Decentralized solar prosumage with battery storage: system orientation required

By Wolf-Peter Schill, Alexander Zerrahn, Friedrich Kunz, and Claudia Kemfert

Starting from a low level, in recent years the battery-supported self-consumption of solar electricity (solar prosumage) has grown significantly in Germany. Its growth is primarily due to the opposing trends in household electricity prices and feed-in tariffs in conjunction with government incentives for battery storage. Various benefits of solar prosumage speak to its positive potential in the German energy transformation. It takes consumer preferences into consideration, may increase general acceptance of the energy transformation—facilitating private participation in investment in the process—and relieves distribution networks. However, solar prosumage also has potential disadvantages, especially with regard to economic efficiency.

Total system costs are lower if decentralized batteries are operated in a system-oriented way and if they are available for further electricity market activities, as compared to a case where distributed storage is purely focused on self-consumption. This is the finding of a model analysis carried out at DIW Berlin. It is also the reason why policymakers should focus on ensuring that photovoltaic battery systems are designed and operated to serve the overall system. Conversely, the Renewable Energy Sources Act (EEG) surcharge for solar prosumage should be abolished. In addition, models allowing tenants to generate and store their own solar electricity should not be disadvantaged, and political scenarios relevant to energy policy must take solar prosumage into adequate consideration. The political framework for photovoltaic battery storage systems must be structured in a way that minimizes undesirable effects.

In the context of the energy transformation, the share of renewable energy in gross electricity consumption rose from approximately three percent in 2000 to 31.7 percent in 2016.[1] By 2025, the German government has targeted a share of 40 to 45 percent, and by 2050 it is intended to reach a minimum level of 80 percent.[2]

Alongside wind power and bioenergy, photovoltaics (PV) is a major contributor to renewable electricity generation in Germany. In 2016, it accounted for 20 percent of Germany's renewable electricity. In comparison to other sources of renewable energy, decentralized solar energy installations are well suited for self-consumption. Electricity from rooftop installations on private or commercial buildings can be used directly on site, without feeding it into the grid. However, electricity self-generated in photovoltaic installations only partially covers the demand on site. For example, the greatest volume of electricity is generated at noon, but peak consumption in private households usually occurs in the evening. This is why European households with rooftop PV installations generally only reach self-sufficiency rates of around 30 to 37 percent.[3] These can be increased by combining the photovoltaic installation with distributed battery storage.[4]

In this *Economic Bulletin*, we examine the possible roles of battery-supported self-consumption from PV installations in the context of Germany's energy transforma-

1 Federal Ministry for Economic Affairs and Energy (BMWi), "Zeitreihen zur Entwicklung der erneuerbaren Energien in Deutschland," (Excel sheet, BMWi, Berlin, 2017). (Available online, in German only; accessed: March 28, 2017; the same also applies for all other online sources mentioned in this report).

2 These targets are stipulated in Section 1 of the Renewable Energy Sources Act (*Gesetz für den Ausbau erneuerbarer Energien*, EEG).

3 See Sylvain Quoilin et al., "Quantifying self-consumption linked to solar home battery systems: Statistical analysis and economic assessment," *Applied Energy* 182 (2016): 58–67.

4 This concept is called prosumage: *producing*, *consuming,* and *storage.* Here, we define prosumage as the self-consumption of solar energy by (small) consumers who are still connected to the grid and use battery storage. In general, the terms "prosumage" and "self-consumption" are somewhat more broadly formulated: they can also include other sources of renewable energy, other energy storage technologies, demand-side measures, commercial or industrial large consumers, and off-grid applications.

tion. We assume that prosumage households will continue to be connected to the distribution network and get their electricity from it at times or feed electricity into it at other times. Our report contains an overview of the pros and cons of expanding solar prosumage, prevailing indirect and direct incentives, and the development of this market segment in Germany. Possible system effects are determined using an open-source optimization model.[5]

Solar prosumage opens up opportunities…

Debates in energy policy cite different arguments for and against an expansion of solar prosumage.[6] Some of them are only applicable from a specific perspective, from that of the installation owner or electricity grid operator, for example, and others apply more to the economic or system perspective.[7] In the following sections, a central, optimized system without distributed storage but with comparable renewable power generation capacity serves as an implicit standard of comparison.

Consumer preferences, participation, and higher acceptance of the energy transformation

Electricity consumers may prefer to use local renewable energy and an electricity supply that is at least temporarily independent of the electricity grid and classical energy suppliers.[8] Surveys have shown that these types of preferences are key drivers for installing battery storage systems.[9] However, the proportion of consumers who share this preference and how pronounced it is are unknown.

From the consumer viewpoint, self-consuming solar electricity can also have the advantage of decoupling the proportion of electricity costs covered by self-consumption from electricity market trends, making this part of their utility bills more predictable.[10]

Solar prosumage could also increase the number of people who embrace the energy transformation because it provides many consumers with the possibility of active participation. This would make it easier to develop private rooftops for PV installations. Further, the level of acceptance should be higher than it is for major infrastructure projects, such as transmission grid construction, large power generation plants, or pumped-storage plant projects. However, decentralized prosumage systems are likely to replace infrastructures like these only partially at best.

And solar self-consumption could set private, comparably low-interest capital free for the investment required in the context of the energy transformation.[11] However, this argument is only plausible to the extent that such investments also make sense for the overall system. For example, right now there is virtually no need for more investment in electricity storage.[12]

Relief for electricity networks

Battery storage coupled with PV installations can contribute to relieving distribution networks, if batteries are operated with this goal. Through a grid-oriented mode of storage operation, a solar installation's maximum grid feed-in can be lowered in comparison to a similar case without grid-oriented storage operation (Figure 1). The same applies to the temporal change in grid feed-in (gradients). In this way, the need for distribution network investment can be reduced. Whether the costs of distribution network expansion saved will be higher or lower than the costs of storage depends to a significant extent on the specific design of individual grids and the cost trend of battery storage. In any case, this type of storage

5 This *Economic Bulletin* is based on a journal article published in March 2017. See Wolf-Peter Schill, Alexander Zerrahn, and Friedrich Kunz, "Prosumage of solar electricity: pros, cons, and the system perspective," *Economics of Energy & Environmental Policy* 6(1) (2017): 7–31. A version with more details on the modeling is also available as *DIW Discussion Paper* 1637 (available online). Parts of the report were developed as part of the European research project RealValue (Horizon 2020, Grant Agreement 646116).

6 Here we present selected arguments without any claim to completeness. For a more extensive discussion of the concept's pros and cons, see Schill et al., "Prosumage of solar electricity."

7 See Wilson Rickerson et al., "Residential prosumers—drivers and policy options (RE-PROSUMERS)," Technology Collaboration Programme for Renewable Energy Technology Deployment (IEA-RETD), (PDF, International Energy Agency, Paris, 2014) (available online). Also see Council of European Energy Regulators (CEER), "CEER Position Paper on Renewable Energy Self-Generation," (PDF, CEER, Brussels, 2016) (available online); and Thies Clausen et al., "Energiewende und Dezentralität. Zu den Grundlagen einer politisierten Debatte," (PDF, Agora Energiewende, Berlin, 2017) (available online). In a somewhat expanded multi-disciplinary context, the pros and cons of decentralized (i.e., self-consumption) and centralized supply concepts are also discussed as part of the Leibniz Research Alliance Energy Transition. See Weert Canzler et al., "Auf dem Weg zum (de-)zentralen Energiesystem? Ein interdisziplinärer Beitrag zu wesentlichen Debatten," *DIW Vierteljahrshefte zur Wirtschaftsforschung* 4/2016 (forthcoming).

8 See Kai-Philipp Kairies et al., "Wissenschaftliches Mess- und Evaluierungsprogramm Solarstromspeicher. Jahresbericht 2016," (PDF, Institut für Stromrichtertechnik und Elektrische Antriebe der RWTH Aachen, Aachen, 2016) (available online); and Tilmann Rave, "Der Ausbau Erneuerbarer Energien im Föderalismus und Mehrebenensystem – neoklassische und neoinstitutionalistische Perspektiven," *ENERGIO—Working Paper* no. 8 (2016) (available online).

9 See Swantje Gährs et al., "Acceptance of Ancillary Services and Willingness to Invest in PV-storage-systems," *Energy Procedia* 73 (2015): 29–36; and Christian A. Oberst and Reinhard Madlener, "Prosumer Preferences Regarding the Adoption of Micro-Generation Technologies: Empirical Evidence for German Homeowners," *FCN Working Paper* 22/2014 (2015) (available online).

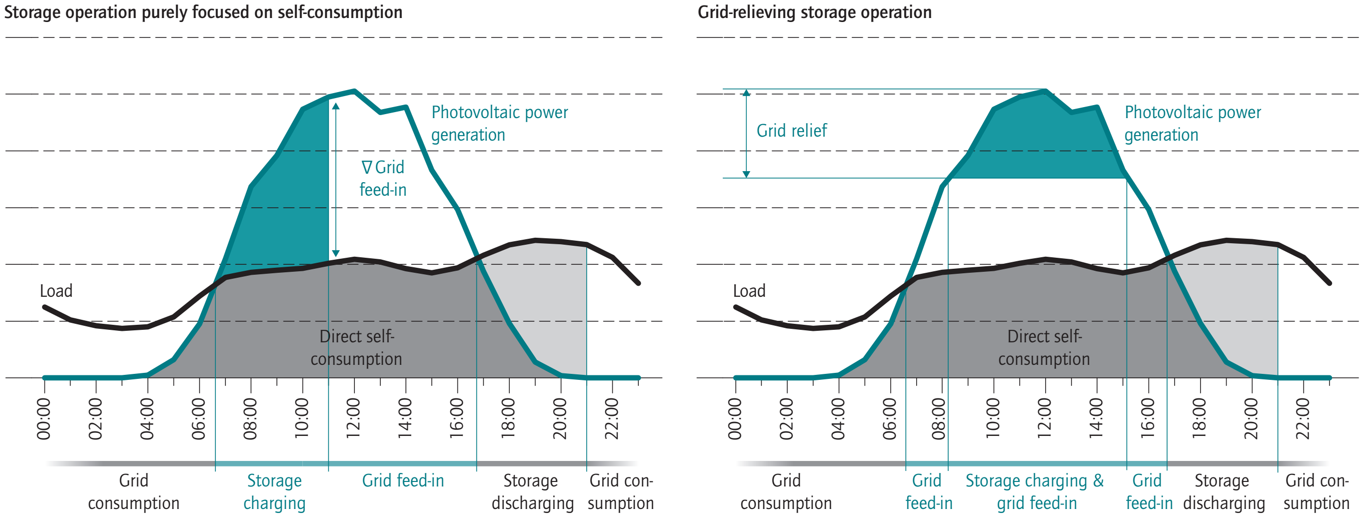
10 See Joern Hoppmann et al., "The economic viability of battery storage for residential solar photovoltaic systems—A review and a simulation model," *Renewable and Sustainable Energy Reviews* 39 (2014): 1101–18.

11 See Jürgen Blazejczak et al., "Energy Transition Calls for High Investment," *DIW Economic Bulletin* no. 9 (2013): 3–14.

12 See Wolf-Peter Schill, Jochen Diekmann, and Alexander Zerrahn, "Power Storage: An Important Option for the German Energy Transition," *DIW Economic Bulletin* no. 10 (2015): 137–46.

Figure 1

Illustration of diurnal patterns of load, power generation, and storage operation in case of solar prosumage
Capacity in kW (illustration)



The figure shows an illustrative standard load profile of 2013 based on ESTW AG (2017) (available online).

Source: Own illustration, based on Schill et al., "Prosumage of solar electricity."

Grid-relieving storage operation reduces both peaks and gradients of grid feed-in.

operation would require corresponding charging strategies—for example, on the basis of forecasting procedures or remote control—and according incentives for system owners.[13] If a need for expanding the transmission grids results from peaks in solar electricity generation, distributed battery storage in conjunction with PV installations could also reduce the need for investment on this level of the network.

Further economic arguments

Households that practice prosumage could develop a higher awareness for tapping previously unused potentials for a more flexible electricity consumption and energy efficiency measures. In this respect, expanding solar prosumage could induce according behavioral changes.[14] Conversely, self-consumption with solar electricity perceived as inexpensive could counteract the effort to be efficient. And prosumage could enable the continued expansion of small PV installations in an environment of decreasing feed-in tariffs for electricity fed to the grid—and thus lower EEG surcharges.

...but also entails risks

Efficiency losses

Using a centrally optimized electricity system with comparable generation capacity but without distributed solar storage as the measure of comparison, battery-supported solar prosumage leads to additional costs or efficiency loss. If a major proportion of the variability in solar power generation and electricity demand are balanced out locally, that is, at the installation site, the cost advantages of an interregional electricity network with partially complementary load and power generation pro-

13 With the help of forecasting strategies, storage operation that largely serves the system can also be achieved without remote control, for example. See Johannes Weniger et al., "Dezentrale Solarstromspeicher für die Energiewende," (PDF, HTW Berlin University of Applied Sciences, Berlin, 2015) (available online); and Janina Moshövel et al., "Analysis of the maximal possible grid relief from PV-peak-power impacts by using storage systems for increased self-consumption," *Applied Energy* 137 (2015): 567–75.

14 On smart meters, see Martin Anda and Justin Temmen, "Smart metering for residential energy efficiency: The use of community-based social marketing for behavioural change and smart grid introduction," *Renewable Energy* 67 (2014): 119–27.

files can only be realized to a minor extent.[15] Central storage and other options for flexibility on the generation or demand side will not enjoy widespread use. From a system perspective, decentralized PV installations with battery storage could be too small and have an unfavorable geographical distribution.[16] Moreover, battery operation that purely focuses on self-consumption can be disadvantageous in comparison to a system-oriented mode of operation; for example, if it leads to grid feed-in gradients that are too high.[17]

Distribution effects

Depending on the regulatory design of electricity price components such as grid fees, surcharges, and taxes, solar prosumage can entail undesirable distribution effects. In many countries, grid fees are the focus of the debate. Still, in the long term, most solar prosumagers will not completely disconnect from the electricity grid.[18] Instead they will likely continue to get power from the grid during the hours that are relevant for the dimensioning of the grid, as on days with high demand and low solar feed-in. In such a case, assuming continued energy-based billing of grid fees (i.e., per kilowatt hour, kWh), growth in solar prosumage will generally lead to consumers unable to do prosumage bearing a greater portion of the fixed costs of maintaining the electricity grid.

In general, the distribution effects are regressive here, that is more likely to benefit upper-income households since solar prosumage requires a roof and capital-intensive investment. However, a more capacity-based structure of grid fees and other now energy-based components of household electricity prices could redress the situation.[19] With regard to the EEG surcharge, this type of regressive effect is not expected to prevail at this time as households do not receive feed-in tariffs for self-consumed electricity and, thus, relieve the EEG accounts.

Incentives for solar prosumage in Germany

In most countries solar prosumage is not yet economical. In Germany, however, the incentives for decentralized battery storage score high in international comparison[20]—resulting from various indirect and direct incentives.

Indirect incentives

Household electricity prices in Germany mainly consist of grid fees, charges, taxes, and surcharges—all energy based (per kWh)—and in recent years their portion has continuously increased. In 2009, they amounted to 63 percent of the average household electricity price and by 2016 the proportion had risen to 79 percent.[21] Since self-consumed solar power is not burdened by these price components—with the exception of a prorated EEG surcharge for larger installations—there is an incentive to self-consume. At the same time, the feed-in tariff for small PV installations has fallen significantly in recent years. At around 43 cents per kWh in 2009, it was much higher than the average price of household electricity. [22] However at 12 cents per kWh, it was much lower in 2016 (Figure 2).

These two trends (rising household electricity prices and falling feed-in tariffs) result in an incentive to self-consume as much solar electricity as possible. The growing gap between solar electricity generation costs and household electricity prices is also more and more of an incentive to invest in battery storage. However, when the Renewable Energy Sources Act was revised in 2014, a mandatory prorated EEG surcharge was implemented for self-consumed solar electricity from larger installations, which counteracts the incentive described above.[23]

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15 For one European depiction of the benefits of this type of grid, see Markus Haller, Sylvie Ludig, and Nico Bauer, "Decarbonization scenarios for the EU and MENA power system: Considering spatial distribution and short term dynamics of renewable generation," *Energy Policy* 47 (2012): 282–90 and for an American example, see Alexander E. MacDonald et al., "Future cost-competitive electricity systems and their impact on US CO_2 emissions," *Nature Climate Change* 6 (2015): 526–53.

16 Solar installations oriented toward self-consumption tend to be rather small and as a result, only partially leverage the potential of available rooftops. Further, distributed storage is subject to economies of scale: small units are relatively expensive in comparison to larger (more centralized) systems. Also see Severin Borenstein, "The private net benefits of residential solar PV: the role of electricity tariffs, tax incentives and rebates," *NBER Working Paper* 21342 (2015) (available online); and European Commission staff, "Best practices on renewable energy self-consumption," (Commission Staff Working Document, European Commission, Brussels, 2015) (available online).

17 See right panel of Figure 1 and for an illustrative modeling, Richard Green and Iain Staffell, "'Prosumage' and the British electricity market," *Economics of Energy & Environmental Policy* 6(1) (2017): 33–50.

18 For specific markets in the US, it was shown that completely disconnecting from the grid could be a rational choice for many consumers in the mid to long term. See Peter Bronski et al., "The Economics of Grid Defection: When and where distributed solar generation plus storage competes with traditional utility service," (PDF, Rocky Mountain Institute, Basalt/CO, 2014) (available online).

19 See Ignacio Pérez-Arriaga, Jesse D. Jenkins, and Carlos Batlle, "A regulatory framework for an evolving electricity sector: highlights of the MIT Utility of the Future Study," *Economics of Energy & Environmental Policy* 6(1) (2017): 71–92.

20 Wilson Rickerson et al., "Residential prosumers."

21 German Association of Energy and Water Industries (*Bundesverband der Energie- und Wasserwirtschaft*, BDEW), "BDEW-Strompreisanalyse Mai 2016: Haushalte und Industrie," (PDF, BDEW, Berlin, 2016) (available online).

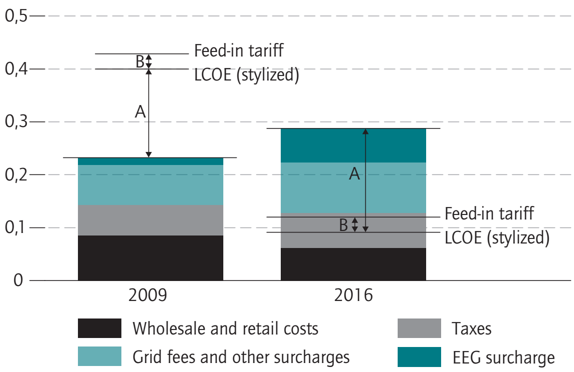
22 EEG 2009 contained a self-consumption premium to bridge the gap between the costs of electricity and household tariffs. It was 25 cents per kWh in 2009, but due to rising household electricity prices and falling photovoltaic generation costs, it was abolished again in 2012. In its short existence, it should not have created any noteworthy incentives to install storage batteries.

23 EEG 2014 implemented a 30 percent mandatory surcharge for PV installations with outputs of over ten kW and self-consumption of over ten MWh per

Figure 2

Household electricity prices, feed-in tariffs, and levelized costs of electricity for photovoltaics, 2009 and 2016

In euro per kilowatt-hour



A depicts the difference between household electricity prices and photovoltaic levelized costs of electricity (LCOE). This difference was substantially negative in 2009, but strongly positive in 2016. B depicts the difference between feed-in tariffs and LCOEs. Self-consumption is more profitable compared to grid feed-in if A is larger than B. The illustration of LCOEs is stylized.

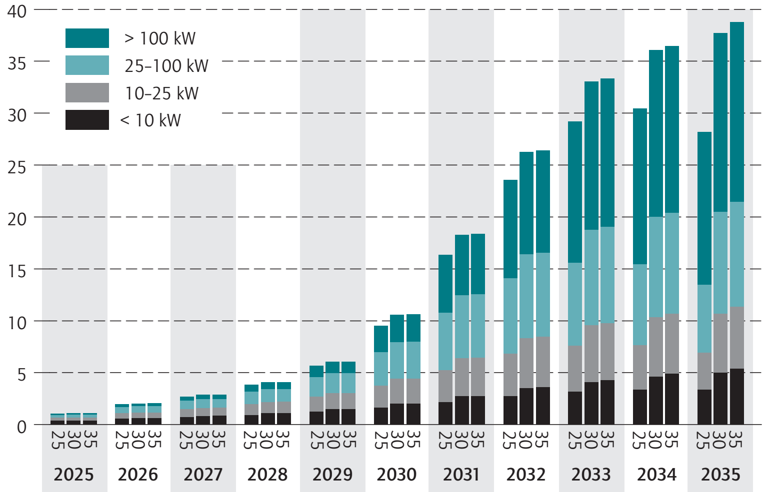
Source: Own illustration, based on Schill et al., "Prosumage of solar electricity."

Higher household electricity prices and lower feed-in tariffs provide incentives for solar self-consumption.

Figure 3

Photovoltaic capacity outside EEG support scheme after 2025

In gigawatt



The figure shows aggregated capacities of different installation sizes assuming technical lifetimes of 25, 30, or 35 years.

Source: Own illustration, based on Open Power System Data (available online), Data Package Renewable Power Plants, version 2016-10-21.

Beginning in the mid-2020s, increasing capacities will drop out of the 20-year EEG support scheme.

Direct incentive with KfW program

Program 275[24] of the state-owned promotional bank KfW is now in its second funding round with a volume of 30 million euro from 2016 to 2018. It provides subsidized loans and repayment subsidies for using battery storage in conjunction with PV installations. The incentive is tied to conditions that intend to provide incentives for system-oriented battery storage design and operation modes. One of the program's conditions is that a PV installation's maximum grid feed-in across its entire service life is limited to 50 percent of the installation's capacity at all times. This should provide an incentive to operate storage in a manner that relieves the distribution network. The program also funds the installation of suitable electronic interfaces for the remote parameterization of grid feed-in and remote control.

A rapidly growing market niche

The latest available monitoring report on the addition of photovoltaic battery storage systems shows an inventory of around 34,000 photovoltaic storage batteries with a cumulative capacity of approximately 200 MWh in Germany.[25] Based on information from KfW,[26] the number of storage installations can be estimated at around 50,000 at the end of 2016.

In sum, the photovoltaic battery storage market is experiencing rapid growth, but starting from a very low level. Until now, the cumulative energy storage capacity of the batteries has been below one percent of the capacity of German pumped hydro storage.[27] The market's future

year. It was recently raised to 40 percent.

24 See KfW, "Merkblatt Erneuerbare Energien 'Speicher'," (PDF, KfW, Frankfurt am Main, 2016) (available online).

25 Kai-Philipp Kairies et al., "Wissenschaftliches Mess- und Evaluierungsprogramm Solarstromspeicher."

26 KfW, "Förderreport KfW Bankengruppe. Stichtag: 31. Dezember 2016," (PDF, KfW, Frankfurt am Main, 2017) (available online).

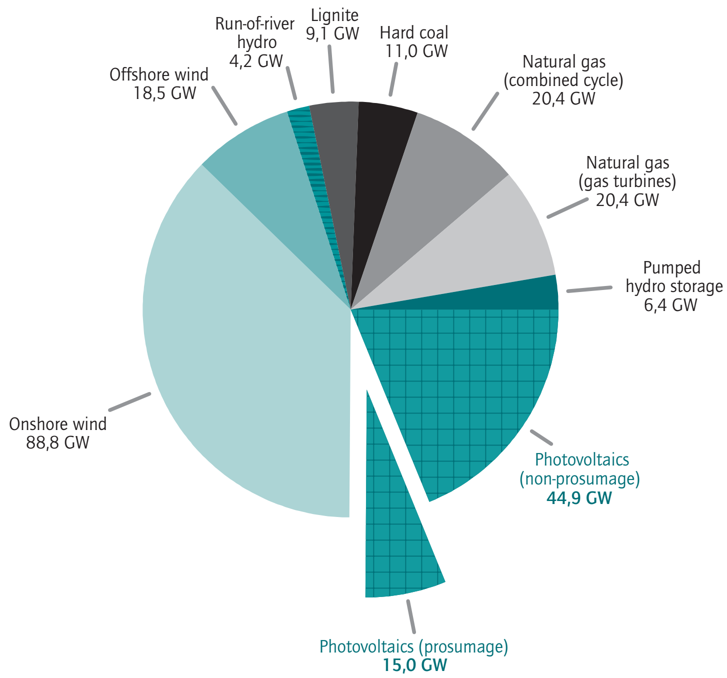
27 See Schill et al., "Power Storage." The pumped hydro storage installations in Germany plus those in Luxembourg and Austria which are directly connected to the German transmission grid have a cumulative output of approximately

Box 1

Modeling the system effects of battery-supported solar prosumage with DIETER

Figure 1

Installed capacity in model calculations



Source: Federal Network Agency, "Az.: 6.00.03.05.", own illustration.

A quarter of the installed photovoltaic capacity is attributed to the prosumage segment.

The calculations this report is based on were carried out with the open-source electricity market model DIETER (Dispatch and Investment Evaluation Tool with Endogenous Renewables). The model code and all input data are open source and can be retrieved from the DIW Berlin website.[1] DIETER minimizes the investment and operating costs of various electricity-generating technologies, storage technologies, and other flexibility options for a one-year period in a resolution of one hour. Constraints ensure that the technical and economic requirements are satisfied and the demand for electricity is covered.

For the present report, we assumed a fixed power plant portfolio for 2035 that corresponds to scenario B1 of Scenario Framework 2025 of the Electricity Grid Development Plan (*Netzentwicklungsplan Strom*) (Figure 1).[2] In this scenario, renewable energy attains a proportion of around 66 percent. Based on these assumptions, additional investment was only possible for storage. Alongside the storage capacity levels, the model results included the hourly utilization of all technologies and the system costs.

For the prosumage analysis, 25 percent of the PV capacity and, in line with annual solar electricity production, three percent of the demand for electricity are allocated to the prosumage segment. Additional constraints ensure that a specific proportion of the demand will be covered by self-generation. In the calculations, this requirement (prosumage share) ranges from 40 to 70 percent. PV-generated electricity can be either

1 See www.diw.de/dieter. In this report we used version 1.2.0.

2 Federal Network Agency, "Az.: 6.00.03.05/14-12-19/Szenariorahmen 2025: Genehmigung," (PDF, Federal Network Agency, Bonn, 2014) (available online).

growth is highly dependent on regulatory conditions and the trend in battery costs, which could drop further as a result of the second-life use of electric vehicle batteries.[28] One current study of the tappable battery storage potential of small solar installations on one- and two-family houses assumed a maximum of 41,000 to 65,000 MWh until 2035. This is comparable to today's pumped hydro storage capacity.[29]

Storage boom possible after 20 years of EEG incentives

The future development of the PV storage segment could be driven by the fact that an increasing number of PV

9,400 MW. With an estimated average discharge duration of six to seven hours, they yield an energy storage capacity of 56,000 to 67,000 MWh.

28 See Sebastian Fischhaber et al., "Second-Life-Konzepte für Lithium-Ionen-Batterien aus Elektrofahrzeugen – Analyse von Nachnutzungsanwendungen, ökonomischen und ökologischen Potentialen. Begleit- und Wirkungsforschung Schaufenster Elektromobilität," (Results paper, Deutsches Dialog Institut GmbH Electromobility Showcase, Frankfurt am Main, 2016) (available online).

29 See Prognos, "Eigenversorgung aus Solaranlagen. Das Potenzial für Photovoltaik-Speicher-Systeme in Ein- und Zweifamilienhäusern, Landwirtschaft sowie im Lebensmittelhandel," (PDF, Agora Energiewende, Berlin, 2016); 29 (available online). The study does not specifically indicate the cumulative battery storage output, but it can be derived from the other material included.

directly consumed or stored in a battery for consumption at a later point. And prosumage households are able to cover their demand by consuming from the grid or to feed the solar power they generate into the grid, thereby making it available to other consumers (Figure 2).

We examined three different modes of operation of PV battery installations:

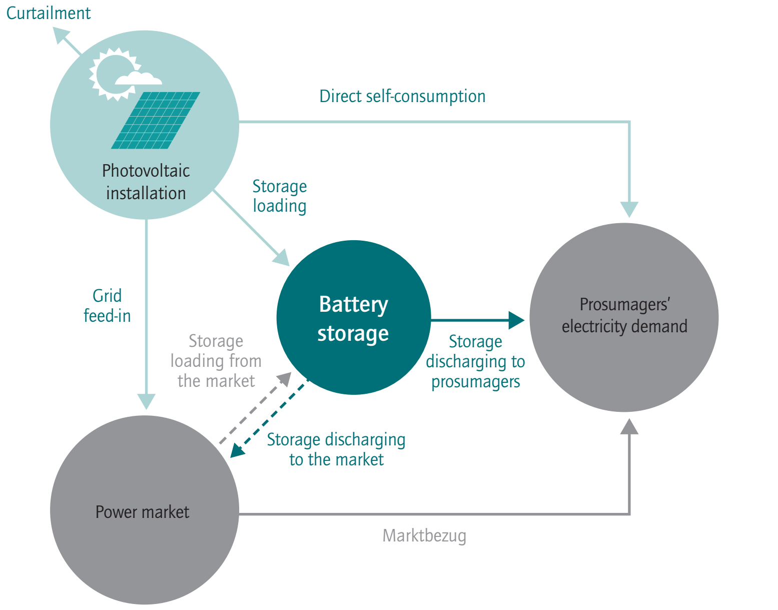
- 1. *Additional market interaction:* In this case, distributed battery storage not only serves system-oriented prosumage, but also provides flexibility for further electricity market interaction. In a system-oriented manner, they allow power to flow in and out of the storage system (dotted arrows in Figure 2).
- 2. *System-oriented self-consumption:* Unlike the previous case, the storage installations do not interact with the market. The batteries serve only the purpose of temporal, system-oriented shifts in solar prosumage.
- 3. *Pure self-consumption:* Here we simplify and assume a mode of storage operation that is neither system- nor market price-oriented. As soon as decentralized power generation exceeds demand, the storage installations are charged until they reach full capacity. As soon as generation falls short of demand, the storage installations are discharged until they are completely depleted (Figure 1 on page 143, left panel). We use the storage capacity levels from case "2. *System-oriented self-consumption.*"[3]

In the first two cases, the implicit assumption is that storage operation is guided by price signals set by the electricity market. Service providers (electricity market aggregators), for example, could implement this. Given all further constraints, this enables the most efficient use of electricity within the entire system, guided by scarcity. For instance, decentral solar electricity will more likely be made available to other consumers in the market in times of high supply.

3 This mode was newly simulated for the present *Economic Bulletin*. The simulation was not included in the journal article by Schill et al., "Prosumage of solar electricity."

Figure 2

Schematic illustration of the power flows of battery-supported solar prosumage in the model calculations



Source: Own illustration, based on Schill et al., "Prosumage of solar electricity."

If additional market interactions are possible, electricity can be stored from the grid or fed back into the grid (dotted arrows).

installations will no longer be eligible for EEG feed-in tariffs. In the middle of 2016, PV installations with a total output of around 42 GW were turning the sun's rays into electricity in Germany. Of them, around six GW were small installations with capacities of less than ten kW and another six GW with capacities between ten and 25 kW. We can assume that most of these installations will be technically able to generate electricity after the 20-year EEG period comes to an end—perhaps with slightly reduced output and replacement inverters. In this case, the installation owners may retrofit them with battery storage capability to boost the proportion of self-consumption. By 2030, the capacity of the installations outside the EEG support scheme will have risen to an approximate four GW for those smaller than 25 kW, and the number is expected to almost triple to over 11 GW by 2035 (Figure 3).

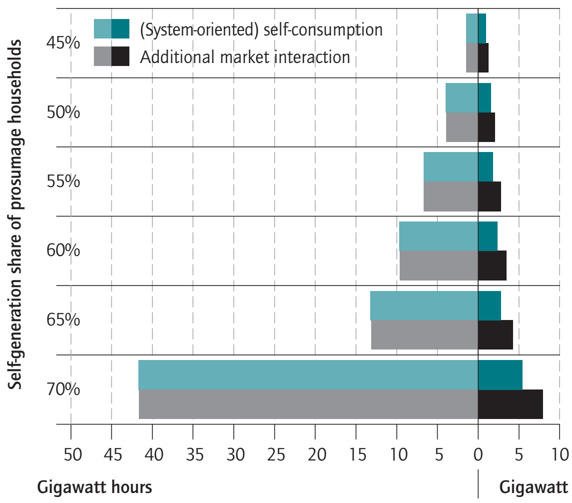
Modeling the effects on the electricity market

At DIW Berlin, we used an extended version of the open-source electricity sector model DIETER (Box 1) to analyze possible system effects of a future expansion in solar prosumage. The model is able to represent different modes of operation for distributed storage systems. We calibrated it to an established scenario for 2035. We assumed that one-quarter of the total PV capacity will be used for

Figure 4

Power rating and energy storage capacity of prosumage batteries

In gigawatt und gigawatt-hours



Source: Own calculations.

Increasing prosumage shares require much larger batteries, as electricity has to be stored over longer periods.

prosumage. Different cases in which the targeted self-sufficiency rate (also referred to as "prosumage share" in the following) ranged from 40 to 70 percent were examined.

Storage capacity grows with degree of self-consumption

Under the assumptions made here, a prosumage share of around 40 percent would be achieved without battery storage.[30] After that point, the required storage capacity would rise moderately to a prosumage share of 65 percent (Figure 4). If even higher self-sufficiency is to be achieved, demand for storage increases disproportionately due to the rising need of buffering longer-term fluctuations in electricity generation. The relationship between an installation's energy storage capacity and power rating (i.e., maximum storage duration) was also calculated to increase from less than two hours for a prosumage share of 45 percent to five to eight hours in the 70-percent case. And optimal storage capacity also increases when additional market interaction is possible: when a storage's power rating increases, it is possible to use it to a greater extent in a system-friendly manner beyond its use for pure self-consumption. However, the energy storage capacity would remain constant since it is determined by self-consumption requirements.

System cost growth most moderate for system-oriented operation

According to the model logic, in comparison to a case without self-consumption, system costs rise for greater self-consumption requirements, since they constitute tighter restrictions on the optimal system operation. The extra costs are set against the beneficial effects discussed above, some of which are difficult to quantify. Likewise, we do not model the advantages of less need to expand the distribution network here. They would have to be examined on a case-by-case basis.

With regard to total German electricity consumption, the additional demand for storage, up to a prosumage share of 65 percent, drive system costs upward to between 0.53 and 0.75 euro per MWh, depending on the mode of storage operation. After that level, the costs rise steeply (Figure 5). If batteries are available for additional market interactions beyond their use for satisfying the self-consumption requirements, the rise in costs is the most moderate because in this case storage yielded an additional system benefit. In the scenario of system-oriented self-consumption without this type of market interaction, the costs are somewhat higher. They are the highest in the case of pure self-consumption.[31] This becomes more evident when the costs of the latter two cases are compared to the case with additional market interactions (Figure 6).

In a sensitivity analysis, we simulated the effect of a 50-percent limit on the maximum grid feed-in of a PV installation. The results show the limit leading to a very low level of additional costs of less than a third of one cent per kWh in the worst case modeled here. Thus, distribution network relief is possible without large cost increases. For high prosumage shares there is virtually no difference, since the PV installations in this scenario do not feed high levels of power into the grid anyway.

Conclusion and energy policy-related implications

Starting from a low level, in recent years solar prosumage in Germany has grown significantly. Its growth is primarily due to the opposing trends of household elec-

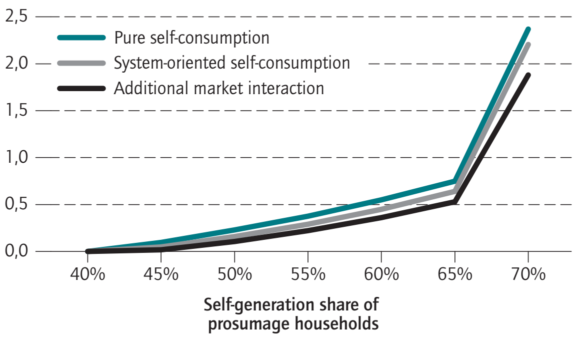
30 Our calculations have an illustrative character since we assumed load and photovoltaic profiles for prosumagers identical to those of the rest of the electricity market. For this reason, the prosumption proportion attainable without storage is somewhat higher than found by Sylvain Quoilin et al., "Quantifying self-consumption".

31 The simulation of the pure self-consumption scenario was not included in the journal article by Schill et al., "Prosumage of solar electricity."

Figure 5

Additional system costs related to overall electricity demand

In euro per megawatt-hour



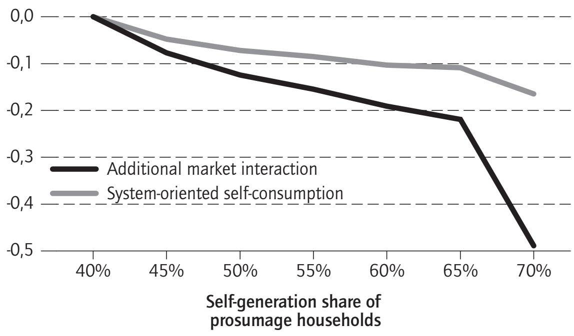
Source: Own calculations.

Higher prosumage shares lead to increasing system costs.

Figure 6

System cost reduction compared to pure self-consumption related to overall electricity demand

In euro per megawatt-hour



Source: Own calculations.

System-oriented storage operation substantially decreases system costs compared to pure self-consumption, particularly if batteries are available for additional market interactions.

tricity prices and feed-in tariffs as well as support for battery storage from KfW. However, prosumage is still a relatively niche market segment.

Various benefits of battery-supported solar prosumage speak to its positive potential in the German energy transformation. They include in particular: taking consumer preferences into consideration, increasing general acceptance of the energy transformation, facilitating private participation in investment, and relieving distribution networks. However, solar self-consumption also has potential disadvantages, such as aspects related to economic efficiency caused by installations that are too small and modes of operation that are not system-oriented. Since many of the effects are difficult to quantify and the empirical evidence is often incomplete, a final overall assessment cannot be made.

Modeling the system effects of a future expansion in solar prosumage showed that storage requirements increase with the degree to which households want to use the electricity they generate. The same applies to system costs driven by additional battery storage capacity, which is redundant from the perspective of a centrally optimized system. System costs rise when distributed storage is only used to satisfy self-consumption requirements and unavailable for further market interaction. They are even higher when the storage installations are not operated in a system-oriented mode.

Based on our analysis, we are able to derive some conclusions for a variety of policy fields (Box 2). For example, policymakers should focus on ensuring that photovoltaic battery systems are designed and operated to serve the overall system. And the battery installations must remain available for further market interaction in order to leverage them to the fullest within the system. Additional system services which are not examined here, such as control reserve provisions, also fall into this category.[32] This would require information and communication infrastructure as well as regulatory adjustment. Of course, issues of IT security and data privacy protection would also have to be considered. In the long term, solar prosumers should orient all their storage- and grid-related activities toward market price signals, which in turn reflect system use.

And in the context of further regulatory adjustments for grid fees and feed-in tariffs, the EEG surcharge for self-generated solar electricity should be abolished and tenant electricity models ensuring equal rights enacted. Solar prosumage should be adequately considered in all scenarios relevant to energy policy.

The political framework for solar prosumage must be structured in a way that minimizes economic inefficiency

32 Deutsche Energie-Agentur GmbH (dena), "Optimierter Einsatz von Speichern für Netz- und Marktanwendungen in der Stromversorgung," (PDF, dena, Berlin, 2017) (available online).

Box 2

Political spheres of activity

Grid- and system-oriented storage operation

Policymakers should set up incentives to encourage decentralized PV-battery storage installations to operate in a grid- and system-oriented manner. With regard to relieving the distribution networks, the feed-in limits incorporated in KfW funding are a first step. The extent to which constraints like this could be implemented by regulatory means other than in an incentive program should be examined. In the next step, there would be an incentive for system-oriented storage operation if prosumagers were guided by market price signals when making all of their feed-in, grid consumption, and storage decisions. This would help them internalize the system benefits or system costs of their activities—at least partially. Service providers (aggregators) could facilitate market-oriented storage operation, regulatory framework permitting.

EEG surcharge on self-consumed electricity

The prorated EEG surcharge for self-consumption was implemented with the goal of expanding the surcharge base, but appears to be unsystematic with regard to the law's purpose. It should be abolished along with simultaneously eliminating distortions in grid fees and feed-in tariffs. Currently, prosumagers are not only benefiting from paying an energy-based grid fee. In case of non-system-oriented storage operation, the market value of the solar electricity they feed into the grid instead of consuming is likely to be significantly lower than the average market value of solar electricity in general.[1] This is also to their benefit, because they receive the same feed-in tariff as operators whose PV plants exclusively feed into the grid. In general, this negatively affects the EEG account. However, the prorated mandatory surcharge for self-consumed electricity partially compensates for it right now.

Further development of the grid fee system

Policy makers may counteract undesirable distribution effects of solar prosumage in the process of taking the grid fee system to the next step,[2] If solar prosumage rises, this could be achievable through grid fees that are more capacity-based. However, there is a multitude of different design options, each with its own incentive and distribution effects that reach far beyond the issue of solar prosumage.[3] Distributed battery storage that is also used for other market interaction (e.g., arbitrage) should be put on equal footing with other electricity storage systems with regard to grid fees for charging from or discharging to the grid.

1 Calculations and findings from Prognos (2016) indicate that this is the case.

2 The Federal Ministry for Economic Affairs and Energy (BMWi) has also declared as one of its goals that grid financing should be "fair" and "meet the needs of the system". See also BMWi, "Discussion Paper – Electricity 2030 Long-term trends – Tasks for the coming years," (PDF, Federal Ministry for Economic Affairs and Energy, Berlin, 2016) (available online).

3 See Nils May and Karsten Neuhoff, "Eigenversorgung mit Solarstrom" – ein Treiber der Energiewende?" *DIW Roundup* 89 (2016) (available online).

and undesirable path dependency. For example, a disorderly photovoltaic battery boom could lead to a technical design that makes system-oriented operation impossible; this could also lead to the individual economic interests of the relevant households receiving a disproportionate heft in the political process. The latter could make it more difficult to adjust the grid fee system later.

In the 2020s, more and more of the PV installations existing today will no longer be eligible for EEG feed-in tariffs, as these were limited to 20 years. By then at the latest, an incentive and regulation framework should be established that both encourages system-oriented solar prosumage and minimizes potentially negative effects at the same time.

Tenant electricity

Currently, tenants are at a disadvantage compared to owners regarding prosumage from rooftop PV installations.[4] This is the case regarding the mandatory full EEG surcharge for self-consumed electricity as well as the lack of remuneration for grid feed-in from unused self-generated electricity, resulting in undesirable, potentially regressive distribution effects. Since the incentives for prosumage should not depend on the ownership model of the residential building or installation, an alignment of the regulatory framework for tenants and owners seems advisable. A regulation based on Section 95 EEG 2017 on the promotion of tenant electricity is currently in preparation. Yet according to a recent draft, the mandatory full EEG surcharge would continue to be in effect and instead of changing it, direct funding would be applied as a means of alignment.[5]

Future of support scheme for PV battery storage installations

Both the first and second rounds of the KfW funding program for incentivizing PV battery storage were politically controversial. Particular justification for the funding was relief for the distribution networks. Before extending the program, the lessons learned and the need for continued support should be thoroughly evaluated. The issue of whether or not individual incentive goals, such as the installations' system orientation, could also be achieved with alternative, budget-neutral measures should be considered in the evaluation.

Inclusion of solar prosumage in relevant scenarios

The option of prosumage with photovoltaic storage installations should be included in all long-term studies and reference scenarios relevant to policy. For example, it is currently part of the first draft of the German transmission system operators' *Netzentwicklungsplan 2030* (Grid Development Plan 2030), although the approach is not completely transparent.[6] In the process, the assumptions as to the mode of operation of distributed storage must be transparently documented and ideally, take different levels of installations' system orientation into consideration.

4 See Prognos and Boos Hummel & Wegerich, "Schlussbericht Mieterstrom Rechtliche Einordnung, Organisationsformen, Potenziale und Wirtschaftlichkeit von Mieterstrommodellen (MSM)," (PDF, BMWi, Berlin, 2017) (available online).

5 See BMWi, "Eckpunktepapier Mieterstrom," (PDF, BMWi, Berlin, 2017) (available online).

6 See 50Hertz Transmission et al., "Netzentwicklungsplan Strom 2030, Version 2017. Erster Entwurf der Übertragungsnetzbetreiber. Szenariorahmen, Ausführliche Fassung," (PDF, 50Hertz Transmission et al., 2017) (available online).

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