storage sizing recommendations used. According to scientific literature [12–15], engineering guidelines and manufacturers recommendations [16–23] the reasons to install thermal storage can

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be summarized to three points: (1) Reduced investment costs for the system, as need for peak capacity is reduced (2) Ensure feasible operation so that minimum unit run times can be kept, (3) Allow flexible operation e.g. to self-consume PV or benefit from varying electricity prices. Further, in Germany most heat pumps are offered a reduced grid fee when the grid operator is allowed to block heat pump operation up to 3 × 2 h a day. If blocking is activated, a thermal storage or high building thermal inertia is needed to keep the indoor temperature within the comfort limits during blocking hours.

For system sizing in the field the established procedures are based on thermal loads of the building and for hot water. For operation under variable electricity prices or on-site PV, sizing procedures are not yet established. In this study, the optimal sizing and operation of an air-source heat pump system are calculated using mixed integer linear optimisation. The case study is performed on a multi-family house situated in Germany with an air-source heat pump, as they are gaining increasing market share [24]. The heat pump is coupled with an electric back-up heater and a water tank used as thermal storage, which is current practice in Germany.

The most important factors that influence the system sizing are identified by varying the building's space heating load, domestic hot water (DHW) load, size of the on-site PV and variability of the electricity price. Optimal sizing and operation is determined by solving a mixed integer linear optimisation problem (MILP), which is briefly explained in Section 3. The problem is solved for 37 scenarios explained in Section 4 to identify the most important factors that determines the system sizing. Studying the optimisation results (presented in Section 5) and comparing them with today's sizing procedures (explained in Section 2), leads to a better understanding of the dominant effects and helps developing sizing recommendations for future heat pump systems (presented in Sections 6 and 7).

2. Sizing procedures according to manufacturers

A heat pump system that provides space heating and domestic hot water (DWH), typically consists of the following components: A heat pump, a back-up heater and a thermal energy storage. Today, sizing of the individual components is based on manufacturers guidelines and textbooks [16–23]. This section presents a summary of sizing recommendations for a variable speed air-source heat pump (ASHP) system with water storage tanks, as this is the focus of this study.

2.1. Sizing of heat pump and back-up heater

The sizing of the ASHP is determined by the heat load, the heat distribution system of the building, and the presence and type of the back-up heater. The latter determines whether the system is monovalent, mono energetic, or bivalent. In the case of monovalent HP systems, the building's space heating and DHW demand is entirely served by the heat pump at all times of the year. In case of a mono-energetic HP system, an electric back-up heater supports the heat pump during thermal peak hours, and the HP unit is sized to cover approximately 95% of the total annual heat demand [20,21]. In case of a bivalent system a non-electric back-up heater is used, which, in Germany, typically is a gas fired boiler. Here, the sizing of the HP is such that it covers about 60% of the annual heat demand.

A sorted annual duration curve of heat demand over ambient temperature is used to determine the exact share of heat covered by the heat pump. The bivalence temperature T_{biv} is the outdoor temperature below which the back-up technology is used to support the heat pump. At that point, the HP size is determined as the sum of the instantaneous space heating load $\dot{Q}_{\text{sh}}$ and an added capacity $\dot{Q}_{\text{DHW}}$ for DHW. The additional heat pump capacity $\dot{Q}_{\text{DHW}}$ for DHW decreases with the number of people in the building due to the smoothing of peaks with increasing number of occupants. Values between 0.88 and 0.17 kW extra capacity per person are recommended for dwellings with 4 up to 10 occupants. Lastly the calculated thermal peak demand for space heating and DHW is multiplied by a safety factor f_{block} for blocking hours:

$$\dot{Q}_{\text{HP}} = f_{\text{block}}(\dot{Q}_{\text{sh}}(T_{\text{biv}}) + \dot{Q}_{\text{DHW}}) \quad [\text{W}] \tag{1}$$

The calculated extra capacity to be added, is the ratio of maximum hours per day to maximum allowed operational hours per day:

$$f_{\text{block}} = \frac{24}{24 - t_{\text{block}}} \quad [-] \tag{2}$$

Although in practice, the additional capacity added for blocking hours according to manufacturers recommendations, is approximately 10% below the calculated value [20–23].

The gap between the maximum HP capacity at minimum ambient temperatures and the thermal peak demand, determines the size of the back-up heater.

The explained sizing procedure can be summarized as follows:

1. Determine heat load and DHW demand of the building
2. Determine space heating supply temperature curve for a given ambient temperature
3. Decide on the operation of the HP – (Monovalent, mono-energetic, bivalent)
4. Size the heat pump for the bivalence temperature, and if needed, add capacity for DHW
5. Size the back-up heater for the minimum ambient temperature
6. Increase sizing for blocking hours

2.2. Sizing of storage for DHW demand

Sizing of the domestic hot water storage is determined by the DHW load profile and the allowed temperature difference ΔT in the storage. As the DHW load profile is dependent on the number of persons and their occupancy behaviour, it is difficult to predict the exact demand, and hence sizing heuristics are applied. In the following, two sizing heuristics are presented.

According to [16] and manufacturers recommendation, the following procedure is applied. First, the annual DHW demand and the peak demand is determined according to DIN 4708 [25] depending on the number of "standard" flats in the house. From this, a characteristic storage parameter depending on the peak demand and the duration of the peak demand is derived. Most manufacturers offer an already prepared look-up table where the needed storage can be directly selected when the characteristic storage parameter is known with respect to allowed temperatures in the storage.

An alternative heuristic is found in [16] where the needed DHW storage capacity is directly determined by the number of persons, as shown in Eq. (3). The formula is valid for the range up to 300 persons, and S is a safety margin between 125% for low numbers of persons, and 105%, for more than 200 persons.

$$V_{\text{DHW}} \simeq S \cdot 65.0 \cdot n_{\text{persons}}^{0.7} \quad [\text{l}] \tag{3}$$

2.3. Sizing of space heating storage

For HP systems only providing space heating demand, the sizing of the buffer storage depends on the type of heat pump, (air- or ground-source), compressor (fixed or variable speed), the minimum runtime of the heat pump unit (usually about 6–20 min), blocking hours and on the thermal inertia of the heat distribution system and the building. In case of variable speed air-source heat pumps, no or only a small storage of about 10–20 l per kW HP is recommended for defrosting and smooth operation.

The minimum recommended buffer tank size is based on the installed heat pump size and calculated to:

$$V_{\mathrm{min,SH}} \simeq 10.0 \cdot \dot{Q}_{\mathrm{HP}} \qquad [\mathrm{l}] \tag{4}$$

However, to overcome blocking hours, the buffer tank needs to be sized such that the maximum heat load of the year Φ_{max} can be supplied to the building for 2 h. Using the specific heat capacity C_{water} of water and the allowed temperature difference ΔT in the storage, the needed storage size when allowing for blocking hours can be calculated according to Eq. (5). Given an allowed ΔT of 10 K this leads to a theoretical storage size of 172 l per kW nominal heat load.

$$V_{\mathrm{theory,SH}} = \frac{\Phi_{\mathrm{max}} \cdot 7200s}{C_{\mathrm{water}} \Delta T} \qquad [\mathrm{l}] \tag{5}$$

In practice however, the building's thermal inertia and relaxation of the indoor comfort temperature requirements, may lead to smaller storage size recommendations. Hence, the manufacturer recommendations for heavy buildings and/or floor heating ranges from approximately 20–60 l per kW maximum heat load, and 50–80 l/kW for lighter buildings and/or radiator heating.

Eqs. (6) and (7) show fits of manufacturer's recommended values for storage size accounting for blocking hours. The coefficients depend on the maximum heat load Φ_{max} and on the thermal inertia of the system [17]. The fits are valid for heat loads up to 108 kW. For smaller units with peak demand below 4.5 kW, no storage is recommended.

For floor heating systems (high inertia, HI), the recommended storage size is:

$$V_{\mathrm{HI,SH}} \simeq 19.4 + 28.1 \cdot \Phi_{\mathrm{max}} \quad [\mathrm{l}] \tag{6}$$

For radiator heating systems (low inertia, LI), the recommended storage size is:

$$V_{\mathrm{LI,SH}} \simeq 81.54 + 53.8 \cdot \Phi_{\mathrm{max}} \quad [\mathrm{l}] \tag{7}$$

2.4. Methods used for optimal energy system sizing in academic literature

In academic literature, various methods for determining the optimal size of energy system components are found. They are either based on parameter variation and simulation, i.e. incrementally changing the parameters of interest and rerunning the simulation, or on structural optimisation.

Parameter variation is presented in [26] for optimised solar thermal and storage sizing. In [27] a scenario based analysis to determine the optimal size of CHP and storage system according to time of use tariffs (TOU) is presented and stated that variable electricity prices lead to increased storage size.

A second approach is to use a simulation model in combination with optimisation techniques. First, the optimal system sizing is found, and secondly, a simulation model is used to calculate annual operation and performance figures. This usually results in a non-linear or even black box formulation of an optimisation problem as in [28], where Tabu Search is used for optimising thermal storage size to increase the use of wind power in an interlinked thermal-electric scenario.

The third approach is to fully formulate the investment and the control problem into one optimisation problem. This approach was applied in [15] showing the impact of optimal heat pump use on the Danish system in 2030. The HP systems including thermal storage, were optimised in size and operation to reduce peak loads and fluctuations created by introducing wind energy into the power system. The problem was formulated and solved as a linear problem, and the HP's coefficient of performance was assumed constant.

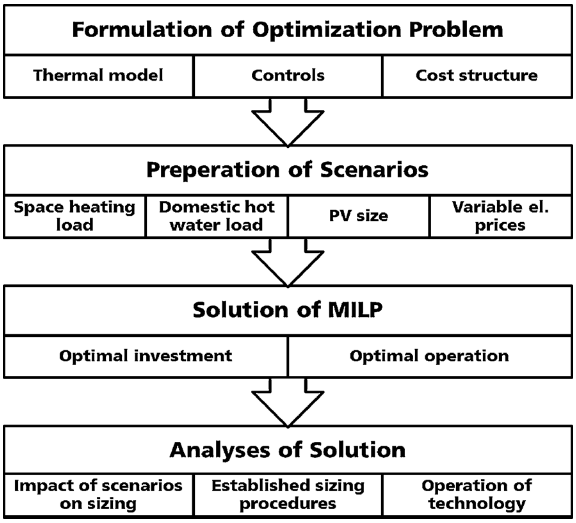


Fig. 1. Description of the general methodology.

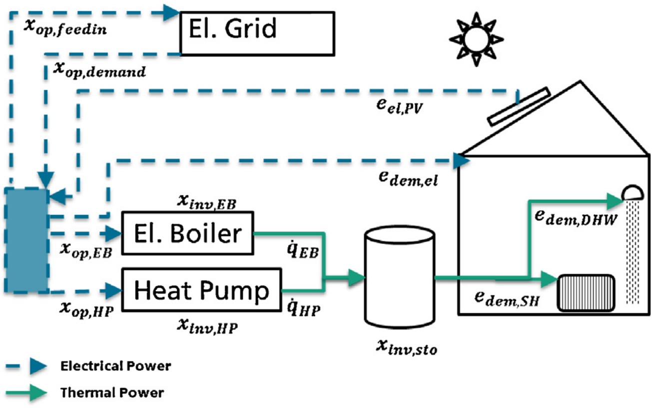


Fig. 2. Description of the system.

In [29] the effects of electricity tariffs on optimal battery sizing, when applied in a residential PV setting are studied and formulated as a mixed integer linear problem.

A framework for optimal investment and operation of building energy systems in the context of zero energy buildings is presented in [30]. A mixed integer linear program is formulated and solved for investment and operation for each hour of the year. The target for optimisation is flexible as to account for minimum cost or minimum CO_2 emissions. This work lays the foundation of the optimisation approach chosen in the presented paper.

3. Method

This section describes the general methodology for investigating the influence of selected factors on sizing of an air-source heat pump system (see Fig. 1).

The ASHP is coupled to an electric back-up heater and thermal storage tank, and is hence a mono-energetic system. A mixed integer linear optimisation model is used to find the optimal system sizing and operation for each scenario. A detailed description of the optimisation framework is provided in [30].

3.1. System description and assumptions

Fig. 2 shows the system under consideration. It is a residential building, with radiator heating system, stratified thermal storage and PV on the roof. The storage tank is used for both domestic hot water and space heating. The heat is supplied to the storage by a variable speed air source heat pump (ASHP) and an electric boiler (EB). The variable speed ASHP is capable of changing its thermal output in the range from 30% to 100% of the capacity. HP efficiency is dependent on the ambient temperature, and the temperature set point needed for DHW or space heating. The storage temperature is kept between the set point and a 10 K offset. Electricity generated from the PV plant is used for serving the electric load in the house and the surplus can be used by the HP unit, or exported to the grid at a price equal to the feed-in-tariff of 0.11 €/kWh paid to the building owner. The HP tariff in Germany at 0.19 €/kWh is set as the buying price for electricity to the heat pump, whereas the electricity price for the electric demand of the building, equals the end-user price in Germany at 0.24 €/kWh [31].

3.2. *Formulation of optimisation problem*

The aim of this study is to find the system configuration and operation which minimizes the total discounted costs over a lifetime of 20 years. The total costs J are the sum of total investment costs and total operation costs which depend on the chosen sizes $x_{\text{inv},i}$ for technology i and its operation $x_{\text{op},i,t}$ on each time step of the year t. Annual operation costs are discounted by $1/(1+r)^a$ for each year a using the nominal interest rate r. This leads to the following objective function:

$$\min_{x_{\text{inv}},x_{\text{op}} \in \mathbb{R}} J = \sum_{i=0}^{I} \left[c_{\text{inv},i} x_{\text{inv},i} + \sum_{a=1}^{20} \sum_{t=0}^{T} \frac{c_{\text{op},i,t} x_{\text{op},i,t} \Delta t}{(1+r)^a} \right] \tag{8}$$

where $c_{\text{inv},i}$ are the specific investment costs and $c_{\text{op},i,t}$ are the operational costs of each technology i at each time step t. The operational decision variables $x_{\text{op},i,t}$ and the demands e_i are visualized in Fig. 2.

To guarantee a physical reasonable operation, the optimisation problem is constrained for all points in time T and all available technologies I by the following set of equations:

No negative invest:

$$0 \le x_{\text{inv},i} \quad \forall i \in I \tag{9}$$

Electric energy balance holds:

$$0 = \sum_{i=0}^{I} x_{\text{op},i,t} + e_{\text{dem,el}} - e_{\text{el,PV}} \quad \forall t \in T \tag{10}$$

Thermal storage content s_t within allowed limits:

$$s_t = \sum_{t=0}^{t} \eta_{\text{sto}}^{t} \left(\sum_{i=0}^{I} \eta_{\text{op},i,t} \cdot x_{\text{op},i,t} - e_{\text{dem,SH},t} - e_{\text{dem,DHW},t} \right) \Delta t$$

$$0 \le s_t \le x_{\text{inv,sto}} \quad \forall t \in T \tag{11}$$

HP thermal capacity within allowed limits:

$$\eta_{\text{op,HP},t} \cdot x_{\text{op,HP},t} \in [0, (0.3, \gamma_{\text{max,HP},t}) \cdot x_{\text{inv},HP}] \quad \forall t \in T \tag{12}$$

EB within allowed limits:

$$0 \le x_{\text{op,EB},t} \le x_{\text{max,EB},t} = x_{\text{inv,EB}} \quad \forall t \in T \tag{13}$$

Storage losses in Eq. (11) are accounted for by means of a storage efficiency η_{sto}, which is the share of storage energy that is available from the previous time step.

3.2.1. *Heat technology models*

The conversion efficiency of electricity to heat $\eta_{\text{op},EB,t}$ at each time t for the electric boiler is as follows:

$$\eta_{\text{op,EB},t} = 0.99 \quad \forall t \in T \quad [-] \tag{14}$$

For the ASHP, the coefficient of performance *COP*, is dependent on the temperature lift between the hot and the cold side, which is a function of the ambient temperature $T_{\text{amb},t}$ and the set point temperature $T_{\text{set},t}$.

$$COP_t(T_{\text{amb},t}, T_{\text{set},t}) = a_0 + a_1 \Delta T_t + a_2 \Delta T_t^2 \, [-] \tag{15}$$

The coefficients a are obtained using a least square fit on HP data from manufacturers [17], where ΔT_t is as follows:

$$\Delta T_t = T_{\text{set},t} - T_{\text{amb},t} \quad [\text{K}] \tag{16}$$

Since the heat pump is modelled as one unit, but operated at two operation points, namely DHW preparation and space heating, the average efficiency $\eta_{\text{op},HP,t}$ at each time t, is calculated as the energy weighted *COP* of both operation points, weighted by the respective heat demands $\dot{Q}$.

$$\eta_{\text{op,HP},t} = [\dot{Q}_{DHW,t} COP(T_{\text{amb},t}, T_{DHW,t}) + \dot{Q}_{sh,t} COP(T_{\text{amb},t}, T_{sh,t})] \cdot \frac{1}{\dot{Q}_{DHW,t} + \dot{Q}_{sh,t}} \forall t \in T \quad [-] \tag{17}$$

The set temperature for space heating T_{sh} is derived from the heat curve for a given building and heat distribution system using the ambient temperature T_{amb}.

The maximal thermal capacity of the heat pump changes with ambient temperature. This is accounted for by introducing a normalized maximum heat pump capacity $\gamma_{\text{hp,max,t}}$ in Eq. (12), which is linearly dependent on the ambient temperature $T_{\text{amb},t}$.

$$\gamma_{\text{max,HP},t} = b_0 + b_1 \cdot T_{\text{amb},t} \quad \forall t \in T \quad [-] \tag{18}$$

The coefficients b are obtained using a least square fit on HP data from manufacturers [17].

3.2.2. *Investment, lifetime and interest rate*

The investment costs for each technology are separated in fixed costs, and specific costs depending on the unit size. The fixed costs are independent of the unit size and specific costs are modelled linearly in the given range. Costs for wear and tear are accounted for by fixed annual operational costs. The used cost data is listed in Table 1.

The specific investment cost per litre storage is transformed into cost per kWh using the specific heat capacity of water in kWh/(l K) and the maximum allowed storage temperature range ΔT, which is set to 10 K. The specific cost per litre is 1.4 €. The interest rate is set to 4% and the lifetime used for calculation is 20 years.

4. Scenarios

The introduction (Section 1), identified that changed operation of the HP systems, due to variable prices or PV self-consumption, might lead to adjustments of today's sizing procedures, presented in Section 2.4. This work investigates the impact of the following four input parameters on the system sizing: (1) building physics,

Table 1
Cost assumptions including VAT.

	Fixed	Specific	
Installation costs:			
ASHP	2000 €	1500	€/kW
Electric boiler		60	€/kW
Thermal storage		60/120	€/kWh[1]
Annual operation &maintenance costs:			
ASHP		1.1	% of invest
Electric boiler		1.4	% of invest
Thermal storage		0	% of invest

[1] Allowing $\Delta T = 10\,\text{K}/\Delta T = 20\,\text{K}$ in storage.

Table 2
Investigated scenarios, reference scenario underlined.

Building	DWH [n persons]	PV [kWp]	El. price Variability	Storage ΔT [K]
Unrefurbished	12	0	Constant	10
Refurbished	6,12,18	0–160	0–100%	10,20
New	12	0	Constant	10

(2) number of persons for DHW consumption, (3) PV electricity generation, and (4) variability of the electricity price. The resulting scenarios are listed in Table 2 and are explained in detail in the following section.

4.1. Reference scenario

The reference scenario is a refurbished German multi family house, with six flats each containing two occupants [32] and without on-site PV generation. A constant electricity price at 24 ct/kWh for the electric demand is applied, and 19 ct/kWh for electricity consumed by the HP system. Potsdam is taken as the reference climate location and measured climate data for 2012 for the given station is used as input.

To investigate the system sizing if either covering the DHW or the space heating demand alone, two additional scenarios are applied, which contains the space heating and DHW demand of the reference scenario separately (see “Single operation” in Fig. 10).

4.2. Building physics

To analyse the impact of different heat load profiles an unrefurbished, a refurbished and a new building are simulated, based on the building parameters provided in [32]. The specific annual heat demand is 188 kWh/m^2, 69 kWh/m^2 and 36 kWh/m^2, respectively.

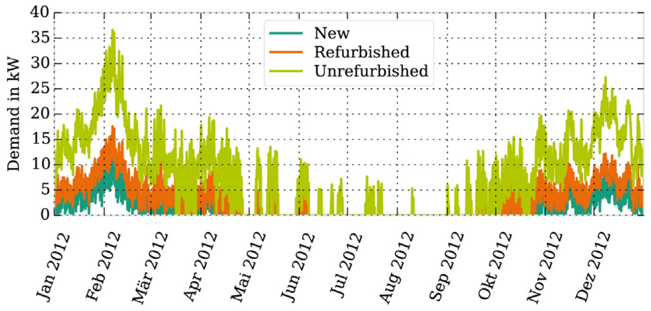
The space heating load is calculated using a 5R1C building model. The model is based on the simplified hourly method according to DIN EN 13790 [33] for calculating heating and cooling demands. The heat load model is presented and validated in [34]. Inputs to the model are irradiation, building physics and internal gains. Internal gains are calculated based on building occupancy and the use of electric devices, obtained from the synPRO behavioural model [35].

Fig. 3 shows the 15 min heat demand and the sorted annual duration curves for the three scenarios. The figure shows that increased energy efficiency of the building, decreases the load peaks and the number of days where the heating system is activated. Particularly during summer and changing season, increased building efficiency leads to fewer heating days.

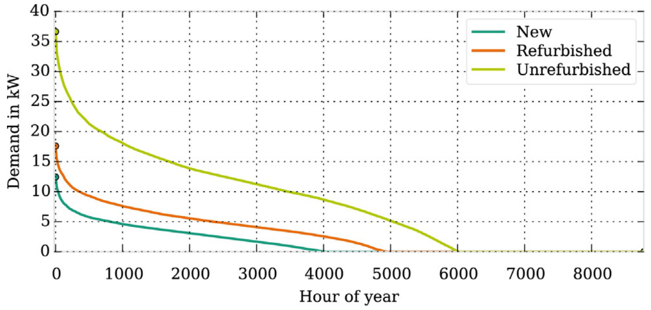
4.3. DHW loads

The influence of increased DHW loads is investigated by changing the number of inhabitants in the reference case, to 8 and 16 people. The domestic hot water consumption is obtained using a stochastic bottom-up model (synPRO), which links user behaviour to the number of tappings, dependent on time of the day. The energy demand for each tapping is calculated based on the volume flow rate, and on the hot and cold water temperatures, taken from VDI 2067 [36]. Detailed information and validation of the DHW load profiles are given in [34].

Fig. 4(b) shows the DHW annual duration curves. It can be seen that the yearly peak increases non-linearly with increasing amount of people, and a smoothing of the load curve can be observed. Further, the shape of the duration curve is less steep in the hours of high demand when adding more people.

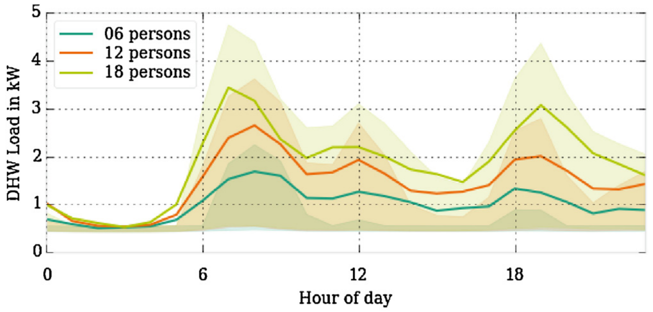


(a) Space heating demand for each 15 min.

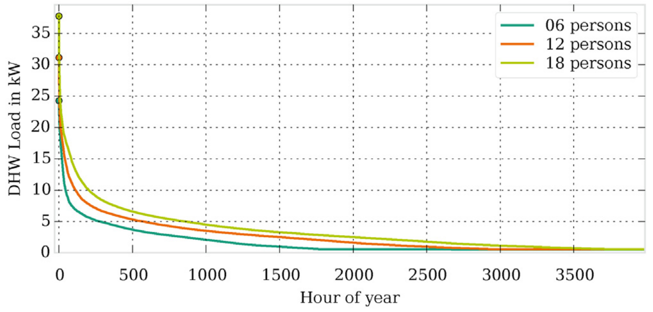


(b) Annual duration curve for each 15 min.

Fig. 3. Scenarios for space heating for different building physics.



(a) Hourly mean daily profile over the year and 0.25/0.75 quantiles.



(b) Annual duration curve for each 15 min.

Fig. 4. Scenarios for DHW consumption with 6, 12 (reference) and 18 persons in the house.

4.4. On-site PV electricity generation

The effect of on-site PV generation is investigated by increasing the size of the installed PV capacity incrementally from 0 to 160 kWp. The PV plant is oriented southward and 35° inclined. A feed-in tariff of 0.11 €/kWh is used, together with a constant electricity price. The generated PV electricity is first consumed by the electric building loads, and the remaining is provided to the heat pump.

PV electricity generation is obtained using a PV model based on the work of Huld [37], which itself is based on the work of King [38] and is widely used in academic literature (e.g. [39]). It is a linear regression model with logarithmic and squared predictor variables, such as ambient temperature and in-plane global irradiation. Electricity losses due to high module temperatures are accounted for by approximating the module temperature T_{mod}, according to the ambient temperature T_{amb} and the in-plane global irradiation E_{poa}^{glob}:

$$T_{\text{mod}}(E_{poa}, T_{amb}) = T_{amb} + \rho \cdot \frac{E_{poa}^{glob}}{E_{poa}^{glob,STC}} \qquad [\mathrm{C}] \tag{19}$$

$E_{poa}^{glob,STC}$ denotes the in-plane global irradiation at standard conditions (1000 W/m^2, 25 °C), and the factor ρ corrects for different types of PV installation and arrangements according to [40].

4.5. Variable electricity price

To investigate the influence of variable electricity prices on the system sizing, a variable electricity price is constructed by dividing the electricity price into a fixed and a variable part. For all scenarios, the yearly mean electricity price is kept constant at 19 € ct/kWh, which corresponds to the heat pump tariff in Germany. The hourly price for electricity of the German day-ahead market is used as a signal for the price variability. Both climate and electricity price time series are taken for the year 2012 to keep the correlation between the price signal and climate conditions. The price of electricity p at time t is calculated for each scenario k according to:

$$p_{\text{demand},t,k} = 19.0 \cdot (1 - v_k) + 19.0 \cdot v_k \cdot \hat{p}_{\text{EEX},t} \qquad [\text{ct/kWh}] \tag{20}$$

where v_k is the price variability in percent and $\hat{p}_{\text{EEX},t}$ is the normalized price signal.

$$\hat{p}_{\text{EEX},t} = \frac{p_{\text{EEX},t}}{\bar{p}_{\text{EEX}}} \qquad [-] \tag{21}$$

The normalized price is the hourly day ahead price for electricity at the European Energy Exchange $p_{\text{EEX},t}$, divided by the annual mean electricity price $\bar{p}_{\text{EEX}}$. The variable share of the price is increased stepwise up to 100%, while the mean value is kept constant. Fig. 5 shows the daily mean electricity price curve averaged for one year, for the different price variability scenarios of 0–100%. It can be seen that fluctuations increase with increasing variability, while the shape of the price signal is conserved.

Fig. 6 shows the annual duration curve of the variable electricity price scenarios. Here, the absolute value of and the number of peak hours of both positive and negative prices, increase with increased variability. Notice that part of the scenario space is unrealistic to be applied to the end customer and is used to study the impact of extreme prices.

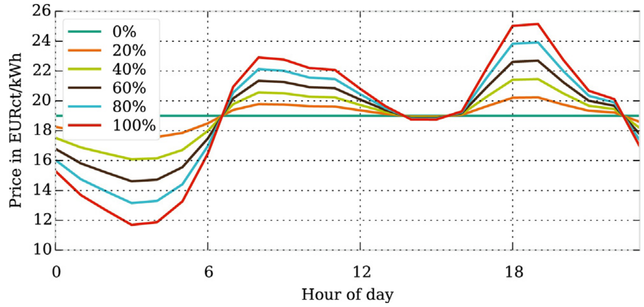
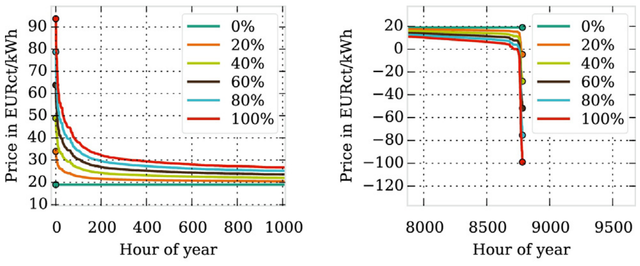


Fig. 5. Daily mean profiles for the electricity price with a variability from 0% to 100%.



(a) Hours with high prices (b) Hours with low prices

Fig. 6. Selected parts of the annual duration curve for the variable price scenarios.

4.6. Operation strategy of the storage

The thermal storage temperature is controlled to be within a tolerance band of maximum 10 K above the set point, which is the minimum temperature required for adequate thermal comfort. The tolerance band is limited to 10 K to avoid high storage temperatures, as this increases the storage losses and lowers the heat pump efficiency. However, in some cases it could be beneficial to allow for higher storage temperatures, which is also technically possible. For instance, when electricity is cheap, or if PV self-consumption should be increased. By increasing the maximum allowed storage temperature additional storage capacity can be enabled [10].

The effect of an operation strategy which allows for over heating of the storage, is analysed for the PV and the variable electricity price scenarios. Hence, these scenarios are both run with 10 K (reference) and a 20 K allowed temperature tolerance band in the storage. For the 20 K scenarios, the minimum storage capacity resulting from the reference scenario is set as lower bound, to avoid a reduction of storage size due to the now eased limitation.

5. Results

The scenarios described in Section 4 are applied to the optimisation model presented in Section 3 to investigate the influence of space heating load, DHW load, PV generation and variable electricity prices on the operation and system sizing. A total of 37 optimisation runs are performed, using a 15 min time resolution.

5.1. Operation

The cost-optimal operation of the heat pump and the electric back-up heater (EB) is obtained at every time step for the cost-optimal system size. Hence, this reflects the best possible control using perfect foresight and no mismatch between the optimisation model and the real world. As the operation costs for each technology are minimized, the control makes a technology to be operated when prices are low and efficiency is high, and the storage will be used when gains exceed the losses.

5.1.1. Operation over time

Fig. 7 shows a carpet plot of the HP operation in the reference scenario, for each hour of the year. It can be seen that during the cold periods (from hour 30 to 50 and 330 to 350) the heat pump is constantly operating at its maximum and not modulating its capacity. The impact of the reduced maximum heat pump capacity with falling ambient temperature, is visible when comparing the peaks of summer and winter operation in the presented graph. When the heat demand is reduced e.g. during changing season, the heat pump is operated at part load, which is also the case during night and early

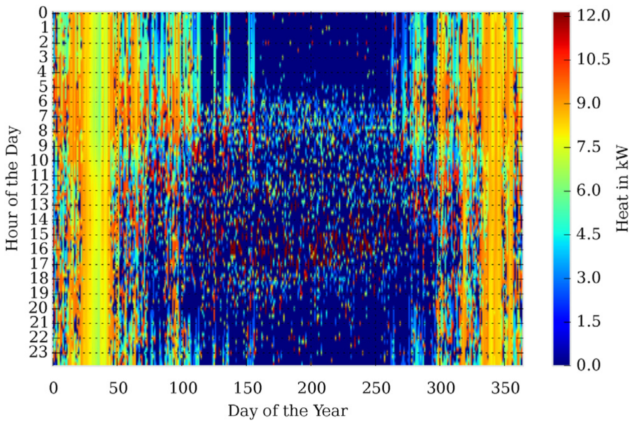


Fig. 7. Operation of the heat pump in the reference scenario.

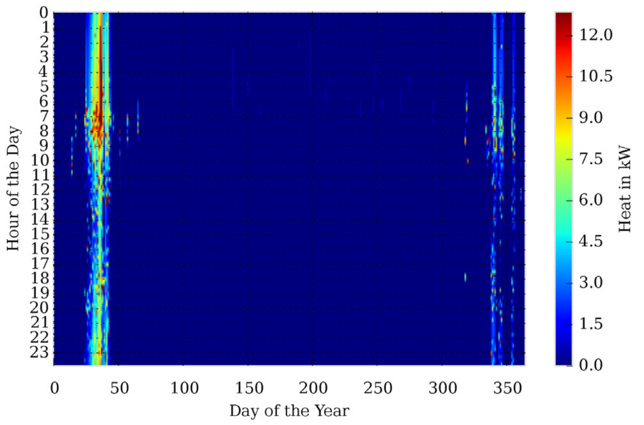


Fig. 9. Operation of the electric back-up heater (EB) in the reference scenario.

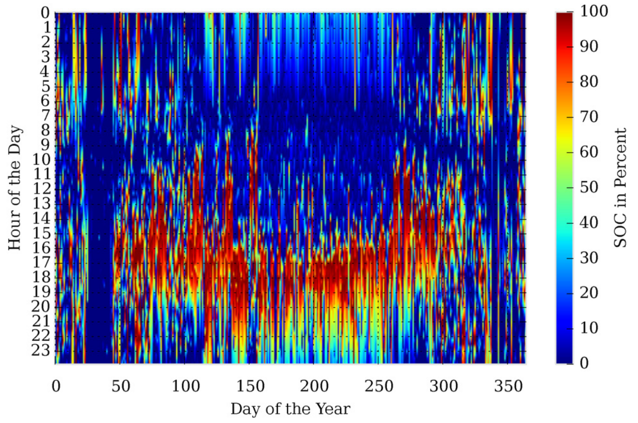


Fig. 8. Storage state of charge (SOC) in the reference scenario.

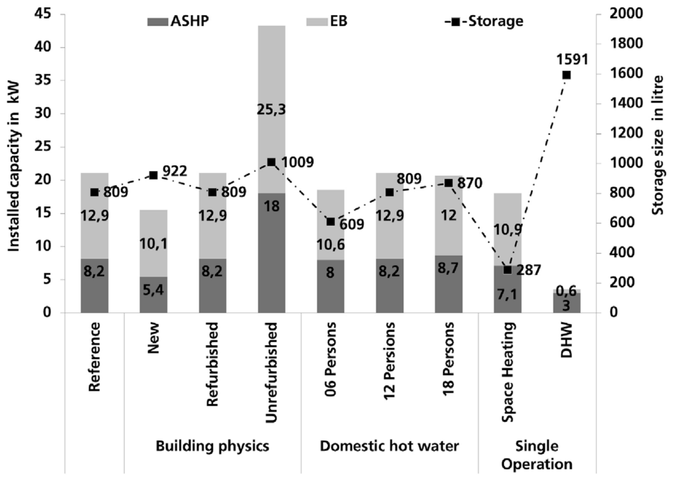


Fig. 10. Optimal system sizing with changed thermal demand.

morning hours. In the summer months, the heat pump is operated mostly during hours with high ambient temperature where heat pump efficiency is high and operational costs are low. During these times, the heat pump is often operated at its maximum capacity to charge the storage.

The storage content for each hour of the year is shown as state of charge (SOC) in Fig. 8. The storage is charged at hours with low operational costs which occurs during daytime when the ambient temperature, and thus the COP of the HP, is high. Especially in summer, the storage is charged at the latest possible time of the day, to preserve heat only as long as needed (until the next morning), in order to limit storage losses. During the coldest days of the year, storage is mostly unused and contributes only to cover short term peak loads. During this part of the year the heat pump capacity is fully used to cover the space heating demand, and there is no extra capacity available for charging the storage. Hence, during the coldest days, the electric back-up heater is used to support the heat pump operation, which is clearly seen in Fig. 9.

The operational characteristics of the reference scenario described above holds for the other scenarios investigated, although the hours of operation change according to the cost. That is, with high electricity prices during daytime, the HP is operated at night, and with high PV generation, the HP is operated during daytime. In general, the characteristics of the system operation is as follows: (1) the possibility to charge the storage in favourable times is utilized when the system is not operated at its limit, and (2) the hours when the storage is charged are dependent on the economic incentive which varies between the scenarios.

5.1.2. Heat generation by source

Investigating the annual thermal energy generation, the heat pump provides approximately 93% of the needed annual heat demand for most scenarios. The exemptions are commented in the following. In the “100%” variable price scenario, the HP covers 91% of the annual heat demand, as the EB is used more often to profit from negative prices. In the pure (or “single operation”) space heating scenario, the storage size is reduced and compensated with increased use of the electric back-up heater, resulting in a share of 91% HP heat. In the pure DHW scenario, the heat pump together with a larger storage, covers 100% of the heat production.

5.2. Technology sizing

This section analyses the cost-optimal design of the HP, the electric back-up heater and the thermal storage, for each of the investigated scenarios.

5.2.1. Influence of building physics and DHW loads

Fig. 10 shows the installed capacity of the heat pump, electric back-up heater and storage when the thermal loads are changed. The reference scenario has a 8.1 kW_{th} heat pump and a 12.9 kW_{th} electric back-up heater, which results in a ratio of back-up-to-HP-capacity of 1.59. The storage size is 808 l, which equals 99 l per kW_{th} installed heat pump capacity.

When the space heat demand is increased in the unrefurbished scenario, the total installed capacity of HP and electric back-up heater increases to 43.3 kW_{th}. However, the ratio of back-up-to-HP-capacity decreases to 1.41, and the specific storage volume also decreases to 55.5 l per kW_{th}.

When the space heat demand is reduced in the new building, the total heat generation capacity is decreased to 15.5 kW_{th}, however the ratio of EB-to-HP-capacity is increased to 1.87. Surprisingly the storage volume increases although thermal load is reduced, and the specific storage volume per installed capacity of HP increases to 169.5 l per kW_{th} HP. As the load duration curve of the space heat demand, shown in Fig. 3, flattens with increased energy efficiency of the building, a larger share of the heat load can be covered with a smaller heat pump unit. To cover the peaks larger back-up heater and storage capacity is needed though. Since the DHW is becoming more dominant in the total heat demand in well insulated buildings, the results indicate that for new buildings, it is more cost efficient to invest in a large storage and cheap electric back-up technology, rather than in a large HP capacity.

In the pure space heat demand scenario, where DHW is neglected, the ratio of EB-to-HP-capacity is only slightly decreased to 1.53, whereas the specific installed storage capacity is decreased considerably to 39 l per kW_{th} HP. Compared to the storage size of the reference case which includes the DHW load, this affirms that the storage is mainly needed for covering DHW peaks.

Compared to changed building physics, changed domestic hot water consumption has less impact on the system sizing. Increasing the number of persons from 6, 12 to 18, heat pump capacity is hardly affected going from 8, 8.2 to 8.7 kW_{th}. The electric back-up heater capacity is increased from 6 to 12 persons, but slightly decreased from 10 to 18 people. The storage capacity is always increased with in increased number of persons, however the incremental increase flattens out with higher number of people, from 33 l per person (from 6 to 12 persons) to 10 l per person (from 12 to 18 persons). This is explained by the lower relative peak loads of the annual DHW load with increased number of persons (see Fig. 4). With a flatter demand curve the heat pump, showing higher investment costs but also lower operation costs, becomes an increasingly attractive option compared to the electric back-up heater. This leads to reduced specific storage and electric back-up heater capacity per person, with increased number of people.

In the pure DHW scenario, where space heating is neglected, the size of the electric back-up heater is reduced to only 20% of the heat pump capacity, and specific storage size is increased to 529 l per kW_{th} HP. Indicating that storage is used for peak coverage and charged over a longer time period.

5.2.2. Influence of PV size

Fig. 11 shows technology sizing for the PV scenarios with an allowed storage ΔT of 10 K and Fig. 12 shows the results for a ΔT of 20 K.

In general, the results show that increased PV size does not influence the size of the heat technologies, but the need for storage increases moderately, especially for PV sizes up to 50 kWp.

With increasing PV and a ΔT of 10 K, the heat pump capacity remains almost unchanged, the electric back-up heater size is slightly decreased, and the storage is slightly increased. This indicates that the thermal demand is the determining factor for sizing of the HP and back-up heater, whereas the storage is affected by the available PV.

When PV size is increased from 0 up to 5 kWp, the storage size remains approximately unchanged. From 5 kWp to 10 kWp, the storage is increased by 13.5 l/kWp and stagnating from 10 kWp up to 20 kWp. Further PV increase up to 60 kWp, and 100 kWp, leads to a storage growth of 4.5 l/kWp and 3 l/kWp, respectively. From 100 to 160 kWp, the storage is increased by 1.5 l/kWp. This clearly indicates diminishing returns of increased storage after 20 kWp.

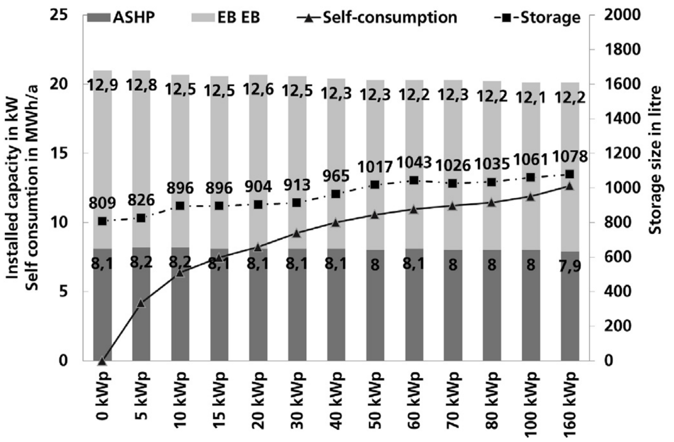


Fig. 11. Optimal system sizing with increased PV installation and an allowed storage hysteresis of 10 K.

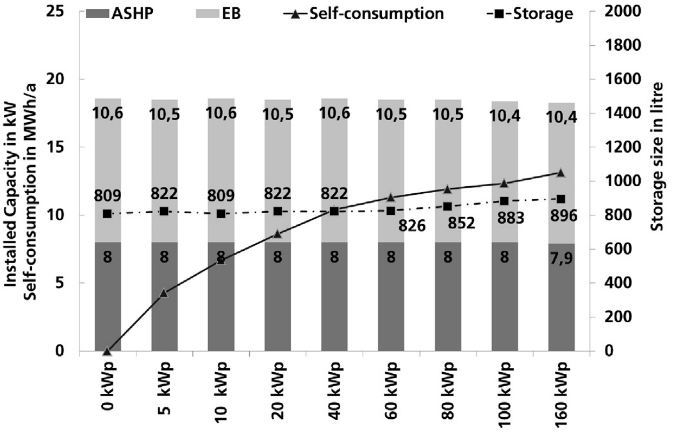


Fig. 12. Optimal system sizing with increased PV installation and an allowed storage hysteresis of 20 K.

Fig. 11 shows that the storage size does not increase for PV sizes from 10 to 30 kWp. The reason is explained in the following. If left as free variable, the cost-optimal size of the PV is 9.3 kWp. In this case, the electricity surplus in the morning and evening hours is now frequently above the minimum required for heat pump operation and is directly used in the HP. As a consequence, the need to store heat for the late afternoon hours decreases. Beginning at 9.3 kWp, the objective function hence enters a flat minimum up to 30 kWp. A further reason that the storage is not increasing is that PV generation appears mainly in summer where thermal demand is mostly for DHW. As a result already for small PV sizes the storage is sufficient to cover DHW demand until the next day. Hence increasing the storage offers only limited additional benefits. This corresponds well with the findings of more detailed studies on PV self-consumption with heat pumps reported in [10,14,6].

When the maximum allowed ΔT of the storage is increased to 20 K (see Fig. 12), a change in storage capacity is hardly observed up to 60 kWp installed PV capacity. From that point onwards, an almost negligible growth of 0.5–0.84 l/kWp is observed. Thus, the option of allowing higher storage temperatures in situations with PV production removes the need for larger storage from an investment point of view. However, increasing the storage temperature comes with a loss of efficiency, which should be examined in detailed simulations.

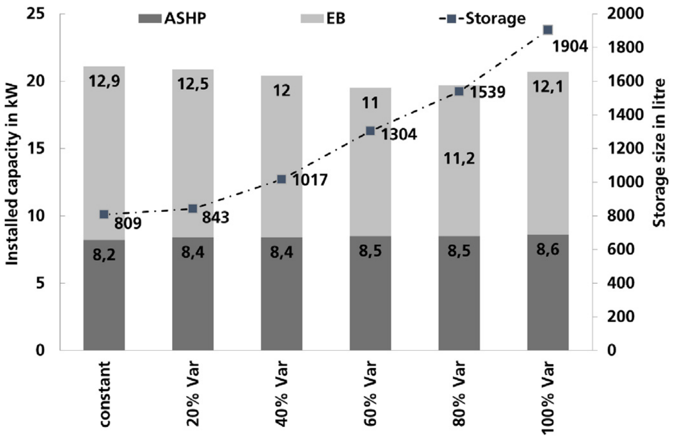


Fig. 13. Optimal system sizing with increased price variability and an allowed storage hysteresis of 10 K.

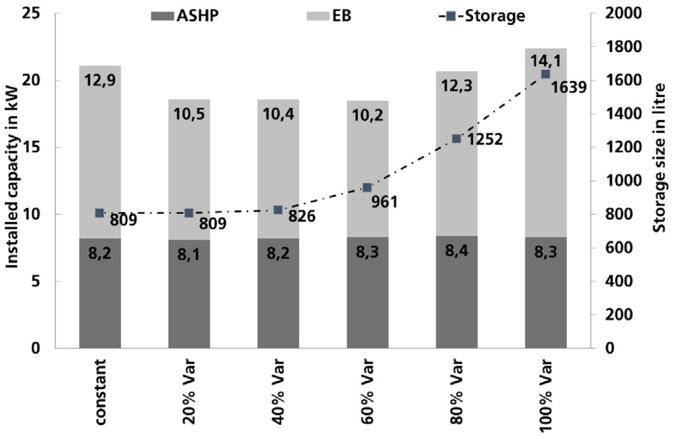


Fig. 14. Optimal system sizing with increased price variability and an allowed storage hysteresis of 20 K.

5.2.3. *Influence of variable electricity price*

Fig. 13 shows the system sizing with increasing variable electricity prices with an allowed storage ΔT of 10 K, and Fig. 14 shows the results for a ΔT of 20 K. Generally, increasing price variability leads to slightly larger heat pump sizes, increased storage capacity and changed sizing of the electric back-up heater.

Up to 40% price variability, the storage size increases non-linearly, the size of the heat pump remains almost unchanged (increased by 2.5%) and the size of the electric back-up heater is decreased by 8%. From 40% onwards, the storage size increases linearly up to 1903.5 l at 100% price variability, where it is charged in hours of low electricity prices. From 60% price variability, the installed heating capacity of the electric back-up heater starts to slightly rise again, which is due to the increased occurrence of negative electricity prices.

Allowing the storage to be overheated, increases the capacity of the heat storage even though its volume is unchanged. As shown in Fig. 14, the electric back-up heater's capacity is immediately reduced due to the increased storage capacity. The storage size remains unchanged up to a variability of 40% and then increases up to 1638 l, while the electric back-up heater capacity is increased by 40%.

Comparing the variable price scenario to the PV scenario, it can be seen that variable prices lead to a stronger increase in storage size than PV. The reason is that price variability occurs during the whole year and thus also in times with high thermal demand when there is sufficient load to be shifted. Whereas in the case of on-site PV, shifting mainly occurs in summer and during changing season when space heating demand is comparably low. Hence, larger storage size with PV does not offer the same benefits as with variable electricity prices.

Table 3
Comparison of optimised storage sizing results with recommended values.

	Base-line	New	Un-ref.	6 Pers.	18 Pers.
Number of persons	12	12	12	6	18
DHW demand [MWh/a]	12.6	12.6	12.6	8.8	16.7
Heating demand [kWh/a]	25.8	13.1	70.6	25.8	25.8
Heat covered by HP [%]	93	92	93	93	93
Storage optimized [l]	809	922	1009	609	870
Storage lower value [l]	635	577	816	454	791
Storage middle value [l]	1420	1101	2431	1239	1576
Storage upper value [l]	1903	1423	3423	1722	2059

6. Discussion

In this section, the findings are further analysed and compared to recommended sizing procedures. Additionally, the influence of selected model assumptions is discussed.

6.1. *Comparing the results to recommended sizing procedures*

The main question of this study is whether HP system sizing procedures need to be adjusted when variable prices and PV will be increasingly introduced in the residential sector. In the following, the findings of this study are compared to the manufacturers recommendations for sizing described in Section 2. The main numbers are listed in Table 3.

As shown in Section 5.1.1, the share of heat covered by the heat pump, resulting from the optimisation results, is around 93%, whereas the recommended value according to [20] is above 95%. Hence, the model chooses a slightly smaller HP size than recommended. However, the numbers are so close that it can be concluded that today's recommendations lead to almost optimal heat pump and electric back-up heater sizes.

Regarding the optimised storage size when compared with the results of current sizing recommendations (see Section 2), three different storage sizes are calculated:

(a) A lower storage size without blocking hours, where the minimum needed storage size for safe HP operation is ensured, see Eq. (4)
(b) A middle storage size, accounting for blocking hours and assuming a building with high thermal inertia, see Eq. (6).
(c) An upper storage size, accounting for blocking hours and assuming a building with low thermal inertia, see Eq. (7).

The needed storage size for DHW is calculated using Eq. (3), and added to the buffer tank for all three storage cases.

The results in Table 3 show that the optimised storage values lie 9–37% above the lower size of the manufacturers recommendations. This indicates that for the given scenarios, even for a variable speed heat pump, a small storage is economically interesting.

When the storage sizing accounts for blocking hours and high thermal inertia of the building and the hydronic system, the recommended storage size is approximately 1.2–2.4 times the optimised values. Sizing according to the middle and upper storage values, leads to storage sizes that are 1.5–3.4 times the optimal solution. Hence, sizing respecting blocking hours leads to suboptimal big storage sizes from an investment point of view. On the other hand, blocking-hours have not been included in the optimisation model, if done so, larger storages might have been experienced.

Comparing the sizing recommendations with the results obtained by varying electricity price and PV size, shows that the currently recommended storage sizes are sufficient to cover most of the scenarios. Thus, most heat pump systems found in the field today can be seen as smart grid ready, although controls need to be adjusted. For the scenarios allowing overheating of the storage ($\Delta T = 20$ K), the need for larger storage is almost eliminated, even when compared to the lower value of the sizing recommendations.

6.2. Assessing model assumptions

One reason that optimisation results are favouring smaller storage sizes is due to the optimal control, which utilises the installed storage capacity in the best possible way. Another reason is the perfect foresight, which eliminates the need for safety margins for storage and unit sizing, since there is no such thing as an unexpected event in the calculations. Further, since the storage is modelled as a mixing tank serving both space heating and DHW demand, the volume can be used for both purposes and thus more efficiently than in a real system – even if stratified. Nevertheless, the calculated results are close and consistent with current recommendations.

For variable speed heat pumps, the efficiency decreases with increasing the thermal output from part load towards full load conditions. In the current MILP model formulation, to avoid non-linearity, heat pump efficiency is set independent of the part load ratio. Hence heat pump operation at full load conditions is not penalized in the objective function. This probably leads to smaller heat pump sizes and a more aggressive operation of the heat pump and the storage.

7. Conclusion

Variable end-use prices for electricity and increased penetration of PV in the residential sector, offer new possibilities and challenges for heat pump operation. In this work, the optimal investment and operation strategy for an ASHP system is analysed using MILP. The sizing results are compared to currently applied sizing procedures. The findings show that today's heat pump and back-up heater sizing is close to the optimisation results and does hardly change if PV and variable electricity prices are introduced. However storage size changes depending on the scenario.

In the scenarios where installed PV capacity is below 30 kWp (corresponding to 2.5 kWp per person) and where the variable share of the electricity price is below 40% (±3.8 € ct/kWh), a storage increase of maximum 30% compared to the reference scenario is sufficient. However, if the storage is allowed to be overheated, even in these scenarios, no change in sizing is necessary. Even though this might come at a cost of increased storage losses and decreased heat pump efficiency.

Hence, based on the given system and price assumptions, the following statements concerning future sizing procedures are made:

1. Thermal demand determines and will determine the sizing of the heat pump and the electric back-up heater.
2. With on-site PV, additional storage capacity of 4.5–9 l/kWp is beneficial. However, if overheating of the thermal storage is allowed, investing in larger storage is not economically viable under current conditions.
3. The optimal PV size for the given case study is between 9.3 and 20 kWp, which corresponds to a range of 0.8–1.6 kWp PV capacity per person.
4. With variable electricity prices, the need for storage capacity rises. Also if overheating of the storage is allowed, additional storage capacity is economically viable. However, up to a price variability of 40%, no or only modest storage increase is needed. This need could be further reduced when actively using the building's thermal mass.
5. Current system sizing procedures correspond well with the findings of the optimisation, and if sizing recommendations are applied in a conservative way (see middle range in Table 3), this will result in sufficiently large storage capacity for the majority of the scenarios. Thus, control might be of more importance than sizing for enabling flexibility from heat pumps.

As a conclusion, the current system sizing as applied in the German residential sector today, does not need radical changes if PV or dynamic prices are introduced. They can thus be seen smart grid ready, given the prior that optimal or close to optimal control schemes are applied. Storage sizing for blocking hours as applied in Germany already leads to sufficient or even too large storage capacity. The storage capacity could be used in a more optimal way than done today, by changing controls and allowing higher storage temperature, providing flexibility for the power system and end customers.

If increased storage and HP capacity is politically wanted or needed to increase flexibility, strong economic incentives or reduced specific investment costs have to applied to motivate heat pump users to invest.

8. Outlook

The findings of this study will be further tested in detailed simulations to investigate the effect of imperfect controls, decreasing part load efficiency of the heat pump and storage stratification on the presented results. The role of actively using building's thermal mass will be investigated in future studies.

Acknowledgements

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