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Potential And Optimal Sizing Of Combined Heat And Electrical Storage In Private Households

Sebastian Zurmühlen[a,b,d,*], Henryk Wolisz[c,d], Georg Angenendt[a,b,d], Dirk Magnor[a,b,d], Rita Streblow[c,d], Dirk Müller[c,d], Dirk Uwe Sauer[a,b,d]

[a]*RWTH Aachen University, Chair for Electrochemical Energy Conversion and Storage Systems, Institute for Power Electronics and Electrical Drives (ISEA), 52056 Aachen, Germany*
[b]*RWTH Aachen University, Institute for Power Generation and Storage Systems (PGS), E.ON ERC, 52074 Aachen, Germany*
[c]*RWTH Aachen University, Institute for Energy Efficient Buildings and Indoor Climate (EBC), E.ON ERC, 52074 Aachen, Germany*
[d]*Jülich Aachen Research Alliance, JARA-Energy, Jülich, Aachen, Germany*

Abstract

The increase in fluctuating renewable electricity generation requires growing flexibility and balancing capacities in the electric energy grid. Storage systems can provide the necessary balancing capacities. Therefore, it is analyzed which potential for flexible energy consumption can be found in private households. Heat and power in private households are heavily interlinked due to increasing numbers of electrical heating systems (e.g. heat pumps). In addition, installed PV systems on roof tops are making renewable electricity an attractive energy source for space heating and hot water supply. To maximize the consumption of self-generated electricity, battery energy storage systems (BESS) and thermal hot-water based storage systems are used in private households. The challenge is to find economically viable configurations for sizing of combined battery and thermal storage units.
The introduced approach simulates a household with a variable size of the relevant components of the thermal and electric system, being the PV system, PV and battery converters (DC linked), the battery (lithium-ion), thermal hot water storage and a heat pump. Profiles for the electrical load are based on empirical analysis of resident behavior coupled with measurements from typical household appliances. The thermal load profiles are derived from representative simulation tools, simulating resident behavior and the resulting heat demand. Based on the simulation results, an optimal sizing of storage units is calculated.

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Keywords: PV home storage system; heat storage; thermal storage; self-consumption; battery energy storage system

* Corresponding author. Tel.: +49 241 80-49368; fax: +49 241 80-649368.
E-mail address: szurmuehlen@eonerc.rwth-aachen.de

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1. Introduction

The rising number of storage units in private households and the already immense feed-in from photovoltaics implicate growing challenges for the distribution grid. One goal is to maximize the self-consumption of own generated PV electricity, while minimizing negative influence on the grid. Together with a growing number of heat pumps in newly built houses the potential for PV battery energy storage systems (PV BESS) to be used for a maximization of self-consumption of own generated electricity is steadily increasing. Ideally, the potential of the heat and electric systems in private houses can also be utilized to relieve the grid.

Fig. 1 shows the development of installed PV peak power in Germany and the rising share of newly built houses which have installed a heat pump for domestic hot water (DHW) and space heating.

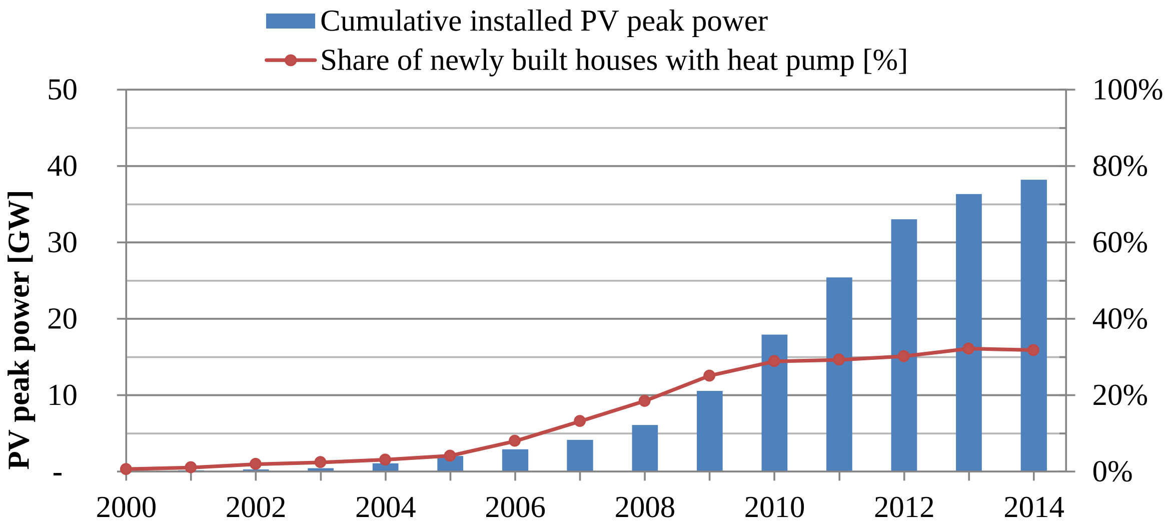

Fig. 1. Development of installed PV power and share of newly built one family houses with heat pump [1, 2].

It can be seen that the share of newly built houses having a heat pump installed has been increasing and is today at around 30 % in Germany. Together with the high level of installed PV peak power this leads to the incentive to investigate the potential to provide as much of the domestic demand for heat and electricity from photovoltaics as possible.

Storage units, especially thermal storage can already be found in today's households, mainly in the form of hot water storage tanks. Additionally, a rising number of PV battery energy storage systems (PV BESS) are being installed in addition to photovoltaics on rooftops. In Germany the installation of such systems is incentivized in the form of subsidies for battery storage systems and credits at reduced rates of interest provided by the KfW Group[1] [3].

1.1. Research objectives

Previous research has shown a distinct potential for relieving the power grid from consumption peaks, as well as renewable generation peaks through dynamic load shifting of electrical and thermal demands in residential buildings [4, 5, 6, 7, 8]. Based on that, we investigate in this study to what extend domestic energy storages empower such demand side management (DSM) in private households. Therefore, the DSM potential of the existing supply systems in one family houses (OFH) in Germany is evaluated and the question which degree of retrofit or new construction of the supply and especially storage systems is beneficial is answered. The goal is to find an optimal

[1] Kreditanstalt für Wiederaufbau

configuration of storage systems which should be installed in a retrofitted or newly built OFH. The investigation will be performed exemplarily for the German market with existing market conditions and for a potential future market scenario. In this analysis a generic one family building is used which is representative for German construction and insulation standards.

Nomenclature

BESS	battery energy storage system
BMS	battery management system
DC	direct current
DHW	domestic hot water
DOD	depth of discharge
DSM	demand side management
EIS	electrochemical impedance spectroscopy
EMS	energy management system
OFH	one family house
PV	photovoltaic
SOC	state of charge
SOH	state of health

2. Methodology and underlying parameters

To determine optimal component sizes for electrical and thermal storage units within a reference household, a simulation model for electrical and thermal loads as well as for the supply of electricity and heat has been applied. Consumptions of heat and electricity were fed into the model as separate time series of power demand.

The construction and insulation standards for private households in Germany are represented in this study by two relevant standards: WSchV 1984 [9] and EnEV 2009 [10]. These dictate steadily decreasing U-values for the thermal transmittance of walls, windows, floor towards ground etc. A large portion of the building stock in Germany is covered by these two standards, thus we focus on WSchV 1984 and EnEV 2009 to emphasize the effect of building insulation on the sizing of storage components. Regulated U-values for EnEV 2009 are half or even less of the values provided by WSchV 1984.

Demand profiles for space heating, domestic hot water (DHW) and electricity for a four-person household were used as input. The different insulation standards result in two different profiles for space heating demand.

2.1. General modeling approach

The simulation model is implemented in Matlab/Simulink. It consists of the PV generator, a DC-coupled PV battery energy storage system including converters, a thermal storage unit and a heat pump. The simulation uses a variable time step, which means that the solver adjusts itself to the smallest temporal resolution needed for each model component. This brings a high flexibility to apply input data from varying sources, but leads to an increase in time required to simulate the model. The model is prepared to run with vectorized inputs, which allows a simultaneous calculation of different input states. This is an additional measure together with a parallel computation of the system behavior within the optimization process and is used to speed up the optimization itself. Figure 2 shows the two different system topologies which have been analyzed to represent retrofitted or newly built houses. The main difference is the substitution of the gas boiler by a heat pump and thus the connection to the gas grid is obsolete in the newly built topology. The gas grid and gas boiler have not been implemented as model components. They are assumed to supply any uncovered remaining heat demand since focus lies on own consumption of electric energy. In addition to the topology of a newly built house, two separate scenarios for the years 2015 and 2020 are discussed.

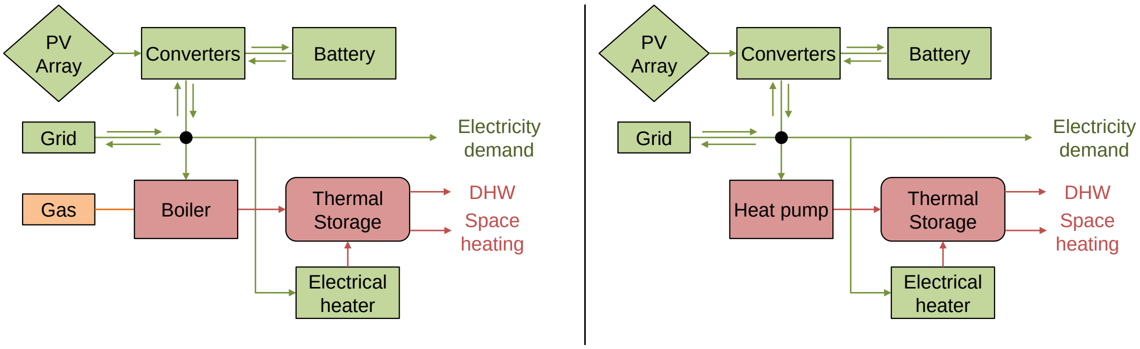

Fig. 2. Topologies for the OFH without (retrofit, left) and with a heat pump (newly built, right).

The converters are modelled based on their efficiency characteristics depending on the respective voltage and power level of each simulation step as presented in [11]. These models have been parameterized within the Sol-ion project [12].

The PV generator model based on [13] uses solar irradiance data as input. The needed input includes time series for diffuse irradiance and beam irradiance on a horizontal surface in W/m², as well as the air temperature in °C and originates from [14]. For the calculation of the resulting power output of the PV generator it is also necessary to set the nominal power (in kilowatt-peak), the surface orientation of the system and the tilt angle. It was assumed that the retrofitted system has an installed PV system of 4 kWp, whereas the newly built house has 10 kWp of PV.

The battery model consists of the battery cells themselves, a battery management system (BMS) and an energy management system (EMS). These three elements are modelled as separate units within the simulation.

The battery cell model consists of a thermo-electrical model and an aging model. The electrical model uses an impedance-based approach and has been parameterized using electrochemical impedance spectroscopy (EIS) measurements [15, 16]. The thermal model takes into account resistive heating of the battery cells during operation. The output of the thermo-electrical model is used to calculate the battery state in terms of cell voltage, current, temperature and state of charge (SOC). This information is then used within the aging model to determine the state of health (SOH) of the battery. The aging consists of two effects: calendar aging and cyclic aging. The lifetime of the battery is calculated from a superposition of both aging effects.

The BMS monitors the voltages and temperature of the battery to make sure operational limits are kept at all times. It limits the power and thus the current for charging and discharging the battery. The maximum power input and output of the battery are restricted depending on battery voltage and temperature.

The EMS collects all information about power generation and demand, as well as information about the battery state provided by the BMS for each step of the simulation. It calculates the residual load and routes the energy flow with regards to this information. The EMS is programmed to match power demand either with generated electricity from the PV system for self-consumption or cover remaining demand from the grid. It also routes power flows from the battery to meet demand or into the battery when there is a surplus of PV generation. It is set to prioritize the battery before the hot water tank in terms of storing excess PV electricity.

The heat pump is modelled using an efficiency curve for an air-water heat pump, applying time series data for air temperature and specific technical parameter sets of the chosen system as input. The resulting electrical load from heat pump operation is added to the electrical demand of the household.

The heat storage is implemented as a stratified system with three separate layers. Each layer has a defined temperature range within which it is operated. The lower and upper temperature of a layer and the respective volume define its thermal capacity. The layers are successively heated up using available excess power from the photovoltaic system until their upper temperature level is reached. The storage can be heated up by the heat pump or an additional electrical heater that is capable of raising the storage temperature up to 98 °C. The heat losses of the storage are calculated for each layer separately, depending on the respective temperature during every time step and the thickness and thermal conductivity of the tank insulation. Remaining excess generation from the PV system is fed into the grid.

2.2. Price data and load profiles

The assumed values for system cost and retail prices for gas and electricity are listed in Table 1. It was assumed that the retail price for electricity would slightly increase, while a price for gas is not applicable for the 2020 scenario of newly built houses. The trend for the capacity price of PV BESS is based on market research and predictions by ISEA [17].

Table 1. Price data for 2015 and 2020 [18, 19].

	2015	2020
Electricity	29 €ct/kWh	30 €ct/kWh
Feed-in tariff	12 €ct/kWh	n/a
Gas	6.38 €ct/kWh	n/a
Battery system	800 €/kWh	600 €/kWh

For newly built houses, the installation of a heat pump was assumed to be standard. Therefore, the price for the heat pump was no part of the overall cost. The same applies to small buffer tanks needed for a proper operation of the heat pump. Additional thermal storage capacities, however, were priced using the volume-based cost function

$$c_{HeatStorage} = V_{HeatStorage}^{0.6347} \cdot (18.179 \cdot 2.4 \cdot c_{Volume}) \quad (1)$$

with $c_{HeatStorage}$ being the cost for the thermal storage, $V_{HeatStorage}$ the tank volume in liters and c_{Volume} the volume specific cost, here assumed to be 1.50 €/liter. Eq. (1) was derived from market prices for buffer tanks with different storage volumes [20].

Load profiles for heat and electrical demand have been derived from existing tools which generate realistic demand profiles from stochastic combination of varying distinctive applications.

The electrical demand profile of a four person household originates from [21]. In their study they derive load profiles from the simulation of a reference household, using load profiles of 32 typical domestic appliances and also taking into account seasonal variations of usage. The resulting profiles have a temporal resolution of one minute and include data over the course of one year. This enables a much more realistic simulation of the actual behaviour of a household in terms of electrical demand in comparison to a standard load profile. The total demand for electricity is 4674 kWh per year.

The corresponding heat load for both insulation standards has been calculated from a detailed thermal model of the OFH as presented in [22, 23]. In the simulation model the indoor temperatures are set to 21 °C between 6 a.m. and 10 p.m., and reduced to 18 °C in the night-time. To keep the conditions of the scenario stable for comparison purposes, no dynamic ventilation activities had been modelled, while the static infiltration rate is set at a constant value of 0.2 air changes per hour. The results of the heat load calculations for the OFH were then used as input time series for the model with a temporal resolution of 1 hour. A higher resolution does not provide additional considerable benefit to simulation accuracy in the case of space heating demand. The different insulation standards result in two profiles for heat demand with a maximum heat load of 19.4 kW and a total heat demand of 15,779 kWh/a for WSchV 1984 and 14.2 kW maximum heat load and 7608 kWh/a total demand for EnEV 2009.

The heat demand for DHW is generated with a calculation tool created and published by the University of Kassel [24]. Within the tool the desired DHW consumption can be set and according to the chosen number of residents the tool generates realistic usage profiles. In this analysis the DHW demand is set to approximately 2 kWh per person per day, which results in a total heat demand for DHW of 2976 kWh per year for the assumed four person households.

2.3. Optimization

The determination of optimal unit size configurations is implemented with a genetic algorithm from the MATLAB Optimization Toolbox. The algorithm varies the size of the applicable storage units and simulates their behaviour, battery aging and storage usage over the course of 20 years. Each candidate solution of the optimization is rated by the net present value of the investment costs and revenues generated by usage of the whole system, including the storage units. The imputed interest rate was 5 %. The resulting levelized cost of energy represents the fitness of each solution. Via crossover and mutation operations the solver aims to calculate the optimal parameter set of storage dimensioning.

3. Results

3.1. Evaluation of thermal losses

Every effort to store energy is accompanied by energy losses while charging, discharging or just keeping the energy within the storage. To get a general feeling for the magnitude of energy losses within this analysis an evaluation of thermal losses for three different sizes of hot water tanks that are common in existing systems for DHW is performed. For this scenario a system setup was assumed that uses electricity from PV to charge a storage tank with a heating rod up to 98 °C under the assumption that all available PV electricity is used to provide energy for DHW. Table 2 depicts the results of this analysis for three different buffer storage sizes that can already be found in today's OFH heating systems.

Table 2. Tank usage and thermal losses for different tank volumes.

Tank size	100 l	200 l	300 l
PV electricity used	878 kWh	1080 kWh	1109 kWh
PV electricity stored in tank	679 kWh	881 kWh	910 kWh
Heat losses from tank	52 kWh	79 kWh	89 kWh
Remaining feed-in	231 kWh	28 kWh	0 kWh

Thermal losses from the storage are by far not negligible and increase with the size of the storage tank. Therefore, energy losses from the tank require thorough observation and consideration for efficient operation of the storage. Especially, when the storage would be charged with cheaper excess electricity from renewable generation, it has to be kept in mind that a distinct part of the stored energy might be lost before the demand occurs.

3.2. Optimal storage sizing for different scenarios

In case of a retrofitted system without a heat pump, the solution of the genetic algorithm does not include a storage system of any kind. The main reason is the granted feed-in tariff in this scenario. The installation cost for storage is distinctively higher than the added revenue due to an increased self-consumption. This revenue is significantly lowered by the existing feed-in compensation. Additionally, the gas boiler was able to cover all heat demand directly at relatively low cost and no hot water tank was therefore necessary.

The new construction scenario with prices for the year 2020 does include a relatively small battery system in the optimal solution from the genetic algorithm. The battery in the optimal solution has a capacity of 4.6 kWh. There is no additional thermal storage introduced to the system. However, for a future scenario assuming that the feed-in tariff will be eventually discontinued by the government, a system configuration with up to 9 kWh of battery capacity and 300 l thermal storage is the most beneficial scenario.

It should be noted that the solution space is very flat for this kind of optimization problem; therefore, the genetic algorithm is not able to determine a guaranteed global optimum. Small variations in the component sizing of the result can have almost identical levelized cost of energy over the 20-years time period and battery aging and time of replacement add to the huge variety of viable solutions.

4. Discussion

Any modern gas powered heating system is capable of providing the needed energy for space heating and DHW without an additional large hot water tank. Therefore, no tank is needed to guarantee a continuous heat supply. This does not change due to the connection of DHW and heating system, since the 4 kWp PV system is not capable of providing enough energy to cover DHW and heating demand anyway. A tank size of more than 300 l is not necessary and also not cost efficient in any case. A maximization of own consumption from PV is not optimal if it comes at the price of adding expensive storage systems. Even a comparably cheap hot water tank cannot compete with a relatively low gas price. Given a gas price of 6.38 €ct/kWh and a feed-in compensation of 12 €ct/kWh it is obviously not favourable to use the PV generation for heating purposes. This changes of course if there is no feed-in compensation available. In this case, it is advisable to make use of existing hot water tanks (typically up to 300 l) by heating up with excess PV generation as much as possible.

In the new construction scenario with a heat pump and prices for 2020, solutions with a higher coverage of demand by own solar generation are more economical than in the 2015 scenario. Thereby, it turns out that the choice of a larger battery is more profitable than the choice of a large thermal buffer tank. The relatively low heating demand of such a modern building and the high efficiency of the heat pump make a large storage tank with its relatively high heat losses economically unattractive. Especially, since even a regular heat pump buffer tank is capable of storing the daily demand of DHW or even more if charged up to almost 100 °C by a heating rod. Since we assume no feed-in compensation and rising electricity costs for the new build scenario, the battery is crucial for an economical operation of the system. Due to the lower battery price, the almost loss-free storage becomes an increasingly profitable alternative to a large buffer tank with high thermal losses. This is mainly since the battery's energy can be used for any purpose at any time, while the thermal energy stored in the tank has to be used as thermal energy within a rather narrow scope of time.

5. Conclusion

In our study we examined the economy of introducing additional storage capacities for heat and electricity to one family houses and options for their usage. The results lead to the conclusion that for today's prices and market conditions it is not economically advisable to add a large hot water tank or battery storage unit to the energy system of a OFH to store excess PV electricity. In our findings we can show that due to the high heat losses large hot water tanks (i.e. 1000 l) are the least economical solution to store excess PV generation in the analysed scenarios. Still, already available thermal storage capacities within a house can be very well used to increase self consumption of domestic PV generation if there is no feed-in compensation for PV electricity. Even more important than a storage tank, however, is a heating rod, which is capable of making excess PV electricity available to the heating system to substitute gas-powered heat generation.

When an extensive retrofit or new construction scenario is considered, the inclusion of a battery energy storage system becomes more economically relevant. Depending on the market situation, especially with regards to feed-in tariffs and component prices, small to medium size battery systems can be a profitable addition to the household's system. Thereby, it is important to emphasise that small battery systems (i.e. 2 kWh) have a much higher relative price than medium or large size batteries (4-10 kWh) today. This is due to economies of scale as well as pricing policies of retailers. Furthermore, cyclic stress put on a larger battery system results in reduced aging due to smaller relative depths of discharge (DOD). With the strongly reduced heating demands in modern buildings the required share of thermal energy becomes less relevant in these cases and thermal storage should only be applied to the extent that is necessary to cover the daily DHW demand and guarantee a proper and efficient operation of the heating system. Such thermal storage installed together with a heat pump can be well integrated in the buildings' energy managements. However, additional large thermal storage capacities have not proven to be profitable in comparison to BESS in the examined scenarios. This is only likely to change if a reduction of grid interaction is encouraged by the system operator via any kind of measures. Therefore, further research focuses on the integration of BESS in DSM approaches for buildings [25] and city districts. Additionally, instead of large storage tanks, the potential of utilizing the intrinsic structural thermal mass of buildings should be evaluated, since that storage capacity is available in any building at no cost [26, 27].

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