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ORIGINAL PAPER

Impacts of self-generation and self-consumption on German household electricity prices

Daniel Fett[1] · Dogan Keles[1] · Thomas Kaschub[1] · Wolf Fichtner[1]

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Abstract
In recent years, more than half of the household PV systems in Germany were installed with battery storage systems to self-consume a higher share of the electricity produced. This development will have a large impact on the share of energy purchased from the electricity grid and this, in turn, will affect the distribution of the cost components of the household electricity price. This contribution therefore analyzes the impacts of increasing self-generation and self-consumption on the electricity price components. To obtain the nation-wide self-consumption potential, the results of a techno-economic optimization model on household system level are scaled up to all (semi-) detached houses in Germany. The additional PV feed-in remuneration and lacking contributions to the different taxes and levies are reallocated to the (remaining) electricity consumption from the grid. Changes in the regulatory framework, such as the abolishment of feed-in tariffs, a self-consumption charge, and different allocation schemes for the grid charges, are examined. The results indicate that under the current regulatory framework conditions, less than one third of the potential electricity price increase stems from self-consumption, while remuneration through feed-in tariffs has a much higher impact. Furthermore, the effects of self-consumption on the electricity price seem to be higher with capacity-based grid charges, because the contributions of PV storage owners to the grid charges are reduced through peak shaving with battery storage systems. Our findings also show that policy makers can strongly influence PV feed-in and self-consumption levels, as well as the resulting electricity price.

Keywords Self-consumption · Photovoltaics · Solar · Battery storage · Electricity prices · Energy policies

JEL Classification Q42 · Q47 · Q48 · M21 · O13

✉ Daniel Fett
daniel.fett@kit.edu

[1] Chair of Energy Economics, Karlsruhe Institute of Technology, Hertzstraße 16, 76187 Karlsruhe, Germany

1 Introduction

Photovoltaics (PV) is one of the main technologies for generating renewable electricity. The possibility of scaling PV from small to very large systems and the high amount of suitable areas for PV modules are main technology drivers. More than 1.5 million PV systems with a nominal capacity of 41 GW have been installed in Germany under the Renewable Energies Act (Wirth 2017). This has led to rapidly declining costs for electricity generated through rooftop PV systems, while electricity prices for households have increased (Staubitz 2016). Around 2012, grid parity was reached, meaning that it was cheaper for a household to generate own electricity through PV than purchasing it from the public grid. As remuneration for PV feed-in is adapted to the falling costs, self-consumption is becoming financially attractive (Wirth 2017). Besides the development of household electricity prices and PV generation costs, Fig. 1 also depicts the combined cost of producing electricity through PV and storing it in a battery. Due to increasing sales of electric vehicles, prices for lithium-ion batteries have declined by more than 45% since 2013 and continue to decrease (Figgener et al. 2017). Soon, it will be cheaper for households to produce their own electricity through PV and store it in a battery (sometimes called "battery parity"), thus increasing their potential for self-consumption. Since 2015, more than 50% of the small-scale PV systems (< 10 kWp) have been installed with battery storage systems (Kairies et al. 2016).

Household PV systems are supported by legislation in many countries. Especially, feed-in tariffs are common and used in 113 countries worldwide and 25 members of the European Union, including Austria, France, Spain, and Germany (REN21 2018). Another frequently used incentive is net metering, which is used in 42 states of the US, but also in 10 member states of the European Union (REN21 2018). There is no net metering in Germany, but self-consumption from small-scale PV systems

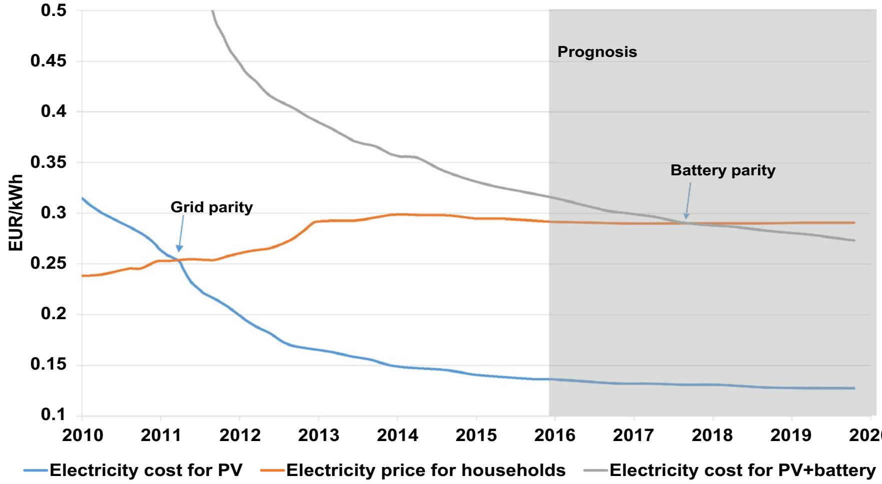

Fig. 1 Development of household electricity prices and electricity costs for PV with battery storage (Staubitz 2016)

(< 10 kWp) is exempted from most taxes and levies, such as grid charges or the renewable energy levy. An increasing number of self-consuming households leads to increasing household electricity prices due to two effects. Firstly, households where PV systems are installed with a battery system still feed surplus energy into the grid, which is remunerated with guaranteed feed-in tariffs. This leads to higher renewable energy charges to fund the fed-in renewable electricity. Secondly, as already mentioned, self-consumption is exempt from most taxes and levies. Grid costs and remunerations from guaranteed feed-in tariffs are for household consumers only allocated to the electricity consumed from the grid, Thus, they have to be allocated to a smaller amount of energy, which in turn increases the grid charges and levies. A growing number of self-consuming households consequently leads to increasing household electricity prices, which incentivizes more households to self-produce their energy. Some authors refer to this process as “utility death spiral” (Davies 2016; Rickerson et al. 2014). The fact that major fractions of the savings from self-consumption are not revenues lost by the utilities, but money not paid to public authorities often leads to discussions whether self-consumption is a “desolidarisation” process (Kairies et al. 2016). While EON’s CEO Johannes Teyssen compared it to illicit distilling, other authors warn that the stigmatization of self-consumption might ruin the reputation of a business model that is well suited for supporting the energy transition (Maubach 2015). A main focus of the debates are the grid costs, because high shares are fixed costs (Friedrichsen et al. 2016). The current German government decided that due to increasing self-consumption it is necessary to evaluate mechanisms to reallocate grid costs more fairly (German Government 2013).

Different authors analyzed the effects of self-consumption on some components of the electricity price. In Figgener et al. (2017), the effects of existing self-consumption on the electricity prices are examined. In Friedrichsen et al. (2016), self-consumption is forecast for 2019 and its effects on the grid charges is calculated. In Moshövel et al. (2015), the electricity price is calculated for 2020, with all households with PV systems being assumed to install battery storage systems and to reach 60% self-consumption and all taxes or levies being reallocated (including components, e.g. the concession fee, that would not be reallocated). Due to the short terms and, hence, low self-consumption, the three studies above revealed minor price increases only. Gerblinger et al. (2014) examined the consumer electricity prices, if either all detached houses or all homes would reach self-sufficiency levels of 30% or 70% and all taxes and levies would be allocated to the remaining electricity consumption of the household sector only. Bardt et al. (2014), Krampe et al. (2016) and Deutsch and Graichen (2015) use models to calculate nationwide self-consumption potentials for Germany and their effects on the renewable energy levy. Both, self-consumption and the resulting electricity price increase, are found to vary strongly depending on the assumptions made in the studies. The results obtained in the papers mentioned above will therefore be discussed in Sect. 3.3. To our knowledge, the effects of self-consumption on all components of household electricity prices when lacking allocation-based electricity price components are reallocated to the remaining electricity consumption of all sectors have not yet been studied. Nor has it been analyzed, how different electricity pricing schemes for households influence the effects of self-consumption on the household electricity price. This article intends to fill this gap in literature. First, an optimization model is used to calculate the most profitable self-generation and self-consumption levels for 88 empirically measured household load curves. For this calculation, different pricing schemes for households are considered as scenarios. The results are then scaled up for all (semi-) detached houses in order to estimate the nationwide self-consumption potential for Germany. The effect on the electricity price is calculated by reallocating the lacking contributions to the different levies and charges to the complete electricity consumption from the public network in Germany. Reduced tariffs for commercial customers and industry are also considered. Finally, by recalculating the levies and charges as components of the end consumer's electricity price, the development of the prices itself can be illustrated.

For this purpose, the remainder of this paper is structured as follows: In Sect. 2 the methodology is described. Section 3 presents the results of our analysis and compares them to values found in literature. In Sect. 4 potential limitations of our work are discussed, before conclusions and policy recommendations are provided in Sect. 5.

2 Methodology and data

2.1 Development of possible policy scenarios for prosumers

In order to analyze the effects of possible policy changes on self-consumption and electricity prices, three different scenarios are defined. They differ in the way how grid charges are allocated for households.

- In the reference scenario (REF) the grid charges are based on power consumption and amount to 7.06 ct[1] per kWh. This scenario is similar to the current cost structure for household customers.
- In the fixed scenario (FIX) the grid charges are included in the basic charge of the electricity tariff of 221.66 euros per year. This fixed charge equals a consumption of 3140 kWh, which is the result of allocating the 128.6 TWh consumed by the household sector to all 40.96 million households in Germany (BDEW 2017; Destatis 2017). In this case, the costs are independent of the actual consumption and may be considered pure costs of grid access.
- In the capacity scenario (CAP) the grid charges are based on the maximum peak load during one year and amount to 18.98 euros per kW. This capacity payment is the result of allocating the grid costs to the average household peak load of 11.68 kW of the 88 empirical household load curves used in this analysis. While such a demand charge is common for industrial customers in Germany, it is not for households.

[1] In this paper cents (or ct) refers to euro cents.

Table 1 Overview of the scenarios considered

Support scheme	Grid charges		
	Consumption-based	Capacity-based	Fixed
Feed-in tariffs	REF-FIT	CAP-FIT	FIX-FIT
Market price	REF-MARKET	CAP-MARKET	FIX-MARKET
Self-consumption charge	REF-SCC	CAP-SCC	FIX-SCC

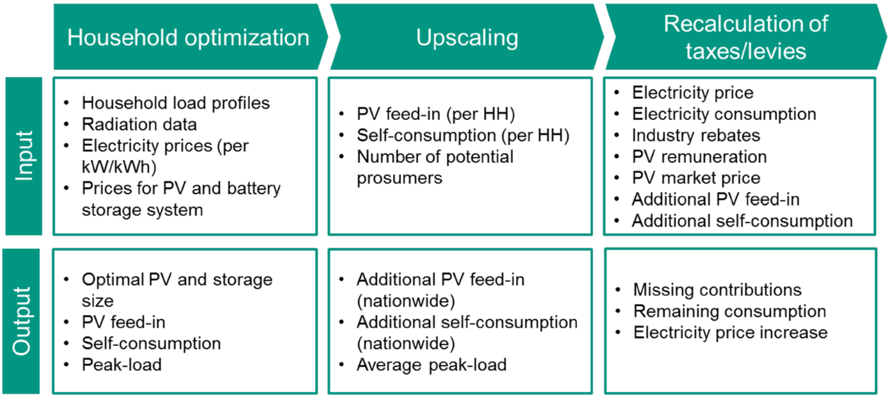

Fig. 2 Schematic overview of the methodological approach

Additionally, two different scenarios for the remuneration of surplus solar energy feed into the grid are considered. In the market scenario (MARKET), each kWh of feed-in is remunerated with an average wholesale price of 3.5 cents. In the feed-in tariff scenario (FIT) each kWh of fed-in electricity is remunerated with 12.0 cents. Both remuneration scenarios are combined with all different scenarios for the grid charges. Furthermore, the effects of a possible self-consumption charge (SCC) of 40% of the current renewable energy levy are examined for the three different grid charge scenarios. All SCC scenarios are without feed-in tariffs, therefore surplus solar energy is remunerated with 3.5 ct/kWh. This results in a total of nine scenarios analyzed, which are shown in Table 1.

2.2 Calculation of self-generation and self-consumption potentials

Figure 2 presents a schematic overview of the methodological approach used in this paper. The different steps will be described in detail below.

The self-generation and self-consumption potentials used to analyze the impacts on the electricity prices are calculated with the model "StorageOpt", which is described in detail in Kaschub et al. (2016) and Kaschub (2017). StorageOpt is a techno-economic optimization model of a household system that endogenously dimensions the PV system and the stationary battery by applying an NPV approach

Table 2 StorageOpt key assumptions

Parameter	Value
Period under consideration	20 years from 2018
Interest rate	4% p.a.
Investment battery	600 €/kWh_{2018}
Investment PV incl. VAT	1600 €/kWp_{2018}
Electricity price increase	2%/a
Lifetime PV	25a
Lifetime storage system	20a/7000 cycles
Annual operating costs PV	1.5% of the PV investment
Roundtrip efficiency BSS	88%
Specific annual yield PV	1000 kWh/kWp

for the assessment of economic profitability (Kaschub et al. 2016). The model maximizes the net present value for the PV and the battery system, including all expenditures for electricity. Charging of the stationary battery is optimized for a whole year in a 15-min time resolution. It is conservatively assumed that the resulting schedule is constant for 20 years, as revenues and costs remain in the same relation over this period. The discounted cash flows allow to consider the total expected lifetime of the system. A simplified battery degradation model includes both cycle and calendar lifetime of the battery and complements relevant influences. The investment in PV and storage systems is considered to be size-independent, which implies a slight underestimation of system sizes (Dietrich and Weber 2018).

Key model input assumptions are shown in Table 2. As patterns of households' load curves are highly diverse, we use 88 empiric load curves of heterogeneous household types. The yearly electricity consumption and peak load of households are shown in Fig. 7 in the "Appendix", additional details on the load curves are given in Kaschub (2017). The average values for self-consumption and self-generation are based on StorageOpt model runs with optimally sized PV and stationary battery storage systems for these 88 input load curves. The results are scaled up to all 17.7 million (semi-) detached houses in Germany (Destatis 2017).

2.3 Calculation of the impacts of self-consumption on the electricity prices

The calculation of the impacts of self-consumption on electricity prices is based on the German electricity prices of the year 2016. A ceteris paribus analysis for the different self-consumption scenarios is then carried out assuming that the complete self-generation and self-consumption potentials are realized in 1 year. That means, it is analyzed what would have been the level of different components of household prices, if all the self-consumption potential had been exploited in 2016. Thereby, the following components of German household electricity tariffs are considered: grid charges, value-added tax, concession fees, renewable energy levies, electricity tax, combined heat and power levies, §19 levies, and offshore liability levies. Both the effect of additional PV feed-in (in the FIT scenarios, Sect. 2.1) and reduced

Table 3 Overview of redistribution effects through self-consumption

Electricity price component	Affected party	Calculation in this paper
Grid charges	Grid operator/other customers	Reallocated to remaining consumption
Value-added tax	German state/tax payers	Recalculated (based on price increase)
Concession fee	Municipalities	Lost payments are estimated
Renewable surcharge	Renewable energy levy account/ other customers	Reallocated to remaining consumption
CHP surcharge	Grid operator/other customers	Reallocated to remaining consumption
§19 surcharge	Grid operator/other customers	Reallocated to remaining consumption
Offshore wind surcharge	Grid operator/other customers	Reallocated to remaining consumption
Electricity tax	State/tax payers	Lost payments are estimated

electricity consumption from the grid are analyzed. Grid charges, renewable energy levies, combined heat and power levies, §19 levies, and offshore liability levies are reallocated to the remaining electricity consumption from the grid. The value-added tax is recalculated on basis of the resulting new electricity price and differences in tax receipts are assessed. For the electricity tax and the concession fees, the lost payments are estimated. Table 3 summarizes the redistribution effects analyzed.

The general concept for the calculation of the increase (A_i) in the ith electricity price component is the same for all components and given in the formula below. The total annual amount of self-consumption ($Y_{self\_consumption}$) is multiplied by the specific value of the electricity price component (C_i to obtain the lacking contributions. In order to determine the expenditures for additional PV feed-in, the difference between the remuneration (R_i) and the payments coming from other taxes or levies (S_i)[2] is multiplied by the amount of PV feed-in (Y_{feed_in}). The sum of lacking contributions and the expenditures for additional PV feed-in is then divided by the remaining weighted consumption,[3] which is the difference between the total weighted consumption (X_i) and self-consumption ($Y_{self\_consumption}$).

$$A_i = \frac{Y_{self\_consumption} \cdot C_i + Y_{feed\_in} \cdot \left(R_i - S_i\right)}{X_i - Y_{self\_consumption}}$$

To obtain the costs of remunerating additional PV feed-in in the FIT scenarios, the following assumptions are made: each additional kWh of PV feed-in is remunerated with the 2016 feed-in tariff for small-scale PV, which equals 12.31 cents (Wirth 2017). The market value of solar power is 3.064 ct/kWh and the avoided grid charges are 0.544 ct/kWh (German TSOs 2015c). These avoided grid charges are

[2] An example for these payments are the avoided grid charges, which are included in the grid charge and credited to the renewable energy levy account.

[3] In Germany, most taxes and levies are lower for commercial/industrial electricity consumers. A weighted consumption is calculated using the consumption quantity and percentage of charges that applies to each consumption group. Hence, we calculate the total consumption equivalent to which the total value of charges applies.

credited to the renewable energy levy account and charged to the grid costs. Therefore, 8.702 cents per kWh of additional PV feed-in have to be allocated through the renewable energy levy.

In order to calculate the effects of increased self-consumption and the reduced energy consumption from the grid, to which grid charges and levies still apply, the complete German electricity consumption from the grid has to be considered. Especially, the discounts for the different taxes and levies of the industrial sector have to be analyzed.

For the combined heat and power, §19, and offshore liability levies, detailed consumption data are available from the German transmission system operators (German TSOs 2015a, b, c). Customers are clustered into the categories A, B, and C depending on their electricity consumption. Category A is for customers with consumptions below 1000 MWh, category C for the energy-intensive industrial customers, and category B for everyone else. Household self-consumption is deducted from category A. There are upper limits for all levies in the categories B and C. These are considered when calculating the new levies after self-consumption. If the upper limits are reached, the rest of the deficit is allocated to category A.

Detailed consumption data is also available for the renewable energy levy (German TSOs 2015c). Customers are divided into non-privileged customers and privileged industrial customers that are granted discount rates of either 15% or 20% of the renewable energy levy. Potential changes in the amounts of electricity consumption covered by the cap or supercap rule are not considered. Under the cap and supercap rule, the renewable energy levy payments of a company are limited to 4% or 0.5% of the gross value added, respectively (BDEW 2016).

The grid costs are calculated based on the averages given for the different sectors (households, commerce, trade, services, and industry) in the monitoring report of the German Federal Network Agency and the corresponding electricity consumption according to the German Association of Energy and Water Industries (BDEW 2017; BNetzA 2016). The industry rebates for grid charges according to §19 and 15% industrial self-consumption are considered in the calculations (BDEW 2016). It is assumed that the grid charges for the different sectors grow at the same rate. In addition to the deficits due to self-consumption, the avoided grid charges for the additional PV feed-in are allocated.

Lost payments of concession fees are calculated based on the averages given in BDEW (2016). Losses in tax revenues from the electricity tax are calculated with the full rate applying to household customers. It is assumed that the small business regulation applies and, hence, no value-added tax is paid for self-consumption. The lower tax revenues due to self-consumption are compared with potentially higher tax receipts due to higher electricity prices.

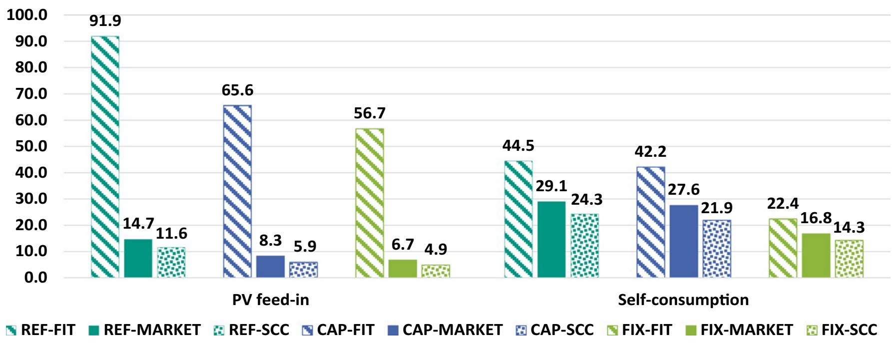

Fig. 3 Self-consumption and PV feed-in in Germany for the scenarios considered

3 Results and discussion

3.1 Self-consumption and PV feed-in

The highest PV generation is reached in the REF-FIT scenario, the current status quo with consumption-based allocation of grid charges and remuneration of surplus PV generation through feed-in tariffs. Self-consumption is about 45 TWh and 92 TWh are fed into the grid (see Fig. 3). Self-consumption would account for around one third of the current electricity consumption of the household sector in Germany (BDEW 2017). PV feed-in of 40 TWh in 2017 would more than triple (Wirth 2017). The high remuneration for surplus PV generation through the feed-in tariff leads to bigger PV systems, resulting in a comparably low self-consumption rate of only 32.5%.

Without feed-in tariffs (REF-MARKET), the self-consumption rate doubles, while the total amount of self-consumption decreases by about one third to 29.1 TWh compared to the FIT scenario. The PV feed-in drops drastically by 84%, resulting in a remaining feed-in of 14.7 TWh. The extension of the self-consumption charge of 40% (REF-SCC) of the renewable energy levy, which is currently applied to systems above 10 kWp only to household customers leads to a further decrease in the size of both PV and battery storage system. Consequently, PV feed-in drops to 11.6 TWh (−21.1% compared to REF-MARKET). Even with the self-consumption charge, self-consumption remains more profitable than feed-in. Therefore, the decrease in self-consumption (−16.5% compared to REF-MARKET) to 24.3 TWh is slightly lower than in feed-in and the self-consumption rate rises to 67.6%.

In scenarios with capacity-based grid charges (CAP) the battery storage system is also used to reduce peak load. For this reason, the battery storage system is larger than in the scenarios with consumption-based grid charges (REF). This leads to an increase in self-consumption rates of between 6.5% (CAP-FIT) and 11.2% (CAP-SCC). Due to reduced profitability of self-consumption (less savings per kWh), however, the PV systems are smaller and, hence, the absolute value of self-consumption drops by about 5% in both scenarios with (CAP-FIT) and without feed-in tariffs (CAP-MARKET). Applying a self-consumption charge (CAP-SCC), the decrease is almost 10% (compared to REF-SCC). As a result of the smaller PV system and the larger battery storage system (compared to consumption-based grid charges), the reduction of PV feed-in is much higher. With feed-in tariffs (CAP-FIT), the feed-in is reduced by 28.6% to 65.6 TWh (see Fig. 3). In the two scenarios without feed-in tariffs the reduction is above 40%.

The introduction of fixed grid charges leads to lower consumption-dependent electricity prices and, hence, significantly reduces the profitability of self-consumption. Consequently, the PV and battery storage systems are smaller and PV generation is lower. Compared to scenarios with consumption-based allocation of grid charges (REF scenarios), the PV feed-in decreases by 38.3% (FIX-FIT) to 57.5% (FIX-SCC). Total self-consumption is smaller by 41.0% (FIX-SCC) to 49.6% (FIX-FIT).

In contrast to scenarios with capacity-based allocation of grid charges, the battery storage system cannot be used for peak shaving in the FIX scenarios and to reduce the contributions to the grid charges. This decreases the profitability and, hence, both PV and battery storage systems sizes. As a result, the total quantity of additional PV feed-in is also 13.5–16.4% lower than in the capacity-based scenarios. The amount of self-consumption drops by 34.5% (FIX-SCC) to 46.9% (FIX-FIT). With 28.3%, the self-consumption rate with fixed grid charges and feed-in tariffs (FIX-FIT) is the lowest of all scenarios. Without feed-in tariffs, the self-consumption rates are higher than with consumption-based grid charges due to smaller PV systems. The self-consumption rates in the FIX scenarios are still lower than in the capacity-based scenarios, where the battery storage systems are also used for peak shaving and, thus, larger.

3.2 Impacts of self-consumption on the electricity price

The impacts of self-consumption and self-generation on the electricity price will be presented in this section. As already mentioned in Sect. 2.3, the electricity price is influenced by the lacking contributions to the different charges and taxes, as a lower amount of electricity is consumed from the grid in case of self-consumption, and the remuneration of the additional PV feed-in because of additionally installed PV storage systems. Here, the combined impact of both effects (lacking contributions and higher RES charge due to additional PV feed-in) as well as the sole effect of self-consumption and the related lacking contributions will be presented for the different scenarios. Since the grid charges and the renewable energy levy account for the largest share of end consumer electricity prices, beside the impact on total price increase the impact on these price components will be separately presented. The development of other taxes, levies, and charges can be found in Table 6 in the Appendix.

3.2.1 Consumption-based grid charges

The household price increase is highest for the current status quo, i.e. with consumption-based grid charges and feed-in tariffs for surplus PV feed-in (REF-FIT). While grid charges increase by 5.3%, the total electricity price increases

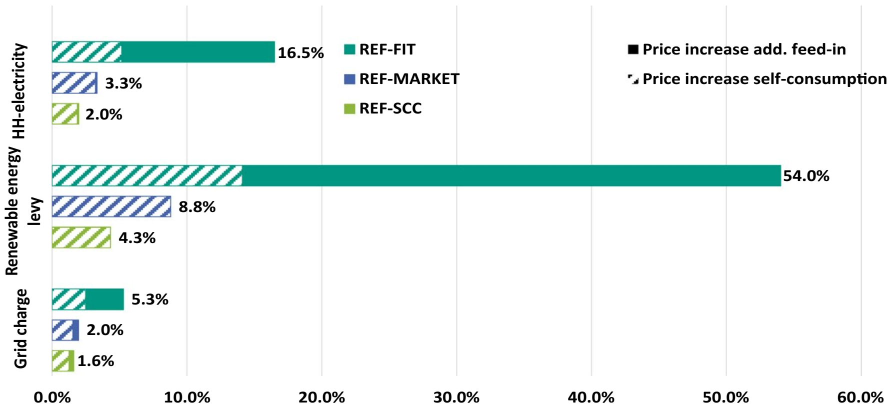

Fig. 4 Changes in electricity prices due to self-consumption or self-generation with consumption-based grid charges

even more strongly by 16.5%. This is mainly caused by a drastic increase of the renewable energy levy of 54% due to high additional PV feed-in. If only the price increase due to self-consumption is considered and additional PV feed-in is neglected, the renewable energy levy rises by 14.1%, the grid charge by 2.5%, and the total electricity price by 5.2%. This means that less than a third of the price increase results directly from self-consumption (see Fig. 4), while the major part of the price increase is caused by the additional PV-feed-in.

The role of the additional PV-feed-in is better visible when the REF-FIT scenario is compared with a scenario without feed-in tariffs (REF-MARKET). In the latter scenario, the share of self-consumption in the price increase rises to 96%. The only remaining differences in price increases between self-generation (with feed-in) and self-consumption (without feed-in) are increased grid charges and, subsequently, value added tax. These increases are caused by the avoided grid charges paid for the PV feed-in. In the MARKET scenario, self-consumption is responsible for an increase of 3.2% in final electricity prices. The increases of the components differ again, i.e. 8.8% of the renewable energy levy and 1.5% of grid charges. Considering both self-consumption and PV feed-in, the electricity price would increase by 3.3%, the grid charges by 2%, whereas the renewable energy levy remains the same. As can be seen, the differences between self-generation (with feed-in) and self-consumption (without feed-in) are very small in scenarios without feed-in tariffs. Therefore, they will not be mentioned below, but are listed in Table 6 in the Appendix.

The extension of the self-consumption charge, i.e. 40% of the renewable energy levy, to all household self-consumption (REF-SCC scenario) reduces self-generation and also lowers the rise of the price components. With a self-consumption charge, the electricity price rises by only 2.0%, the renewable energy levy by 4.3%, and the grid charges by 1.6%.

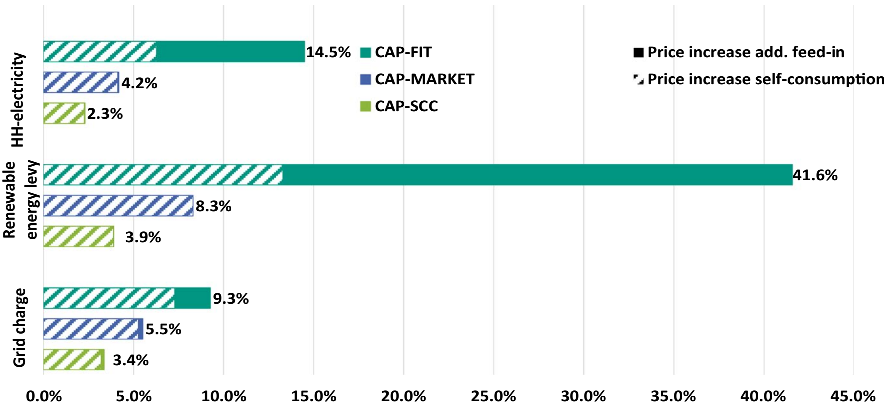

Fig. 5 Changes in electricity prices due to self-consumption or self-generation with capacity-based grid charges

3.2.2 Capacity-based grid charges

In case of capacity-based grid charges (CAP) instead of today's consumption-based grid charges, the maximum increase of the electricity price amounts to 14.5% (see Fig. 5), if surplus PV generation is remunerated through feed-in tariffs (CAP-FIT). Mainly due to lower PV feed-in, the rise of the renewable energy levy is smaller than with consumption-based grid charges (41.6% compared to 54% in REF-FIT). Although self-consumption is also lower, however, the grid charges increase more strongly (9.3% compared to 5.3%). This is due to the fact that the battery storage systems are used to reduce the peak load of the prosumer households and, hence, their contribution to the grid charge.

If the sole effect of self-consumption is analyzed excluding the effect of additional PV feed-in, it can be noted that the higher increase in grid charges (7.3% compared to 2.5% REF-FIT) even causes a higher increase in the household electricity price (6.3% compared to 5.2%), although all other taxes and levies increase more slowly with capacity-based grid charges.

In case of remuneration without feed-in tariffs (CAP-MARKET), the same explanation applies even for the price increases due to self-generation. Because of the higher increase in grid charges of 5.5% (compared to 2.0% in REF-MARKET), the overall electricity price increase is also higher (4.2% compared to 3.3%). This does not change, if a self-consumption charge (CAP-SCC) is introduced. Only the rise in the electricity price is slightly lower due to lower self-generation as a result of smaller system sizes. The grid charges increase by 3.4% (compared to 1.6% in REF-SCC) and the household electricity price by 2.3% (compared to 2.0% in REF-SCC). Again, the renewable energy levy increases less (3.9% compared to 4.3%) than with consumption-based grid charges. The results for all scenarios with capacity-based grid charges are summarized in Fig. 5.

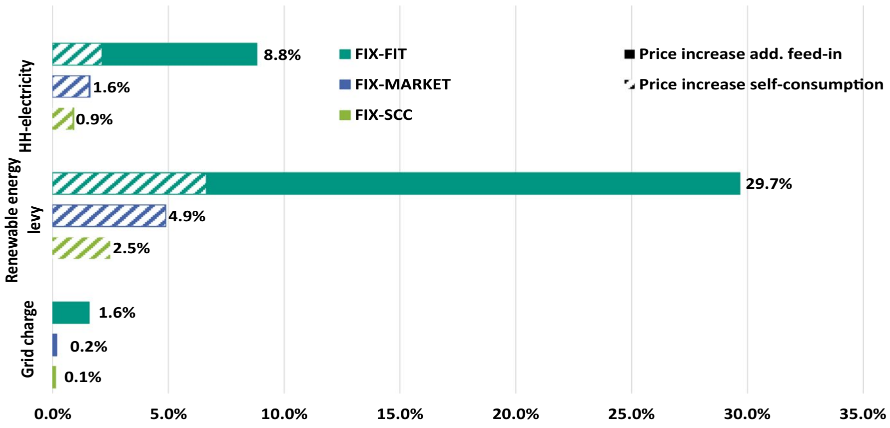

Fig. 6 Changes in electricity prices due to self-consumption or self-generation with consumption-based grid charges

3.2.3 Fixed grid charges

The inclusion of fixed grid charges into the basic charge of the electricity tariff results in the smallest effects of self-generation on the electricity price. The maximum electricity price increase in the scenario with feed-in tariffs (FIX-FIT) is 8.8%. The increases in the renewable energy levy (29.7%) and especially in grid charges (1.6%) are significantly smaller than with consumption- or capacity-based grid charges. This can be explained as follows: neither self-consumption nor peak shaving can be used to reduce the contributions to the grid charges. Combined with the lower consumption-dependent electricity prices and, hence, lower profitability of self-consumption, this leads to smaller PV and battery storage systems installed by the households, which, in turn, leads to lower feed-in and self-consumption amounts. As self-consumption does not have any effect on grid charges, the proportion of the price increase caused by self-consumption (24.3%) is also smaller. If only self-consumption is considered and the additional PV feed-in is neglected, the renewable energy levy rises by 6.6% and the electricity price by 5.2%.

Without feed-in tariffs (FIX-MARKET), the renewable energy levy increases by 4.9%, the grid charges by 0.2%, and the electricity price by 1.6%. The differences caused by avoided grid charges are so small that the electricity price increases due to self-generation and self-consumption are the same (see Fig. 6). This does not change with the introduction of a self-consumption charge (FIX-SCC). As in the scenarios with consumption- and capacity-based grid charges, the self-consumption charge leads to smaller system sizes, reduces feed-in and self-consumption, and consequently limits the electricity price increases. The renewable energy levy increases by 2.5%, the grid charges by 0.1%, and the total electricity price is subject to the smallest increase, i.e. only 0.9%. Hence, fixed grid charges combined with self-consumption charges lead to the lowest price increase. However, this comes with the lowest amount of exploited RES electricity at household level.

3.2.4 Comparison to industry rebates

One of the main reason why the different electricity price components increase at different rates when self-generation rises are industry rebates. According to Freericks and Fiedler (2017), the volume of industry rebates rose from 10.7 billion euros in 2005 to 17 billion in 2016. Around 11.5 billion were reallocated to other consumers, of which 6.5 billion were spent for the renewable energy levy. In the scenario with the highest price increase (FIT), a comparable amount (12.5 billion euros) is reallocated (10.8 billion from the renewable energy levy). Lacking contributions from self-consumption and additional feed-in remuneration amount to 15.8 billion euros. If only self-consumption is considered, only 3.8 billion euros are reallocated (2.8 billion from the renewable energy levy) to the remaining consumers and the total lacking contributions are 7.3 billion.

3.3 Comparison of effects on prices and self-consumption potentials with literature

Existing literature can be divided into two different categories: Forecasts of self-consumption potentials and calculation of possible effects of self-consumption on electricity prices. Therefore, first our results on self-consumption potentials will be compared with those given in the related literature.

In Dehler et al. (2015) the optimization model for the European electricity market, E2M2, is used to forecast self-consumption potentials from PV for German households in 2030. Total PV generation is expected to be 61.20 TWh, direct self-consumption is 10.14 TWh and could be increased to 13.86 TWh, if battery storage systems are used.

According to Figgener et al. (2017), current self-consumption from PV battery storage systems is around 165 GWh only and has a minimum influence on the electricity prices. In Friedrichsen et al. (2016) the effects of self-consumption on the grid charges are analyzed. For 2019, the authors expect a self-consumption of 1.9 TWh which increases grid charges by 0.05 ct/kWh. In Moshövel et al. (2015) the authors estimate that the maximum possible price increase due to self-generation and self-consumption would be around 3%. In this case, all existing and newly built household PV systems would have to be equipped with a battery storage system by 2020, resulting in autarky levels of 60% for each household and, consequently, in a nationwide self-consumption of around 8 TWh. Due to the limited time horizons, the above results are not comparable to the findings presented in this paper. The studies above analyze exploitable potentials until a specific year in future, while our analysis focuses on the total economic self-consumption potential independently of what share is exploited until a point of time in future. That is why our study yields a multiple of the potentials found in this literature.

A study comparable with ours can be found in Deutsch and Graichen (2015). According to the PV battery breakthrough scenario presented in Deutsch and Graichen (2015), up to 78 TWh of self-generation from PV systems on household rooftops can be reached by 2033. The authors assume self-consumption levels of 70% with battery storage systems, corresponding to 55 TWh of self-consumption. This would cause an increase of 1 ct/kWh (18.2%) of the renewable energy levy compared to the basic scenario for 2033. The highest self-generation estimates in our study, which are achieved with consumption-based grid charges and feed-in tariffs, are 136.4 TWh and therefore much higher, while the self-consumption potential of 44.5 TWh is lower. In scenarios with feed-in tariffs and therefore comparably large PV-systems, the self-consumption rate with battery storage systems is limited due to profitability. As mentioned by the authors, profitability was not the focus of their analysis and, hence, it was not considered. Consequently, the self-consumption rate of 70% is much higher than the 33% resulting from the household optimization in our study (Table 4).

Besides, there are different studies analyzing the price effect of self-consumption. In Gerblinger et al. (2014), autarky levels of 30% (prosumers with PV) or 70% (prosumers with PV and battery storage) are assumed for German households considering the average annual consumption of 3467 kWh for all households in Germany. The results are scaled up for four cases: a) households with existing PV systems, b) households with existing PV systems installed after 2009, c) 50% of the detached houses in Germany, d) 50% of all owner-occupied homes in Germany. The resulting self-consumption potentials range from 0.75 to 43.7 TWh per year. The lacking contributions to taxes and levies are then allocated to the remaining household

Table 4 Overview of self-consumption potentials and their impacts on the electricity price in literature

Source	Year	Self-consumption (TWh)	Price increase (ct/kWh)	Remark
Dehler et al. (2015)	2030	13	–	–
Figgener et al. (2017)	2016/17	0.165	–	–
Friedrichsen et al. (2016)	2019	1.9	0.05 (grid charge)	–
Moshövel et al. (2015)	2020	8	3%	All components reallocated
Gerblinger et al. (2014)	–	0.75–43.7	0.35–3.19	Reallocation to HHs only
Deutsch and Graichen (2015)	2033	55	1.0 (renewable energy levy)	–
Krampe et al. (2016)	2035	4.6–24	0.5 (renewable energy levy)	24 TWh includes agriculture and retailers/wholesalers
Bardt et al. (2014)	2014 + 10/15 years	6–105	2.39 (renewable energy levy)	Includes micro-CHP (combined heat and power)
This paper	2018 + 20 years	14.3–44.5	0.26–4.74 (with feed-in) 0.26–1.5 (no feed-in)	Increase of fixed charge converted for comparison

consumption (not to the electricity consumption of all other sectors). The effects of additional PV generation on the renewable energy levy in scenarios c) and d) are not considered. With increases of up to 0.35 ct/kWh (1.14%), self-consumption from existing PV systems has only minor effects on the electricity prices. Under the assumption of half of the detached houses reaching an autarky level of 30%, nationwide self-consumption would rise to 13.27 TWh, which would increase electricity prices by 0.86 ct/kWh (2.82%). With an increased autarky level of 70%, self-consumption increases to 30.97 TWh, resulting in an increase of electricity prices by 2.15 ct/kWh (7.06%). If instead of half of the detached houses, half of all owner-occupied homes in Germany would be able to reach that autarky level, nationwide self-consumption further increases to 43.68 TWh, causing an increase of electricity prices by 3.19 ct/kWh (10.5%). In our study the self-consumption potential also includes the semi-detached houses, which explains the higher self-consumption potential of 44.5 TWh compared to 30.97 TWh. However, the resulting household electricity price increase of 5.2% or 1.48 ct/kWh is smaller, because the lacking contributions are reallocated to the remaining consumption of all sectors rather than just the household sector, which is more compatible with the current price regulation.

Model-based forecasts of the nationwide self-consumption in 2035 are presented in Krampe et al. (2016). In a first scenario, only direct self-consumption without storage is considered. Self-consumption is expected to range between 4.6 TWh (if storage systems are built according to the EEG mid-term planning) and 14.5 TWh (if the complete economic potential is realized). With storage, the self-consumption potential increases to 38.6 TWh. However, only 20.3 TWh substitute grid electricity. The remaining 18.3 TWh are used for electric heat generation to replace gas or oil. In addition to the household sector, the segments of agriculture and retailers/wholesalers are examined. The self-consumption potential in those sectors is 3.8 TWh. Realization of the complete self-consumption potential of 24 TWh (excluding heat generation) would cause an increase of the renewable energy levy by 0.5 ct/kWh. In our study a comparable self-consumption potential of 22 TWh leads to an increase in the renewable energy levy of 0.42 ct/kWh. However, this result is obtained under a different regulatory framework with fixed grid charges. With consumption-based grid charges and feed-in tariffs, the self-consumption potential is significantly higher and amounts to 44.5 TWh. The authors mention that their approach of fixed system sizes leads to lower estimates compared to model-endogenous sizing. Furthermore, the assumed number of potential prosumer households is lower with 10.15 million compared to 17.7 million in our calculations.

In Bardt et al. (2014) the economically optimal size of a PV system, a battery storage system, and a micro-CHP system is calculated for various household sizes and then scaled up to calculate the Germany-wide self-consumption potential. Standard load profiles are used to characterize household consumption. Different scenarios with variations in the regulatory framework are examined. Without feed-in tariffs and exemptions from taxes and levies, self-generation becomes uneconomical. With exemption from most taxes and levies and feed-in tariffs, a total self-consumption of 105.3 TWh is expected. 4 TWh of CHP generation and 6.3 TWh of PV generation are fed into the grid. The renewable energy levy would increase by 38.3% or 2.39 ct/kWh (from 6.24 ct/kWh in 2014), if the complete self-consumption potential of 105.3 TWh was realized. Our results for the corresponding scenario (FIT) are much lower in both self-consumption potential (44.5 TWh) and increase of the renewable energy levy (1.48 ct/kWh and 5.2%). The much higher potential in Bardt et al. (2014) may be explained by the inclusion of apartment buildings as well as micro-CHP systems, which account for most of the self-consumption potential.

3.4 Discussion of reasonable tariff and charging schemes

Our calculations show, that the regulatory framework has a strong impact on the PV feed-in and self-consumption levels as well as on the resulting household electricity price. Therefore, policy can be used to limit the electricity price increase, but different and sometimes contradictory objectives must be considered.

An abolishment of the feed-in tariff strongly changes the effect of self-consumption on the electricity price and limits the price increase to a maximum of 4.2%. Without FIT, however, prosumers would solely optimize their PV systems for self-consumption. Only a small fraction of the available roof area would be used for photovoltaics, which may not be efficient in terms of reaching the RES targets (May and Neuhoff 2016). The future PV feed-in could drop by more than 80%, self-consumption by at least 25%. Policy makers should monitor whether the remaining self-generation is high enough to reach the emission targets. Under current legislation, feed-in tariffs for PV will be granted only until the total installed PV capacity reaches 52 GWp (Wirth 2017).

Another possible measure to reduce the impact of self-consumption on the electricity price is to change the allocation of grid charges. Fixed or peak load-based grid charges are often considered appropriate, because the electricity grid has a high share of fixed costs (Friedrichsen et al. 2016; May and Neuhoff 2016; Praetorius et al. 2017). According to Friedrichsen et al. (2016), legitimate expectations do not prevent to change the allocation of grid charges for existing prosumers. However, secondary effects should be considered. Excluding the grid charges reduces the consumption-based electricity price (per kWh) and might therefore reduce the incentives for energy-saving and energy efficiency measures (Kaschub et al. 2016; May and Neuhoff 2016). Moreover, the electricity costs for small households with a low level of electricity consumption might increase (Friedrichsen et al. 2016; Praetorius et al. 2017).

The inclusion of the grid charges in the basic charge of the electricity tariff has the advantage of being very simple and no additional metering being necessary (May and Neuhoff 2016). However, due to the lower electricity prices, the attractiveness of self-consumption is further reduced. Self-consumption drops by more than 40% and PV feed-in by more than 35% compared to consumption-based grid charges. Our calculations show, however, that it is an effective way to limit the electricity price increase. The price increases are about 50% lower than with consumption-based grid charges.

Some authors like Jägemann et al. (2013) or Speith (2014) recommend peak load-based allocation of the grid charges in order to include prosumers in the financing of the electricity grid and reduce the self-reinforcing effects of self-consumption.

In order to avoid the necessary additional metering (Regulatory Assistance Project 2014), circuit breakers could be installed in households with lower load limits (Kaschub et al. 2016). These capacity-based grid charges are used in France, Italy or the Netherlands (BNetzA 2015; Friedrichsen et al. 2016; Kaschub et al. 2016). Our results show that even though the self-consumption drops by 5–10%, the household electricity price increases due to self-consumption are still higher than with consumption-based grid charges. Households invest in larger storage systems in order to be able to reduce peak load. Consequently, their resulting contributions to the grid costs are lower than with consumption-based grid charges and the costs increase for the remaining consumers. Only in the scenarios with feed-in tariffs is the price increase in case of consumption-based grid charges higher than with capacity-based pricing, but only because of the much higher PV feed-in in the FIT scenarios. An advantage of peak load-based grid charges is, however, that they might reduce the costs for grid expansion, since the required grid capacity is mainly driven by the peak load (May and Neuhoff 2016).

To further decrease the impact of self-consumption and self-generation on the electricity price, the de minimis threshold for the self-consumption charge could be removed. That would mean that households would pay 40% of the renewable energy levy on self-consumed electricity independently of the size of their PV installation. While the total amount of self-consumption decreases by more than 14% in this case, the self-consumption rate actually increases due to smaller PV systems. The resulting price increases are at least 40% lower than without self-consumption charge. This limits the electricity price increase due to self-consumption and self-generation to a maximum of 2.3%. A disadvantage of the self-consumption charge is that its introduction might be complex and that from the customers' point of view, it is hard to understand why their self-produced heat from solar thermal systems is not charged, but self-consumption from PV systems is (Kaschub 2017). Besides, it is not clear how such a measure would depress the achievements in terms of RES expansion.

3.5 Discussion of benefits of self-consumption

As shown in the previous sections, increasing self-consumption could cause problems due to lacking payments of the different charges, taxes, and levies. However, self-consumption also has positive effects, which will be discussed briefly in this section.

Presently, the feed-in tariffs for small-scale PV systems are higher than the renewable energy levy for households. Hence, the avoided remuneration in case of self-consumption outweighs the missing contribution to the renewable energy levy. Furthermore, the purchase and installation of a battery storage system to increase self-consumption generates value added tax incomes. Different studies have shown, that currently the economic effects of self-consumption more or less equal each other out (Flaute et al. 2016; Hirschl 2015; Kairies et al. 2016).

Other indirect economic effects are harder to evaluate. This includes two effects on the wholesale electricity price: First, the additional PV feed-in could reduce the average wholesale electricity price through the merit order effect (Hildmann et al. 2015). Second, there could be a potential leveling of wholesale electricity prices due to lower PV feed-in at noon and lower household demand in the evening and night hours. Furthermore, local economy is strengthened. Most battery storage systems installed so far are from national manufacturers (Kairies et al. 2016). Additionally, jobs are created or preserved in installation and maintenance of PV or battery storage systems. Under an adequate regulatory framework, self-consumption from battery storage systems could also be grid-relieving (Kairies et al. 2016). According to Krampe and Peter (2016), the necessary expansion of the distribution grid is mainly driven by increasing PV feed-in. With a grid-relieving operational strategy, it is possible to reduce peak feed-in power to 40–50% with only little energy losses (Weniger et al. 2014). Thus, it is possible to integrate more PV systems without the necessity of grid expansion. Moreover, household battery storage systems can be used to provide ancillary services besides self-consumption (Stephan et al. 2016).

Germany has set ambitious targets for the expansion of renewable energies (BMU 2016). However, new wind farms are facing increasing acceptance problems (Quaschning et al. 2015). In contrast to this, solar energy has the highest acceptance of all renewable energies (Renewable Energies Agency 2016). Especially self-consumption bears the potential to increase the acceptance for the German energy transition (Krampe et al. 2016; May and Neuhoff 2016; Quaschning et al. 2015).

Finally, in order to fulfil the German emission targets, higher shares of sector coupling are necessary (BMU 2016). The high electricity prices in Germany often prevent the installation of electrical heating or warm water supply (Praetorius et al. 2017). With self-consumption, the installation of heat pumps or heating rods is often profitable (Flaute et al. 2016; Krampe et al. 2016). Since this self-consumption replaces gas rather than grid electricity, it reduces CO_2 emissions without having a direct effect on electricity prices.

4 Limitations and future work

In this paper, the most profitable self-consumption and self-generation levels for 88 empirical household load curves are scaled up to all (semi-) detached houses in Germany. The results more likely represent the upper bounds of the economic potential for households. It can be expected that not all rooftops are suited for PV e.g. due to orientation or shading. Moreover, the self-reinforcing effects of self-consumption are not taken into account when calculating the most profitable self-consumption and self-generation levels. Furthermore, lacking contributions to the different levies and fees are allocated to all different sectors as accurately as possible. While detailed data are available regarding the renewable energy levies, combined heat and power levies, §19 levies, and offshore liability levies, the grid charges had to be calculated based on average values. In addition, it is assumed that the electricity prices are influenced by decline of non-privileged end consumption and the remuneration of the additional PV feed-in only. Effects on wholesale electricity prices or changes in grid costs due to increased decentralized energy generation are not considered. Nevertheless, this analysis gives valuable insights into the dimensions of possible price increases based on the best available data. Despite the simplifications mentioned above, comparison of the different regulatory changes allows us to evaluate the impact of policies on the exploitable level of self-consumption and resulting price increases.

Similar trends with increasing self-consumption can also be observed in the commercial sector, thus increasing the self-reinforcing effects also for the household sector. Therefore, future studies could analyze the combined effects of both sectors. As mentioned above, the effects of self-consumption and self-generation on the wholesale electricity price were not taken into account. Therefore, it is planned to integrate household self-consumption into the electricity market model PowerACE (Keles et al. 2016) in order to examine mutual influence on changes of the wholesale electricity price and the electricity mix. It was assumed that the complete self-consumption and self-generation potential is realized in one year and that the grid costs are static. Future research could integrate investments in varying times and implement a grid model to analyze changes in grid costs due to increasing decentralized energy generation.

5 Conclusions

The current regulatory framework strongly benefits self-consumption, and falling prices for PV systems as well as for battery storage systems will lead to a high level of exploitation of self-consumption potentials. Self-consumption has many benefits, e.g. positive effects on the local economy, which are not quantified, but discussed in this paper, as well as on additional expansion of GHG-free solar power generation. However, as discussed in the introduction, self-consumption also causes increasing electricity prices for all other electricity consumers due to lacking contributions to the different taxes and levies. This leads to controversial discussions about policy changes. This paper contributes to the discussion by analyzing those changes and quantifying their impacts.

The results show that the regulatory framework has a strong impact on the resulting PV feed-in (5–92 TWh) and self-consumption levels (14–45 TWh), as well as on the self-consumption rates (32–79%). The resulting household electricity price increases range from 0.9 to 16.5%. Even in the most restrictive scenario (no feed-in tariff, grid charges included in the basic charge, and self-consumption charge), the self-generation potential still is more than twice the current power generated by household PV systems (Fett et al. 2018).

Moreover, our calculations show that even in the scenario with the highest electricity price increase, the industry rebates in the amount of up to 17 billion euros (Frericks and Fiedler 2017) are still higher than the lacking contributions from self-consumption and additional feed-in remuneration (15.8 billion euros). The higher share of the increase in this scenario is caused by additional PV-feed-in remunerated by feed-in tariffs. If only self-consumption is considered, the maximum electricity price increase is 6.3% in a scenario with capacity-based grid charges. In this case, the lacking contributions from self-consumption sum up to 8.9 billion euros, of which 4.7 billion euros are reallocated to the remaining electricity consumption from the grid. For this reason, the introduction of capacity-based grid charges, which are often considered a fair way for prosumers to participate in the financing of the grid, might actually lead to higher price increases due to self-consumption, as long as future grid expansion is not reduced considerably.

Policy makers should decide on a tariff and charging scheme, which limits the price increases to a tolerable level, but still incentivizes rooftop PV generation to a level that is high enough to reach the emission targets. Moreover, possible side effects have to be considered, such as e.g. increased electricity costs for small households or reduced incentives for saving electricity in case of higher shares of fixed components in the electricity bill.

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Appendix

See Tables 5, 6 and Fig. 7.

Table 5 Data basis for calculations

Data	Source
Electricity prices for the different sectors	BDEW (2016), BNetzA (2016)
EEG-, CHP-, Offshore-, §19.2 levies	German TSOs (2015a, b, c, d)
Net electricity consumption per sector	BDEW (2017)
Current self-generation in the industrial sector	BDEW (2017)
Number of (semi-) detached houses in Germany	Destatis (2017)
Self-generation and self-consumption for households	Kaschub (2017)

Table 6 Changes of the different components of the electricity prices due to self-generation or self-consumption

	FIX-SCC	FIX-MARKET	FIX-FIT	CAP-SCC	CAP-MARKET	CAP-FIT	REF-SCC	REF-MARKET	REF-FIT
Self-generation									
Grid charges (%)	0.1	0.2	1.6	3.4	5.5	9.3	1.6	2.0	5.3
Value-added tax (%)	0.9	1.6	8.8	2.3	4.2	14.5	2.0	3.3	16.5
Concession fee (mln €)	238.1	278.4	372.2	364.3	458.2	701.0	402.9	483.0	738.4
Renewable surcharge (%)	2.5	4.9	29.7	3.9	8.3	41.6	4.3	8.8	54.0
CHP surcharge (%)	5.8	6.9	9.4	9.2	11.9	19.4	10.3	12.6	20.7
§19 surcharge (%)	5.8	6.9	9.4	9.2	11.9	19.4	10.3	12.6	20.7
Offshore wind surcharge (%)	3.7	4.3	5.9	5.7	7.3	11.7	6.4	7.8	12.4
Electricity tax (mln €)	294.0	343.8	459.7	449.9	565.8	865.7	497.5	596.4	911.8
Total (%)	0.9	1.6	8.8	2.3	4.2	14.5	2.0	3.3	16.5
Only self-consumption									
Grid charges (%)	0.0	0.0	0.0	3.2	5.3	7.3	1.3	1.5	2.5
Value-added tax (%)	0.9	1.6	2.1	2.3	4.1	6.3	1.9	3.2	5.2
Concession fee (mln €)	238.1	278.4	372.2	364.3	458.2	701.0	402.9	483.0	738.4
Renewable surcharge (%)	2.5	4.9	6.6	3.9	8.3	13.3	4.3	8.8	14.1
CHP surcharge (%)	5.8	6.9	9.4	9.2	11.9	19.4	10.3	12.6	20.7
§19 surcharge (%)	5.8	6.9	9.4	9.2	11.9	19.4	10.3	12.6	20.7
Offshore wind surcharge (%)	3.7	4.3	5.9	5.7	7.3	11.7	6.4	7.8	12.4
Electricity tax (mln €)	294.0	343.8	459.7	449.9	565.8	865.7	497.5	596.4	911.8
Total (%)	0.9	1.6	2.1	2.3	4.1	6.3	1.9	3.2	5.2

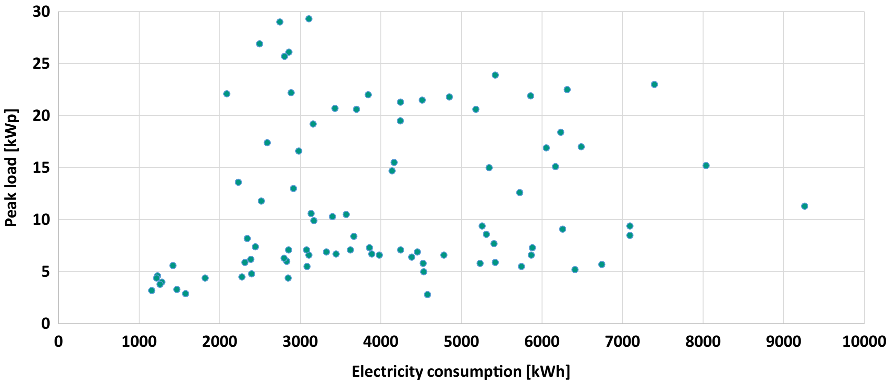

Fig. 7 Yearly electricity consumption and peak load of the empirical household load curves

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