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# The effect of electric vehicles and heat pumps on the market potential of PV + battery systems

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ABSTRACT

Despite the many uncertainties about their profitability, it is apparent in many countries that a market for stationary batteries is developing. In this study, the market potential of PV + battery systems is modelled up to 2040. The focus is on the effect of electric vehicles and heat pumps on the market potential of stationary batteries. The model uses 415 individual household consumption, heat pump and vehicle charging profiles to address differences in consumption behaviour. It was found that the increasing electricity consumption with the installation of heat pumps and electric vehicles generally increases the household's profit from a self-consumption system. Further, the diffusion of electric vehicles can increase the market for stationary batteries by enabling consumers to charge their electric vehicles with self-produced PV power in the evening hours. Particularly so, if the heating loads can be scheduled for hours with PV production. Although the diffusion of electric vehicles and heat pumps significantly affects the market for stationary batteries, the share of households with these technologies remains relatively low in the short to medium term. Moreover, the market potential of PV + battery systems for the purpose of self-consumption stands and falls with electricity and equipment prices.


## 1. Introduction

The European electricity system is undergoing a profound transformation process that will persist for several decades. The transformation includes the increasingly active market participation of formerly passive consumers via the installation of a photovoltaic (PV) system for decentralized production and on-site consumption of electricity, so-called self-consumption. Self-consumption is particularly profitable in markets with high electricity purchasing prices and relatively low levelized costs of electricity (LCOE) for PV. Relatively low or no feed-in remuneration promote high self-consumption rates.[1] The potentially large margin for self-consumed electricity leaves room for households with a PV system to increase their self-consumption, even if it involves additional costs for technologies such as stationary batteries and active load control [1].

### *1.1. The influence of new technologies on self-consumption*

Self-consumption enhancing technologies can generally be grouped into technologies that enable a shift of electricity consumption, which improves the match between onsite production and demand, such as stationary batteries or flexible household appliances, and technologies that enhance self-consumption rates by increasing the household's electricity consumption in hours of PV electricity production. The household's electricity consumption is generally increased by substituting other forms of energy consumption with electricity, so-called electrification. In this study, the focus is on the three currently discussed technologies that are likely to affect residential self-consumption in the short to medium term: *stationary batteries*, *heat pumps* and *electric vehicles*. The three technologies cover both forms of self-consumption enhancement: electric vehicles and heat pumps both increasing the household's electricity demand, and heat pumps and batteries add flexibility to the households' consumption.

#### *1.1.1. Batteries*

Self-consumption ratios can be improved by installing onsite electricity storage systems. Lithium-ion batteries are currently the dominant technology [2]. Due to increasing production capacities,

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[1] In Germany, the volumetric household end-consumer price of around 26 EUR/MWh (without fixed costs) is opposed by a feed-in tariff of 12 EUR/MWh, close to the LCOE of PV. Thus the value of self-consumed electricity is 14 EUR/MWh.

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which are mainly driven by the anticipated market uptake of electric vehicles, prices for lithium-ion battery packs are projected to fall from 300 EUR/kWh to 100 EUR/kWh in 2020 [3,4]. Second-life batteries from electric vehicles could even sell for less: Fischhaber et al. [5,6] expect the price to be 50 EUR/kWh in 2020. Batteries for the enhancement of self-consumption are therefore widely discussed, since they also promise larger potentials than the optimal scheduling of existing appliances. In a previous study, 415 households in Germany and Austria were evaluated and it was found that a 7.5 kWh battery can increase the self-consumed electricity of a 5 kW PV system by about 1000 kWh/yr on average [7].

#### 1.1.2. Heat pumps

Heat can be provided by heat pumps either in form of direct electric heating or in combination with a thermal storage unit. In the first case, only the building substance works as heat storage, in the latter case the most common thermal storage is a water tank. In scenarios that project the electrification of residential heat, heat pumps have become the dominant technology [8,9], since their installation is part of the renewable energy target in the EU.[2] Therefore, ownership rates of heat pumps are generally increasing, although they vary between the EU countries [10]. Thus, many studies analysing the effect of electric heat on self-consumption ratios focus on heat pumps. See for example [11,12], [13]. The expected potentials are promising: With the installation of a heat pump and a 500 l hot water storage, Vrettos et al. [12] for example find an increase of the self-consumption ratio by 15% for a single family home with a 10.8 kW PV system. It has to be considered though that the largest share of heat is required during the cold season, when less PV power is produced.

#### 1.1.3. Electric vehicles

In the discussion about electric mobility in the household sector, the focus is almost exclusively on electric cars. Concerning their contribution to improved self-consumption, only a limited potential is seen due to the low match between PV production and the charging patterns of electric vehicles. The car's battery is usually charged in the late afternoon after returning home [14]. Osawa et al. [15] find for selected cases that the rate of self-consumption improvements is below 2% when a household adopts an electric vehicle. The development of the electric vehicle market is nevertheless noteworthy as it can potentially improve the economic case of the above-described stationary battery: PV power could be stored temporarily to charge the electric car later.

Due to its current dynamic diffusion, the discussions of self-consumption enhancing technologies primarily focus on stationary batteries: Even though the economic profitability of batteries for the enhancement of self-consumption is still controversial, Germany already sees an estimated 60,000 installed batteries in private households [16]. Several other countries show similar signs of market formation.

In a previous study, I addressed the profitability of PV + battery systems for self-consumption to explain its current and potential future market diffusion (see Ref. [7]. However, the effect of other new technologies on the profitability of PV + battery systems has been neglected. Since the broad diffusion of heat pumps and electric vehicles in the household sector is to be expected, their effect on self-consumption should be analysed and is thus the focus of this study.

[2] Within the EU, ambient heat that is captured by heat pumps is classified as renewable, "provided that the final energy output significantly exceeds the primary energy input required to drive the heat pumps" [43,44].

### 1.2. Previous studies, important aspects and research gap

For the vast majority of households, the decision to invest a PV + battery system is primarily driven by its expected economic performance [17–19]. The economic performance is mainly determined by the technology costs, end-consumer electricity prices, the regulatory regime, insolation, and the ratio of self-consumption. The ratio of self-consumption is in turn influenced by the household's electricity consumption behaviour [20] and, like stated earlier, is also influenced by the electricity consumption of new technologies such as electric vehicles and heat pumps.

Since consumption behaviour plays a crucial role in the modelling of PV self-consumption, it is advisable to apply individual electricity load profiles to reflect the heterogeneous consumption behaviour in the residential sector. The importance of using individual profiles is also stressed by Luthander et al. [21] and Klingler and Schumacher [20]; and by Gnann et al. [22] for driving profiles.

There are already a few studies that address PV self-consumption potentials. Market potentials are for example modelled by Prognos [47], Huber et al. [48], Kaschub [23]; Bardt et al. [24]; Jägemann et al. [25]; Winkler et al. [26] and my previous study [7]. Jägemann et al. [25]; Klingler [7] and Kaschub [23]; in particular, consider the enhancement of self-consumption with batteries. In all of the studies, economic considerations are seen as the main driver for the adoption of a self-consumption system. Economic drivers such as cost development and feed-in remuneration are therefore implemented in all of the models applied in the studies.

In addition, all studies consider consumption behaviour, in the form of residential load profiles, to some extent. However, only three of the studies above account for the differences of consumption behaviour between individual households: Jägemann et al. [25] use 250 synthetic load profiles to represent the electricity consumption behaviour of households with 1–5 residents, Kaschub [23] and Klingler [7] both apply empirical load profiles: Kaschub [23] uses 88 and Klingler [7] 415 individual profiles.

Regarding the influence of technology on self-consumption, Winkler et al. [26] include heat pumps in the consumers' investment decision for a self-consumption system and thus model the interdependencies between the two technologies. However, Winkler et al. [26] only address battery systems in a sensitivity calculation. Electric heat is also addressed by Huber et al. (2013): Their study focussed on the application of direct electric heat to increase self-consumption rates. Kaschub [23] focusses on the effect of electric vehicles on the profitability of self-consumption. The electric vehicles are represented by individual charging profiles and different charging options are considered.

In general, it can be said that several aspects of self-consumption have been addressed in recent studies. However, the influence of new technologies on PV self-consumption and battery enhanced PV self-consumption in particular has not been addressed in a holistic way. Existing studies focus either on just one new technology or the heterogeneity between individual household consumers is neglected by using only one load profile to represent the entire household sector.

## 2. Individual household consumers

Electricity consumption profiles of private households are the main input data for simulating self-consumption. Here and in the following, a consumption profile is defined as the electricity consumption of an individual household or appliance, which is recorded in a high time resolution and therefore provides information not only about the consumed amount of electricity, but also about consumption behaviour.

The consumption profiles used in this study have to be recorded for at least 12 months. This necessity arises due to the seasonally fluctuating nature of PV electricity production, which requires an analysis over the entire course of the year in order to address PV self-consumption. Furthermore, to address the match between electricity production and consumption, the profiles are required to be recorded in a high time-resolution, since fluctuations in electricity production and consumption can cause mismatches between the two. These mismatches are evened out by aggregating over time [27] and therefore a low time resolution will lead to an overestimation of self-consumption [21]. Luthander et al. [21] suggest at least an hourly time. Even with the application of hourly data compared to 1-min resolution, sharp load peaks are underestimated. However, due to complexity and limited data availability it was decided to use profiles with an hourly time resolution. The potential overestimation of self-consumption will be further discussed in Section 5.

The following section describes the applied profiles for individual households and potential self-consumers.

### 2.1. Residential electricity consumption

The applied household data originates from a smart-meter field study that was conducted in 2009 and 2010 in Germany and Austria. The data has been used in a previous study, and therefore its preparation and analysis is described in Ref. [7]. In total, 415 load profiles from individual households in self-owned one- and two-family homes were fit to be used within this study.

Besides hourly-recorded consumption data, the data set comprises additional information on the individual households (such as household size, living space, presence of different appliances, number of children and age). Such information is used to assign charging profiles of electric vehicles and heat pump profiles to the individual households. Furthermore, the information is used to exclude households that have any form of electric space heating and thus avoid double counting, when the heat pump profiles are added.

### 2.2. Charging profiles of electric vehicles

The electric vehicle charging profiles are simulated based on vehicle usage data: The vehicle usage data originates from the German Mobility Panel (MOP, [28]). MOP is a household travel survey that has been conducted since 1994 with 1000 participants every year. The participants report their trips during one week and give additional information about their socio-demographics in a questionnaire. The vehicle usage data is translated into charging and discharging profiles, considering battery size, charging power and the availability of a charging point. In this study, charging is only possible at home where self-produced PV electricity can be used. It is assumed that the vehicles 40 kWh battery is charged with 3.7 kW (single-phase connection). The simulation of charging profiles is described in Ref. [29]. Since the vehicle usage data is only available for one week, also the charging profiles are only simulated for one week. To obtain the charging behaviour for the entire year, the charging profiles for Monday to Sunday are combined to form a year-long profile, considering the daily structure of the year as well as national holidays.

To assign a charging profile to each individual household, the similarity in socio-demographic characteristics between each household and each charging profile was calculated. Matching variables are: *age*, *sex*, *education* and *employment* of the respondent as well as *household size*, *income* and *type of household*. Four different household types have been distinguished: Small households (1–2 persons) with employed people, small households without employed people (mainly retirees), households with children, and households without children (3 or more adults).

For each household, the charging profile with the highest match is selected. Since there are more charging profiles available than household profiles, each household has several equally matching charging profiles. To ensure a high heterogeneity, each charging profile is only selected once and therefore 415 different charging profiles are used within this study.

The average electric vehicle charging profile resulting from the above-described assumptions, is depicted in Fig. 1. Note that most of the electric cars are charged in the evening and others during the day, which results in a different usage of the PV + battery systems as will be shown later.

### 2.3. Load profiles of heat pumps

The load profiles representing the operation of a heat pump in the individual households originate from a standard load profile (e.g. available from Ref. [30]), which is depicted in Fig. 2. Most of the heat pump consumption takes place during the cold season, however, even in the warmer summer days, heat pumps are operated for hot water provision and increase the household's electricity consumption.

In this study, it is assumed that heat pumps are installed with a thermal storage and therefore the load of the heat pump can be shifted to maximize self-consumption in the household, thus the structure of the initial load is less important than in the case of electric vehicles. The (normalized) load profile is therefore the same for every household, but it is scaled according to the individual yearly heating demand. The yearly heating demand $D^j$ for each household $j$ is calculated as

$$D^j = d_{SH} \cdot A^j_{Living} + d_{HW} \cdot N^j_{Persons} \tag{1}$$

with the specific space heating demand $d_{SH}$ and the household's living space $A^j_{Living}$, and the specific sanitary hot water demand $d_{HW}$ and the number of persons in the household $N^j_{Persons}$. According to [31] the specific space heating demand in Germany is around $d_{SH} = 100\,\frac{kWh}{m^2}$ per year and the specific hot water demand around $d_{HW} = 516\,\frac{kWh}{person}$ per year. When the heat pump's coefficient of performance (COP) is considered in addition to the heating demand, the

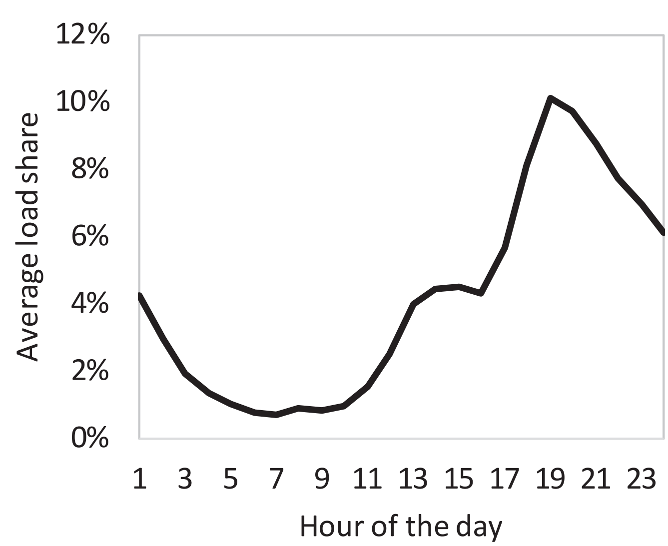


**Fig. 1.** Average of the applied load profiles of electric vehicle charging.

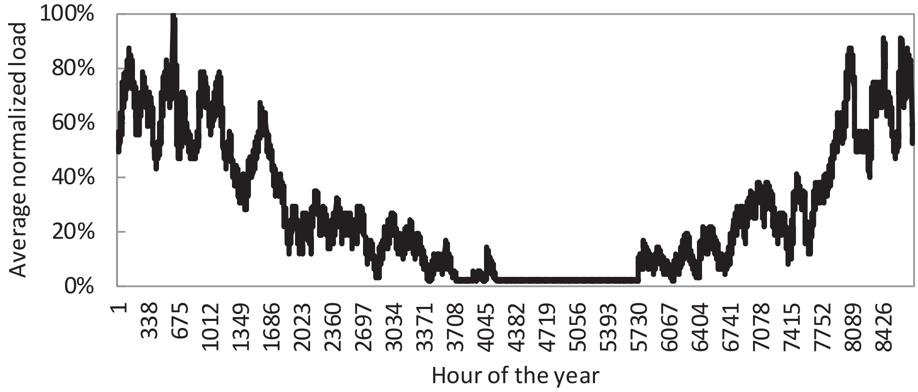


**Fig. 2.** Average of the applied heat pump profiles over the course of the year.

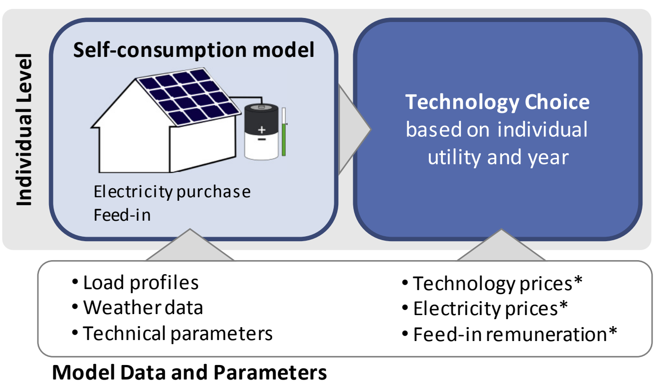


**Fig. 3.** Overview of the applied model for the market potential of PV + battery systems. Parameters with an asterisk are applied in a sensitivity analysis.

annual electricity consumption of the heat pump can be calculated for each household:

$$E^j_{HP} = D^j \cdot \frac{1}{COP} \tag{2}$$

with an average $COP = 3.5$.

### 2.4. Model data and parameters

Besides electricity consumption profiles, PV production profiles are a required model input. The PV production profiles are simulated based on hourly radiation and temperature data provided by the German Meteorological Service from a weather station near the city of Würzburg [32]. In order to maintain consistency, the weather data was taken for the same time period as the electricity consumption recordings, i.e. from November 2009 till November 2010. The PV production model is based on [33]. The self-consumption systems in this study consist of PV panels of sizes between 2.5 and 10 kW that are combined with lithium-ion batteries of capacities between 2.5 and 12.5 kWh.

To facilitate an easier analysis, the same PV production profile as well as the same heat pump and vehicle charging profiles are applied for every year (present and projected), thus ignoring potential future technology improvement and behavioural changes.

The shares of households with a heat pump and the number of electric vehicles in each year are taken from Ref. [34]. There are no studies that address the distribution of electric vehicles among occupants of detached and semi-detached houses, thus assumptions have to be made: To assess the share of households with electric vehicles, the assumption was made that the ownership of the electric vehicles is equally distributed between all households, either (semi-)detached houses or apartments. It is further assumed that the decision to purchase an electric vehicle and a heat pump are not connected. These assumptions lead to the shares of households depicted in Fig. 7 (right part) and listed in Table 1. Since there are no studies addressing these assumptions, the shares will be subject to a sensitivity analysis (see section 4.3).

In this study, conclusions about economic benefits for the consumers and the market potentials of PV self-consumption are drawn. The necessary framework data concerning technology and electricity prices is taken from an existing study on behalf of the German Ministry for Economic Affairs and Energy [26], see Table 2. The German battery subsidization program by the German

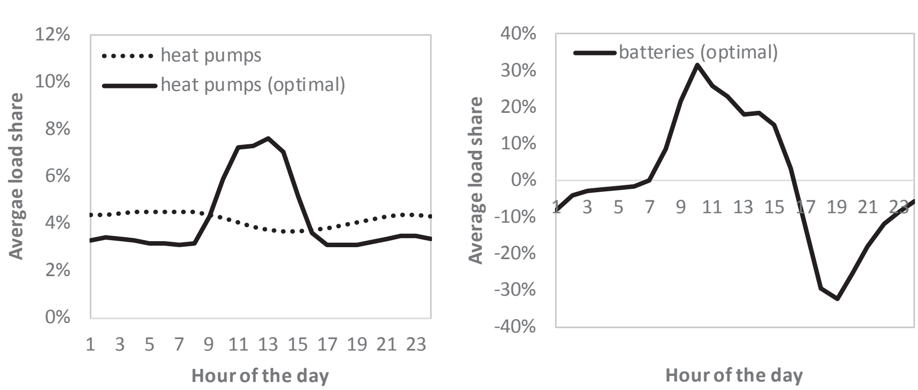


**Fig. 4.** Average load share for heat pumps before and after optimal scheduling (left) and for batteries (right) with a 5 kW PV system.

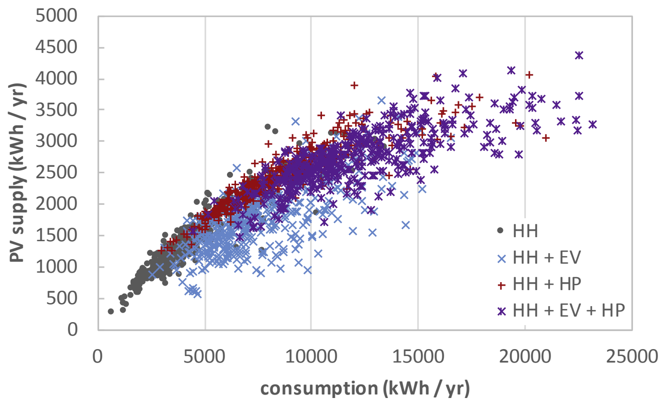


**Fig. 5.** Simulated electricity supply from a 5 kW PV system as a function of yearly electricity consumption. Individual households (HH) (N = 415) with or without an electric vehicle (EV), a heat pump (HP) or both.

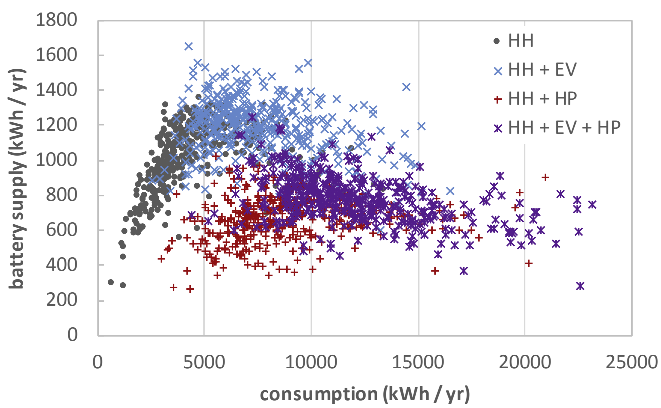


**Fig. 6.** Simulated electricity supply from a 7.5 kWh battery system as a function of yearly electricity consumption. Individual households (HH) (N = 415) with or without an electric vehicle (EV), a heat pump (HP) or both.

development bank is considered. The program supports stationary batteries for self-consumption purposes with low interest loans and payment bonuses. In the first phase, payment bonuses could be up to 30% of the investment for the battery system. In the second phase, the bonus started with 25% and has since been gradually decreased to 10% at the end of the program in 2018 [35]. The discount rate in the assumption was updated, since the assumed rate of 4% in Ref. [26] seems conservative in comparison of the current interest rates (e.g. 0.5% for 10-year federal bounds[3]) and the low interest loans that are provided by the battery subsidization program. Referring to currently offered product warranty periods and, the lifetime of a PV system is assumed to be 20 years, and the lifetime of a battery is 10 years. It is further assumed that battery degradation is primarily dependent on its lifetime, since the number of full cycles is relatively low in the case of PV self-consumption.

## 3. Model simulation

In this section, the modelling steps are described. The model applied in this study includes the simulation of heat pumps and electric vehicles and extents the market diffusion model for PV + battery systems used in Ref. [7]. The first step of the model is to determine the optimal operation of the heat pump (section 3.1). Since heat pumps are considered to be installed in combination with a thermal storage, i.e. hot water tank or thermal mass of the building, its optimal operation is the most economic solution to increase the household's self-consumption. In this study, the timing of charging electric vehicles is not optimized, but all vehicles are charged after the last trip. Most of the vehicles are not at home during the day [49], so the possibility to shift charging loads to midday hours to increase direct self-consumption is limited. Further, the shifting of charging effects the vehicles readiness for the next trip and therefore the user's acceptance is of fundamental importance [36]. Load scheduling for electric vehicles can be a benefit, if time-variable electricity tariffs are applied or charging at the workplace is encouraged [22].

In a second step, the battery operation for each household with its individual electricity consumption profiles is determined, using different sizes for PV panel and battery (section 3.2). The objective is to minimize the electricity purchase from the public grid and maximize self-consumption rates. Based on the electricity supply simulations, the economic utility for each household with different system configurations is calculated individually. Finally, the individual utility-maximizing decisions are aggregated to the market potential of PV + battery systems (section 3.3). The model is structured as in Fig. 3.

The operation of both technologies, heat pump and battery, is optimized to favour the consumption of self-generated electricity with the implementation of the following cost function ($A < B$):

$$C_h = \begin{cases} A, & P_{HH,h} + P_{Batt,h} + P_{ls,h} \le P_{PV,h} \\ B, & else \end{cases} \tag{7}$$

with the household's electricity demand $P_{HH}$ that includes the non-optimized heat pump consumption, battery load $P_{Batt} = P_{Batt,pos} + P_{Batt,neg}$, shifted heat pump load $P_{ls}$, and the PV production $P_{PV}$. Note that the amount of A and B is in this case not important, as long as A < B the battery operation is optimized to maximize self-consumption.

### 3.1. Optimization of heat pumps

As described above, in a first step the optimal scheduling of the heat pump load is determined by solving the following linear optimization problem (LP): The objective function of the LP minimizes the costs of the load shifting activity:

$$Min \sum_{i=h_{min}}^{h_{max}} \sum_{j=h_{min}}^{i} P_{ls,ij} \cdot \left(C_j \cdot (1 + |j - i| \cdot cif_{ls}) - C_i\right) \tag{3}$$

with the shifted load from hour $i$ to hour $j$ $P_{ls,ij}$, the hourly electricity price $C$ and the consumption increase factor $cif_{ls}$, where $i \neq j$ and $i,j$ ϵ $[h_{min}; h_{max}]$ within the optimization interval of one day in this study, i.e. $[h_{min}; h_{max}] = [0;24]$. Technologies that include a thermal storage, such as heat pumps, show an increase in consumption if the time of heat production and demand is displaced [37].

The ability of a process to adjust its load is primarily restricted by the load bounds, i.e. the minimal and maximal load $P_{min}$ and $P_{max}$, respectively:

$$P_{min} \le P_h + P_{h,ls} \le P_{max} \tag{4}$$

with the original charging load in each hour $P$, the shifted load to and from each hour $P_{ls}$, and the discharge of the storage $P_{dis}$.

[3] https://www.bundesbank.de/Navigation/EN/Statistics/Time_series_databases/Macro_economic_time_series/its_details_properties_node.html?nsc=true&https=1&https=1&tsId=BBK01.WT1010&dateSelect=2014.

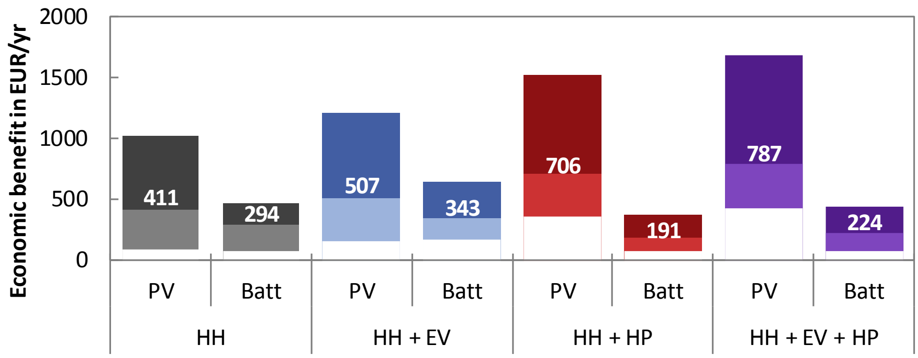


**Fig. 7.** Minimum, mean (bold white figures) and maximum savings in EUR/yr that can be achieved with a 7.5 kWh battery in combination with a 5 kW PV system for equipment with an electric vehicle (EV), a heat pump (HP) or both; evaluated for the year 2015.

**Table 1**
Share of households (HH) with electric vehicles (EV), heat pumps (HP) or both for 2020, 2030 and 2040.

| | HH + EV (+HP) | HH (+EV) + HP | HH + EV + HP |
|---|---|---|---|
| 2020 | 2% | 6% | 1% |
| 2030 | 15% | 13% | 6% |
| 2040 | 44% | 19% | 13% |

**Table 2**
Model parameters for the economic evaluation of self-consumption.

| | unit | 2015 | 2020 | 2030 | 2040 |
|---|---|---|---|---|---|
| Electricity price | €/MWh | 28.8 | 28.6 | 27.8 | 26.6 |
| FIT | €/MWh | 12.8 | 11.3 | 0 | 0 |
| PV price | €/kWp | 1553 | 1226 | 1077 | 926 |
| Battery price | €/kWh | 907 | 655 | 548 | 441 |
| Discount rate | % | 2 | 2 | 2 | 2 |

Additionally, the load shifting ability is restricted by the storage capacity:

$$SFL_{min} \le \sum_{h=h_{min}}^{i} P_h - \sum_{h=h_{min}}^{i} \sum_{j=h_{min}}^{i} P_{ls,\,hj} + \sum_{h=h_{min}}^{i} \sum_{j=h_{min}}^{i} P_{ls,jh} \cdot (1 + |j - h| \cdot cif_{ls}) - \sum_{h=h_{min}}^{i} P_{dis,h} \le SFL_{max} \quad (5)$$

with the minimal and maximal storage fill levels $SFL_{min}$ and $SFL_{max}$, respectively. Instead of calculating the thermal storage size in absolute terms, the storage size is calculated based on the initial heat pump and a heat demand (i.e. storage discharge) profile for the entire year. The hourly deviation of the storage level is determined relative to the initial storage level under the non-optimized process load $P_h$. The maximum deviation is assumed to represent the storage size. The formal description of the determination of the storage bounds is published in Ref. [37].

### 3.2. Optimization of battery[4]

In the second modelling step, the optimal battery operation is determined: Subject to the technical restrictions of the installed battery as well as the household's electricity consumption and PV production profile, charging and discharging loads are determined for each hour of the optimization interval $h$ for each user by minimizing the objective function

$$\text{Min} \sum_{h=h_{min}}^{h_{max}} C_h \left( \frac{1}{\eta} P_{Batt,pos,h} + \eta P_{Batt,neg,h} \right) \quad (6)$$

with the control variables $P_{Batt,pos}$ (charging) and $P_{Batt,neg}$ (discharging) and the electricity price $C$. Efficiency losses due to energy conversion in the battery and the AC-DC inverter are considered via the efficiency factor $\eta = \eta_{Batt} \cdot \eta_{AC-DC} = 88\%$. The objective function is subject to technical restrictions, such as capacity limits. For all battery sizes, a maximum charging rate of 0.5C is assumed, and a minimum state of charge (SoC) of 10%.

Note that different battery capacities and PV panel sizes are applied and the battery operation is simulated for each PV + battery combination to meet the needs of the individual households. The electricity supply is simulated for each of the 415 consumption profiles with the self-consumption model described above. The results are aggregated into two indicators for each individual household and PV + battery system configuration: the household's *electricity purchase* from the public grid and its (remunerated) *PV feed-in*. Both indicators are applied within the subsequent utility calculation.

### 3.3. Total cost of ownership and utility calculation[5]

With the simulated heat pump and battery operation and the resulting electricity purchase, each user's total cost of ownership (TCO) is calculated for different PV + battery systems. The annual total cost of ownership ($TCO_a$) consists of the investment annuity (i.e. capital expenditure) $a^{capex}$ and the yearly operating expenditure $a^{opex}$

$$TCO_a = a^{capex} + a^{opex} \quad (8)$$

The operating expenditures consist solely of operation and maintenance costs. The equivalent annual cost method is used to calculate the investment annuity

$$a^{capex} = \frac{(1+i)^n \cdot i}{(1+i)^n - 1} I_0 \quad (9)$$

with the discount rate $i$ and the investment for the PV + battery system $I_0$.

[4] This part of the model has been published before in Klingler [7].

[5] This part of the model has been published before in Klingler [7].

Additionally, the annual cost of electricity purchase ($CEP_a$) is considered, which is calculated as the sum of electricity supplied from the grid $p_e$ in kWh times the cost for electricity $E$ in EUR/kWh over the course of one year. The cost of electricity purchase is reduced by the amount of excess electricity feed-in $e_e$ in kWh per year times the remuneration $F$ in EUR/kWh:

$$CEP_a = \sum_{t=1}^{8760} (E(t)p_e - F(t)e_e) \tag{10}$$

In case of high feed-in tariffs or large PV systems, the $CEP_a$ can also become negative. Finally, the factors $TCO_a$ and electricity purchase are combined to the utility of the different PV + battery options. In each year $a$, the utility is calculated for each household and each PV + battery system configuration $\tau$ and it is assumed that each household buys the option that maximizes its individual utility, i.e.

$$\max_{\tau}(-TCO_{\tau a} - CEP_{\tau a}) \tag{11}$$

Calculating the electricity supply option for each user and year that maximizes the utility and summing up all households for which this would include a PV or PV + battery system, the shares of potential self-consumers in the sample are obtained as well as the average installed PV panel size and battery capacity for each year. This part of the model has been published before in Ref. [7].

## 4. Results

This section aims to validate and present results of each modelling step of the proposed model using individual consumption data. Results will be given for each modelling step with a focus on the special opportunities when using many consumption profiles.

### 4.1. Load scheduling

Fig. 4 shows the results of the average loads for heat pumps and batteries with optimal load scheduling to maximize self-consumption. The loads are depicted as the average load share, which is in the case of the batteries the ratio of the average load to the maximum load.

Heat pumps and batteries are operated preferably during midday hours with high PV production and the batteries are generally discharged in the evening hours with high electricity demand, which correlates with the higher activity in the households during these hours.

### 4.2. Individual households

The key factors affecting the economics of PV self-consumption and its enhancement through a battery are the amount of direct consumption of the self-produced, and the amount of self-produced electricity that is stored in the battery and supplied to the household at a later point in time. In order to analyse the influence of consumption behaviour on self-consumption rates and profitability for the consumer, the evaluation is in this section limited to one PV + battery system configuration. A 5 kW PV system is assumed, which is the average installed system in German households (calculated from Ref. [38]. This system is combined with a 7.5 kWh battery, which is currently the average installed capacity in Germany [16].

Fig. 5 shows the yearly amount of direct consumption of the PV produced electricity as a function of the household's total yearly electricity demand. As described in section 2, an individual heat pump profile and a charging profile for an electric vehicle were added to each household to simulate the self-consumption for households that own an electric vehicle (blue x symbols), a heat pump (red cross symbols) or both, an electric vehicle and a heat pump (purple asterisk symbol). As can be seen in the figure, the amount of direct consumption varies strongly among different households. Generally, the higher the household's yearly electricity demand, the higher the amount that can be consumed directly from the PV system. The electrification of the supply of the household's heating and mobility demand with heat pumps and electric vehicles alters the consumption behaviour on the one hand in terms of the yearly consumed amount, and on the other hand in terms of the demand structure and thus affects the ability of the households to self-supply their electricity demand. In general, the increased electricity demand enables a higher direct use of the PV electricity production: with an electric vehicle, the direct self-consumption increases on average by 333 kWh/yr (23%), which is significantly more than in the selected cases of [15]. With a heat pump, direct self-consumption increases by 1032 kWh/yr (72%) and with both technologies by 1407 kWh/yr (99%). The heat pumps that are able to shift their load towards hours with high PV production contribute more to the increased direct consumption than the electric vehicles, which are charged mostly in the evenings.

Fig. 6 shows the yearly amount of self-produced electricity supplied by the 7.5 kWh battery. Corresponding to the higher share of direct consumption, the equipment with a heat pump reduces the electricity supply from the battery by 358 kWh/yr (35%) on average. Since the load of the heat pump can be shifted, less excess electricity is produced that can be stored in the battery. In contrast, households with an electric vehicle increase the usage of a battery by an average of 98 kWh/yr (9.5%) when the charging load in the evenings is supplied with stored electricity. In comparison, this is not very much, considering that each electric vehicle in this scenario can store 40 kWh of electricity.

The discussed values for the electricity amounts supplied by the PV system and the battery are listed in Table 3 for the different household types. Note that with increased self-consumption, directly and through the battery, the self-sufficiency rates of the household decline.

**Table 3**
Mean total electricity consumption, electricity supply form a 5 kW PV system and from a 7.5 kWh battery, and self-sufficiency rates $r_{SF}$ with the PV and PV + battery system for the household sample equipped with an electric vehicle (EV), a heat pump (HP) or both. $c_v$ denotes the sample's coefficient of variation.[a]

| | unit | HH | | HH + EV | | HH + HP | | HH + EV + HP | |
|---|---|---|---|---|---|---|---|---|---|
| | | mean | $c_v$ | mean | $c_v$ | mean | $c_v$ | mean | $c_v$ |
| Total | kWh/yr | 4344 | 0.12 | 7623 | 0.33 | 8754 | 0.33 | 12,061 | 0.28 |
| PV | kWh/yr | 1427 | 0.36 | 1760 | 0.30 | 2452 | 0.20 | 2733 | 0.17 |
| Battery | kWh/yr | 1021 | 0.19 | 1191 | 0.13 | 663 | 0.19 | 777 | 0.18 |
| $r_{SF\mid PV}$ | | 34% | 0.15 | 24% | 0.23 | 29% | 0.14 | 24% | 0.17 |
| $r_{SF\mid PV+Batt}$ | | 61% | 0.18 | 41% | 0.22 | 37% | 0.17 | 31% | 0.19 |

[a] The coefficient of variation of a sample is defined as the ratio of the sample's standard deviation $s$ to the sample mean $\bar{x}$: $c_v = \frac{s}{\bar{x}}$.

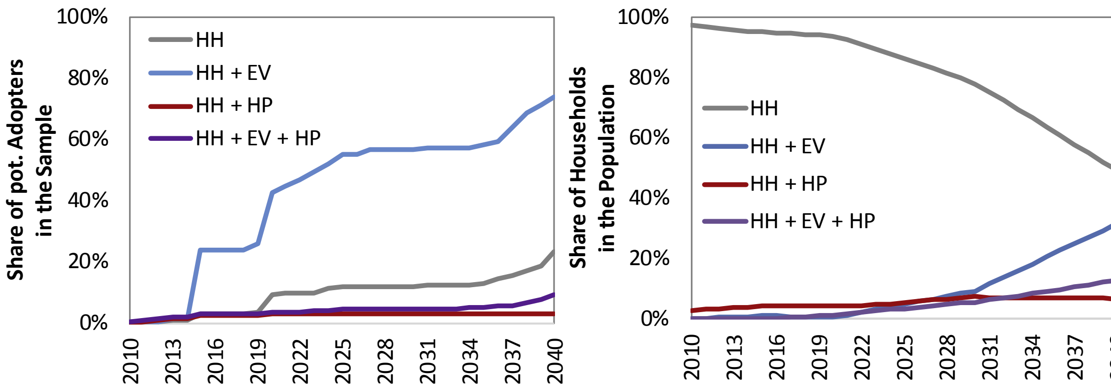


**Fig. 8.** Share of potential adopters in the sample of considered households (left) and share of the considered households in the population (right).

## 4.3. *Market potential in different user groups*

Electrified heating and mobility through heat pumps and electric vehicles, which increase the households' electricity consumption and change the consumption structure significantly influence self-consumption and the economic benefit of a stationary battery. Electric vehicles, which are charged predominantly in the evening hours, increase the households' load in hours without PV production and thus make the option of a battery to shift the load towards sunny hours more attractive. With the framework parameters for the year 2015 (cf. Table 2), the average benefit of the considered battery is 343 EUR/yr, 17% higher for households with an electric vehicle than for conventional households (see Fig. 7). Heat pumps on the other hand, which can shift their load towards hours with high PV production, allow a higher direct self-consumption. While increasing the total electricity demand, the average benefit of a battery is thus with 191 EUR/yr even 35% lower than for the conventional households. The households equipped with both new technologies show a combination of both effects and get with 224 EUR/yr on average a slightly better, if lower benefit (24% compared to conventional households). In benefit of a PV system (without a battery) increases with increasing electricity consumption and therefore with more equipment.

Although households with electric vehicles have the greatest potential for the installation of batteries, the population of these households is currently very small. To calculate the potential adopters of PV + battery systems, both the profitability of the system within each group as well as the share of each group in the entire population of households has to be taken into account. Fig. 8 compares the share of potential adopters within each group (left part) with the share of the group in the population (right part). Not that in this figure, all sizes for PV and batteries are considered. Particularly in the early years, small self-consumption systems are adopted (most frequently the smallest possible system size 2.5 kW PV + 2.5 kWh battery is chosen by the model).

While a battery is economically feasible for around 20% of the households with an electric vehicle as early as 2014, the share of this group within the entire population of households is lower than 1% in 2014; in 2040 it reaches 31%. Fig. 8 depicts the share of potential adopters considering both, the share of potential adopters in the sample and the share of the households in the entire population. The left part shows the share of potential adopters until 2040 distinguished by equipment groups. Only from 2033 on, households with an electric car are the major group within the potential adopters. Households equipped with a heat pump, whether with or without an electric vehicle, make up a very small group within the potential adopters since their share in the population remains relatively small through all projected future years. Additionally, for these groups, a battery is less feasible than for conventional households. The combination of both effects leads to the share of potential adopters in the entire population of households, which is depicted in Fig. 9.

The market potential in every year is subject to many uncertainties. To address these uncertainties, a sensitivity calculation was executed. Depending on the input parameters, the number of potential adopters, for which a battery system is feasible, ranges from almost non to almost all households in the midterm future. Especially the development of electricity purchasing prices and battery system prices is crucial for the future market potential. The effect of the individual parameters on potential adopters is shown in Fig. 10 for the year 2030. Starting from the year 2017 (the first year without empirical data): the input parameters were increased and decreased by 25% and 50% relatively to the base-case parameters. Compared to the conditions observable in reality, this is a relatively strong parameter variation, aiming to show the model's reaction to changing input values. However the development is not impossible: Strongly decreasing battery costs for example can to occur in the case of second-life usage of batteries from electric vehicles and should therefore be considered [5,6].

It is clear that the effect of the shares of the different household groups (with or without heat pumps and electric vehicles) is marginal in comparison to the financial input parameters. Regarding the electricity price, even an increase of 25% has a huge effect on the market potential of stationary batteries, resulting in a potential, which is 6 times higher in 2030 than the base case. An additional increase then only has a very small effect. The battery system price has an equally big effect on the market potential in 2030. The market potential is more than 5 times higher when the prices are lower by 25% compared to the base case. Only for a small number of households, even a drop in the battery price of 50% does not make the installation of this technology profitable. Compared to the effect of electricity and equipment prices, the shares of households with heat pumps and electric vehicles have a relatively small effect on the market potential. However, with a higher diffusion of electric vehicles and a lower diffusion of heat pumps, the market potential increases.

## 5. Discussion

In this study, it was found that households with an electric vehicle generally profit more from a stationary battery to enhance self-consumption. The battery is used to store PV power to charge electric vehicles. The charging takes place in most cases in the evening hours. With the diffusion of electric vehicles, also the

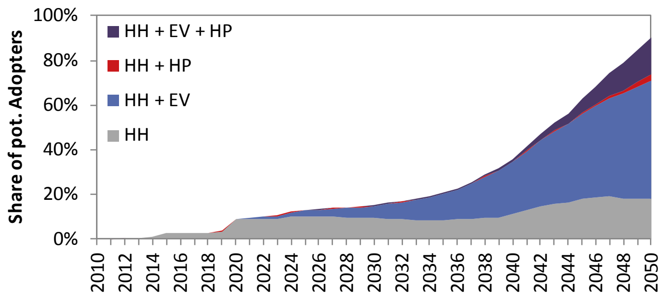


**Fig. 9.** Share of potential adopters in the entire population of households distinguished by groups.

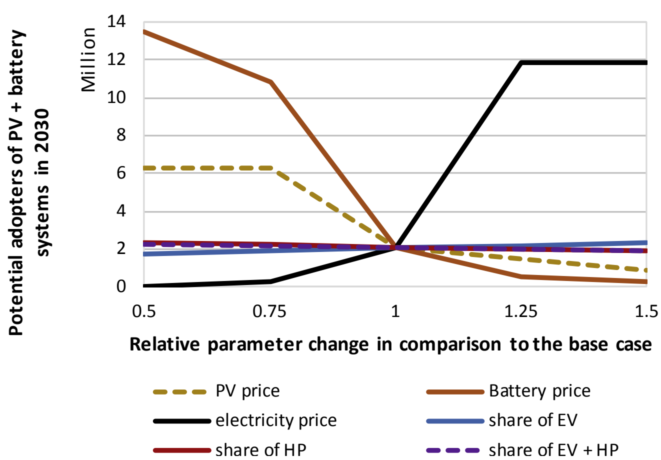


**Fig. 10.** Results of the sensitivity calculations: Potential adopters of PV + battery systems as a function of the relative parameter change.

availability of second-life batteries increases and possibly reduces the cost of stationary battery systems, thus the effect of electric vehicles on the market for stationary batteries is potentially twofold. However, the latter effect is beyond the scope of this study.

For the calculations of self-consumption in households with an electric vehicle, each individual household electricity consumption profile was combined with an individual charging profile. The applied profiles were only available in an hourly time-resolution. As discussed earlier, a higher resolution would allow for a more accurate assessment of PV self-consumption. However, particular in comparison with the other, more substantial assumptions, the advantage of using individual charging profiles outweigh the disadvantages of an hourly time-resolution.

In the conducted simulations, each household is considered to be equipped with only one electric car. A second electric vehicle could further increase the benefit of the battery, but was not part of the analysis. Further, charging at home was assumed for all electric cars, since the objective was to increase the self-consumed amount of PV electricity. In the future, it is possible that charging electric vehicles at work is incentivised or otherwise encouraged, since additional charging options are supposed to increase the flexibility in the energy system [39]. This option could reduce or even nullify the effect of vehicle charging on self-consumption.

Concerning the effect of heat pumps, it was found that, particularly with the option of load scheduling, direct self-consumption is increased, therefore the benefit of a battery system is reduced. However, the decreasing heat demand, which is a result of the ever better insulation of buildings, was not considered. In the considered time horizon, the effect could be significant.

In addition to the improvement of individual self-consumption ratios, the above described solutions to dispatch the residential load enable the option to participate in the balancing power market. Due to complicated legislation, this option is currently only applied to battery systems,[6] but is theoretically seen as viable for dispatchable residential appliances [40,41]. This option could further increase economic benefits [42].

The presented results of this study give an insight into the market potential of stationary batteries and the effect of the currently diffusing technologies heat pumps and electric vehicles. However, there are several uncertain developments and marketing strategies that are beyond the scope of this work. The model that is applied here is found to be particularly sensitive to electricity and equipment prices.

## 6. Conclusions

The results of this study show that the diffusion of electric vehicles can potentially increase the market for stationary batteries to enhance self-consumption, because they enable the charging of electric vehicles with self-produced PV power and thus intensify the battery's usage. In contrast, the installation of heat pumps or other forms of electric heating systems increases the direct consumption of PV power and therefore reduces the profitability of a stationary battery. This is particularly the case, if the heat can be stored and the heating loads are scheduled for hours with PV production.

However, although the diffusion of electric vehicles and heat pumps affects the market for stationary batteries, the market potential of PV + battery systems for the purpose of self-consumption stands and falls with electricity and equipment prices. An increase of the electricity price by 25% results in a market potential in Germany that is 6 times higher than the base case scenario. A reduction of the battery system price by 25% has a similar effect. The sensitivity to other parameters is significantly lower.


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