TATuP Zeitschrift für Technikfolgenabschätzung in Theorie und Praxis
Journal for Technology Assessment in Theory and Practice

oekom

RESEARCH ARTICLE

Prosuming – energy sufficiency and rebound effects:
Climate impact of changing household consumption patterns in Germany

Nesrine Ouanes*[1], Jan Kegel[1], Jan Wiesenthal[1,2], Clara Lenk[1], Hannes Bluhm[1,3], Julika Weiß[1], Lukas Torliene[1]

Abstract • Changes in energy consumption patterns after becoming a prosumer household are rarely associated with negative environmental effects, as prosuming is intuitively assumed to be emission-reducing. This paper demonstrates the importance of sufficiency-oriented energy prosumer behavior for climate neutrality goals by quantifying GHG emissions for photovoltaic (PV) prosumers at the German household and energy system level. Based on the results, recommendations are derived for promoting energy sufficiency in prosumer households.

***Prosumer – zwischen Energiesuffizienz und Rebound-Effekten**:*
Klimawirkungen sich verändernder Haushaltsverbrauchmuster
in Deutschland

Zusammenfassung • *Änderungen im Energieverbrauchsverhalten durch den Wechsel zum Prosuming werden selten mit negativen Umwelteffekten in Verbindung gebracht, da intuitiv angenommen wird, dass Prosuming immer emissionsmindernd ist. Ziel dieses Beitrags ist es, die Bedeutung des Suffizienzverhaltens von Energie-Prosumern für die Klimaneutralitätsziele nachzuweisen und die Treibhausgasemissionen auf Haushalts- und Energieystemebene in Deutschland zu quantifizieren. Basierend auf den Ergebnissen werden Empfehlungen zur Förderung der Energiesuffizienz in Prosumer-Haushalten abgeleitet.*

---

* *Corresponding author: nesrine.ouanes@ioew.de*
[1] *Institute for Ecological Economy Research, Berlin, DE*
[2] *Leuphana University Lüneburg, Lüneburg, DE*
[3] *Europa-Universität Flensburg, Flensburg, DE*

https://doi.org/10.14512/tatup.31.2.18
Received: Feb. 05, 2022; revised version accepted: Apr. 25, 2022;

Keywords • *energy rebound, prosumer self-consumption, sufficiency, LCA*

This article is part of the Special topic "Energy sufficiency: Conceptual considerations, modeling, and scenarios for less energy consumption," *edited by B. Best, F. Wiese, M. Christ and T. Santarius. https://doi.org/10.14512/tatup.31.2.10*

Introduction

To decarbonize the energy system and achieve climate protection goals, significant increases in renewable energy production are needed. Yet the expansion of renewables is still a huge challenge in terms of planning and operation, especially as new players, e.g., sector-coupling technologies, enter the energy markets. A timely energy transition, therefore, will also require reductions of energy demand through both sufficiency and efficiency measures. Solar photovoltaics (PV) are an essential part of this transition and the contribution of PV prosumers – households that produce their own electricity – is becoming increasingly relevant.

PV prosuming not only influences the electrical energy mix in the household, it can also lead to behavioral changes influencing energy consumption patterns (Dütschke et al. 2021; Galvin 2020). On the one hand, these changes can occur in the form of rebound effects, which we define in this context as *increases in energy consumption* subsequent to an increase in renewable energy use (Galvin et al. 2021). On the other hand, PV prosuming may result in *reductions in energy consumption*, which we understand as sufficiency-oriented behavior. Depending on the methodology and socio-technical variables used, studies focusing on rebound effects from PV prosuming find evidence for both trends, with a varying scope that can range from a reduction or no significant increase in consumption (Li et al. 2020; Oberst et al. 2019) to substantial rebound effects, potentially equivalent to the rate of self-consumption (Frondel et al. 2020).

The findings of the German research project *EE-Rebound* indicate increasing electricity consumption, especially for households that installed their PV-systems after 2011. This may be attributed to self-consumption becoming economically more profitable than grid feed-in after this date. Based on a survey among prosumer and non-prosumer households with a subsequent matching of their socio-technical characteristics, the post-2011 PV prosumer group was shown to exhibit an approximately 18 % higher electricity consumption than comparable non-prosumer households (Galvin et al. 2022).

The reasons leading to higher consumption can be manifold, but economic incentives play a crucial role. The currently low feed-in tariff may encourage a higher energy consumption, since households favor the maximization of self-consumption over feed-in remuneration (Galvin 2020, Weiß et al. 2021). The availability of equity financing with low ongoing costs can also encourage generous consumption. Prosumers practicing load shifting, i.e., moving power consumption into the sunny hours of the day when solar PV output is greatest, and those effectively using smart metering techniques are examples of energy-conscious behavioral changes in the other direction. Galvin (2020) and Dütschke et al. (2021) provide empirical findings on the significance of this prosumer group that comprehensively monitors energy consumption. Studies show that using extensive feedback systems can generally lead to decreases in energy consumption of 8 to 12 % (Dromaque and Grigoriou 2018; Gährs et al. 2021).

So far, the environmental implications of consumption changes in prosumer households remain uninvestigated. One could argue that household demand is largely met by PV output, with thus little or no environmental effect on either the household or the overall energy system. The goal of our research is to investigate the validity of this argument: how can we quantify the environmental effects of the changes in energy consumption patterns by PV prosumers and how relevant are these effects at household and system level?

First, we present the modeling of energy flows at household level and the upscaling to system level. Second, we elaborate the methods for environmental assessment in terms of greenhouse gas (GHG) emissions and apply these to the resulting energy flows and upscaling. Finally, we conclude with a summary and deduce recommendations for policy makers, civil society and prosumers with respect to increasing awareness of the importance of PV prosuming and its related consumption patterns.

Modeling of energy flows and upscaling scenarios

An examination of energy flows between a single household and the main grid is intended to help us investigate how the absence of energy sufficiency dampens the prosumer contribution to the energy transition. By upscaling the results of individual households to the system level in Germany, we provide insights into the overall effects of consumption patterns.

Method, input data, and scenarios

First, to investigate the effects on the grid exchange of a variety of consumption patterns, we rely on the IÖW Energy Prosumer Model. The model has been described in detail in Gährs et al. (2020). It provides a bottom-up simulation of energy flows in a household and allows us to simulate preset levels of electricity consumption based on a given household size and efficiency class (co2online 2022). We investigate the following scenarios for a 3-person and a 5-person prosumer household:

- *Reference (Ref):* Average consumption according to co2online (2022) (3-person household: ~3,700 kWh; 5-person household: ~5,200 kWh)
- *Sufficiency (S–10):* Reduced electricity consumption of approximately 10 %. We take this value as an average from the findings of the studies presented in the introduction.
- *Rebound (R+10; R+20):* An overconsumption of 20 % is chosen as an approximation of the aforementioned survey results of the project *EE-Rebound*. An overconsumption of 10 % is investigated as an intermediate step, since values on solar rebounds reported in the literature vary greatly.
- *Rebound and load shifting (R+10 & LS; R+20 & LS):* These scenarios encompass prosumers who, in addition to increasing their consumption, also practice load-shifting as described above.

Second, we use available data to analyze the development of the German PV market and the share of small-scale PV prosuming systems with and without battery (AEE 2020; Bundesnetzagentur 2021; Figgener et al. 2021). We assume a dynamic growth for PV capacity of +0.7 GWp per year leading to approximately 140 GWp in 2030 (from ~60 GWp in 2021). While in line with other studies targeting 130 to 150 GWp (BDEW 2021; dena 2021), the capacity goal investigated here represents a moderate development of the PV market. This is emphasized by the recent draft for the amendment of the Renewable Energy Source Act (EEG), which targets 200 GWp by 2030 (BMWK 2022). Furthermore, we assume that PV prosuming < 100 kWp will almost quadruple compared to historical data.

Third, based on the average solar irradiation in Germany weighted by geographic distribution of the PV systems (DWD 2021) and our simulated energy flows for the various household sizes, we estimate the effect of different consumption patterns by PV prosumers across Germany. Further detailed assumptions can be found in Kegel et al. (2022).

Results and discussion

Results of the simulation at the household level show that overconsumption can only be partly met by self-consumption. Load shifting and battery storage can in part mitigate this demand, but with a more substantial increase in energy demand (e.g., R+20), the overconsumption has to be met largely by the grid. The described effects are presented in Table 1 for a 3-person household. Given that the results for a 5-person household are similar, they are omitted here, but can be found in our related paper (Lenk et al. 2022).

	Without battery storage		With battery storage	
	Self-consumption [kWh/a]	**Grid supply** [kWh/a]	**Self-consumption** [kWh/a]	**Grid supply** [kWh/a]
Ref	732	2,966	1,880	1,875
S–10	672	2,552	1,809	1,471
R+10	838	3,228	1,993	2,131
R+10 & LS	905	2,808	2,079	1,693
R+20	939	3,508	2,089	2,415
R+20 & LS	1,159	3,304	2,324	2,197

Tab. 1: Results of simulated self-consumption and grid supply for a 3-person household with a 3.5 kWp photovoltaic system, and 3.5 kWh battery: electricity fed into grid equals electricity produced (3,431 kWh in all scenarios) minus self-consumption. *Source: authors' own compilation*

Results at the system level (including both 3- and 5-person prosumer households) indicate that upscaling the R+10 and R+20 scenarios lead to a comparably low effect on the current overall electricity demand in Germany (1.2 and 2.4 TWh in 2020, respectively). However, a significantly increased demand of 6 to 12 TWh is anticipated in 2030 (R+10 and R+20, respectively). In the case of the R+20 scenario, this translates to about 1.7 % of the forecasted electrical power demand for Germany in 2030 (BMWK 2022). Of this additional demand, 70 % would have to be grid-supplied. In contrast, if prosumers would tend towards more sufficient consumption patterns in the future (S–10), power savings of around –8.5 TWh could be achieved in 2030 (–2 TWh in 2020).

The potential aggravation of both sufficiency and rebound effects in 2030 is largely dependent on PV market development. Even a moderate development of the installed PV capacity, as assumed in our study, may result in the need for substantial additional renewable energy installations or longer operation of fossil-based power plants.

Greenhouse gas emissions due to changes in energy consumption patterns

In the following, we first describe our methodological approach to determining GHG emissions at the household and energy system level. We then present and discuss the results.

Methods

To assess the climatic impact of changing consumption patterns at the household level, we carry out a life cycle assessment (LCA) based on international guidelines (DIN EN ISO 14044:2006). The system analyzed is the same PV prosumer household as described above. The system is compared to the various sufficiency and rebound scenarios, both with and without load shifting. System boundaries cover energy technologies and their life cycle, as well as energy flows from the grid. All energy and material flows and the resulting environmental impacts are related to our single household's power consumption for 2020 (i.e., the functional unit). The impact assessment is limited to climate change as impact category and the corresponding GHG emissions (CO_2eq) are according to the IPCC (2007) characterization factors.

For the impact assessment, we use three emission factors:

- *PV electricity:* 0.056 kgCO_2eq/kWh, derived from Lauf et al. (2021). The factor represents a generic device based on currently installed PV capacities in Germany.
- *Battery:* 12.195 kgCO_2eq/kWh of storage capacity and year, derived from Ökobaudat (BMI 2018). The value refers to a lithium iron phosphate battery system with a lifetime of 20 years.
- *Electricity from the grid:* 0.391 kgCO_2eq/kWh, based on Lauf et al. (2021) and on official statistics by AGEB (2021).

The factors for PV and battery include GHG emissions from peripheral equipment (e.g., cables, inverters); all factors are valid for 2020.

In order to investigate the changes in emissions of the entire German power sector, we apply two supply side approaches and the corresponding emission factors to the upscaled scenarios presented in the previous section:

- *Average generation mix (AGM):* The supply for additional consumption is equivalent to the average generation mix in a year. To depict past production mixes, we use official statistics by AGEB (2021). The 2025 and 2030 electricity mixes are based on Prognos et al. (2021). The actual implementation of such an approach would require an active response to changing consumption patterns by adjusting planned power plant expansions, especially with regards to renewable energies.
- *Natural gas power plants (NGPP):* Additional demand is provided by marginal generators in the German electrical power market. For practical reasons, we follow a common approach in life cycle modeling and assume natural gas turbines as single and constant marginal technology (Rehberger and Hiete 2015), which represents a strong simplification of market mechanisms. The approach is also relevant to actual changes in the German power plant fleet. Nuclear and coal

https://doi.org/10.14512/tatup.31.2.18

Scenario	Without battery		With battery	
	Emissions [kgCO$_2$eq]	cf. to Ref [%]	Emissions [kgCO$_2$eq]	cf. to Ref [%]
Ref	1,201	0	878	0
S–10	1,036	–14	716	–18
R+10	1,310	8	984	11
R+10 & LS	1,239	3	904	3
R+20	1,425	16	1,101	20
R+20 & LS	1,357	12	1,030	15

Tab. 2: Emissions for a 3-person household with a 3.5 kWp photovoltaic system (Ref is the scenario without behavioural changes). *Source: authors' own compilation*

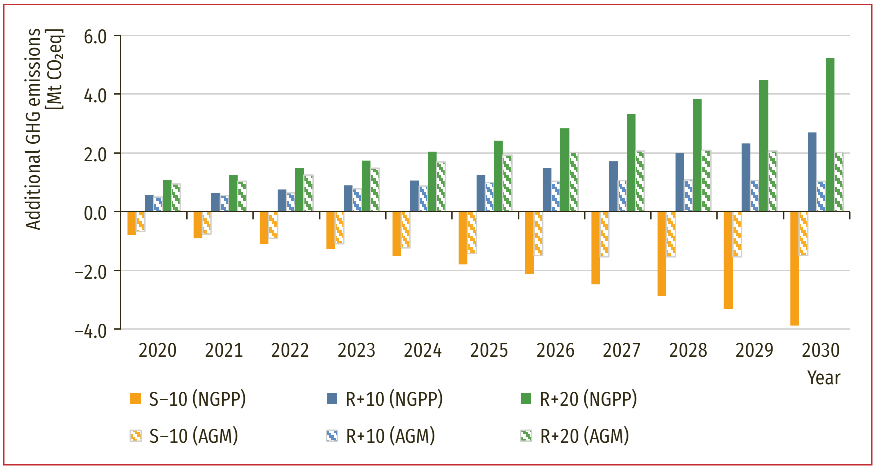

Fig. 1: Additional greenhouse gas (GHG) emissions per year until 2030; supply by natural gas power plant (NGPP) and by average generation mix (AGM). *Source: authors' own compilation*

power plants are to be phased out, whereas capacities of dispatchable gas power plants shall be expanded, according to the intentions of the current German government (SPD et al. 2021) and scenarios approved by the German Federal Network Agency (Bundesnetzagentur 2020).

Given that both approaches assess large-scale structural changes and consequences of two opposing options for decision-making, they conform to the approach of consequential life cycle inventory modeling (EC JRC IES 2010; Zamagni et al. 2012).

Technology-specific emission factors for electricity production including direct and indirect emissions of the upstream chains are taken from Lauf et al. (2021). The emission factors related to gross electricity production were adjusted for the power plants' own consumption. Furthermore, we neglect network losses and trade with neighboring countries.

The NGPP approach uses a fixed emission factor of 0.453 kgCO$_2$eq for each additional net kWh that is consumed. The emission factor in the AGM approach decreases from 0.391 kgCO$_2$eq/kWh in 2020 to 0.174 kgCO$_2$eq/kWh in 2030 due to the changes in the power plant fleet and electrical power production (our calculation based on Lauf et al. 2021; Prognos et al. 2021).

Results and discussion

An overview of the resulting GHG emissions at the household level is displayed in Table 2. Our 3-person household's GHG emissions for 2020 sum up to 1,201 kgCO$_2$eq (no battery) and 878 kgCO$_2$eq (with battery). Lower emissions with battery are due to the greater volume of PV self-consumption, which also overcompensates for additional emissions from battery production. Generally, the scenarios with rebound effects lead to higher GHG emissions both with and without battery when compared to the Ref scenario. In the sufficiency scenario, the household's GHG emissions decrease in both cases. Furthermore, a symmetrical rebound or sufficiency effect of 10 % leads to asymmetrical changes in GHG emissions (e.g., +8 and –14 % without battery), since changes in consumption have an effect on volumes of GHG-intensive grid supply rather than on PV self-consumption. With load shifting, emissions can be mitigated by up to eight percentage points.

In cases without battery, the emissions are mostly due to energy supply from the grid (~96 %) and to a lesser extent PV power supply (~4 %). In cases with battery, electricity from the grid remains the main source of GHG emissions (80–86 %), followed by PV (10–14 %) and the battery (~5 %).

Results for the impact assessment at the system level are shown in Figure 1 with the AGM approach, the S–10 scenario results in savings of 0.7 MtCO$_2$eq in 2020 and up to 1.5 MtCO$_2$eq in 2028. These savings remain at a similar level thereafter, since the yearly emission factor is falling towards 2030. Thus, decreasing consumption leads to less GHG savings per unit. Additional GHG emissions in the rebound scenarios peak in 2027 (R+10: 1.1 MtCO$_2$eq, R+20: 2.1 MtCO$_2$eq) and, subsequently, decline towards 2030 (1.0 and 2.0 MtCO$_2$eq, respectively) as the sinking emission factor overcompensates for the increase in electricity consumption.

The NGPP approach results in continuously decreasing emissions for the sufficiency scenario (S–10). Emissions of up to 3.9 MtCO$_2$eq in 2030 can be saved in 2030. In contrast, GHG emissions in the rebound scenarios are steadily increasing. In 2030, the additional burden sums up to 2.7 MtCO$_2$eq (R+10) and 5.2 MtCO$_2$eq (R+20).

The results show furthermore that load shifting has almost no effect on GHG emissions since we apply fixed emission factors per year, whereas this flexibility measure affects the household's power supply during the year.

Compared to the reduction target for the German energy sector in 2030 (108 $MtCO_2eq$ according to the Federal Climate Change Act, KSG (2021)), GHG emission savings due to a reduced energy demand (sufficiency) can account for a share of up to 1 % (AGM) and 4 % (NGPP). Additional emissions due to increased energy consumption (rebound effects) account for a share of up to 2 % (AGM) and 5 % (NGPP).

Since additional emissions fall toward 2030 in the AGM approach, our results might suggest that rebound effects become less of an issue over time. However, this conclusion neglects that the expansion of renewables is already becoming a challenge today. Therefore, additional GHG emissions in the case of overconsumption may impede climate targets, making a revision of consumption projections and renewables planning necessary.

Quantifying the degree of over- or underconsumption when a household turns prosumer, however, remains challenging. First, because empiric data on the behavioral effects of PV prosuming indicate cases of varying tendencies; second, because a clearer distinction between consumption associated with sector coupling vs. mere rebound effects is still pending. Upscaling magnifies these uncertainties further, as the same consumption patterns are applied to the entire German PV capacity < 100 kWp. This demands a more detailed investigation of consumption patterns with different PV system characteristics.

Using static, inner-annual emission factors of the average energy market mix or of marginal suppliers is common practice in LCA (EC JRC IES 2010; Rehberger and Hiete 2015). This approach, however, neglects dynamics in the power system. Lund et al. (2010) show that assuming natural gas power plants as a single marginal technology results in lower GHG emissions compared to a modeling approach that reflects dynamic market interactions. These dynamics are becoming even more relevant as volatile renewable energies enter the market. Furthermore, our impact assessment is limited to climate change, whereas other impact categories are also relevant for electrical power production (Barros et al. 2020). Finally, the actual changes in GHG emissions depend very much on the quantity and speed of renewable energy expansion and fossil fuel phaseout.

Conclusion and recommendations

Households tend to reduce their emissions when switching to prosuming (Lenk et al. 2022); this can be enhanced by sufficient behavior or diminished by rebound effects. As shown by our results at household level, greater energy consumption, triggered by prosuming, leads to greater GHG emissions. These can be mitigated by load shifting and the use of larger-sized PV systems, since, in both cases, the increased demand is more closely associated with the PV-produced electricity. In the defined sufficiency scenario, the results showcase decreasing emissions and a greater share of electricity fed into the grid.

The results of upscaling show that rebound effects can add up to relevant additional GHG emissions as the number of prosumer households increases and the politically intended market diffusion of PV and PV battery systems materializes. Load shifting can hardly reduce this effect, since the PV power used to meet the increased demand can no longer be fed into the grid.

Based on our analyses, we offer, in the following sections, recommendations to incentivize energy sufficiency and avoid rebound effects. We address measures to both encourage behavioral changes at the household level, as well as collective energy sufficiency strategies. Furthermore, tariffs and services are discussed. Finally, we present the needs identified for future research.

Information and consultation

Due to the fundamental importance of individual participation in the energy transition, it is key that we provide prosumers with the advice and information needed such that they can support climate goals with their consumption practices. In consultation, instead of focusing on self-consumption and the economic advantages of PV systems (Kratschmann and Dütschke 2021), the potential contribution of the prosumer to the energy transition should be emphasized more strongly.

Sufficiency-oriented behavior can furthermore be supported by real-time feedback on energy consumption. Smart meters can be used for this purpose, as they not only have a positive effect on power consumption, but are also economically and ecologically worthwhile (Gährs et al. 2021).

Political and regulatory framework

The Renewable Energy Sources Act (EEG) in Germany is currently fostering self-consumption among prosumer households as it is the most cost-effective option. This might be advantageous for acceptance and the fast expansion of solar PV. But it does not lead to sufficient consumption patterns, and often limits the size of the PV system being installed. As shown by Li et al. (2020), prosumer consumption tends to decrease, when feed-in increases; thus, increasing incentives for grid feed-in could support greater sufficiency-oriented behavior.

In addition, the EEG-rule, ensuring that small PV systems may feed in only 70 % of the rated power supports overconsumption, as some prosumers erroneously fear that up to 30 % of the electricity they produce, is "wasted" (Galvin 2020; Weiß et al. 2021). Targeted information on the actual low significance of this curtailment rule could reduce this problem.

Tariffs and services

Among the cloud and community tariffs identified in Lenk et al. (2022), some offer solutions to limit generous consumption. For instance, credit financing of the PV system with monthly installment payments can smooth out the uneven distribution between high initial investment costs and low ongoing operating costs of a

PV system. In addition, incentives like a cash-back system, where unused electricity quantities are paid out, can promote sufficiency-oriented behavior. (This, however, leads to additional household income, which, depending on how it is used, could lead to a monetary rebound and therefore to other ecological impacts.)

Further research

The environmental effects of changing consumption patterns as a consequence of becoming a prosumer household have so far not been addressed in energy system modeling, nor in climate neutrality trajectory planning. We urge further investigation of these linkages, e.g., by conducting more extensive interdisciplinary research and making scenarios with such behavioral effects a more common practice in modeling.

For the environmental assessment methods, future research could address models to investigate inner-annual dynamics in the power market. Further studies might also broaden the assessment to additional impact categories.

Funding • The authors wish to thank the German Federal Ministry of Education and Research for supporting the projects EE-Rebound (Grant No. 01UT1705A) and SteuerBoard Energie (Grant No. 01UU2005B).

Competing interests • The authors declare no competing interests.

References

AEE (2020): Installierte Leistung Photovoltaik. Übersicht zur Entwicklung Erneuerbarer Energien in allen Bundesländern. Available online at https://www.foederal-erneuerbar.de/uebersicht/bundeslaender/BW|BY|B|BB|HB|HH|HE|MV|NI|NRW|RLP|SL|SN|ST|SH|TH|D/kategorie/solar/auswahl/183-installierte_leistun, last accessed on 27.04.2022.

AGEB – AG Energiebilanzen e.V. (2021): Evaluation tables of the energy balance for Germany. Energy data for the years 1990 to 2020. Available online at https://ag-energiebilanzen.de/wp-content/uploads/2020/09/awt_2020_e.pdf, last accessed on 27.04.2021.

Barros, Murillo; Salvador, Rodrigo; Piekarski, Cassiano; de Francisco, Antonio; Freire, Fausto (2020): Life cycle assessment of electricity generation. A review of the characteristics of existing literature. In: The International Journal of Life Cycle Assessment 25 (1), pp. 36–54. https://doi.org/10.1007/s11367-019-01652-4

BDEW – Bundesverband der Energie- und Wasserwirtschaft e.V. (2021): Die Energiewende braucht einen PV-Boom. Berlin: BDEW.

BMI – Bundesministerium des Innern für Bau und Heimat (2018): ÖKOBAUDAT – Process data set. Available online at https://oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?lang=en&uuid=10c531c8-329c-479a-bbe9-17990ca5dfd6&version=20.19.120, last accessed on 27.04.2022.

BMWK – Bundesministerium für Wirtschaft und Klimaschutz (2022): Entwurf eines Gesetzes zu Sofortmaßnahmen für einen beschleunigten Ausbau der erneuerbaren Energien und weiteren Maßnahmen im Stromsektor. Berlin: BMWK

Brandes, Julian et al. (2021): Studie. Wege zu einem klimaneutralen Energiesystem. Freiburg: ISE.

Bundesnetzagentur (2020): Genehmigung des Szenariorahmens 2021–2035. Bonn: BNetzA.

Bundesnetzagentur (2021): Marktstammdatenregister. Available online at https://www.marktstammdatenregister.de/MaStR, last accessed on 07.04.2021.

co2online (2022): Stromspiegel für Deutschland 2021. Available online at https://www.stromspiegel.de/fileadmin/ssi/stromspiegel/Broschuere/stromspiegel-2021.pdf, last accessed on 27.04.2022.

dena – Deutsche Energie-Agentur (2021): Leitstudie Aufbruch Klimaneutralität. Eine gesamtgesellschaftliche Aufgabe. Berlin: dena.

DIN – Deutsches Institut für Normung e.V. (2006): Environmental management. Life cycle assessment, Requirements and guidelines (ISO 14044:2006).

Dromaque, Christophe; Grigoriou, Rafaila (2018): The role of data for consumer centric energy markets and solutions. Brussels: ESMIG.

Dütschke, Elisabeth; Galvin, Ray; Brunzema, Iska (2021): Rebound and spillovers. Prosumers in transition. In: Frontiers in Psychology 12, p. 636109 https://doi.org/10.3389/fpsyg.2021.636109

DWD – Deutscher Wetterdienst (2021): Globalstrahlungskarten. Monats- und Jahressummen. Available online at https://www.dwd.de/DE/leistungen/solarenergie/lstrahlungskarten_su.html?nn=16102, last accessed on 27.04.2022.

EC JRC IES – European Commission Joint Research Centre Institute for Environment and Sustainability (2010): International Reference Life Cycle Data System (ILCD) Handbook. General guide for life cycle assessment. Detailed guidance. Luxembourg: European Commission.

Figgener, Jan et al. (2021): The development of stationary battery storage systems in Germany. Status 2020. In: Journal of Energy Storage 33, p. 101982. https://doi.org/10.1016/j.est.2020.101982

Frondel, Manuel; Kaestner, Kathrin; Sommer, Stephan; Vance, Colin (2020): Photovoltaics and the solar rebound. Evidence for Germany. In: SSRN Electronic Journal USAEE Working Paper No. 20-475, 38 p. https://doi.org/10.2139/ssrn.3716945

Gährs, Swantje et al. (2021): Potenziale der Digitalisierung für die Minderung von Treibhausgasemissionen im Energiebereich. Berlin: UBA.

Gährs, Swantje; Deisböck, Alexander; Cremer, Noelle; Cremerius, Paula (2020): Regionale Flexibilitäten in Haushalten und Supermärkten. Berlin: IÖW.

Galvin, Ray (2020): I'll follow the sun. Geo-sociotechnical constraints on prosumer households in Germany. In: Energy Research & Social Science 65, p. 101455. https://doi.org/10.1016/j.erss.2020.101455

Galvin, Ray; Dütschke, Elisabeth; Weiß, Julika (2021): A conceptual framework for understanding rebound effects with renewable electricity. A new challenge for decarbonizing the electricity sector. In: Renewable Energy 176, pp. 423–432. https://doi.org/10.1016/j.renene.2021.05.074

Galvin, Ray; Schuler, Johannes; Atasoy, Ayse Tugba; Schmitz, Hendrik; Pfaff, Matthias; Kegel, Jan (2022): A health research interdisciplinary approach for energy studies. Confirming substantial rebound effects among solar photovoltaic households in Germany. In: Energy Research and Social Science 86, pp. 102429. https://doi.org/10.1016/j.erss.2021.102429

Kegel, Jan; Lenk, Clara; Ouanes, Nesrine; Wiesenthal, Jan; Weiß, Julika (2022): Prosumerverhalten und Energiewende. Berlin: IÖW.

Kratschmann, Martina; Dütschke, Elisabeth (2021): Selling the sun. A critical review of the sustainability of solar energy marketing and advertising in Germany. In: Energy Research and Social Science 73, pp. 121471. https://doi.org/10.1016/j.erss.2021.101919

KSG – Klimaschutzgesetz (2021): Federal Climate Change Act. Available online at https://www.gesetze-im-internet.de/englisch_ksg/index.html, last accessed on 27.04.2022.

Lauf, Thomas; Memmler, Michael; Schneider, Sven (2021): Emissionsbilanz erneuerbarer Energieträger. Bestimmung der vermiedenen Emissionen im Jahr 2020. Dessau-Roßlau: UBA.

Lenk, Clara; Torliene, Lukas; Weiß, Julika; Wiesenthal, Jan (2022): Wie wirken Rebound-Effekte von Prosumern? Berlin: IÖW.

Li, Xingzhi; Lim, Ming K.; Ni, Du; Zhong, Bo; Xiao, Zhi; Hao, Haitian (2020): Sustainability or continuous damage. A behavior study of prosumers' electricity consumption after installing household distributed energy resources. In: Journal of Cleaner Production 264, pp. 121 471. https://doi.org/10.1016/j.jclepro.2020.121471

Lund, Henrik; Mathiesen, Brian Vad; Christensen, Per; Schmidt, Jannick Hoejrup (2010): Energy system analysis of marginal electricity supply in consequential LCA. In: The International Journal of Life Cycle Assessment 15 (3), pp. 260–271. https://doi.org/10.1007/s11367-010-0164-7

Oberst, Christian; Schmitz, Hendrik; Madlener, Reinhard (2019): Are prosumer households that much different? Evidence from stated residential energy consumption in Germany. In: Ecological Economics 158, pp. 101–115. https://doi.org/10.1016/j.ecolecon.2018.12.014

Prognos; Öko-Institut; Wuppertal-Institut (2021): Klimaneutrales Deutschland 2045. Wie Deutschland seine Klimaziele schon vor 2050 erreichen kann. Berlin: s.n. Available online at https://static.agora-energiewende.de/fileadmin/Projekte/2021/2021_04_KNDE45/A-EW_209_KNDE2045_Zusammenfassung_DE_WEB.pdf, last accessed on 11. 05. 2022.

Rehberger, Max; Hiete, Michael (2015): Considering supply and demand of electric energy in life cycle assessments. A review of current methodologies. In: Materiaux et Techniques France, 103 (1), pp. 1051–1059. https://doi.org/10.1051/mattech/2015006

Solomon, Susan (2007): Climate change 2007. The physical science basis. Working Group I contribution to the Fourth Assessment Report of the IPCC. New York, NY: Cambridge University Press. Available online at https://www.ipcc.ch/site/assets/uploads/2018/05/ar4_wg1_full_report-1.pdf, last accessed on 27. 04. 2022.

SPD; Bündnis 90/Die Grünen; FDP (2021): Mehr Fortschritt wagen. Bündnis für Freiheit, Gerechtigkeit und Nachhaltigkeit. Koalitionsvertrag zwischen SPD, Bündnis 90/Die Grünen und FDP. Berlin: grün gedruckt.de. Available online at https://www.spd.de/fileadmin/Dokumente/Koalitionsvertrag/Koalitionsvertrag_2021-2025.pdf, last accessed on 27. 04. 2022.

Weiß, Julika; Gährs, Swantje; Galvin, Ray (2021): Rebound-Effekte und Prosumer. Die Rolle der Rahmenbedingungen für den Stromverbrauch bei Photovoltaik-Erzeugern. In: Ökologisches Wirtschaften 36 (1), pp. 17–19. https://doi.org/10.14512/OEW360117

Zamagni, Alessandra; Guinée, Jeroen; Heijungs, Reinout; Masoni, Paolo; Raggi, Andrea (2012): Lights and shadows in consequential LCA. In: The International Journal of Life Cycle Assessment 17 (7), pp. 904–918. https://doi.org/10.1007/s11367-012-0423-x

DR. JAN KEGEL

studied renewable energy systems. He is involved in research projects investigating the technical aspects of decentralized energy systems.

Bildquelle: IÖW/Gordon Welters

JAN WIESENTHAL

has been researching in the field of energy prosumers and energy system modeling at the IÖW. He is currently also doing his PhD at Leuphana University in this field.

CLARA LENK

studied environmental engineering. The focus of her work at IÖW is mainly the ecological assessment of various aspects concerning the energy sector.

Bildquelle: IÖW/Gordon Welters

HANNES BLUHM

is a researcher at IÖW. His focus is on life cycle assessment and digitalization in the energy sector. He is currently pursuing a PhD at Europa University Flensburg.

Bildquelle: IÖW/Gordon Welters

DR. JULIKA WEISS

has led numerous projects dealing mainly with energetic refurbishment and climate-friendly heat supply. Rebound effects and consumer behavior have been focal points in recent years.

NESRINE OUANES

studied renewable energy systems with a focus on mathematical modeling. She works on decentralized electricity markets and their design instruments.

LUKAS TORLIENE

studied industrial engineering. He works on several research and policy consulting projects regarding climate and energy concepts as well as simulations and economic efficiency.