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The value of smart charging at home and its impact on EV market shares – A German case study

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HIGHLIGHTS

- Effect of smart charging with different appliances in Germany in 2030 analyzed.
- Households benefit most from solar power and home energy management systems.
- Additional storage batteries cannot pay off over time.
- Electric vehicles sales can especially be increased for small vehicles.

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ABSTRACT

The future increase in electric consumers in households, especially electric vehicles and heat pumps, as well as the rising solar power installation, allows for a certain degree of grid-independency and cost savings through self-generated electricity. Both the use of self-generated electricity and cost savings may be increased through the implementation of smart energy management systems at home, which may also have a beneficial impact on electric vehicle sales. In this paper, we combine two models that optimize the energy consumption at household level and a market diffusion model for alternative fuel vehicles to address this aspect for Germany in 2030. Results show that the use of smart energy management systems can result in savings of up to €900–€1200 per year for households with heat pumps, photovoltaics, and electric vehicles, depending on the daily and annual mileage. The results of our analyses indicate that additional battery storage systems are unlikely to be cost-effective with electric vehicles in place. Market shares of battery electric vehicles can be increased, especially for households with small vehicles, where price sensitivities are highest. However, smart charging without solar power only returns small savings and has no impact on electric vehicle market shares.

1. Introduction

The transition towards a more sustainable future, which was internationally decided upon in the Paris Agreement [1], is leading to an increasing electrification of the heat and transport sectors. This is evident in the residential sector through the use of heat pumps and electric vehicles. This transition is crucial for reducing carbon emissions and therefore achieving international and national climate targets (see e.g. [2,3]) and results in increasing electricity costs for residential consumers. As the electricity bill constitutes an increasing portion of their expenses, residential consumers are actively trying to mitigate these costs by exploring effective cost-saving strategies.

The transportation sector is responsible for 23 % of the CO_2 emissions worldwide [4]. Especially when combined with renewable energy sources, e.g. from solar or wind power, battery electric vehicles can contribute to reducing these emissions substantially: While the well to wheel efficiency of conventional internal combustion engine vehicles (gasoline, diesel) ranges from 11 to 37 %, it can be up to 72 % for electric vehicles (EV) [5]. However, the attractiveness and thus diffusion of electric vehicles does not only depend on vehicle prices but also on the availability of charging infrastructure and the charging costs.

Digitalization in the energy sector, specifically smart meters and smart energy management systems (SEMS) that manage the energy demand of households, offer innovative solutions for optimizing a

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residential consumer's electricity consumption. Smart meters can provide real-time data on a household's energy consumption, facilitating informed decisions about when to use electricity. Smart energy management systems are systems to automatically adjust and coordinate the operation of technologies such as electric vehicles, heat pumps, photovoltaics (PV) or home battery storage systems (BSS). The combination of both technologies enables residential consumers to adapt their electricity consumption in response to dynamic electricity prices, unlocking potential cost savings with minimal effort. The pricing of dynamic electricity tariffs varies according to the time of the day, with different price levels applicable at different periods of the day. They can be designed in different ways [6]. This study focuses on so-called Real Time Pricing (RTP), where a different price level applies for each hour of the day, based on the day-ahead or intraday spot market [7].

The regulatory landscape has evolved in the past years, supporting technological advancements. The European Union issued a directive requiring all residential consumers with a smart meter to be offered at least one dynamic electricity tariff starting 2025 [8]. With this initiative, the adoption of energy-saving measures and an enhancement of the financial viability of sustainable technologies is encouraged.

While in Germany there are only a few electricity suppliers offering dynamic electricity prices based on the day-ahead spot market (e.g. [9,10]), in other countries such as Norway, these types of dynamic tariffs are already standard practice. A tariff based on the day-ahead spot market prices reflects the real-time of electricity production and supply and offers residential consumers the access to lower prices during periods of low demand and high renewable generation. With the increasing shares of renewables in the power market, price spreads are also likely to increase further. Thus, consumers adapting to dynamic prices would not only promote a better integration of electricity from renewables but also opens up opportunities to reduce electricity costs. Yet, the question of if this cost saving effect is sufficiently substantial to have an impact on electric vehicle diffusion and thus, how it influences the electric vehicle market is still to be answered.

1.1. Background

Several key strands of research are pertinent to our paper. In our literature analysis, we focus on studies addressing the potential of smart charging of electric vehicles from the energy system perspective, look at research on prosuming in the residential sector and review the literature on market diffusion models for EVs.

When evaluating controlled charging, we have to distinguish unidirectional and bi-directional charging. While the concept of feeding electricity back to the grid is known since 2008 [11], it was long associated with high battery degradation [12]. Nowadays, due to improvements in battery technology, this factor is less prominent. Yet, due to missing communication protocols and commercially available bi-directional charging infrastructure, the technology is still not available in a commercial, standardized setting [13]. We, therefore, consider bi-directional charging in this literature review but will focus on smart, unidirectional charging in this paper.

1.2. The potential of EV smart charging

The potential of controlling EV charging with the aim of reducing charging costs has been part of many earlier studies and observed from different angles. While early studies mention future cost savings and propose ways to address these [14,50,51], others study the willingness-to-pay [52], actors, business models and innovation activity systems [53] or policies to be introduced [54,55].

In our own research, we investigated the system impact of smart charging. On the one hand, we investigated the load shifting potential of EVs depending on the amount of charging infrastructure available [15]. On the other hand, we also examined, how the smart charging of a large number of EVs must be controlled and orchestrated in order to avoid an overreaction to dynamic prices [16]. With a similar modeling approach, various researchers assessed the combination of economic and CO_2 emissions reducing effects of smart charging, e.g. [12,17,18], all drawing a positive conclusion with regard to charging patterns that turn towards the spot market price signal.

1.3. EV smart charging of prosumers in the residential sector

In [19], the influence of battery storage in case of PV battery storage systems and EVs on the total cost of electricity for households situated in the Greater London area is analyzed. They find cost savings to be higher the larger the storage capacity is. Further, they report cost savings of up to 30 % with standard tariffs and up to 80 % for tariffs with real time pricing.

[20] analyzed the potential savings from combinations of EV and PV in Finland. They find annual savings with average driving behavior between 25.4 % and 51.9 % for price optimized charging compared to uncontrolled charging. The study asserts that the greater the frequency of EV use, the more cost-effective price optimized charging becomes.

[21] study four charging strategies for combinations of EV, PV and a RTP tariff for a fictive German vehicle fleet. The vehicle driving behavior stems from a load curve tool based on vehicle movements from MiD2017. The four charging strategies analyzed are: direct charging, optimizing self-sufficiency, optimizing electricity costs with day-ahead real-time pricing (DA-RTP) with and without PV system. They find results to be best for electricity cost reduction with the optimizing self-sufficiency strategy (35 % cheaper than direct charging), followed by optimizing electricity costs with DA-RTP and a PV system (34.5 % cheaper).

Borge-Diez et al. [22] analyze the impact of bi-directional charging for a Spanish case study and determine the energy cost savings for vehicle-to-home and vehicle-to-building with three day-night tariffs [22]. With simplified vehicle movements taken from a Spanish mobility survey, they conclude that bi-directional charging should be considered in market diffusion analyses as carbon intensity for the case study can be largely reduced.

[23] examine how flexibility options in combination with a home energy management system affects the decision in favor of a dynamic tariff and find that particularly households with a heat pump and a stationary battery are suitable for dynamic tariffs. In [24], this is also extended towards effects on the low-voltage grid.

1.4. Electric vehicles diffusion models

Market diffusion models for EVs should firstly be distinguished by market area. For the German and European Market, several models are published (refer to [25–27] for overviews). Methodologically, distinctions can be drawn between e.g., probabilistic approaches [28], conjoint adoption experiments [29], agent-based models [30–33], the latter appearing to be the most prominent approach due to its ability to take into consideration multiple heterogeneous factors like the availability of charging infrastructure, energy prices and social interaction leading to a vehicle purchase.

1.5. Research gap and objective

So far, most studies focus on cost-saving potential through smart or bidirectional charging, utilizing exemplary vehicle movements for their analysis. There is a large number of market diffusion models for electric vehicles integrating and considering multiple factors for the diffusion. In some studies on smart charging, especially with a focus on the systemic effects of EVs, a diffusion model is used to compute the number of vehicles in the system. However, since there is clear evidence that smart charging – both in a unidirectional and a bi-directional manner – reduces energy costs, this raises the question how smart charging influences the costs of owning an EV. Yet, no study could be found by the authors that analyzes the impact of smart charging (savings) on the market diffusion of electric vehicles. Therefore, in this study, we use real-world vehicle driving profiles to derive cost savings through smart home charging with different appliances (PV, BSS, SEMS) and different heating systems (gas boiler vs. heat pump (HP)). We use the resulting cost savings from the analysis in a market diffusion model to understand their impact on EV sales.

Thus, this study analyzes two research questions:

- What are the potential cost savings that can be achieved for different residential consumers by integrating electric vehicles with PV systems, home battery storage systems, and SEMS?
- What are the implications of cost savings through smart home charging on the market diffusion of EVs?

We use the following approach to answer the outlined research questions:

- We use the model FLEX-Operation to simulate households with different technology configurations (EVs, HPs, BSS, PV).
- The same model is then used to optimize the households' energy consumption behavior when a dynamic tariff is applied.
- We evaluate cost saving potentials for different technology combinations, also looking at varying driving patterns as well as varying battery and PV sizes
- These results are given to the EV market diffusion model ALADIN, in which a total cost of ownership approach is used to compute the future EV market and to assess the market shares for EVs (and correspondingly other drive trains) with regard to the influence of self-consumption, prosuming and smart charging

We focus on Germany and the year 2030 and on smart, unidirectional charging. The following section presents the methodology and assumptions (Section 2). The results of the cost savings analysis and the implications on the market diffusion are presented in Section 3. The results are then discussed and conclusions are drawn in Section 4.

2. Methodology and assumptions

In this section, we introduce the modeling framework for this study – coupling (1) FLEX-Operation model for the individual households at the micro-level, and (2) ALADIN model that simulates the penetration of electric vehicles in the market. Finally, we introduce the data and assumptions we used in the analysis.

2.1. The model FLEX-operation

FLEX-Operation is an energy system model for individual households/buildings that models the heating dynamics of the building as well as the operation of technologies in hourly resolution. These include PV systems, BSS, heat pumps, thermal storages (incl. Hot water tank and building mass), and EVs [34].

FLEX-Operation takes the household information, energy price, and weather data as input, including the behavior profiles of a household, prices of energy carriers and feed-in tariff, and the parameters of different technologies in the system (refer to Fig. 1). The technical details and equations of the model can be found in [34].

The heating demand ($Q_{heating}$) of the building is modeled within the 5R1C framework (DIN ISO 13790), which represents the building as five resistances and one capacity, considers the building mass as thermal storage, and calculates the heating and cooling demand in hourly resolution. Plus, the demand of domestic hot water (Q_{dhw}), the power of the heating system in each hour ($P_{hs,t}$) is calculated as:

$$P_{hs,t} = \frac{Q_{heating,t} + Q_{dhw,t}}{COP_t}$$

In case of a heat pump, the coefficient of performance (COP_t) is calculated as $COP_t = \eta \bullet T_{s,t} / \left(T_{s,t} - T_{src,t}\right)$, with $\eta = 0.4$ denoting the efficiency factor, $T_{s,t}$ denoting the supply temperature and $T_{src,t}$ denoting the source temperature.

FLEX-Operation can run in two modes:

- First, in the simulation mode, it considers the households as consumers or prosumers (with PV installed) not explicitly utilizing their flexibility. The operation of available technologies is simulated based on a PV-first strategy, e.g., the PV generation is first used by the households, then the surplus is stored to the battery if one is available, and additional surplus is sold to the grid.

  Overall, this means that energy flows are not optimized based on forecasts or other information.

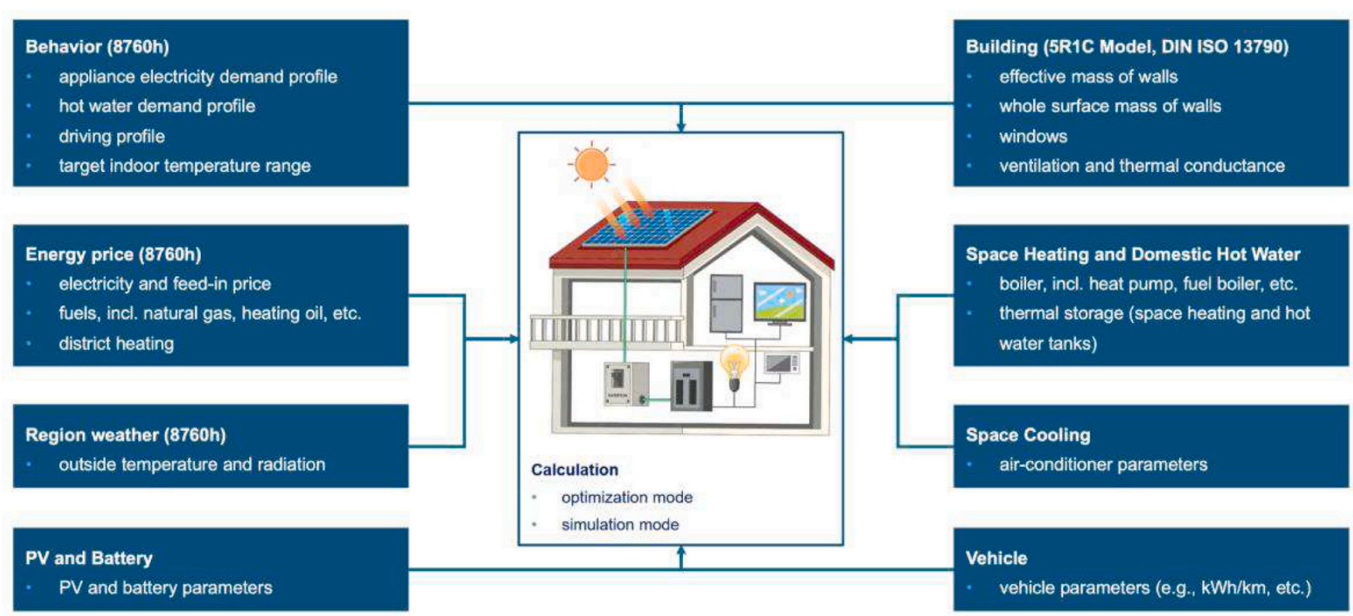

Fig. 1. Structure of FLEX-Operation; Source: [34].

- Second, in the optimization mode, it considers the households as "prosumagers", which explicitly utilize their flexibility. They usually have a PV system installed, that can "produce" and "manage" simultaneously based on a SEMS, with the aim to minimize the energy cost through the 8760 h in a year.

As a result, for a given configuration of a household's behavior, building, and technology adoption, FLEX-Operation can calculate the total annual operation cost of the system. So, by comparing the total energy cost under counterfactual scenarios, FLEX-Operation shows how the interaction between technologies could impact the cost and benefit of adopting one technology. In this paper, we use FLEX-Operation to show the impact of the operation of PV systems, battery storage systems, EVs, and heat pumps on households' adoption of EV, when a SEMS is utilized.

2.2. The model ALADIN

The model ALADIN (Alternative Automobiles Diffusion and Infrastructure) has been part of various analyses and studies [15,35,36] (cf. Fig. 2).

The model is based on a large number of vehicle driving profiles, which include all driving performed by vehicle users over a period of at least one week. Additionally, the profiles contain socio-demographic information about the drivers and vehicles involved (more details in Section 2.4.2). For each individual profile, a battery simulation for both a battery electric vehicle (BEV) and a plug-in hybrid electric vehicle (PHEV) is performed to determine the technical feasibility (BEV) and electric driving share (PHEV). For every year t and point in time τ the battery state of charge ($SOC(\tau,t)$ is calculated as:

$$SOC_i(\tau+\Delta\tau,t)=\begin{cases}\left(SOC(\tau,t)-d(\Delta\tau)\bullet c^{e}_{r,s}(t)\right. & \text{for } d(\Delta\tau)>0\\ \min\left(SOC(\tau,t)+\Delta\tau\bullet P_l(\tau,t)\,;C_{r,s}(t)\right) & \text{for } d(\Delta\tau)=0\end{cases}$$

While we a assume a fully charged battery with full usable battery capacity $C_{r,s}(t)$ for size r and drive train s $(SOC(\tau_i^o,t)=C_{r,s}(t))$. The distance driven in time fraction $\Delta\tau$ is given by $d(\Delta\tau)$ and the vehicle is discharged in the first case with electric consumption $c^{e}_{r,s}(t)$ whenever the vehicle is driving ($d(\Delta\tau)>0$). If the vehicle is not driving, we assume it can be charged with power $P_l(\tau,t)$ up to the full battery capacity while there might not be charging infrastructure available at every location l.

In a second step, the most suitable drive train is determined based on a utility function that considers the total cost of ownership, the willingness-to-pay-more for an electric vehicle as favoring and the limited availability and individual charging infrastructure cost as obstructing factors. The annuitized utility $u^{a}_{i,s}(t)$ of user i for drivetrain s is calculated by the total cost of ownership (TCO) of the vehicle $TCO^{a,veh}_{i,s}(t)$, the TCO of individual charging infrastructure $TCO^{a,CI}_{i,s}(t)$ and the WTPM for EVs $WTPM^{a}_{i,s}(t)$:

$$u^{a}_{i,s}(t)=-TCO^{a,veh}_{i,s}(t)-TCO^{a,CI}_{i,s}(t)+WTPM^{a}_{i,s}(t)$$

Based on this utility, the utility maximizing drive train of the vehicle is determined. The share of vehicles with the same drive train within a vehicle size r, i.e. the number of vehicles $n_{r,s}$ with vehicle size r and drive train s divided by the number of vehicles of the size class n_r, is considered to be the market share:

$$s_{r,s}(t)=\frac{n_{r,s}}{n_s}$$

A year-by-year calculation allows for the aggregation of vehicles in a stock model.

In this paper, we focus on the simulation and results for private BEV owners. A detailed analysis for commercial vehicle owners can be found in [37]. Also, we take a deeper look at the charging, driving and parking behavior as in [15]. Individual hourly charging, driving and stopping profiles are outputs transferred to FLEX-Operation.

2.3. Linking FLEX-operation and ALADIN

As shown in Fig. 1, FLEX-Operation takes the driving profile of the household as an input. This can significantly impact the operation of the household's energy system: first, when a PV system is installed, the EV can be charged when there is generation surplus to increase self-consumption of PV; second, under dynamic electricity prices, the EV can be charged from the grid when the electricity price is lower.

To capture such details, namely (1) the interaction between EV and other technologies, and (2) the impact of smart charging, FLEX-Operation considers the "driving behavior" of a household as two profiles:

- First is a binary location profile (8760 h) with ones implying the EV is at home and zeros indicating the EV is en route;
- Second is the driving distance profile (8760 h), which then is multiplied with the energy intensity of the EV (kWh/km) for the discharging en route.

Consequently, for a given driving profile and the preconfigured incorporation of other technologies, FLEX-Operation is capable of calculating the counterfactual impact of SEMS on the cost and benefit of EV adoption. When SEMS is installed, the model will charge the EV when it is parked at home, and there is PV surplus, or the electricity price is lower to minimize the total energy cost of the year. Subsequently, the results of FLEX-Operation are integrated into the ALADIN model, to show the potential impact of flexible operation on the market penetration of EVs at the macro level.

2.4. Data and assumptions

The study is set in the year 2030. We consider a representative household with three persons living in a single-family-house (SFH) in Germany. The household's behavior – appliance electricity and hot water demand profiles – are developed based on the Eurostat data (calculated in kWh/person), then allocated to the hourly generic profiles developed in the HOTMAPS project[1]. The "appliance electricity" only refers to the electricity demand of devices including lighting, cooking, television, refrigerator, etc. The electricity used for space heating/cooling or hot water is not included. To represent the building efficiency, we selected one single-family house in Germany and used its two renovation-statuses representing the low and high efficiency, keeping the same floor area for comparability among the scenarios defined with different technology configurations. The heating and cooling demand of the two buildings are calculated following the DIN ISO 13790 implemented in FLEX-Operation. Finally, we equipped the high efficiency building with a heat pump and the low efficiency building with a gas boiler. Excluding EV and other technologies (PV, battery, and SEMS), the energy consumption of the two households is calculated with FLEX-Operation in the simulation mode, as shown in Table 1. Due to the different thermal characteristics, the high efficiency building has lower space heating and space cooling demand. They have the same appliance electricity and hot water demand because we assume the same household composition for the two buildings.

In ALADIN, we use a large data set with driving of 6339 drivers derived from the publicly available German mobility panel in which the movements of 1000 households are collected annually since 1994 (KIT

[1] https://www.hotmaps-project.eu/

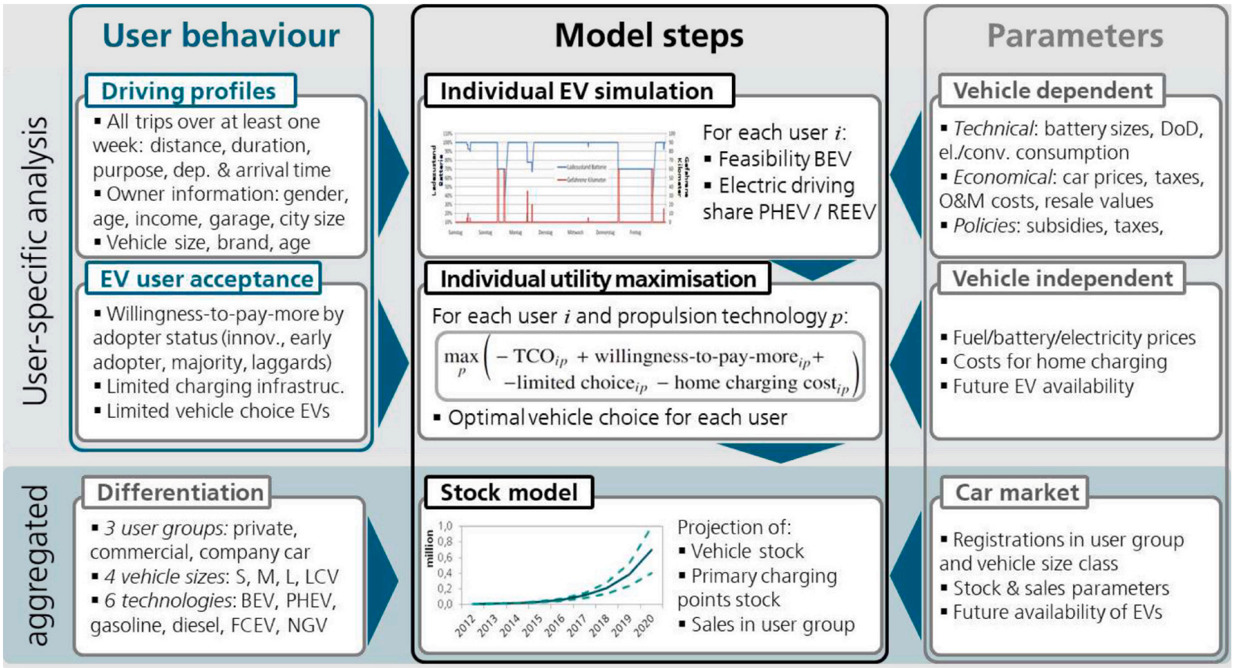

Fig. 2. Overview of the ALADIN model; Source: [36].

Table 1
Annual energy consumption of the representative households (in kWh).

	High efficiency building – heat pump	Low efficiency building – gas boiler
Appliance electricity	3840	3840
Hot water	4061	4061
Space heating	2142	9690
Space cooling	727	1886
Total	10,770	19,477

[38]). We use these profiles to determine the driving behavior of vehicles based on the household members.[2] These profiles can be considered representative for the German vehicle fleet as well as for new vehicle registrations [39].

In this paper, we particularly focus on the individual hourly parking and driving profiles. Here, we use the individual simulation of ALADIN and store all results in two (6339 × 8760)-matrices. In the parking matrix, we use 1 denoting the vehicle is parked at home and 0 denoting the car is outside, including being parked publicly. Then, in the driving matrix, we saved the distance driven by each vehicle in each hour, which is then converted to electricity consumption to reflect the discharging and for SOC calculation in FLEX-Operation. The distinction of stops is particularly helpful in avoiding an overestimation of the load shift potential, as it is only possible to shift the load to times when the vehicle is parked privately.

The assumptions for the different technologies applied to achieve cost savings are presented in Table 2 and taken from [40]. These assumptions can be considered as average values for PV and battery installation for households in Germany in 2030.

Regarding the electricity price time series considered, we utilize the

Table 2
Assumptions for PV, battery and SEMS investment in 2030 based on [40]. Monetary values in €$_{2020}$.

Attribute	PV	Battery	SEMS
Size	5 kWp	7 kWh	–
Investment [€]	6000	3000	1000
Usage time [a]	15	15	15

hourly shadow prices resulting from the German Long-term Scenario[3] project and add all relevant taxes, levies, and surcharges, which are results in average electricity prices of 0.34 €/kWh. The hourly feed-in remuneration electricity generated by the PV system is fixed at 0.07 €/kWh as of today. The price for natural gas price is at 0.137 Euro/kWh.

The assumptions for market diffusion modeling are taken from also taken from the long-term scenarios while a summary of the main parameters is presented in Table 3. Here, we show battery capacities for BEVs[4], vehicle investment, consumption and operations & maintenance cost for the battery electric, gasoline and diesel vehicles as well as price assumptions for batteries, gasoline and diesel. These values represent average values for the size classes considered while there will be differences in new sold cars in 2030. All values are taken from literature discussed in [41,42].

2.5. Scenario definition

The case study is divided into two parts. First, we look at the cost savings potential with smart operation of flexible assets for different household configurations:

- Households without a BEV

[2] A description of the assignment of person trips to vehicles can be found in (Gnann [1].).

[3] The German Long-term scenarios are utilized as standard forecast for many studies and are considered as the main energy forecast of the Federal German Government. https://langfristszenarien.de/

[4] Here, we show the gross capacity of the vehicle to be able to easily calculate the investment, while we assume 90 % of the battery to be usable capacity for driving.

Table 3
Further assumptions for market diffusion modeling for 2030. All monetary values in €$_{2020}$.

Attribute	Unit	Small vehicle	Medium vehicle	Large vehicle
Battery capacity	kWh	38	69	100
BEV investment (chassis + battery)	€	10,234 + 3800 + VAT	16,642 + 6900 + VAT	29,522 + 10,000 + VAT
BEV consumption	kWh/km	0.153	0.188	0.203
BEV operations & maintenance	€/km	0.018 + VAT	0.033 + VAT	0.051 + VAT
Gasoline vehicle investment	€	11,437 + VAT	18,767 + VAT	33,245 + VAT
Gasoline vehicle consumption	kWh/km	0.490	0.590	0.769
Gasoline vehicle operations & maintenance	€/km	0.026 + VAT	0.048 + VAT	0.074 + VAT
Diesel vehicle investment	€	13,668 + VAT	21,086 + VAT	35,611 + VAT
Diesel vehicle consumption	kWh/km	0.378	0.440	0.530
Diesel vehicle operations & maintenance	€/km	0.027 + VAT	0.049 + VAT	0.076 + VAT
Battery price	€/kWh	100		
Gasoline price	€/l (€/kWh)	1.796 (0.182)		
Diesel price	€/l (€/kWh)	1.651 (0.188)		

- Households with an average BEV
- Households with varying driving behavior

For each of these configurations, different technology combinations are considered, which are presented in Fig. 3.

We calculate the total energy costs per household in every technology combination and scenario and compare them to a base case without additional technology. Subsequently, we analyze the correlation of the cost savings potential with the driving behavior and socio-demographics of households and conduct a sensitivity analysis regarding the installed PV capacity and the usable battery capacity. We further include an analysis on self-consumption rates for households with a PV system.

In the second part, we include the obtained results from the modeling of individual households into the ALADIN model and analyze the effects of smart home appliances on BEV market shares. The sensitivity analysis regarding the installed PV capacity and the usable battery capacity is included as well.

3. Results

3.1. Cost savings potentials for different technology combinations

3.1.1. Cost savings potential without BEVs

We begin by presenting the differences in technology combinations in households without BEVs. Fig. 4 presents the total annual energy costs (for driving, heating and appliances) and capital expenditure for the technology bundle in the upper panel, as well as the changes in annual energy costs compared to no technology adoption in the lower panel.[5] It can be observed that the installation of a PV system results in cost savings of up to 780 €/a, while the combination of PV&SEMS is slightly higher than the combination of PV&SEMS&battery (780 €/a and 760 €/a, respectively). Here, the battery does not increase the self-consumption rate of the household as much as it costs more per year (green bar). The installation of only a SEMS might result in a slight positive outcome if a heat pump is installed in the house and the load is somewhat shifted. However, the savings remain marginally above zero. When comparing the combinations with a gas boiler to those with a heat pump, the savings are consistently higher in scenarios with a heat pump. This is due to the heat pump's ability to utilize a significant amount of electricity from an installed PV system.

3.1.2. Cost savings potential with an average BEV[6]

Now, a battery electric vehicle as an additional electric consumer is added to the households instead of the conventional one in the previous section. In Fig. 5, we use the same display and technology combinations as before. With an average BEV (average annual mileage and complete charging at home with 0.34 €/kWh), the total annual energy costs decrease about €2000 in all cases compared to the non-BEV (conventional car) cases (compare Fig. 4 and Fig. 5) and vary between 3000 and 6000 €/a between technology combinations.[7] Highest savings can be achieved by households with a PV system and a SEMS or with an additional battery, with savings of approximately 1000 €/a when a HP is used and around 700 €/a when a gas boiler is operated. This allows to use even more self-generated electricity from the PV system. Other technology combinations with only a PV system can achieve savings of 600 €/a for households with a HP and 300 €/a for households with a gas boiler. Without a PV system, only a SEMS is slightly beneficial.

3.1.3. Results for varying driving behavior

As the driving behavior of individual persons is heterogeneous, vehicles don't all drive the same daily and annual distances and they also differ in trip lengths and number of trips within certain time periods. Using the vehicle charging profiles described in Section 2.4, we can distinguish the users according to their driving behavior and be more precise concerning the savings compared to a scenario with an EV, but none of the other appliances (no SEMS, battery, PV) considered at home. Fig. 6 contains the results for all vehicle driving profiles and their individual driving behavior.

Here, the white part of the boxplots contains the medium 50 % of observations (from 25 %- to 75 %-quartile) with the median separating the upper and lower 50 % of observations. The grey bar contains the 10 %- and 90 %-quantile, while minima and maxima are given with dashes and the arithmetic mean with red dots. The scenario with a gas boiler is presented in the upper panel, the HP scenario in the lower panel.

First of all, it is evident that the means for the scenarios with a battery or with a battery and a SEMS are negative, which translates to a cost increase, yet there are some users (<10 %) that can achieve cost savings. This supports the need for a user-based analysis. We further find cost savings for installing a SEMS in most cases with a gas boiler. For all cases, where a PV system is present, all households can achieve cost savings, regardless of the heating technology. Looking at the cost savings achievable when only a PV system is present in a household additionally to the EV, achievable cost savings lie around 700–800 €/a for the case with a HP as heating technology. There is not much variation through user driving behavior, which can be seen by the very dense boxplot. If PV and SEMS are both installed (with and without battery), possible cost savings lie between 400 and 1000 €/a with a gas boiler and 900 and 1200 €/a with a HP. The increased variation compared to a system without a SEMS stems from the different driving behaviors and we will analyze this in more depth in the following section.

To summarize, we find that installing an additional battery does not lead to higher cost savings as additional savings can only cover the capital expenditure of the battery. The highest cost savings can be

[5] This difference is calculated as the total cost in the base case (without technologies) subtracted by the total cost in the case of consideration plus the annuity for the technology investment.

[6] Here, we use the average savings over all vehicle profiles which are also shown in the following section.

[7] For energy prices, please refer to Table 3.

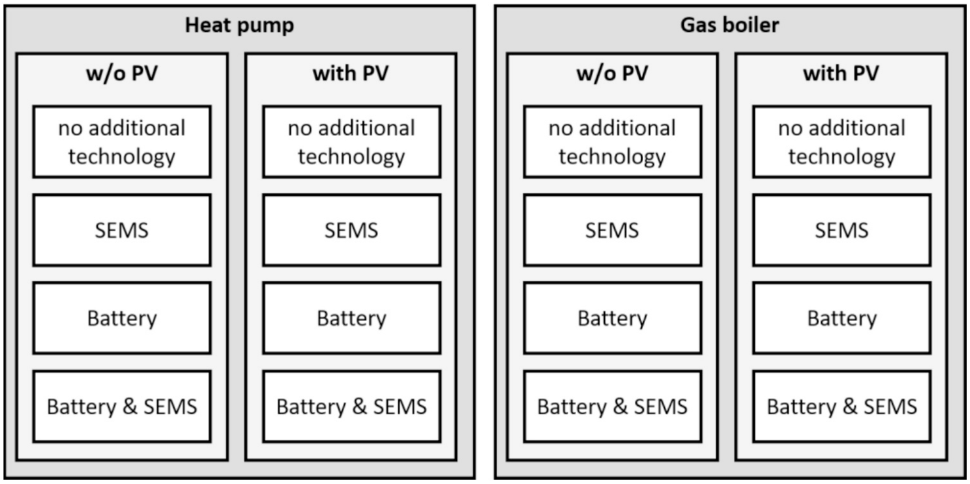

Fig. 3. Technology combinations considered within this study.

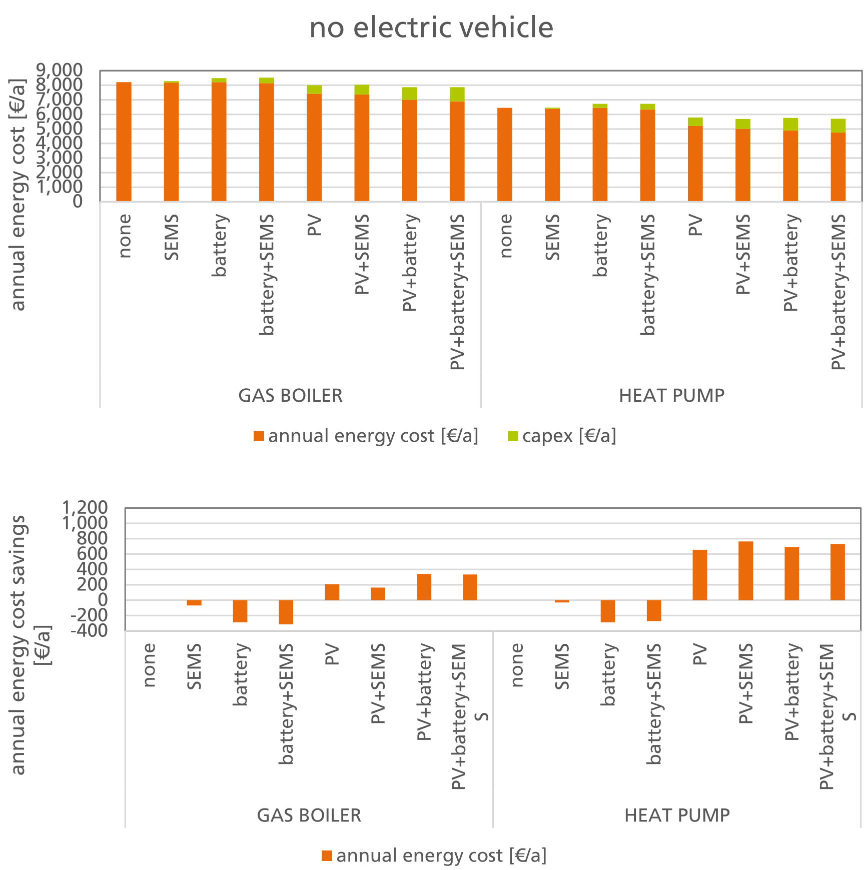

Fig. 4. Annual energy cost and capital expenditure for technology combination (upper panel) and annual energy cost savings compared to no technology adoption (lower panel) in 2030. Results for gas boiler and HP scenario without BEV.

achieved when a PV system for self-generated energy and a SEMS for load shifting are available in a household.

3.1.4. Sensitivity: Varying PV installation and battery capacity

To obtain more comprehensive results, we test the impact of a variation in PV and battery size on annual changes in energy costs. For this purpose, we double both parameters and run the calculations for a PV system with an installed capacity of 10 kWp and a battery with 14 kWh capacity. Fig. 7 uses the same display as Fig. 6, the annual savings for different technology combinations for a household with a gas boiler in the upper panel and a household with a HP in the lower panel.

We identify several changes to the results, including the absolute height and a few more concise ones. One notable change compared to the previous calculations is that none of the households can pay off their investments in the technology combinations involving a battery or a battery and a SEMS in the gas boiler or HP scenario. While the cost savings associated with the technology combinations involving a SEMS, a PV-system or a PV-system and an additional battery in the gas boiler

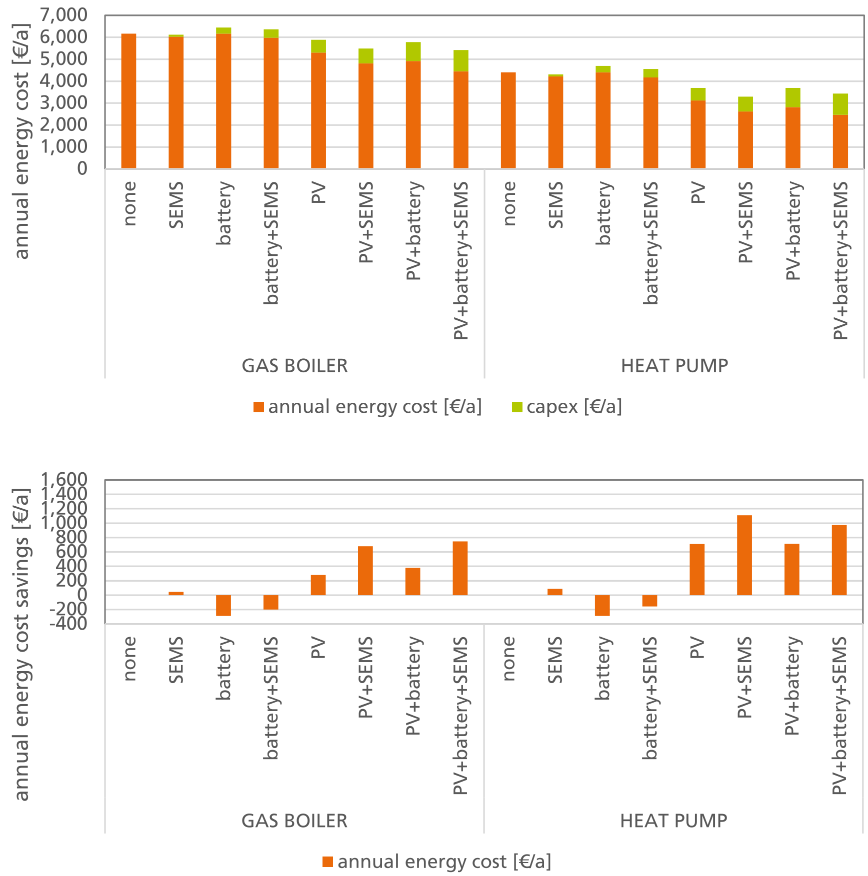

Fig. 5. Annual energy cost and capital expenditure for home energy technologies (upper panel) and annual energy cost savings (lower panel) in 2030. Results for multiple technology combinations for gas boilers and heat pumps with an average BEV.

scenario are relatively modest, ranging from approximately −50 to 400 €/a, they are considerably more pronounced in the HP scenario, where savings range from 700 to 1000 €/a. In this case, the HP allows for a higher self-consumption, leading to higher cost reduction. The highest savings can be achieved for the technology combinations PV & SEMS and PV & SEMS & battery in the gas boiler scenario (300–1100 €/a) and in the HP scenario (800–1700 €/a). In this case, the higher PV capacity compared to the base case may result in an increase in annual energy savings of approximately one third. Consequently, for users with a high energy consumption, a higher PV and battery capacity is a logical choice, although it is not a financially viable option for low energy households.

3.1.5. PV self-consumption

In all scenarios with a PV system installed, it is possible to analyze the self-consumption rate of the household, which represents the proportion of solar energy used by the home itself. Table 4 presents the results for all technology combinations, along with the variations in PV and battery size.

Looking at the first row, it is evident that more electronic appliances (e.g., an additional EV and/or an additional heat pump) increase the self-consumption of solar power. Hereby, the potential of a SEMS can be used to a larger extent and can increase the self-consumption to a level comparable to the use of a battery (if there are enough electric consumers). With a PV system with 5kWp installed capacity and 7kWh battery capacity and all other appliances (SEMS, EV and HP), it is possible to utilize almost all of the solar energy produced at home. An increase in the PV and battery size can result in a slight increase in savings (see previous section), but only a portion of the energy produced would be usable at home (up to 75 %).

3.1.6. Correlation of results with driving behavior and socio-demographics

The scenario with the highest achievable cost savings, e.g. households with a HP, a PV system and a SEMS, is chosen for testing for correlation with driving behavior and socio-demographics. The following variables for driving behavior were tested:

- number of trips
- mean distance of trips
- total distance in the week of observation
- parameter μ of the lognormal distribution based on [43]
- parameter σ of the lognormal distribution based on [43]
- standing time at home
- standing time at work
- standing time in public
- time driving
- annual vehicle kilometers travelled
- charging time at home
- charging time at work
- charging time in public

A strong positive correlation can be found between lognormal's μ (0.59) and annual vehicle kilometers travelled (0.41), while all other variables do not show a meaningful correlation (−0.03 to 0.12). Thus,

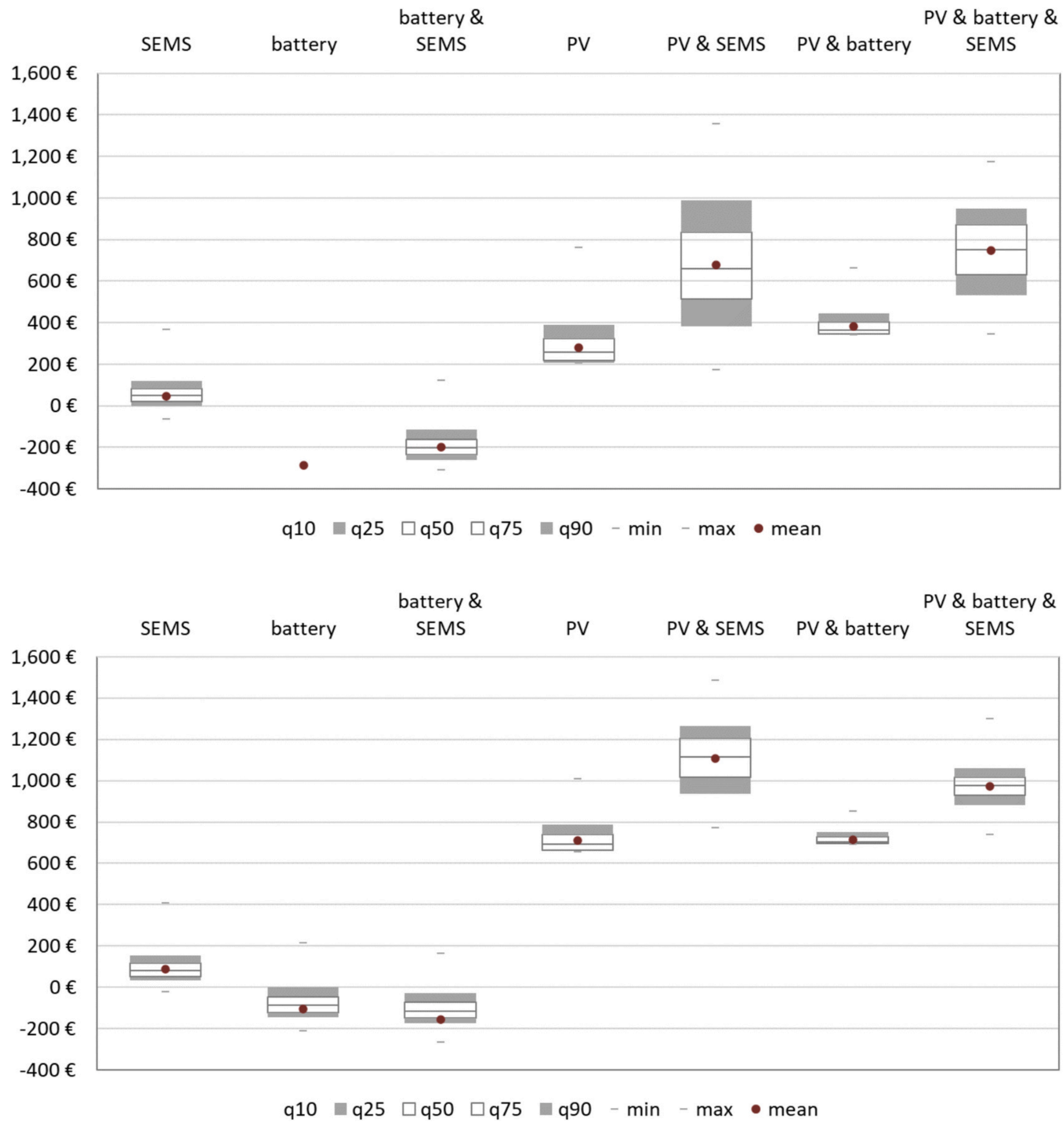

Fig. 6. Annual energy cost savings [€/a] for household with a gas boiler (upper panel) and a HP (lower panel) in 2030. Shown are boxplots with the 25 %- to 75 %-quartile in white bars and median in between, the 10 %- and 90 %-quantile in grey. Minima and maxima with small dashes, mean with red dot. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the more vehicles are driven daily[8] or annually, the higher are their potential cost savings.

Furthermore, the following socio-demographic variables are tested:

- the number of vehicles in household
- the sex of the vehicle owner
- the birth year of the vehicle owner
- the level of education
- the employment status
- the settlement structure
- the number of inhabitants of the vehicle owner's hometown
- the income
- the availability of a garage
- the brand of the vehicle
- the age of the vehicle
- the size of the vehicle
- the size of the household

While the majority of correlations fall within the range from −0.15 to 0.15, we observe a correlation of 0.32 for the size of the vehicle. Given that the vehicle size is a factor in the optimization, this makes perfect sense and will be considered in further analyses in ALADIN in Section 3.2.

3.2. *Impact on BEV market diffusion*

We will now examine the results of the ALADIN model. In this section, we first present the market shares of BEVs in 2030 in different technology equipment scenarios (Section 3.2.1). Secondly, a sensitivity analysis is presented in which a larger PV and battery module are considered (Section 3.2.2).

3.2.1. *Impact of smart home appliances on BEV market shares*

This section presents the market diffusion results of the ALADIN model in a base case (T45-electricity from [41]) in comparison to scenarios where all users benefit from the different smart home equipment

[8] The expectance value of the lognormal distribution $E(x) = e^{\mu}$ can be considered as average daily driving [43].

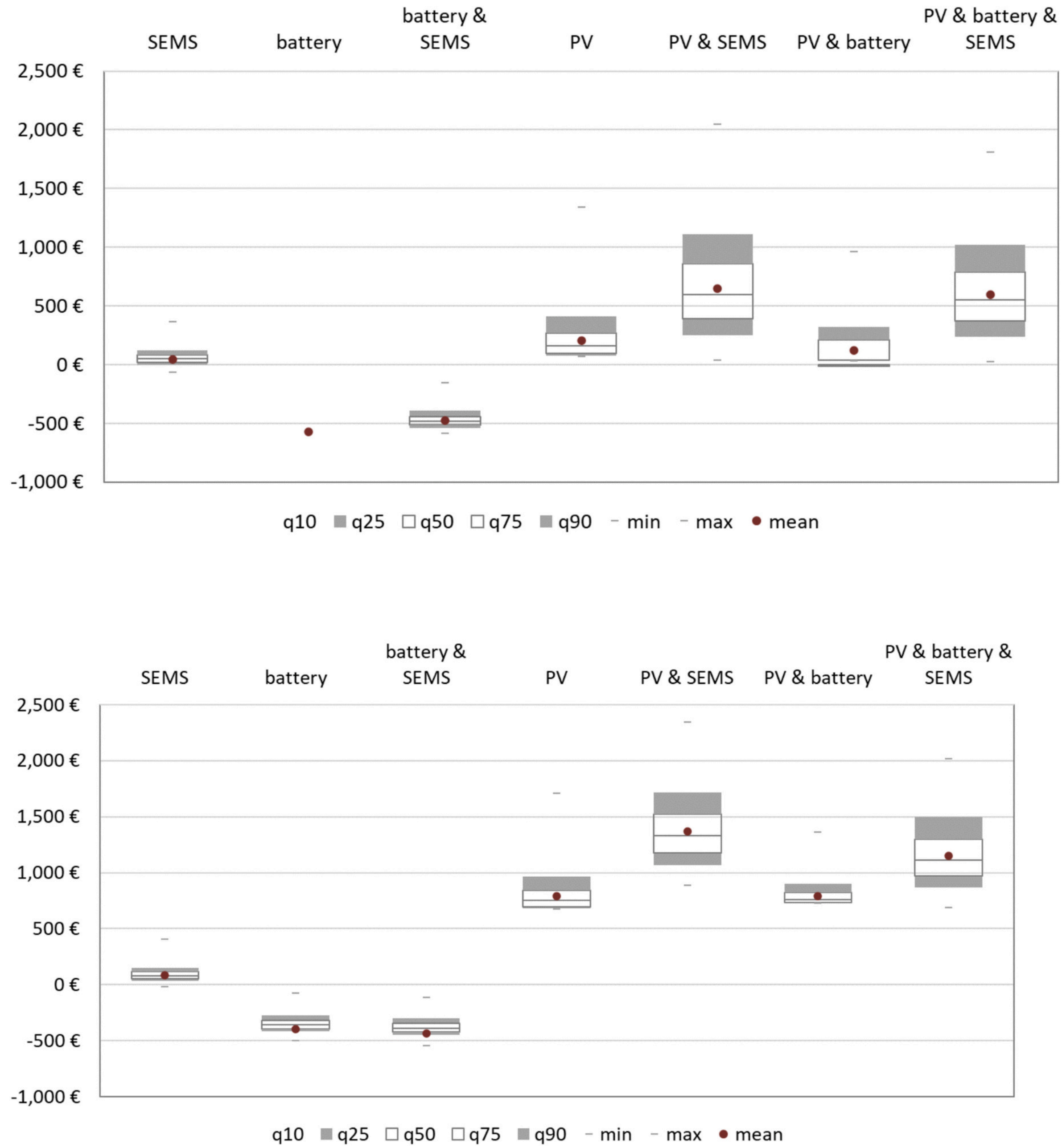

Fig. 7. Annual energy cost savings [€/a] for households with a gas boiler (upper panel) and a HP (lower panel) with a larger PV system (10 kWp) & battery (14 kWh) in 2030. Shown are boxplots with the 25 %- to 75 %-quartile in white bars and median in between, the 10 %- and 90 %-quantile in grey. Minima and maxima with small dashes, mean with red dot. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 4
Self consumption rate in different technology settings (average of all households) in 2030.

PV	battery	SEMS	Gas boiler		Heat pump	
			no EV	EV	no EV	EV
5kWp	none	none	28 %	34 %	64 %	68 %
		SEMS	33 %	64 %	77 %	94 %
	7kWh	none	61 %	64 %	88 %	89 %
		SEMS	65 %	88 %	91 %	99 %
10kWp	none	none	16 %	21 %	40 %	44 %
		SEMS	18 %	38 %	49 %	64 %
	14kWh	none	37 %	40 %	64 %	66 %
		SEMS	38 %	57 %	61 %	75 %

analyzed before. E.g., in the scenario with SEMS only, all vehicle buyers consider the financial benefit of SEMS in their vehicle buying decision. Fig. 8 presents the BEV market shares for the technically non-equipped scenario (orange) and several technology combinations of smart home appliances. The left panel depicts a household heated with gas, while the households on the right side utilize heat pumps. All results are distinguished by vehicle size, as there is a significant difference between the various categories.

As can be seen already for the base case in both the gas boiler and the heat pump scenario (orange bar in Fig. 8), ALADIN calculated BEV market shares above 65 %. This is mainly due to projected decreasing vehicle prices compared to vehicles with an internal combustion engine (ICE) and the assumptions made with regard to fuel costs (i.e. electricity and gasoline).

The results vary considerably, especially in relation to vehicle size

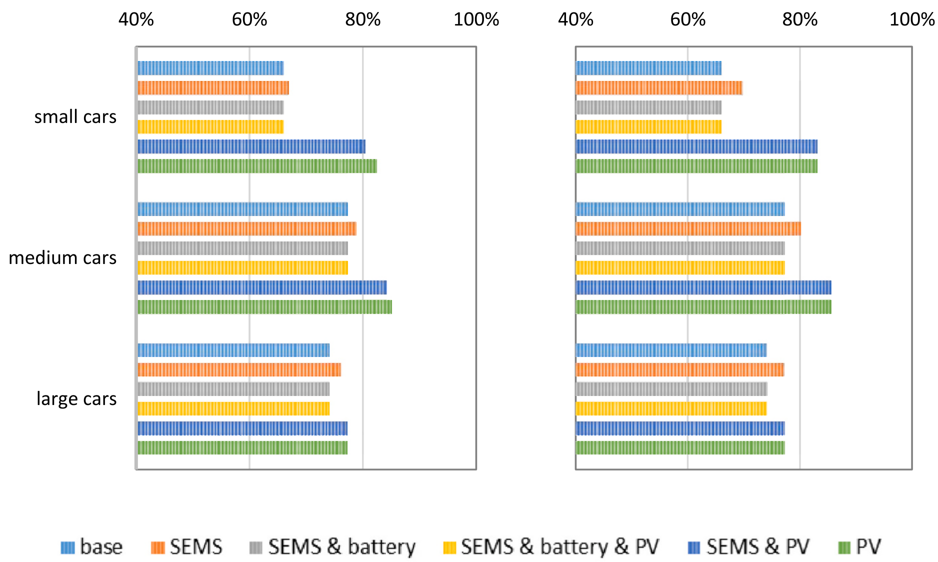

Fig. 8. BEV market shares in 2030 for different technology combinations distinguished by vehicle size. Left panel: gas boiler for heat provision. Right panel: Heat pump for heating.

and the availability of a PV system. While the number of BEV sold for large cars does not increase significantly, regardless of the heating system installed, there are a few additional users in the medium car segment. The highest gains in market share for smart home charging equipment are observed in the case of small cars. Including a PV system in the analysis leads to a doubling of the market shares for BEVs. Furthermore, the results are independent of the inclusion of a SEMS for both heating systems (gas boiler or heat pump) or a battery (only for gas boilers). Consequently, it is possible to increase the BEV sales in 2030 by incorporating the financial benefits of a PV system installation (and a SEMS) into the vehicle purchase decision.

A more detailed examination of the market shares for different annual driving distances is presented in Fig. 9 for the heat pump scenario. The base case, which does not include technologies for smart home charging, is presented on the left panel. The scenario with a PV system is shown on the right panel. The total 100 %, i. e. the surface below each of the curves, represents the small vehicle market share. Consequently, in the base case, users with – for example - annual vehicle kilometers travelled ranging from 4000 to 5000 km are divided into 3.1 % ICEV buyers and 4.2 % BEV buyers. These figures are significantly altered in the scenario with a PV system, with the proportion of ICEV buyers dropping to 0.6 % and BEV buyers increasing to 6.7 %.

It is evident that ICEV market shares exhibit a peak around 6000–7000 km in the base case. These low-distance drivers (the average for small cars in Germany is around 10,000 km) are unable to pay off the additional upfront investment through lower operating costs for a BEV compared to an ICEV. In the PV scenario, operating cost for BEVs is substantially lower because of the low cost for self-produced solar electricity. Therefore, the number of ICEV users almost disappears completely. Consequently, the use of smart home appliances is particularly beneficial for users with a lower annual mileage, in accordance with the aforementioned assumptions.

3.2.2. *Sensitivity: Varying battery size and PV installation*

As before in Section 3.1.4, we examine the results for dependencies on assumptions regarding the PV and battery capacity. Fig. 10 employs the same display as Fig. 8 and presents the market shares of BEVs with varying technology equipment (bars), vehicle sizes (categories) and

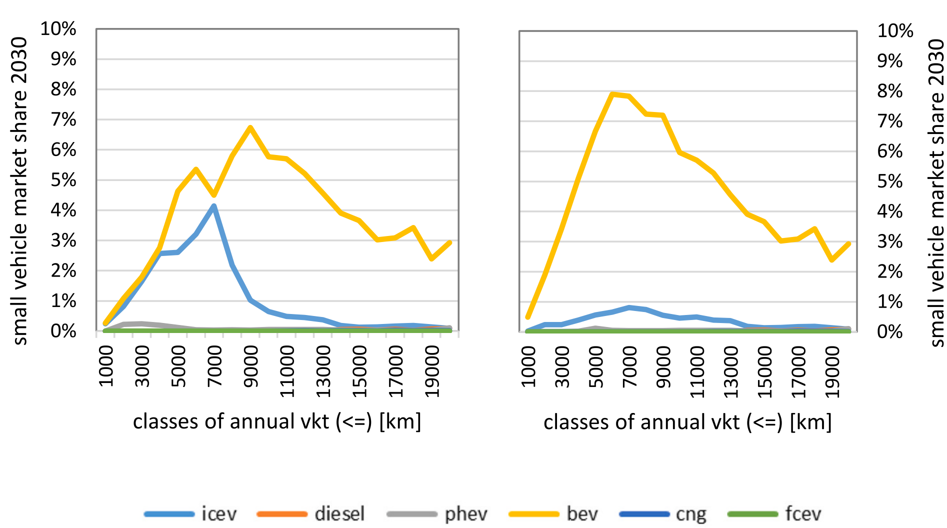

Fig. 9. Dependency of market shares in 2030 for different drive trains to annual driving distance in scenario with heat pump. Vkt = "vehicle-kilometers travelled". Left panel: base scenario (no technology equipment). Right panel: Scenario with PV.

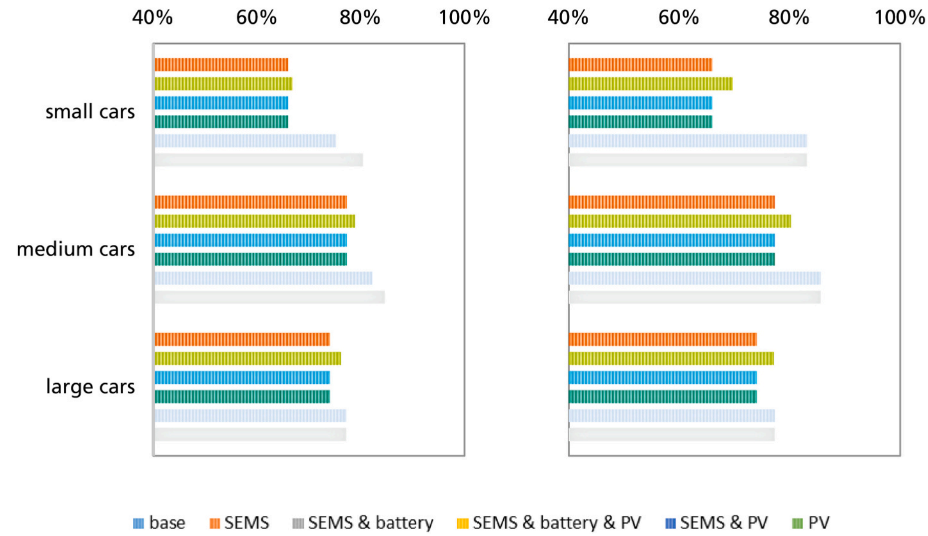

Fig. 10. BEV market shares in 2030 in different technology combinations distinguished by vehicle sizes with doubled PV and battery capacity. Left panel: gas boiler for heat provision. Right panel: Heat pump for heating.

heating systems (panels).

The results are very close to those of the previous calculations with lower PV and battery capacity. They differ for small cars in the scenario with gas heating, where the technology combination SEMS&battery&PV does not further increase market shares and the additional users though the technology combination PV&SEMS are cut in half. Additionally, medium and large vehicles that previously benefited from the use of the technology combination SEMS&battery&PV do not differ from the base case. The reason behind this is the high investment required for the additional equipment, which cannot be paid off over time. Consequently, the earnings for a user are insufficient to influence the vehicle buying decision. This aligns with the findings in Section 3.1.4, which revealed cost savings of 300–1000€/a for the technology combination SEMS&battery&PV compared to Section 3.1.3, which yielded cost savings of 500–900 €/a. Notably, these savings are concentrated among users with high annual mileage, a group that is already inclined to purchase BEVs (see Fig. 9). Hence, the marginal increase in average savings resulting from a doubling of the PV and battery capacity does not significantly change or negatively influence BEV market share results.

4. Discussion and limitations

The authors acknowledge that this modeling exercise is not without limitations with respect to data, assumptions and approach.

In this analysis, we focus on data for the everyday driving behavior of users and neglect their long-distance trips, as these are not part of the driving data sample. In reality, these account for 10–20 % of the annual driving, which would result in a reduction in the cost savings from smart home appliances in the same magnitude. The impact on market diffusion may be less pronounced, but this is a topic for further research.

Furthermore, other data for driving behavior could have been used for driving behavior as e.g. in [44]. However, the use of a dataset with a large number of users with a certain amount of driving has been proven useful in earlier works to understand the average driving behavior of a large number of users [39].

In our analysis, we use assumptions for 2030 which could be criticized. We chose this year to receive a relevant price spread in the annual electricity generation cost curve and because data was available for this year from the long-term scenarios. By selecting an earlier year, the results in scenarios without solar power would be less positive and so would be the effects on market diffusion, while a later year would reveal the same. All scenarios with solar power would be less impacted since the cost of solar power would be cheapest in most cases in the medium-term and thus be less affected. Especially the assumptions for PV and battery capacity could be criticized and several other combinations could be of interest. However, we use average values for current PV and battery installations in Germany and double them in the sensitivity analysis without receiving different general results for technology combinations as well as EV market shares. Thus, the effect of other PV/battery combinations on EV market share results is assumed low, while there could be some changes savings.

Furthermore, it is uncertain whether PV systems could be installed everywhere in Germany and whether all users would benefit equally. Here, a focus on standalone garage owners could be one option for future research. However, a recent study shows a garage availability of more than 80 % for Baden-Württemberg and more than 70 % for Mecklenburg-Vorpommern (German Federal states) which reduces the deviation of this aspect [45].

We did not differentiate households according to their energy consumption, household size or number of inhabitants. Here, we are lacking socio-demographic information for the households that could have been used to combine driving profiles with households directly, although some publications show socio-economic characteristics to be less impactful on household energy consumption than energy-saving technologies [46]. For some households the electricity consumption could thus be higher and in scenarios with PV installation, the solar energy available for driving could be lower as well as savings and effects on market potential. A lower energy demand, which could be even more probable with more efficient appliances and probably also a higher willingness to reduce the personal energy demand, the effects would be even more positive for cost savings and EV market potential.

In this analysis, we focused on Germany in 2030 with all the local conditions. Most other European countries would have smaller energy price differences due to lower energy prices which would result in lower savings in scenarios without solar power. If solar power is considered, Southern European countries would be in favor of higher solar irradiation and could achieve higher cost savings than in Germany and vice versa for Northern European countries. An international comparison could be interesting for further research.

5. Summary and conclusions

5.1. Summary

In this modeling exercise, we combine the FLEX-Operation model, which optimizes household energy consumption, with the ALADIN model, which simulates the market diffusion of alternative fuel vehicles. The coupling is performed through a user-specific evaluation of household energy optimization with different driving profiles from ALADIN, after which the change in annual energy costs obtained from the results of the FLEX-Operation model are included in the ALADIN model to evaluate the effects on BEV market diffusion.

The results of the household optimization study for 2030 indicate potential energy cost savings of up to 500–700 €/a for households without an electric vehicle and a heat pump, and approximately half of this amount for those with a gas boiler for heating. These savings can be further increased by the introduction of a BEV, with potential savings of 900–1200 €/a with a heat pump and 600–1000 €/a with a gas boiler. In both scenarios, a SEMS and a PV-system are sufficient, and an additional stationary battery does not result in additional savings if the household owns a BEV (with a conventional car, the it might be useful, cf. Section 3.1.1). Moreover, a strong positive correlation between changes in energy costs and driving distances on a daily and annual basis is observed. An increase in the capacity of the PV system and battery may result in greater savings but may also lead to a broader distribution. Thus, depending on the heating system and driving behavior, the financial effect in combinations with solar power can be quite meaningful compared to the total energy cost per household with savings up to 25 %. If only smart charging is considered, most cases are only slightly positive and thus not recommendable to reveal cost savings in the medium-term.

The analysis of the impact on the BEV market diffusion shows that installing a PV system is sufficient and obligatory to increase market shares for BEV. In particular, users who drive small cars with low annual driving distances benefit the most, with the potential for a 25 % increase in market shares for small cars in the given scenario assumptions. The increase could even be higher in a less ambitious scenario with market shares of more than 50 % in the base case. This positive effect of PV and BEV adoption is consistent with empirical findings from Germany, where a significant proportion of BEV owners also own a PV system [47]. In addition to the aforementioned positive impact on BEV market shares, this also has a positive impact on the environment, as renewable electricity is used to charge the BEV. Smart charging alone does not affect market shares at all.

6. Conclusions

Given the results of this analysis, future support schemes could include both BEV and PV systems, as these are highly profitable for users. Furthermore, solar panels could be paid off in a relatively short period of time. In summer 2023, a comparable support scheme was implemented in Germany, which facilitated the financing of a BEV, a PV system, and a wallbox and was sold out within one day [48]. Nevertheless, our results show that users of small cars would particularly benefit and a focus should be put on them. This would also benefit lower-income households and ensure better equality and probably also be an incentive against the SUV trend. Additionally, automobile manufacturers could potentially profit from offering a bundle of BEV and PV to their customers. These profitable combinations would also facilitate the accelerated sales of BEVs and PV systems. A combined offer of BEV, PV and SEMS could also reduce the immediate need for distribution grid expansion since a lot of electricity would be consumed from self-produced solar power.

With the change of the German energy industry law at the end of 2023, smart tariffs will become more evident than they are today [49]. One potential way of increasing the appeal of SEMS and batteries to private households is the introduction of a base payment by the grid operator. This could be a means of making these technologies more financially viable for individual consumers, as they do not pay off by themselves from a consumer point of view (cf. [14]).

CRediT authorship contribution statement

Till Gnann: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Songmin Yu:** Writing – review & editing, Writing – original draft, Software, Resources, Methodology, Data curation, Conceptualization. **Judith Stute:** Writing – review & editing, Writing – original draft, Validation, Investigation. **Matthias Kühnbach:** Writing – review & editing, Validation, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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