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Solar energy storage in German households: profitability, load changes and flexibility

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HIGHLIGHTS

- Domestic photovoltaics (PV) and storage systems are techno-economically analyzed.
- PV & storage are profitable in the medium term due to high self-consumption rates.
- Controlled electric vehicle charging improves load flexibility and self-generation.
- External procurement of electricity drastically changes and decreases to 48–58%.
- Dynamic tariffs e. g. with load limits or demand charges incentivize load shifting.

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ABSTRACT

The developments of battery storage technology together with photovoltaic (PV) roof-top systems might lead to far-reaching changes in the electricity demand structures and flexibility of households. The implications are supposed to affect the generation mix of utilities, distribution grid utilization, and electricity price. Using a techno-economic optimization model of a household system, we endogenously dimension PV system and stationary battery storage (SBS). The results of the reference scenario show positive net present values (NPV) for PV systems of approx. 500–1,800 EUR/kW$_p$ and NPV for SBS of approx. 150–500 EUR/kWh. Main influences are the demand of the households, self-consumption rates, investment costs, and electricity prices. We integrate electric vehicles (EV) with different charging strategies and find increasing NPV of the PV system and self-consumption of approx. 70%. With further declining system prices for solar energy storage and increasing electricity prices, PV systems and SBS can be profitable in Germany from 2018 on even without a guaranteed feed-in tariff or subsidies. Grid utilization substantially changes by households with EV and PV-SBS. We discuss effects of different incentives and electricity tariff options (e. g. load limits or additional demand charges). Concluding, solar energy storage systems will bring substantial changes to electricity sales.

1. Introduction

It is the declared objective of the United Nations to drastically reduce greenhouse gas emissions in the future decades (United Nations, 2015). This requires comprehensive changes especially in the energy and transport sector. In both sectors one key to reach this objective is to improve energy efficiency and switch to carbon-free technologies.

Among other sources, decentralized electricity generation by solar power with photovoltaic (PV) systems penetrated the German market successfully during the last two decades. About one and a half million PV systems were installed until 2014 (BSW, 2014). This was possible with a feed-in tariff (FIT) guaranteed by the renewable energy law (EEG, 2014). This guaranteed FIT for PV feed-in decreased during the last years and grid parity for household customers in Germany was achieved in 2012 already (Wirth, 2015). The FIT is going to be eliminated in some years. This

Abbreviations: CHP, combined heat and power; EEG, (Erneuerbare Energien Gesetz) Renewable Energy Act; EV, electric vehicle; EV2H, electric vehicle to home; NPV, net present value; PV, photovoltaics; SD, standard deviation; SBS, stationary batteries system; SoC, state of charge; ToU, time of use; UoSC, use of system charge

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development incentivizes increase in domestic self-consumption[1], which leads to a decreasing electricity demand from the grid and increasing electricity feed-in with high simultaneousness.

The reduction of greenhouse gas emissions in the transport sector is currently focusing on the electrification of passenger cars (Jochem et al., 2015). Technological developments and falling prices of large-scaled batteries (Nykvist and Nilsson, 2015) are accelerating this development. Worldwide the share of electric vehicles (EV) increases, however, still at low levels (IEA, 2015). These EV cause an additional electricity demand in combination with a high charging power demand to households (Jochem et al., 2014). Depending on the charging strategy and implementation, this demand could be shifted in time and charging power could be limited. With falling prices for large-scaled batteries, also stationary batteries systems (SBS) come into focus. In Germany until 2016, in a first market phase with about 34,000 sold units and falling prices by about 18% per year were observed (Kairies et al., 2016). Such systems bring further flexibility into the demand side. But the profitability is not yet clear.

Based on these outlines, it seems to be likely that the electricity demand will change drastically, if technologies like EV and PV-SBS enter the mass market. There might already be millions of EV and households with PV-SBS in a few years from now. Consequently, these households will drastically change external procurement of electricity and will have high feed-in peaks during noon. Such households might have a negative net external procurement of electricity within a year – but with high fluctuations. This might lead to a game changer due to the following developments: Decreasing electricity sales by utility companies and decreasing peak-load prices at spot market due to massive mid-day PV power feed-in lead to further decreasing revenues; increasing energy prices for household customers due to increasing shares for network charges and surcharges might accelerate this development. We are therefore analyzing the question, whether today's pricing schemes in Germany are appropriate for this probable future and which adjustments appear useful. Consequently, we first analyze the profitability of the systems in order to obtain an insight into system sizing, market potential, and the corresponding impact on the load. In addition, new incentives to control the demand side might be necessary.

In this contribution we are focusing on the profitability of PV-SBS for different households with EV and show the corresponding impact on electricity demand. For this purpose, we developed a techno-economic optimization model (mixed integer programming) of a household with the mentioned applications. Using this model, we evaluate 225 households and discuss the influence of different pricing schemes and give political advice for future adjustment of electricity pricing.

The structure of the paper is as follows. In chapter 2 we give a short literature review. In the following chapter 3 we outline the developed model, the underlying technologies and data as well as a scenario overview. The subsequent chapter 4 presents all results for the PV-SBS (Section 4.1) including the impact of integrating EV (Section 4.2). The influence of several scenarios on the load is given in Section 4.3 and further aspects in Section 4.4. We conclude the results by sensitivity analyses in Section 4.6. Chapter 5 comprehensively discusses our results and the implications for the German electricity sector. Chapter 6 concludes our analysis and gives comprehensive policy recommendations.

[1] The self-consumption rate is the PV electricity production, which is self-consumed in the household, divided by the complete electricity production by the PV system.

2. Literature review

In recent years, literature on the issue of combining PV and SBS in households increased significantly. These publications examine the integration of PV and SBS in different applications, countries, and with different methods. Komiyama and Fujii (2014) show a massive potential for integrating PV systems in Japan, whereas decentralized storage of electricity from PV in households currently is not profitable in most countries (Dufo-Lopez and Bernal-Augustin, 2015; McHenry, 2012; Zucker and Hinchliffe, 2014). The situation improves when including the grid and market perspective. Here, SBS provide grid services and grid congestions are prevented (Rudolf and Papastergiou, 2013). In some cases, SBS in combination with national FIT already today lead to profitable applications (Ratnam et al., 2015; Schmiegel and Kleine, 2014; Bruch and Müller, 2014). Hence, the economic success of the first installations on the market strongly depends on the definition of parameters.

An increasing market penetration of EV and their charging demand will further increase the electricity demand by households, which has a positive effect on the economic value of the PV system. Simultaneously, bottlenecks in the grid might be increased, if the charging process is not sufficiently controlled (Babrowski et al., 2014; Weiller, 2011). The charging strategies might lead to different levels of battery degradation. For the current battery technology, lifetime-extending charging e. g. with battery cycling at medium state of charge (SoC) seems to be economically advantageous for vehicle owners rather than a purely arbitrary objective on electricity markets (Lunz et al., 2012). From the system perspective, however, vehicle-to-grid (V2G) concepts facilitate in principle the integration of electricity from renewables and, therefore, might reduce overall system costs (Loisel et al., 2014).

In general, deterministic optimization models (Erdinc, 2014; Kanngiesser, 2013) or simulation models (Dufo-Lopez and Bernal-Augustin, 2015; McHenry, 2012) are used. Uncertainties like price or tariff developments or weather effects are addressed either by a sensitivity analysis (Komiyama and Fujii, 2014), by integrating probabilistic approaches (ElNozahy et al., 2015) or by approaches to minimize forecast uncertainties (Ghofrani et al., 2014; Moshövel et al., 2015). Not in all cases are the uncertainties of relevance to the results (Cai et al., 2013).

Both EV charging and use of SBS increase the load-shifting potentials of households substantially. An inclusion of these potentials in the electricity markets by demand response mechanisms has already been analyzed by several studies from the household perspective (Erdinc, 2014; Sandoval and Leibundgut, 2014; Yoza et al., 2014) and from the utility perspective (Zhao et al., 2013). However, most of these studies neglect the investments in infrastructure for enabling demand response measures. Investigating these costs leads to more pessimistic results (Gottwalt et al., 2011; Lyon et al., 2012). Nevertheless, in the future electricity system these technologies might be an alternative to grid capacity enhancements (Poudineh and Jamasb, 2014).

3. Methodology and data

3.1. Model overview

An integrated analysis of load flexibilities by EV and PV-SBS, including dimensioning and operation of these technologies combined with alternative tariffs, is still missing in literature. Only such an integrated analysis of these systems allows evaluating the influences and its controllability. With this contribution we extend the existing research to reduce this gap. Therefore, we developed