Prosumage of solar electricity: batteries, heating and mobility

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Wolf-Peter Schill[*], German Institute for Economic Research (DIW Berlin)

Alexander Zerrahn, German Institute for Economic Research (DIW Berlin)

Michael Pahle, Potsdam Institute for Climate Impact Research

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Abstract: Self-consumption of locally generated solar energy has gained relevance in many markets. We investigate effects on the power system for three such prosumage options, also comprising decentral sector coupling: stationary batteries, electric storage heaters, and battery-electric vehicles. We apply an extended version of the open-source model DIETER to a German 2030 scenario. If only batteries are considered, system costs grow excessively for high self-consumption shares. In this case, over-sized investments into energy storage capacity are required to balance diverging PV generation and load profiles. Battery investments and system cost decrease substantially if electric storage heaters are used, and even more so if electric vehicles are available. These options allow to flexibly consume a higher proportion of decentral PV generation. We conclude that sector coupling options are likely to play an important role when considering scenarios with increasing solar self-consumption.

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[*] Corresponding author. Mohrenstraße 58, 10117 Berlin, Germany | +49 30 89789 675 | wschill@diw.de.

1 Introduction

Spurred by technology development and regulatory incentives, self-consumption of local renewable electricity generation has gained relevance in many power markets. Building on the concept of “prosumers” (producers and consumers), the term “prosumage” has emerged, which additionally includes decentral energy storage (producers, consumers and storage, cf. von Hirschhausen 2017).

In the following, we define prosumagers as grid-connected domestic electricity consumers who deploy both PV installations and different types of energy storage to produce and consume their own electricity at times, draw electricity from the grid at other times, and feed electricity to the grid at yet other times. In earlier work, we discussed arguments in favor of and against increasing prosumage and presented a quantitative model analysis of system effects, focusing on decentral batteries (Schill et al. 2017).

In the present paper, we expand this earlier work and explore the system effects of prosumage in the context of additional decentral energy storage and sector coupling options, specifically, electric heating and electric vehicles. To do so, we use an extended version of our open-source electricity market model DIETER and apply it to a stylized 2030 scenario of Germany. Compared to purely battery-facilitated prosumage, electric storage heaters and electric vehicles trigger different system effects as they come with different flexibility characteristics and also increase prosumagers’ electricity demand. Throughout the paper, we assume that households engage in prosumage, without explicitly considering their incentives; in this way, we adopt a system perspective.

Depending on the perspective and on the assumed reference scenario, increasing decentral prosumage activities may bring about both opportunities and challenges in the context of a low-carbon energy transition (Schill et al. 2017). To start with potential benefits, households may have preferences for generating their own renewable electricity and for being less dependent on energy utilities (Oberst and Madlener 2015). Households may also be interested in less volatile and, potentially, lower electricity costs, as self-consumption allows detaching from uncertain retail price developments to some extent (Hoppmann et al. 2014). In Germany, the desire to actively participate in the *Energiewende* has been mentioned as another motive for prosumage (RWTH 2018). PV-coupled decentral batteries can also help to relief distribution grids if they are operated in a network-oriented way (Moshövel et al. 2015).

On the downside, solar prosumage may lead to increasing system costs compared to centrally optimized systems, as it implies increased local balancing of variable renewable supply and electricity demand. Accordingly, the benefits of wider-area balancing, related to geographical smoothing of demand and generation patters, can be realized only to a smaller extent (Fraunhofer IWES 2015). Likewise, decentral batteries may not be used in a system-oriented way (Green and Staffell 2017). Further, detrimental distributional impacts of solar self-consumption have been discussed extensively in the literature, particularly in connection with energy-based network tariffs (Parag and Sovacool 2016; Borenstein 2017). To resolve this issue, different types of capacity-based or hybrid charging schemes have been proposed (Pérez-Arriaga et al. 2017).

Previous model-based analyses often did not include decentral sector coupling, but focused on prosumage facilitated by battery systems only. In a review, Luthander et al. (2015) find that 0.5-1.0 kWh storage per kW of installed PV capacity allows increasing self-consumption shares by around 13-24%. Quoilin et al. (2016) simulate domestic solar self-consumption for different EU countries and determine typical rates of 30-37% without using batteries. With higher battery capacities, the self-consumption rate increases. We contribute to this stream of literature by adding both electric storage heating and battery-electric vehicles and investigating their interactions.

The remainder is structured as follows. In Section 2, we describe the optimization model. Section 3 introduces the most important input parameters. We show and discuss results in Section 4, looking at system cost, storage investments, battery charging levels, and the optimal shares of decentral PV generation used by different prosumage options. Subsection 4.5 includes results of a sensitivity with smaller PV installations. We qualitatively discuss the implications of some relevant model limitations in Section 5. The final Section concludes.

2 The model

We use an extended version of our open-source electricity market model DIETER.[2] The model's objective is to minimize overall system costs over a full year in hourly resolution. Thus, it mimics the perspective of a benevolent social planner or, assuming perfect foresight and perfect information, the outcome of a perfectly competitive market. It is a linear program that is implemented in the General Algebraic Modeling System (GAMS) and solved with the commercial solver CPLEX.

Model inputs comprise data on costs, availability and installations of technologies for electricity generation and storage as well as hourly time series of energy demand and renewable capacity factors. Endogenous decisions variables are the hourly use of technologies and investments into decentral batteries and electric heaters. Model results encompass system costs, hourly dispatch as well as various derived indicators.

We add a prosumage segment to the model by specifying a certain share of the installed solar PV capacity and a corresponding share of the electric load. Within this prosumage segment, we do not explicitly model households' incentives for prosumage, but approximate these with a self-consumption restriction. That is, prosumager households have to make use of specified shares of their potential yearly PV generation. We vary these shares exogenously.[3] To do so, households have different options for making use of their PV electricity (Figure 1):

(i) directly satisfy the household's electricity demand, that is, in the hour of generation;
(ii) charge a decentral, stationary lithium-ion battery, which in turn is used to meet electricity demand at later times;
(iii) charge smart electric thermal storage (SETS) heaters; or
(iv) charge a battery-electric vehicle (BEV).

In addition, prosumagers can also

(v) transfer their PV electricity to the non-prosuming market segment; or

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[2] The standard setup of the model is described by Zerrahn and Schill (2017). The extended model version used here is available on request. After potential revisions of this work, a final model version will be published on DIETER's homepage www.diw.de/dieter.

[3] In the previous model analysis documented in Schill et al. (2017), we applied a minimum self-generation restriction, i.e. specified a share of a household's electricity consumption that had to be satisfied by self-generated PV electricity. In the present analysis, we alternatively constrain the share of decentral PV electricity generation that has to be used by prosumagers.

(vi) curtail their PV electricity.

Figure 1 also indicates that the model additionally includes a connection between decentral prosumager batteries and the electricity market. The batteries could, in principle, also be used as a grid storage facility, for smoothing the grid feed-in of prosumage PV, or for smoothing the grid consumption of prosumager households. While these features are explored in Schill et al. (2017), we disable them in the present analysis for conciseness and clarity (indicated by the red crosses in Figure 1).

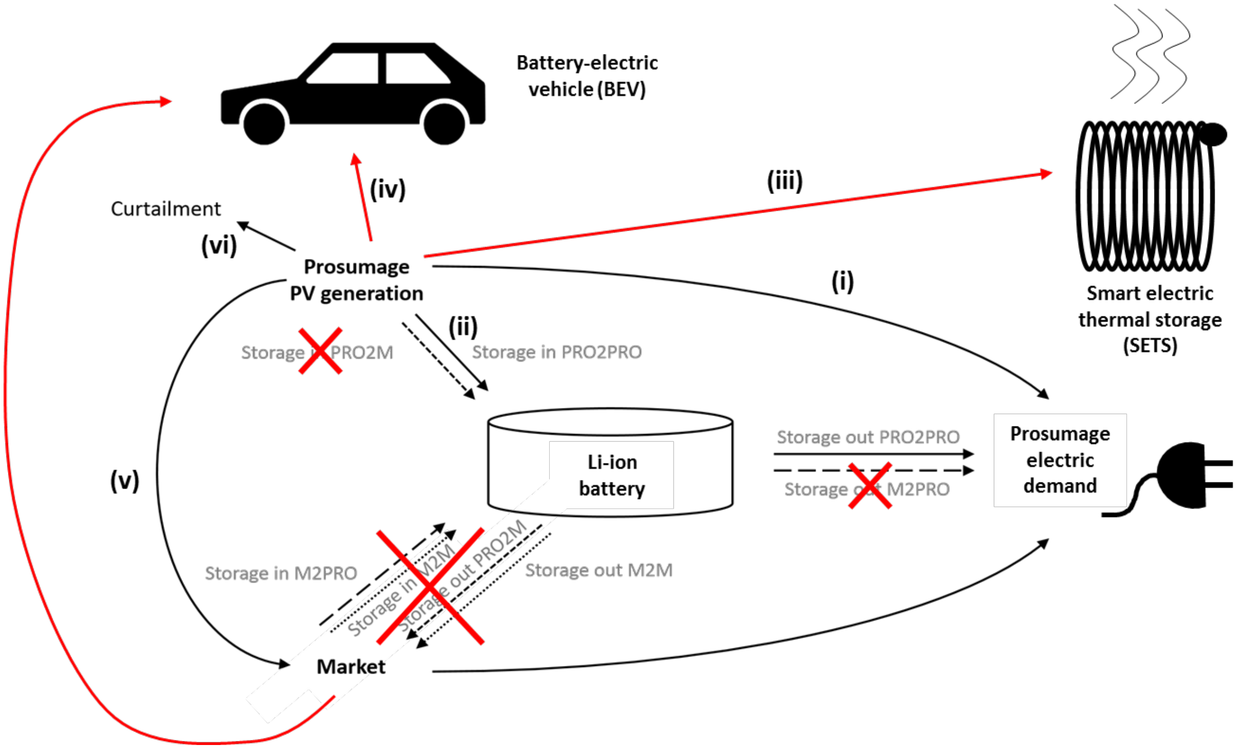

Figure 1: Options for making use of prosumagers' PV electricity in the model

Under the given model setup, all prosumage decisions are implicitly guided by system needs. For example, loading and discharging of the stationary battery is carried out such that system costs are minimized, while still ensuring that the specified minimum self-consumption share is met. This may, for instance, be facilitated by aggregator firms controlling the decentral facilities. Importantly, prosumage decisions are guided by overall system costs; in this respect, the model abstracts from regulatory components, such as grid fees or taxes.

Table 1 lists some assumptions on the different options for increasing prosumagers' self-consumption shares. For example, while li-ion batteries and SETS by assumption only use self-generated PV electricity, electric vehicles may also be charged from the grid. Further, the objective function fully accounts for investment costs of li-ion batteries and SETS, but there are no investments costs for electric vehicles. For convenience, we assume one BEV per household. Making use of vehicle batteries for increasing a household's self-consumption thus has a "free lunch" characteristic.[4] For SETS, we assume that these are backed up by existing domestic heating systems fueled with natural gas. If households install SETS, this, accordingly, lowers natural gas fuel costs in the objective function, but incurs no savings with respect to the fixed costs of the backup heating system (which is not explicitly modeled at all).

Table 1: Assumptions on different prosumage options

	Electricity supply	**Constitutes additional electricity demand?**	**Investment cost**	**Other assumptions**
Stationary li-ion batteries	Only self-generated	No (only losses)	65 €/kW 300/kWh	• E/P free • No connection to grid
Smart electric thermal storage	Only self-generated	Yes	350 €/kW (=44 €/kWh)	• E/P 8 hours • No connection to grid • Natural gas back-up assumed • Fluctuating heat demand profile
Battery-electric vehicles	Self-generated and from grid	Yes	- (one vehicle per household)	• 3.7 kW / 30 kWh • „Free lunch" • No V2G • Time-varying charging availability profile → available in 90% of hours

3 Input data

We model the German power system in a stylized future scenario of 2030, leaning on the latest EU Reference Scenario (European Commission 2016). For simplicity, we focus on Germany and abstract from power exchange with neighboring countries. We further assume fixed generation capacities and only allow for investments into decentral li-ion batteries and SETS.

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[4] We abstract from modeling endogenous investment in electric vehicles because (i) vehicles would have to come in discrete numbers per household, which would make the model non-linear; and (ii) the additional costs of electric vehicles are highly uncertain and would require additional assumptions on differences in fixed and variable costs compared to the conventional vehicles which they would substitute.

Installed generation capacity (Figure 1) is taken from European Commission (2016) wherever possible, but some technologies are only provided as aggregate figures there. To differentiate between lignite and hard coal, we lean on the 2030 scenario Vision 3 of the ten year network development plan 2016 (ENTSO-E 2015). For the split between onshore and offshore wind, we follow the medium scenario (B) of the most recent German Network Development Plan for 2030 (50Hertz Transmission et al. 2018). We further assume 6.5 GW (45.5 GWh) of pumped-hydro storage (PHS) capacity, reflecting current installations in Germany. With this generation portfolio, renewables have a share of around 53% in yearly electricity consumption.

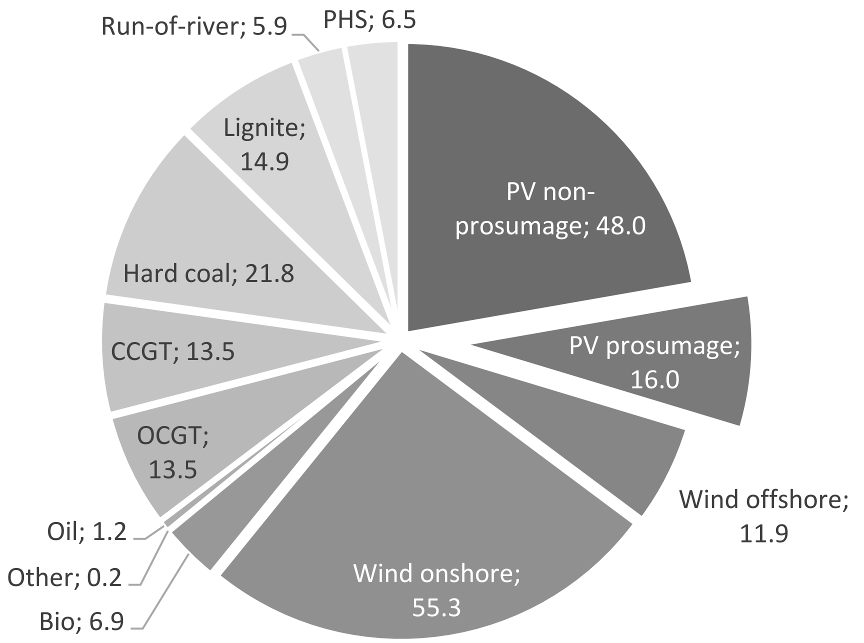

Figure 2: Installed generation capacity

Of the total 64 GW installed PV capacity, we exogenously attribute 25% (16 GW) to the prosumage segment. We further assume a typical yearly electricity demand (excluding SETS and BEV) of a prosumager household of 4000 kWh and a sizing of prosumage PV installations such that the yearly potential electricity generation matches the 4000 kWh demand. This results in around 3.5 million prosumage households with PV systems of 4.6 kW_p each. This PV capacity is hold constant in all model runs (except for the sensitivity described in section 4.5), irrespective of the use of decentral SETS and BEV. We further assume that prosumage households have the same hourly profiles of electricity demand and PV availability as the overall system.

Hourly time series of load and of the availability of variable renewables reflect historic German data from 2016 and are sourced from the Open Power System Data platform (OPSD 2018). Heat demand of prosumage households is taken from the EU Horizon 2020 project RealValue (O'Dwyer et al. 2018). To be precise, we use an hourly heat demand profile of one-family homes with a yearly heating energy demand of 112 kWh per square meter (Figure 3).

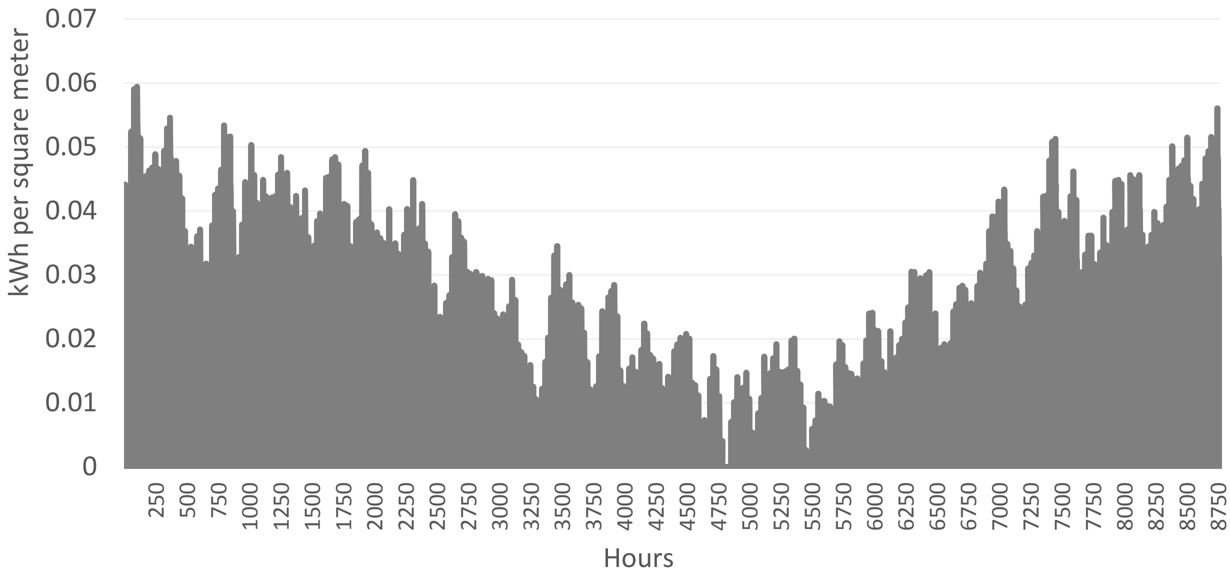

Figure 3: Hourly heating demand of prosumage households per square meter (O'Dwyer et al. 2018, chapter 3.2)

Concerning battery-electric vehicles, we assume that each prosumage household owns one vehicle with a battery of 30 kWh. We only consider flexible charging of vehicle batteries and abstract from subsequent discharging to the grid (V2G). We use synthetic hourly time series of the vehicle's electricity consumption and charging availability. These are generated from empiric German mobility data and reflect a typical household's car use (Kramer 2018). The vehicle charging capacity is assumed not to exceed 3.7 kW, and the vehicle is on average available for charging in 90% of all hours.

Additional parameter assumptions on li-ion batteries, SETS and BEV, including specific investment costs and E/P ratios, are summarized in Table 1.

4 Results

The model parameterization described in the previous section leads to a baseline self-consumption rate between 40% and 50%. That is, an average prosumage household could make direct use of nearly half of its potential PV generation without investing in energy storage or being engaged in additional sector coupling. Increasing this self-consumption share beyond 50% requires investments into batteries or SETS, or the use of BEVs. In the following, we first focus on system costs differences of different prosumage options for increasing self-consumption shares, then turn to storage investments and battery usage patterns, and finally illustrate the shares of decentral PV generation used by the different prosumage options. Subsequently, we illustrate the effects of smaller PV installations in a sensitivity. In doing so, we always differentiate three cases: (a) stationary batteries only, (b) batteries plus SETS, and (c) batteries plus SETS plus BEV.

4.1 System costs

We first look at the system cost effects of purely battery-driven prosumage (blue line in Figure 4). Increasing the self-consumption share to 70% incurs a moderate increase of yearly system cost of around 190 Euro per prosumage household. Beyond this share, costs explode to extreme levels (note the log scale in the Figure). Costs are lower by around an order of magnitude or more if we allow for investments into smart electric thermal storage in addition to batteries. If battery-electric vehicles are also available, costs are, again, lower. Compared to the baseline (in that case also considering the vehicles' additional electricity demand), increasing self-consumption to 90% incurs a system cost increase of only 32 Euros per household. Yet achieving 100% self-consumption is still relatively expensive with around 680 Euro extra costs per household.

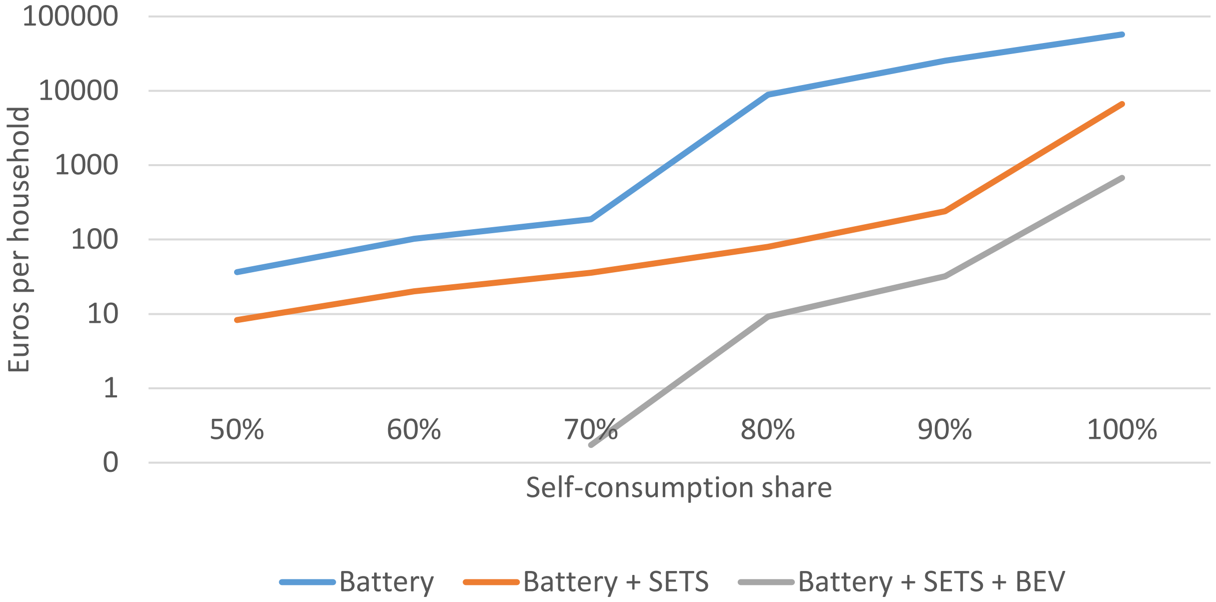

Figure 4: System costs increases compared to baseline, related to prosumager households

The cost increases as well as the cost differences between the three prosumage options are driven by different investment costs of batteries and SETS, different flexibility characteristics, and different overall electricity demands. SETS and electric vehicles increase a household's electricity consumption and thus enable more readily consuming a higher proportion of PV electricity generated by a prosumager. This is not the case for stationary batteries (or only to a minor extent considering roundtrip losses). Accordingly, batteries have to align the different hourly profiles of PV generation and the households' "normal" electricity consumption over the whole year. This is not the case for SETS and BEV. Here, variable PV generation also has to be aligned with variable time profiles of heating and mobility demand, but there is more flexibility as there is still the option of backup heating (SETS) or grid electricity (BEV). Accordingly, battery storage capacities required for high prosumage shares, and eventually costs, can become extremely large, as illustrated in the next section.

4.2 Storage investments

With respect to storage power capacity, required investments in stationary batteries and SETS are moderate even for a self-consumption share of 100% (Figure 5). This reflects the fact that domestic PV installations are assumed to be relatively small (4.6 kW_p).

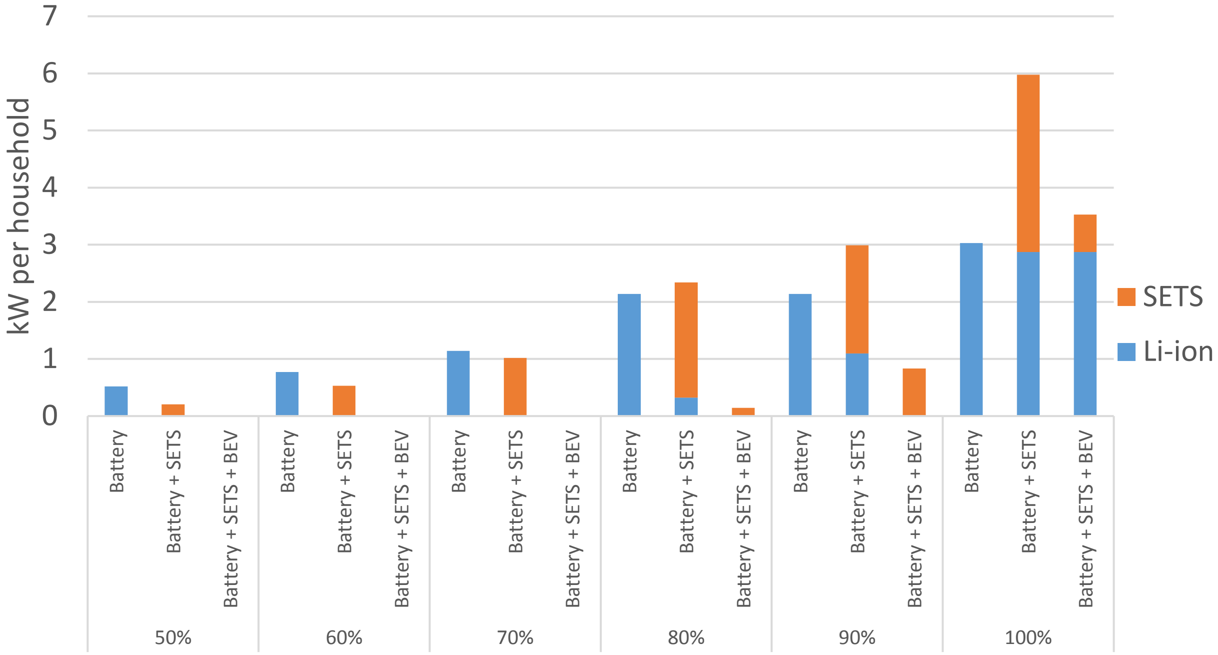

Figure 5: Investments into storage (power) per prosumager household

Yet the picture looks very different for investments into storage energy capacity (Figure 6). If stationary batteries were the only available option, increasing self-consumption requires moderate investments only below a self-consumption share of 70%. This corresponds to the findings synthesized by Luthander et al. (2015). Yet beyond 70%, very large energy storage capacities would be required, with more than 2000 kWh per household in the 100% case. This is because perfectly balancing the diverging hourly time profiles of prosumagers' variable PV generation and electricity demand would trigger storage capabilities which may be considered as a kind of "seasonal storage" for high self-consumption shares; with an E/P ratio of almost 700 hours in the most extreme case. If additional investments in SETS are considered, stationary batteries are only needed in the 90% and 100% cases, and at substantially lower levels. If BEV are present, these provide most of the flexibility for accommodating renewable self-generation, and batteries are only necessary in the 100% case (around 22 kWh per household).

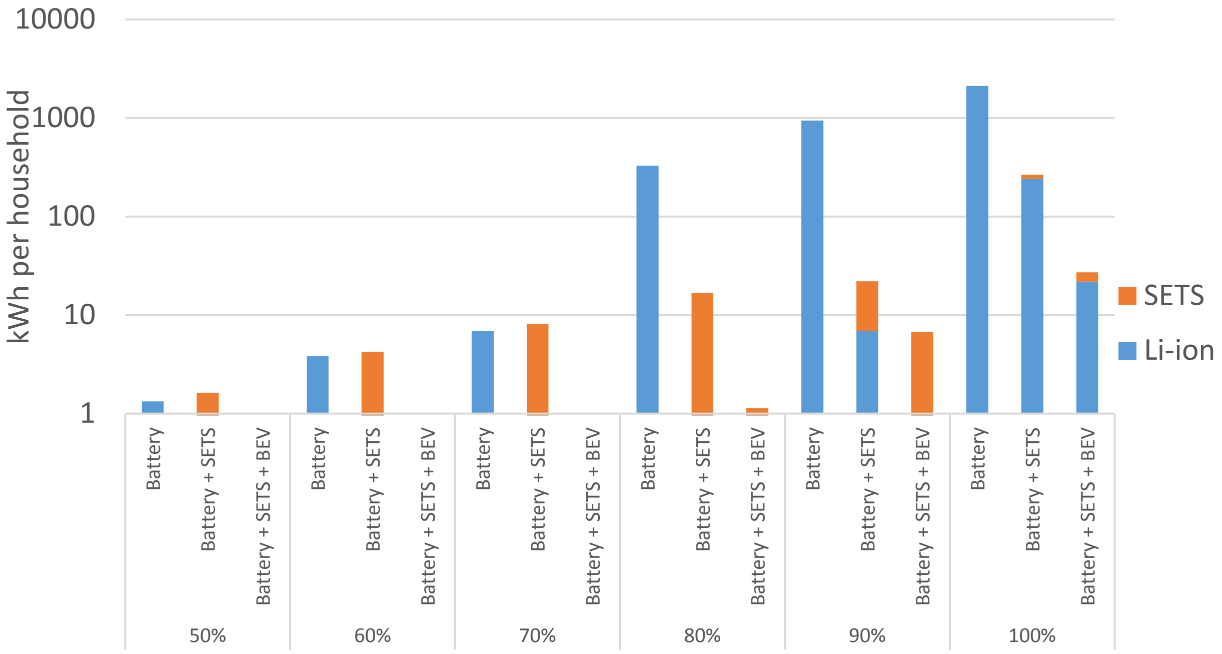

Figure 6: Investments into storage (energy) per prosumager household

4.3 Battery storage use

An examination of the hourly charging level of stationary batteries raises complementary insights. To do so, we focus on the cases with a 100% self-consumption requirement. If stationary batteries are the only option, these are used for seasonal smoothing, i.e., shifting PV generation peaks from summer to times of high demand in winter (blue line in Figure 7). Obviously, this storage strategy would require very large energy storage capacity, which causes the excessive cost increases illustrated above (see Zerrahn et al. 2018 for a related discussion). If additional investments in SETS are considered, the battery storage level still follows a seasonal pattern, but it also indicates some shorter-term balancing of supply and demand. If BEV are present, these even out all seasonal fluctuations, and stationary batteries are, accordingly, used for much shorter-term balancing. Here, the battery charging level shows a pattern much more plausible for lithium-ion batteries, which are usually considered a short-term storage option because of their high energy-related costs.

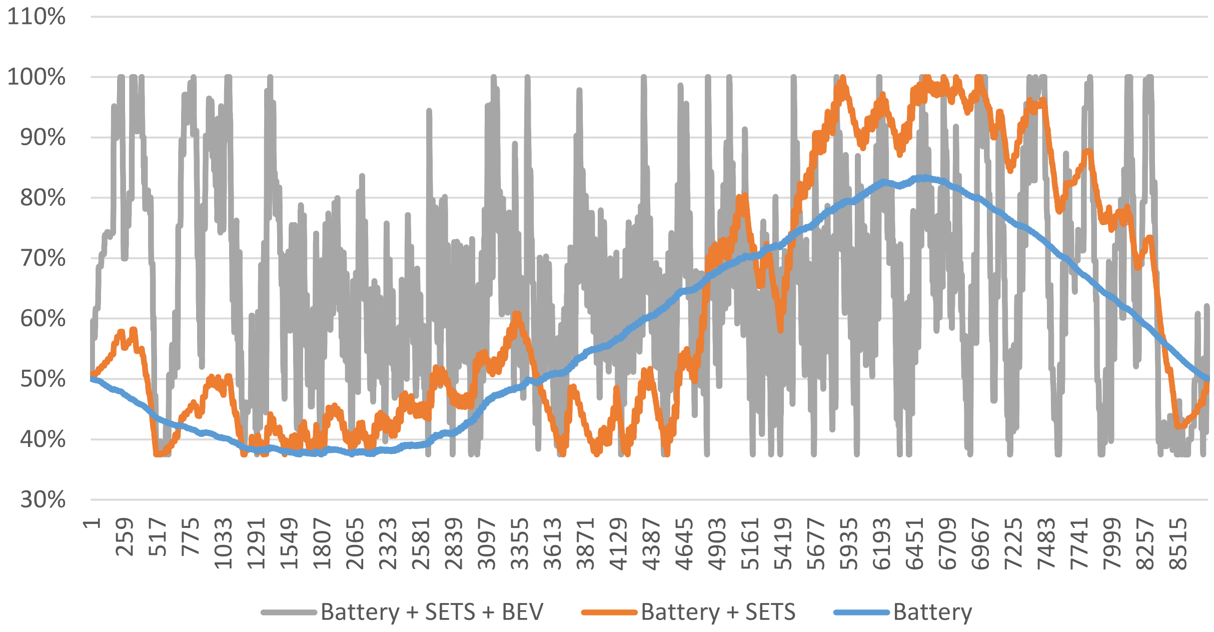

Figure 7: Hourly storage charging level of stationary prosumager batteries (100% self-consumption)

4.4 Shares of decentral PV generation used for different prosumage options

The differences in optimal capacities of li-ion batteries and SETS are also reflected in the shares of decentrally generated PV electricity allocated to the different uses (Figure 8). If investments in batteries are the only option, these must absorb all PV electricity that a household cannot utilize directly. Investments in SETS generally lead to higher shares of direct self-consumption and lower shares of battery loading. If BEV are available, these, in turn, crowd out SETS.

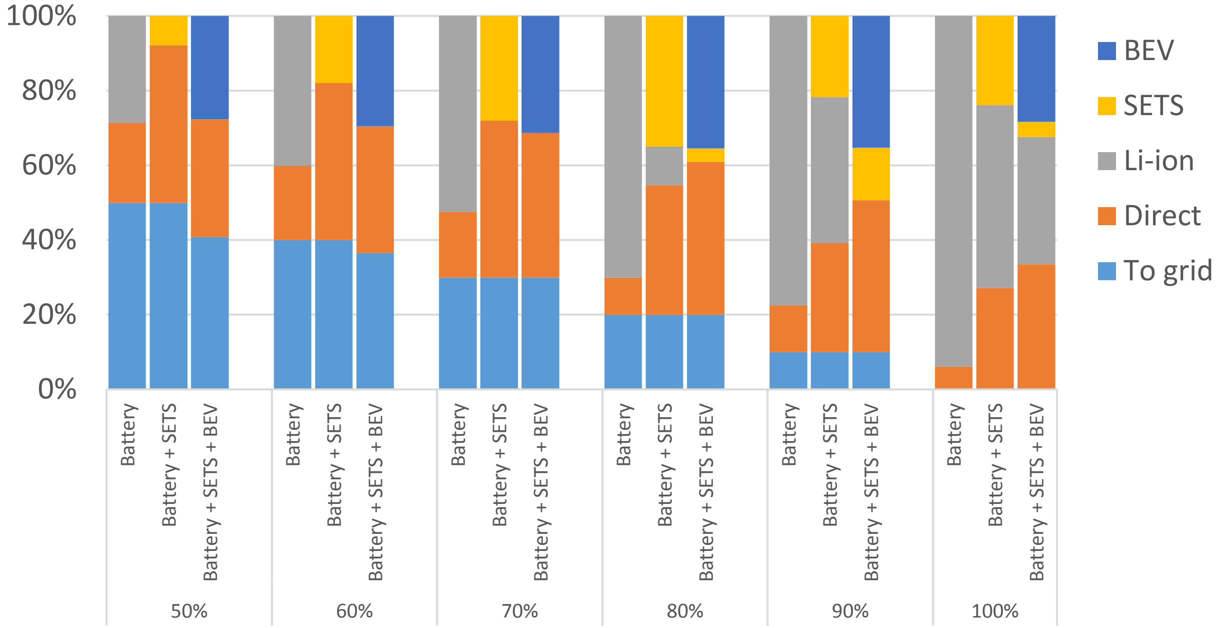

Figure 8: Shares of decentral PV generation used by different prosumage options

4.5 Sensitivity: 50% smaller PV installations

The results discussed above obviously depend on the dimensioning of prosumagers' PV installations. With larger installations than assumed in the base case, even more investments into batteries and SETS would be required for achieving the self-consumption shares discussed above. For smaller PV installations, the opposite is true. We briefly illustrate the latter in the following, assuming that prosumage PV systems are only half the size compared to the base case above (2.3 kW_p), i.e. they generate only half of a household's yearly electricity consumption.[5] In such a setting, the baseline self-consumption rate is higher. Prosumage households can achieve a self-consumption share of somewhat below 70% without making use of batteries, SETS or BEV.

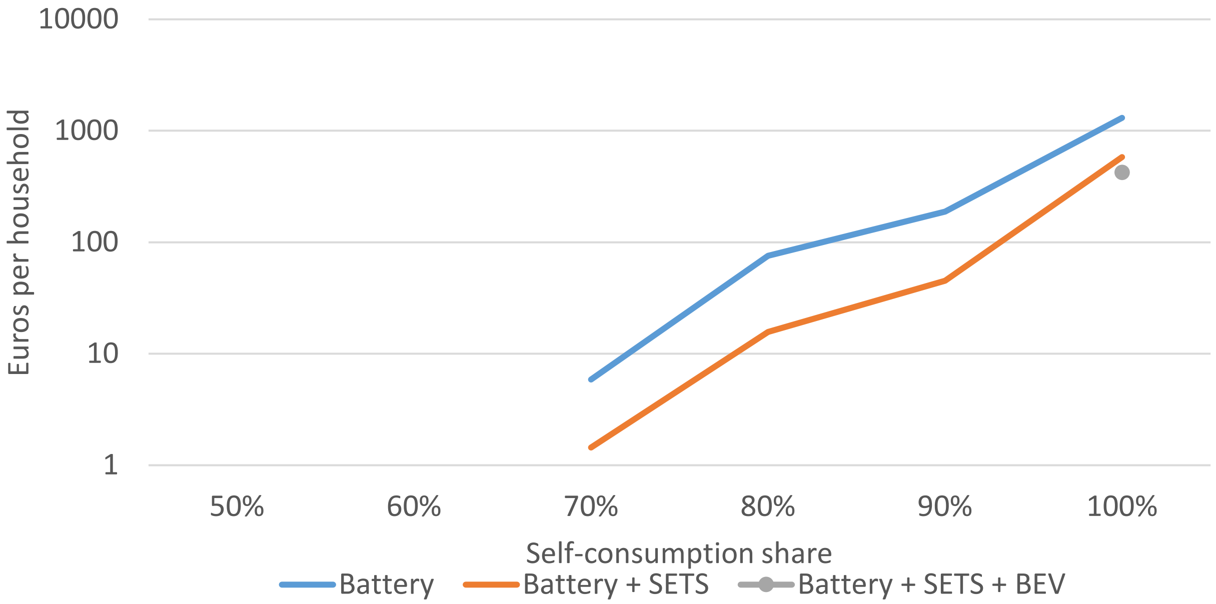

Figure 9: 50% smaller PV installations: System costs, related to prosumager households

Likewise, increasing the self-consumption share toward 100% incurs much lower additional costs compared to the baseline (Figure 9). This is driven by much lower energy storage needs (Figure 10). Accordingly, achieving high self-consumption shares is much more plausible with smaller PV installations. Put differently: households interested in consuming as much of their PV generation as possible have an incentive to choose relatively small PV installations.

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[5] As we keep the overall prosumage PV capacity fixed, this means that we assume twice as many prosumage households in this sensitivity compared to the base case.

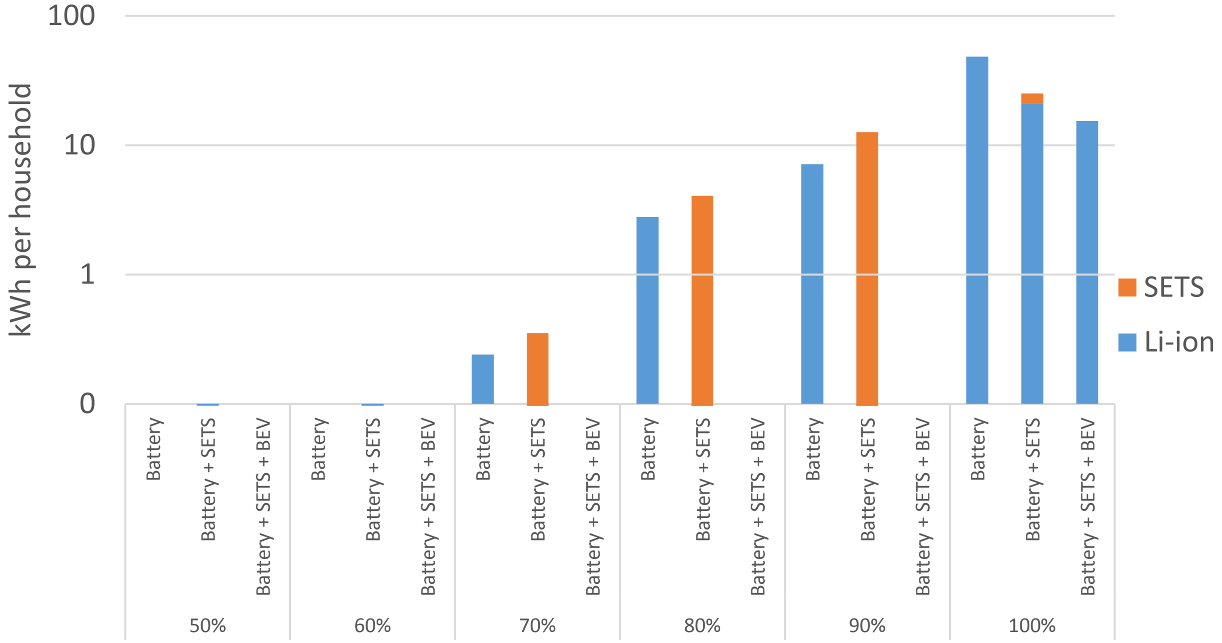

Figure 10: 50% smaller PV installations: Investments into storage (energy) per prosumager household

5 Discussion of limitations

Our analysis is stylized in several respects because our main intention is to illustrate some generic effects, and not to focus on particular numbers. If more detailed model formulations and more realistic input data were used, this would certainly change the quantitative outcomes, but likely not so much the qualitative findings.

For example, we assume that prosumage households have the same hourly time series of load and renewable availability as the overall system. This is likely to overestimate the baseline self-consumption rate as households' electricity demand tends to be smaller at day-time and higher in the evening hours compared to the system average, i.e., it is relatively lower in hours of high PV availability. Accordingly, our baseline self-consumption share is slightly above the one modeled by Quoilin et al. (2016). Yet we would not expect qualitative outcomes to differ if more realistic profiles would be used.

As regards the storage heater option, our stylized assumption of existing back-up natural gas-fired heating systems may lead to an underestimation of SETS' system benefits. If investments into storage heaters would not only save natural gas costs, but also allowed to decrease the fixed costs of the backup heating system, SETS might perform better compared to our results. Then again, SETS may not be the most viable technology compared to other power-to-heat options. Including alternative technologies such as hybrid (resistive) electric heating in gas-fired boilers or heat pumps in the model could provide complementary insights.

The hourly availability profiles of electric vehicles generally have a large impact on outcomes. The profile we chose here is derived from empiric German mobility data, but it may be overly optimistic with respect to charging availability at daytime. Alternative profiles with lower charging availability in hours of decentral PV generation would lead to lower benefits of BEV-driven prosumage and relatively better performance of the other options considered. At the same time, alternative (i.e., higher) assumptions on the available charging capacity beyond 3.7 kW may work in the opposite direction – particularly if larger PV systems were assumed. Thus, we consider exploring the effects of alternative vehicle profiles an important aspect for further investigations.

Another obvious limitation relates to the exogenously specified capacity of prosumagers' PV installations. These capacities appear less plausible for higher self-consumption shares and for increasing decentral sector coupling activities. For example, for self-consumption shares approaching 100%, PV installations tend to become implausibly large; conversely, if BEV are available, PV installations tend to be implausibly small. We thus consider endogenizing prosumagers' PV capacity as a promising avenue for future research.

6 Conclusions

Self-consumption of decentrally generated solar electricity started as a niche application, but it increasingly emerges as an important trend in many countries. The further growth of the prosumage segment depends on consumer attitudes, technology cost developments, and regulatory frameworks. With the present analysis, we do not aim to make an assessment whether increasing levels of prosumage are desirable or not in the context of a low-carbon energy transition. Rather, we explore the potential role and selected system effects of prosumage facilitated not only by stationary batteries, but also by decentral sector coupling with a focus on electric storage heaters and electric vehicles.

Focusing on a 2030 scenario for Germany, we find that batteries alone can hardly be considered a viable option for increasing self-consumption levels, as aligning variable hourly profiles of solar PV generation and demand quickly requires excessive energy storage capacities. In contrast, investments into SETS and even more so battery-electric vehicles can facilitate high self-consumption shares at much lower costs – despite additional restrictions related to hourly profiles of heating and mobility demand.

Based on our model analysis, we draw a high-level – and possibly preliminary – policy conclusion: if consumers aim to achieve higher levels of solar self-consumption, it is both likely and desirable that sector coupling options play an increasing role. Thus, policy makers and regulators should aim to reduce distortions at the borders between the electricity, heating, and mobility sectors.

While our analysis explicitly adopts a system perspective, a complementary strand of research would be desirable that explores the incentives of individual prosumers to engage in different storage and sector coupling options in more detail. Likewise, it appears promising to explore other potential benefits of sector-coupling prosumage options. Previous research indicated that demand-side flexibility potentials are often hard to tap, for example, because people may be reluctant to give grid operators or aggregators control over their devices (Wilson et al. 2017; Palm et al. 2018,). But if electric heating or electric vehicles are connected to self-generated solar electricity, this may help to actually unlock their flexibility potentials, as only "own" electricity is involved (Roth et al. 2018). Linking decentral solar PV generation to electric vehicle charging could also ensure that these vehicles are actually charged with renewable electricity. Previous work has shown that cost-minimizing vehicle charging from the grid, guided by wholesale market prices, does not necessarily contribute to renewable integration, but may rather increase the use of emission-intensive baseload generators (Schill and Gerbaulet 2015). Further research on this particular aspect also appears promising.

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