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# The Economic Potential of Grid Defection of Energy Prosumer Households in Germany

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**Abstract**

The fast decline in solar photovoltaics (PV) prices has brought grid parity or near grid parity to household systems, with alternative energy sources generating power at a cost less than or equal to the price of the power from the electric grid in many countries. This price decline, also aligned with a reduction in battery prices, has prompted new societal, scientific, and political discussions about the possibility of installing a PV-battery system and "unplugging from the grid" or "living off-grid." We present a new decision support model to assess the economic feasibility of defecting from the grid. In addition, a sensitivity analysis is carried out for critical parameters such as technology costs, different load profiles, and feed-in tariff. From an economic perspective, a wide spread of autark households does not seem to be a realistic projection of the future. Our findings indicate that, for Germany, leaving the grid is not the best economic choice, and that retaining the grid connection could be more profitable simply minimizing the electricity purchased from the grid by installing an optimized size of the PV-battery system. The system's financial feasibility can also be achieved with new forms of energy negotiation, such as peer-to-peer (P2P) trading or household clustering, allowing prosumers to sell their excess energy locally as an alternative to grid feed-in.

**Keywords:** off-grid, autarky, PV-battery hybrid system, private household, death spiral, self-sufficiency, prosumer, peer-to-peer trading

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# 1 Introduction

In recent years, the considerable decrease in the cost of solar photovoltaics (PV) systems has caused strong alterations in the German electricity supply mix. With the commoditization of solar panels, inverters, and associated components following the same path, PV system installation has become quite popular [1]. The possibility of generating power on the demand side and converting from a "consumer" to a "prosumer" (producer-consumer) has numerous advantages in terms of energy efficiency. Besides that, prosumerism can reduce power losses in the electric grid, the carbon footprint of households, reserve energy and capacity needs, and support the develop of smart grid structures [2].

Along with other forms of distributed generation and battery energy storage, the topology and operation of future electricity networks may become even more different from what it is today [3].

The fast decline in PV system prices has also brought grid parity - when alternative energy sources generate power at a cost that is less than or equal to the price of power from the electric grid - or even lower in many countries [4]. For instance, in many locations, it is feasible to install PV systems at the household level even if grid supply is available [2, 5, 6]. Since solar energy is not available all the time, the best way to improve self-consumption is through storage of excess energy. Although the high cost of batteries in the past has traditionally prevented its use, the price of electricity storage components started to decline in recent years. It is anticipated that battery technology may follow the rapid downward price trajectory of PV as the economies of scale and supporting policies increases [7–9]. In addition to that, in light of several new technical improvements such as black silicon, the International Renewable Energy Agency (IRENA) predicts that PV system component prices might fall by another 60% over the next decade [10].

The new trend in PV and energy storage technologies incentivizes customers to go beyond just being prosumers. Grid defection or home autarky, where utility customers self-generate their electricity, without being connected to the public grid any longer, is already a reality and has more potential to expand [11].

Due to the variable nature of renewables, there is a misconception that consumers will still have to stay connected to the grid. Moreover, the reliability of the German electricity system is among the best in Europe [12], giving no reasons for customers to rely on other sources of power supply. However, other reasons push consumers to defect from the grid [5], such as the demand for cleaner energy, the pursuit of better economics, frustration with the utility and/or grid operator, and regulatory changes. Other studies, such as [13], also confirm additional reasons, such as avoiding high electricity prices, a desire for self-sufficiency, and simply wanting to lead a more sustainable lifestyle.

In the German case, electricity price increases also escalated adoption of PV systems. Germany has been the world leader in installed solar power per capita, and the residential sector is responsible for 15% of the installed capacity [14]. Furthermore, around half of all new residential solar PV systems are now installed in conjunction with a battery [15] which makes Germany an ideal place for a case study.

Based on the identified gaps in the literature, this paper adds to the knowledge in the financial analysis of the economic viability of off-grid residential buildings in Germany. The expected results from applying the proposed model is to support decision-makers regarding the adoption of a hybrid PV-battery system, the possibilities regarding size, the investment needed, and the expected return on investment. Since the topic of grid defection in Germany was already covered in the literature [16–18], we focus on two main aspects that distinguish our study from previous ones: First, other models exclude the grid connection in their assumptions, making their financial analysis disconnected from the grid. In our study, the main goal of a household may not be to disconnect from the grid but to be completely independent (100% autarky). Therefore, we maintain the grid connection, thus enabling to use the excess energy for grid feed-in, i.e. selling at the prevailing FiT, creating a source of revenue for electricity that is ignored in other models. Second, following the same idea that the key for autarky models is to find a way to deal with the excess energy, we added to the literature on prosumers and smart grid structures with empirical data. By doing so, we approach two different topics that could help new potential businesses. Again, by analyzing what could potentially increase the profitability of autark systems, we used the P2P structure as a source of revenue for the excess energy.

In this study, we investigate possibilities on how to manage the high amount of excess energy in such systems by analyzing possible solutions emerging from using new prosumer markets [19]. The "Prosumer market" is a definition that involves many different arrangements, such as peer-to-peer (P2P), clean/citizen energy communities (CEC), energy clustering, microgrids, and virtual power plants (VPP). Although with different goals and rules, we treat these notions here equally subsuming them as any smart-grid structure enabling local community members with PV and/or energy storage systems to sell their self-generated energy to individual community members or the community they are part of without the need of an intermediary [20]. We believe the exploitation of these structures will benefit the effects of scale. Moreover, capitalizing on the excess energy can potentially result in positive side effects such as new investments in local PV and energy storage systems. These effects can lead to an elevated share of renewable electricity in the (local) grid, as well as reduced peaks in the demand load, potentially (*cet. par.*) resulting in lower energy system costs overall [20].

It is also worth mentioning that in the literature many different concepts have been introduced that deal with prosumers self-generating 100% of their energy (often on balance only, i.e. not necessarily defecting from the grid) [2, 5, 11, 21]. However, note that in this paper the terms "autarky", "autonomy" and "self-sufficiency" are considered plainly as synonyms.

The remainder of the paper is organized as follows. In Section 2, the related literature is reviewed. In Section 3, the model and data used are described. In Section 4, the results and main findings are reported and discussed. Section 5 concludes.

# 2 Literature review

The study of grid defection is particularly hard since data on households are normally reported from the perspective of being connected to the electric system, rather than disconnected [22]. Hence, more studies are needed to find out which types of households, and where and why households have chosen to live off-grid [23].

Despite the need for more studies, it is important to notice is that, although the grid defection might seem an individual alternative due to financial and personal choices, it might not be economically beneficial for the whole community. As grid defection happens, more prosumers leave the grid, and the network costs will be distributed among fewer and fewer customers. Likewise, the separate network charges can be expected to increase; consequently, there is an increase in electricity system charges, reinforcing the interest of even more consumers to leave the grid, referred to as the "death spiral" for the grid [24]. If every household adopts a PV aiming at full time self-sufficiency, the current utility business model can implement additional market interventions to address the death spiral problem. These interventions aim at reducing the ratio between the electricity tariff and the cost of domestic hybrid PV-battery systems. These measures can include: the internalisation of the transmission/distribution costs involved the electricity flows of a household, increasing the transition costs of solar PV systems; the modification of compensation methods to prosumers (i.e. from FiT to net metering); and the introduction of back-up fee, already applied in countries, such as in Spain, where prosumers have to pay fees on solar self-consumption [25].

In recent years, a growing number of researchers have investigated the economics of off-grid solar battery systems in detail, for example, [2] showed that, for a 100% off-grid system, the approach is typically asymptotic. An increasingly higher capacity of the PV and battery system is required to achieve full independence for the last few high demand/low solar operating hours in the year. The conclusion is that such a large system is costly and leads to a high proportion of curtailed electricity for much of the year (in the absence of any other use of the generated electricity). Although several PV-battery systems show a positive NPV after ten years, due to site limitations none of these were capable of providing 100% grid independence.

Off-grid systems were also considered in precarious situations where no access to the grid exists. For instance, [26] analyzed the economic feasibility of small-scale systems for rural electrification in Africa. The author also compared the electrification costs of wind, solar PV, and diesel generator systems across that continent. The results show that PV is often the least-cost technology over the largest continental area, followed by diesel and wind.

Observing the same idea, [27] investigated the barriers to the diffusion of hybrid PV-wind mini-grids and calculated the techno-economic potential of these systems in Kenya. The results show that PV-wind hybrids have a large technical and economic potential in all countries in principle, but that the high costs of implementation are still a major barrier.

[28] also investigated the potential of using off-grid hybrid energy systems for private industries in Nigeria. Using the Hybrid Optimization of Multiple Energy Resources (HOMER) model, they found that these systems are economically viable for a wide array of industries. Moreover, the Levelized cost of energy (LCOE) is lower for every sector analyzed with the inclusion of solar PV, even lower with the coupling of batteries, and more reliable than the current grid-provided electricity.

As well as in developing countries, grid defection is also recurrent in developed countries for several reasons. Australia is a country drawing attention to this topic mainly because of two factors: it possesses the highest proportion of residential PV in the world, and it is has been a focal point of marketing for residential battery storage by international companies such as Tesla, LG Chem, and Samsung, with recent data revealing that 20,789 batteries were installed by households in Australia in 2017, up from 6750 in the previous year [29].

[30] also studied the technical and economic feasibility of grid defection in Australia. Using a mixed-integer linear optimization (MILP) model, weekly simulations were performed to investigate the optimal PV and battery size range, focusing on the week in a year with the lowest solar PV output and the highest demand as input. The simulation results show that the cost for the off-grid PV-battery hybrid system is relatively higher than staying grid-connected. However, the PV-battery system is economically feasible for customers willing to accept lower reliability in exchange for a lower cost, but still expecting a reliability level of up to 80%.

Studying grid defection in the northern United States, [6] analyzed a system consisting of a PV array, battery storage, and natural gas generator for medium and small-size enterprises. Using HOMER, they conclude that it is already technically and economically viable for all scales of commercial customers of a utility to install a solar PV, battery, and natural gas hybrid electricity system. However, it is important to mention that price fluctuations can influence the system's viability when relying just on natural gas.

[11] studied the incentives for both load defection and grid defection in the US residential sector. By developing a model for the optimal sizing of an off-grid system, the authors found limited ability of solar PV/home battery storage systems to substitute for grid services, apart from technical barriers, the economic results show that off-grid systems are shown to be more expensive overall compared to the traditional hierarchical power supply system architecture. However, 1% of the households might disconnect from the utility service in a scenario that accounts for future off-grid costs and updated tariff designs. Customers with very low electric demand would have the strongest incentive to defect from the grid in a high fixed-charge environment. If customers relax their reliability

requirements, more grid defection is possible for between 1% to 7% of the households.

# 3 Methodology

This study uses a financial model to investigate the feasibility of grid defection in Germany. We utilize an optimization method to identify the most profitable PV-battery system size combination that still allows a private household customer to cover 100% percentage of their electricity needs from on-site generating. We used the German city of Munich, in the southern federal state of Bavaria, in a case study that shows how to integrate both LCOE and net present value (NPV) in our model.

The focus is on the city of Munich, because of its location in the South of Germany and where solar irradiation is higher than in the rest of the country. At an average of 1,200 kWh/m$^2$, a 1 kW$_p$ PV system generates on average 1,190 kWh of electricity per year [31]. In the north of Germany, in comparison, solar irradiation amounts to 1150 kWh/m$^2$, and an optimally inclined PV system is expected to produce 1,000 kWh per kW$_p$ of installed capacity [32]. Given that our model results depend heavily on the level of solar irradiation, the difference between locations in the North and the South of Germany is approximately 20–25%, influencing directly the model results.

The analysis includes several houses regarding energy consumption and many different residents. We believe that this range consists of all possible different load profiles in Germany, and broadly also in Europe, and so can be used also for comparison with other countries. In Europe, for instance, according to the Association of the German Energy and Water Industries *(Bundesverband der Energie- und Wasserwirtschaft - BDEW)* [33], the annual average electricity consumption of a German household is 3079 kWh. Therefore, we consider this value and others in our models, trying to capture as many household profiles as possible.

We restricted our analysis to owner-occupied family homes because residents of these housing units have higher energy consumption and income than others, and thus a personal incentive for investing in energy infrastructure for their houses. Besides, an autarky system will require a larger area for installation, which can be a barrier to apartments. We have considered four main steps for our analysis:

1. to estimate electric consumption of the households;
2. to estimate the size of PV and battery systems required to achieve an off-grid house;
3. to estimate the necessary investment costs needed to achieve 100% electricity self-generation, and to maximize the NPV of this system regarding current market values, such as investment costs and feed-in-tariffs (FiT);
4. to apply a sensitivity analysis with the main variables of the system and how we expect new arrangements to improve the financial return.

Concerning the first step, choosing load profiles could lead to distinct results based on the input data. This paper uses synthetically generated load profiles where the load of each type of household considered is simulated individually. We use standard load profiles for households' electricity consumption in Germany at an hourly resolution for a year based on the Load Profile Generator (LPG) [34]. This model considers the geographical and climatic characteristics of different regions in a stochastic approach. The software is publicly available and has been used extensively in different studies in the past [35–39]. Aiming at different compositions to cover as many situations as possible that are close to real-life problems, we studied the following types of family households:

- 2 adults;
- 2 adults and 1 child;
- 2 adults and 2 children;
- 2 adults and 3 children;
- 2 adults, 2 children, and 2 seniors.

Concerning how the inhabitants spend their time, we follow the load profile literature in which the occupancy model has been applied, using behavioral aspects and time-of-use of electrical appliances in their models. The adults are assumed to work full-time, spending the evening at home, whereas the children spend their day first at school (weekdays) and then in the house, and the seniors are assumed to spend most of their time at home. [40]. While there is a certain logic in the behavioral pattern of adults and children, since their activities (work and school) influence heavily their occupancy patterns, this is less clear concerning the behavior of senior citizens. However, the literature supports the idea that senior citizens spend more time in their residence and numerous studies have made the same assumption [41–44].

Concerning step 2, the main problem when optimizing the size of a system is, on the one hand, that if the size is underestimated, then the system will not generate enough energy, and the consumer will face a blackout. On the other hand, if the system is over-dimensioned, with a larger PV-battery capacity than necessary, both the investment costs and the percentage of curtailment will increase unnecessarily, thus affecting the financial return negatively. For simplicity reasons, we assume here that neither space to install nor investment capital are a limiting factor to these sets of household occupants. However, it is important to notice that earlier studies tackling the same topic included both battery and solar PV size in their restrictions. An average-sized household roof (of a two story home of 250 $m^2$ of living space) could accommodate a maximum of some 20 kW of solar PV capacity, and up to 84 kWh of a battery energy storage system similar to a Tesla Power Wall [11, 45].

The generation profile for the rooftop solar PV system is obtained from the National Renewable Energy Laboratory online weather database provided by the U.S. Department of Energy [46]. The PV generation profile obtained has an hourly frequency and uses a series of solar irradiation data recorded at all hours of all days for one year to compute the expected output for a given PV system. For this location, a system loss of 14% was assumed with both azimuth and slope angles optimized corresponding to a southward orientation and a tilt of 30° [47]. Both models, although from different sources, have an hourly resolution and use the same weather condition for computing the hourly electricity generation and load profile. With that, it is possible to merge the two data sets and match the hour load profile with energy generation.

The dimensioning of the battery size allows the independence of a house from the electrical grid during the whole year, especially during the winter season when the solar irradiation is considerably lower. In contrast, especially during the summertime, a great part of the electricity is expected to superfluous. In Germany, prosumers can sell their electricity to the grid in return for a guaranteed FiT. Consequently, in our analysis, the excess energy will be sold and used as a source of revenue in the financial model. Later, in step 4, we will trade the electricity to other consumers instead of using the grid FiT.

The lifetime of the battery was assumed to be ten years. We use a lithium-ion battery, and for minimum degradation, the battery state of charge (SOC) will vary from 15%-85% [48]. Within this period studied, we expect two replacements of the battery, each estimated at 60% of the original price including installation costs. The degradation of the PV unit is considered to be 0.05% every year and the battery efficiency is assumed to be 95% [49]. In addition, we assume there is no limitation of the battery in terms of power capacity. This issue has been addressed before [11], but since our analysis involves domestic systems, and the battery is always used gradually, the usual c-rate of commercially available batteries can deal with daily activities of charging/discharging.

Discussions about the controlled operation of hybrid systems have been presented in the literature (e.g. [50–52]). Therefore, it is not the goal of this paper to dig into this literature. Here, we control charge and discharge a battery storage unit each hour using a simplified heuristic: whenever the local electricity generation is available, it should meet a household's demand. After matching the household's energy requirements, the remaining energy is used to charge the battery. After this step, we refer to it as "excess energy", – which is fed into the grid as a source of revenue that is determined by the prevailing, guaranteed FiT schemes. At this point, there is no possibility of buying energy from the grid, so the electricity supply system of the household must be completely autark, and the total supplied load (TSL) must be at least 100%. With this heuristic control, we increase the quantity of locally consumed energy from on-site generation while simultaneously minimizing the amount imported from the grid. In step 4, instead of feeding the excess energy into the grid at some guaranteed (but typically lower) FiT, the excess energy is sold to other local energy consumers (for the results see subsection 4.3).

The expected NPV of an investment in a PV-battery system is calculated as the potential benefit of the system minus costs. Regarding this, the system usually requires large capital investment for electric parts and support structures, whereas operation and maintenance (O&M) costs are relatively low [53]. Therefore, the benefits here are defined as the revenues from the surplus sold to the grid in terms of FiT, the difference between the LCOE from the autark system, and the price of electricity from the grid.

The objective function maximizes the NPV for different households with 100% TSL and is calculated as follows:

$$NPV = -I_0 + \sum_{n=0}^{N} \frac{CF_s + CF_{fit}}{(1+i)^n}, \tag{1}$$

where $I_0$ includes the investment costs for both the PV and battery system and $CF_s$ denotes the cash flows from the energy cost savings of the system, here defined as the difference between electricity prices from the grid and the LCOE cost of the system, showed in equation 2. $CF_{FiT}$ comprises the revenue from the electricity fed into the grid and its remuneration FiT in year $t$. The $CF_s$ cash flow originated from the difference between the national grid system electricity cost and the household PV-battery system is calculated as:

$$= \frac{\sum_N^{t=1} \frac{IC_t^{PV} + O\&M^t}{(1+r)^t}}{\sum_N^{t=1} \frac{EG_t^{PV}}{(1+r)^t}} + \frac{\sum_N^{t=1} \frac{IC_t^{Bat}}{(1+r)^t}}{\sum_N^{t=1} \frac{ES_t^{Bat}}{(1+r)^t}}, \tag{2}$$

where $EG$ includes the PV electricity generated, $IC$ is the investment costs regarding PV in the year, $OM$ are the operation and maintenance costs, and $ES$ includes the electricity stored in the battery; $IC$ is the investment costs of the battery (including the replacement of batteries), and $r$ is the discount rate. The remaining data necessary for the model is given in Table 1.

Table 1
*Parametrization used in this study*

| Category | Price | Sources |
|---|---|---|
| PV cost | 800 €/kW$_\mathrm{p}$ | [14, 31] |
| Battery cost | 800 €/kW | [14, 31] |
| Inverter | 0.17 €/$W_p$ | [14] |
| Operating expenses | 2.5% of CAPEX | [14, 31] |
| Installation costs | 8% of the system cost | [54] |
| Discount rate | 3.50% p.a. | [55] |
| Project lifetime | 30 a | Up to 3 battery replacements |
| Feed-in-tariff | 8.91€-ct per kWh | [12] |

After optimizing the PV-battery hybrid system for 100% TSL, in step 4, we propose a sensitivity analysis to value residential electricity-autark systems for several different scenarios. The first proposed framework aims at identifying an alternative use of excess energy instead of feeding it into the grid at the prevailing FiT. Next, we show how the system's profitability would be affected if a smart-grid arrangement connecting many houses were available between prosumers and consumers (thus enabling P2P trading). For this scenario, we replace the traditional low value of the FiT with the current price of residential electricity in Germany and see how this affects revenues and the final economic result of the system (from a household/micro level perspective).

The second framework evaluates the financial outcome of different levels of TSL. Starting from the initial group of 100%, we assess the NPV with 99%, 95%, and 90% TSL. For this step, we follow the same rule as in step 2 but now open the possibility to buy energy from the grid in situations where neither PV generation nor battery can supply the load demand. All the steps are taken and the operation of the system is illustrated in Figure 1.

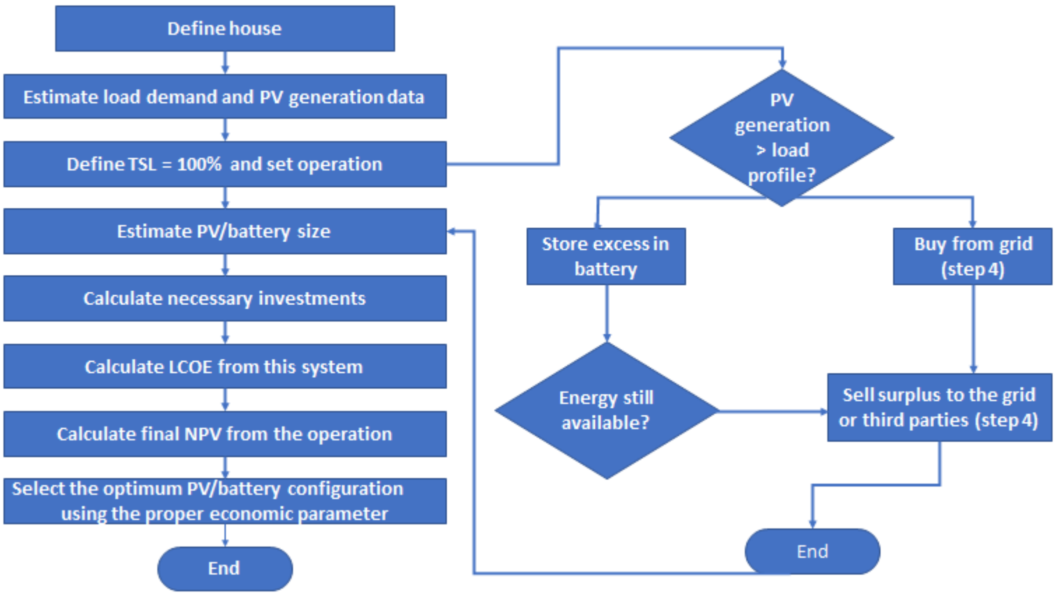


FIGURE 1
*Flowchart with procedural steps*

# 4 Results and discussions

## 4.1 Estimation of electricity consumption of the households

The residential buildings (detached houses) with different occupancies analyzed are located in Munich, in the South of Germany, where solar irradiation is more favorable than in most of the rest of the country. The electricity consumed during a whole year (January 1 to December 31) for different household types is shown in Figure 2.

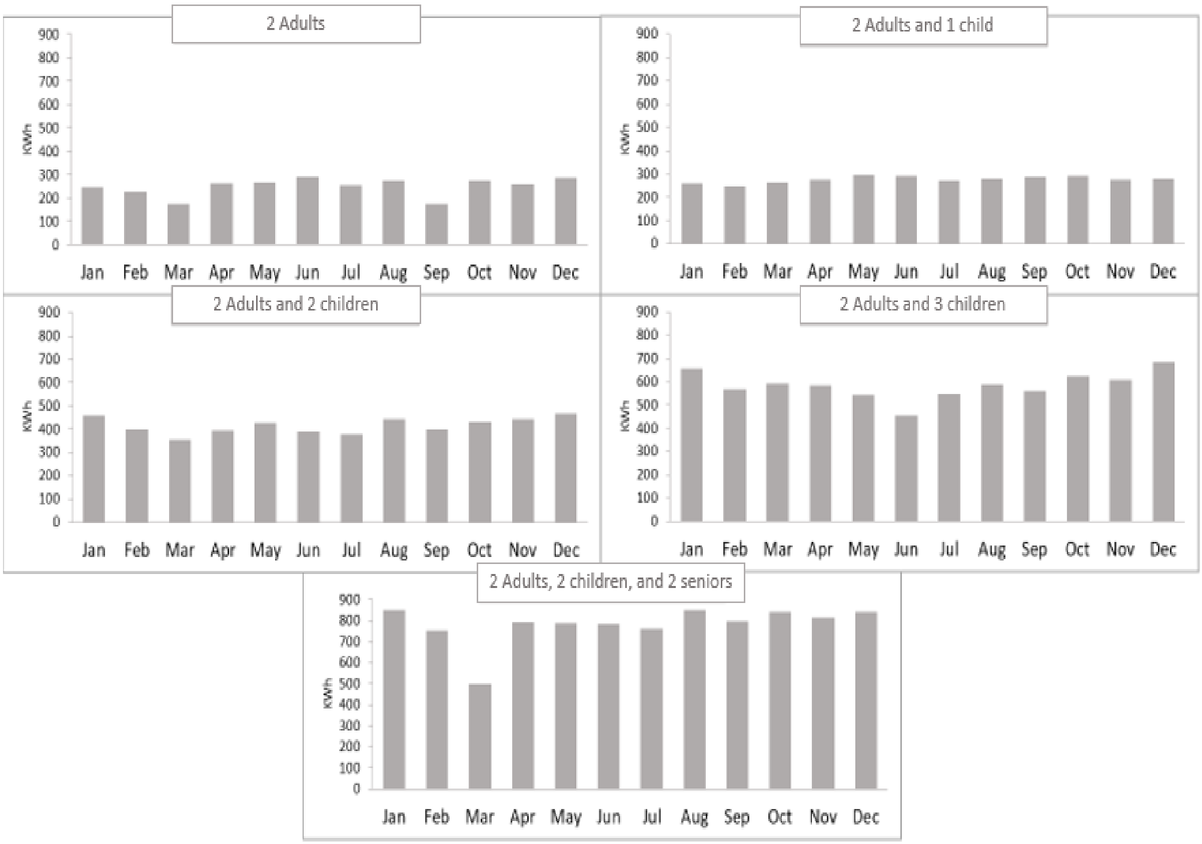


Figure 2
*Monthly electricity consumption over an entire year for all five types of households considered*

For all types of households considered, the electricity load depends on the day of the week and the month. In addition, several weather variables are likely to affect electricity consumption, such as temperature and daylight [56, 57].

As Figure 2 shows, consumption does not follow a clear pattern, for some cases we see a trend of a slight decrease in consumption during the summer months and an increase during wintertime. Note that the values inside the same profile do not deviate much because our analysis considers electricity consumption only. If we had considered heating costs, the graphs would be very different; in our case, the increase in consumption in the winter months is mainly because of fewer hours of sunlight. The idea is that during days with less daylight, electricity demand increases. Demand increase is strongest in the evening because at 6 pm in the summer, people do not need to use lighting, while in wintertime, they do, and people also spend more time outdoors during summer than in winter [57–60]. For certain countries, nighttime consumption is higher in winter, mostly due to off-peak heating, or in summer because of air conditioning (e.g. Italy and Spain) and country-specific lifestyles (e.g. eating late and staying up until late at night). In Germany, during winter we noticed an evening peak similar or even higher than the morning one, most probably caused by lighting, cooking and home appliance use (i.e. staying more at home during the cold season) [59].

Among the other variables that can influence electricity consumption is floor area [61] and the number of residents [62]. In our example, it is the case that the higher level of consumption comes from houses with more residents and larger sizes. The only exception can be noticed when the residents are not at home, which may be the case during absence because of vacation.

Besides that, it is also important to highlight that the aim of a vast body of literature is the studying and modeling of electricity consumption and that the authors of the current study do not aim to extend this literature. However, it is important to note that several factors might influence consumption. The main idea behind this study is not to discuss this but to gather as many diverse profiles as possible to test several types of households under grid defection.

What can be observed is that electricity consumption increases at a lower rate when the number of household members doubles [63]. This increase can be explained because, for some activities, home appliances are complements. For instance, for cooking, it can be expected that some meals are cooked and eaten together. During cooking, about half of all appliances are used jointly in a household [64]. Besides that, the amount of time one person spends at home [63, 65], employment conditions, and gender [66] influence electricity consumption. Moreover, other behavioral and motivational variables matter, such as purchases, e.g., the number and efficiency of appliances, and intensity of use of the appliances [63, 65].

Given the electricity profiles of each household, we estimate the size of PV and battery systems required to achieve an off-grid house next. For this step, the state of charge was set to 10 kW for all house types. The optimal size of the PV-battery system with a 100% TSL and the best financial result are shown in Figure 3.

As can be seen in Figure 3, there is a great discrepancy between the ratio of solar PV capacity and battery capacity size. In Germany, most of the PV system adopters who want to maximize their self-consumption usually choose a battery with a relatively small energy capacity. Typically, a 10 $kW_p$ PV system is equipped with an energy storage capacity of 7 kWh, or a 5 $kW_p$ PV system is combined with an energy storage capacity of 5 kWh [67]. Our results show that the current standard size of PV-battery hybrid systems is far from enabling 100% self-sufficiency, although the wider adoption of batteries over the past years (more than every second PV system sold has been equipped with a home battery unit [67]) indicates that households want to maximize their self-consumption.

Notice that this ratio does not exist at any of the analyzed home types in our study. One can observe that, for an autark house, the total load profile is one of the indicators of the system size; the distribution of the peak loads is more relevant since they are the bottleneck of the system, requiring large investments for benefitting just short periods of the day.

Next, we use our house occupancy profiles as examples. The household with two adults needs a 46 $kW_p$ solar PV system and 11 kWh energy capacity battery; the household with

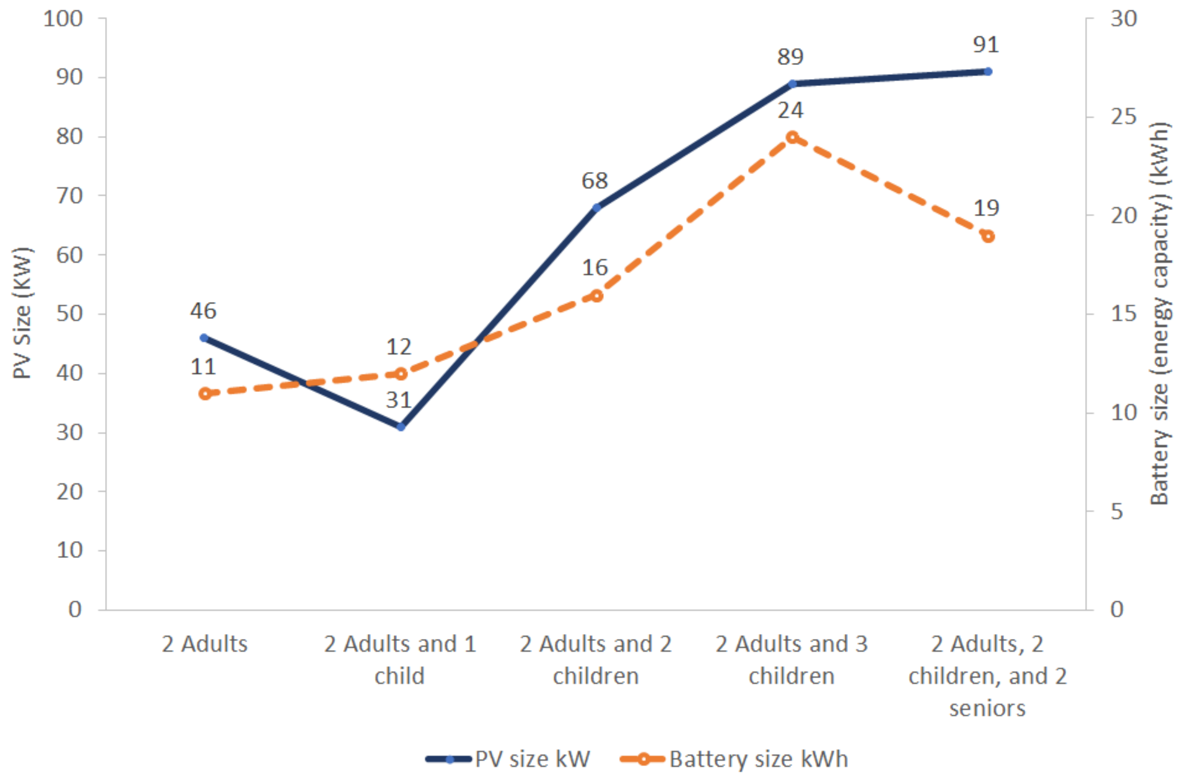


Figure 3

*Optimal required size of the PV and battery for all five types of households considered*

two adults and one child needs a 31 $kW_p$ solar PV installation and 12 kWh of battery energy capacity. However, the great difference between the system size is to cover just a small gap between the two household electricity consumption levels.

If the energy system of the home occupied by the two adults has an equal size to the two adults with one child (31 $kW_p$ and 12 kWh energy capacity battery), just 30 hours of the entire year would not be covered by self-generation. Therefore, we assume here that the marginal investment to cover the last hours of the system is the highest. Consequently, we can conclude that always aiming for a 100% TSL might cause significant financial loss.

## 4.2 Investment costs needed to achieve 100% TSL

To calculate the LCOE and the NPV of the mentioned systems, we first need to estimate the necessary investment costs for each type of home considered. The results are shown in Figure 4.


FIGURE 4
*Necessary initial investment costs for all five types of households considered*

We can conclude that the investment level does not necessarily follow the number of residents. Although the energy consumption might correlate with the number of residents, and can thus be represented by a linear relation, that does not occur for the system investment. One of the reasons is that the assets in an autark system do not necessarily follow the average energy consumption but the peak demand; therefore, we can conclude for autark systems that the distribution of electricity demand is more important than the demand level itself.

### 4.2.1 Levelized cost of energy and grid parity

Now that we know the total costs involved in each system, we can calculate the LCOE. This value is important; therefore, we can confirm that grid parity has been indeed achieved in Germany for different household profiles and large domestic systems.

TABLE 2
*Generated electricity per year, LCOE and percentage of excess energy for all five types of households considered*

| Household type | Electricity. gen. p.a. (kWh) | LCOE (€-ct/kWh) | Excess electricity (%) |
|---|---|---|---|
| 2 Adults | 47,024.49 | 5.3 | 46.95 |
| 2 Adults and 1 child | 31,690.41 | 6.0 | 44.93 |
| 2 Adults and 2 children | 69,514.46 | 5.3 | 49.90 |
| 2 Adults and 3 children | 90,982.16 | 5.4 | 46.11 |
| 2 Adults, 2 children, and 2 seniors | 93,026.70 | 5.1 | 45.76 |

The most important information in Table 2 are the LCOE. For all types of home occupancy considered, using different profiles, and under other peak-load influences, the outcomes show the systems' economic feasibility since they apparently all reach grid parity. Given that the current electricity price in Germany is nationally quite uniform and at a value of 29.23 €-ct/kWh [68], in all systems considered in our study the electricity generated is cheaper than that bought from the grid.

Here, we consider the retail price because that is the price to avoid as a consumer. Despite that, we recognize that this comparison is not completely fair since the final retail price includes other components in addition to the cost of electricity generation itself, such as EEG surcharge, taxes, levies, and grid-use fees. However, electricity generation from lignite has a LCOE ranging from 4.59 €-ct/kWh to 7.98 €-ct/kWh, whereas that for hard coal-fired power plants is significantly higher at 6.27 €-ct/kWh to 9.86 €-ct/kWh [31]. Concerning renewable sources, the LCOE of onshore wind turbines ranges between 3.99 €-ct/kWh and 8.23 €-ct/kWh and for biogas power plants between 10.14 €-ct/kWh and 14.74 €-ct/kWh. So even in comparison with the LCOE of conventional and renewable power plants, our results show a lower cost.

We also see that for all types of households the excess energy not used is rather high. We also point that for our case, the reverse power flow does not cause grid instability. At the present, the situation can be solved with low-cost methods, implemented on the household level in contrast to expensive measures, such as grid reinforcements. For our model, we already had included in our previous installations costs, the necessary inverters to deal with larger hybrid PV-battery system. However, questions might arise if the current grid can handle significant reverse power flows or overloading of network lines and transformers, which are the key concerns in low voltage (LV) networks, especially during periods of strong PV power injection and low demand [69]. Technical studies bring solutions to this problem and we see that the situation can be solved at the household level [70–72] or with more expensive measures, such as grid reinforcement [73].

#### 4.2.2 Impact of feed-in-tariffs

The value of the FiT in Germany is regulated by the German Renewable Energy Sources Act (EEG), according to which new PV systems up to the size of 100 $kW_p$ can receive a fixed feed-in tariff for 20 years. Since all systems are below that limit, all households are assumed to receive a fixed FiT on their sale of excess energy from the PV systems to the grid. Therefore, the value of FiT generated revenues received at the beginning of 2019 for a new large PV system is assumed to be 0.0891 €/kWh [68].

For the amount of energy bought from the grid, the price considered is 0.2923 €/kWh including VAT [31]. Since this is the average residential end-customer electricity price considering all types of consumers in Germany, it is used for the analysis. The amount of energy considered as saving costs on the electricity bill results from self-consumption from the PV system and power stored in the battery. Therefore, this energy is the one that a household does not have to buy anymore from the grid.

Hence, the saving per kWh can be considered as being the same as the rate of buying electricity. Nevertheless, according to [67], the consumers who have a PV system larger than 10 $kW_p$ have to pay a portion of the EEG surcharge, which is 40% of the total EEG surcharge for self-consumed energy. The EEG surcharge in Germany, including VAT, amounts to 0.0762 €/kWh. Since the size of PV systems considered in our study is greater than 10 $kW_p$, a household must pay 40% of the EEG levy, which amounts to around 0.03 €/kWh of self-consumed energy. Considering this, the benefit of self-consumption reduces to 0.2623 €/kWh.

Table 3 shows what we consider to be the revenues from the system: the revenues from the FiT, the revenue concerning the difference between the costs of self-generation, and the original costs to buy electricity from the grid.

Table 3
*Annual revenues from self-generation (avoided cost) and FiT payments received, for all types of households considered*

| Household type | Revenues from self-generation (€ p.a) | FiT payment (€) |
|---|---|---|
| 2 Adults | 620.88 | 1,967.03 |
| 2 Adults and 1 child | 640.07 | 1,268.75 |
| 2 Adults and 2 children | 884.68 | 2,904.71 |
| 2 Adults and 3 children | 1,396.52 | 3,737.56 |
| 2 Adults, 2 children, and 2 seniors | 1,544.61 | 3,793.01 |

As discussed later, we can define this system as asymptotic; in other words, we need substantial investment in a large system to achieve full grid-independence (100% autarky) for all hours of the year. The result is a high portion of unutilized energy being sold to the grid at a lower price than the economic gain from self-consumption.

The absolute difference between the revenues from the electricity fed into the grid at the FiT and the cost savings from the self-generated consumption shows that a greater part originates from the excess electricity. However, in relative terms, this is not advantageous. The value per kWh from the FiT is €0.0891, whereas the value per kWh from avoiding buying the grid electricity is €0.2623, i.e. almost three times higher. Therefore, we can conclude that maximizing consumption and avoiding a high percentage of excess energy is economically beneficial.

### 4.2.3 Present value

We consider annual expenses for the operation and maintenance of the system at 0.1% of the initial investment. Besides that, every ten years the battery needs replacement at cost of 60% of the initial battery costs. Regarding the revenues, as already mentioned, the excess energy is remunerated at 0.0891 €/kWh. Apart from the FiT, the other source of revenue comes from the difference between the LCOE of each system and the cost of purchased electricity from the grid. Here, we considered a value of 0.2623 €/kWh, already taking into account the EEG surcharge for domestic systems larger than 10 $kW_p$. The results are shown in Figure 5.

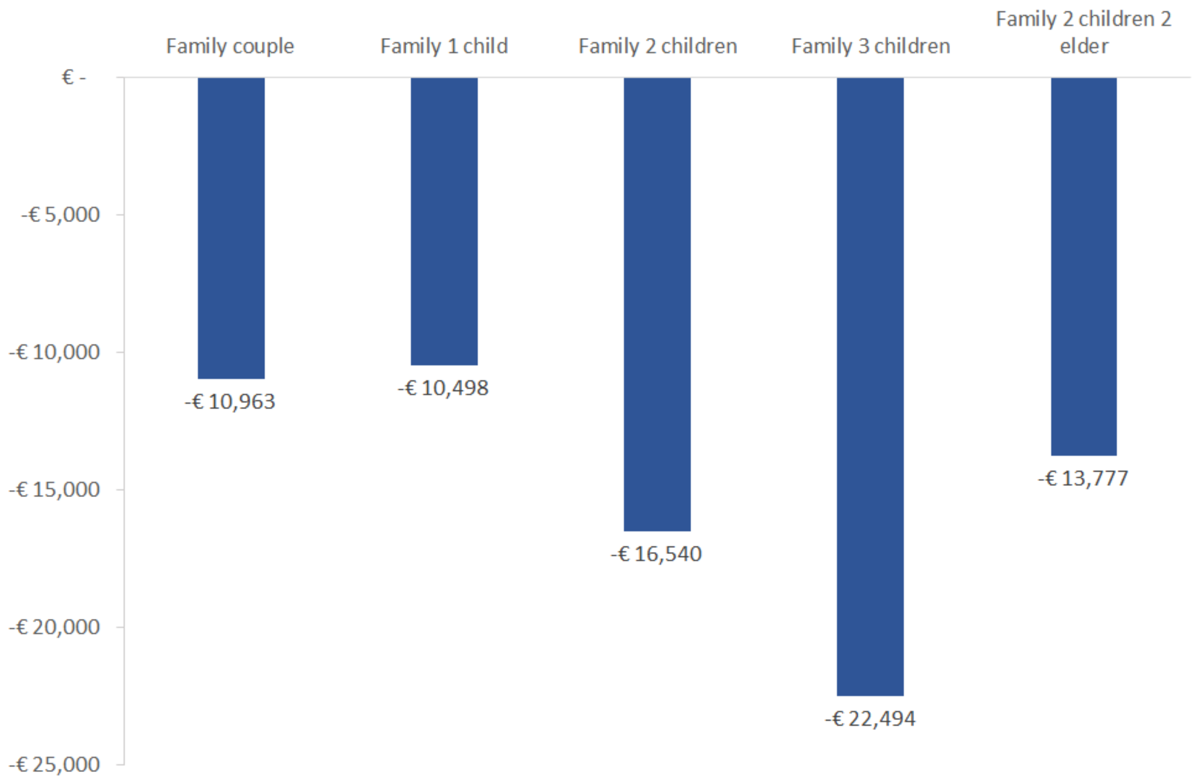


FIGURE 5
*Net Present Value of the PV-battery system, by type of household*

We can see that all types of household show negative net present values. We can also see that the results are not related to the amount of energy consumed or the number of household occupants. For these types of houses, the most relevant variable is the peak consumption of electricity. When a high amount of electricity is consumed simultaneously, we need more investments to cover this particular period, making the investment costs significantly higher, than otherwise but creating excess energy.

## 4.3 Sensitivity analysis

### 4.3.1 FiT substitution

At this point, we can conclude that the initial investment and the percentage of excess energy play an important role in a system's financial results. Next, a sensitivity analysis is pursued to investigate how to balance a household's expectations and keep a system economically viable. First, it is analyzed how to manage the high percentage of excess energy when selling the same amount of electricity not under a FiT regime but to another household. The results are shown in Figure 6.

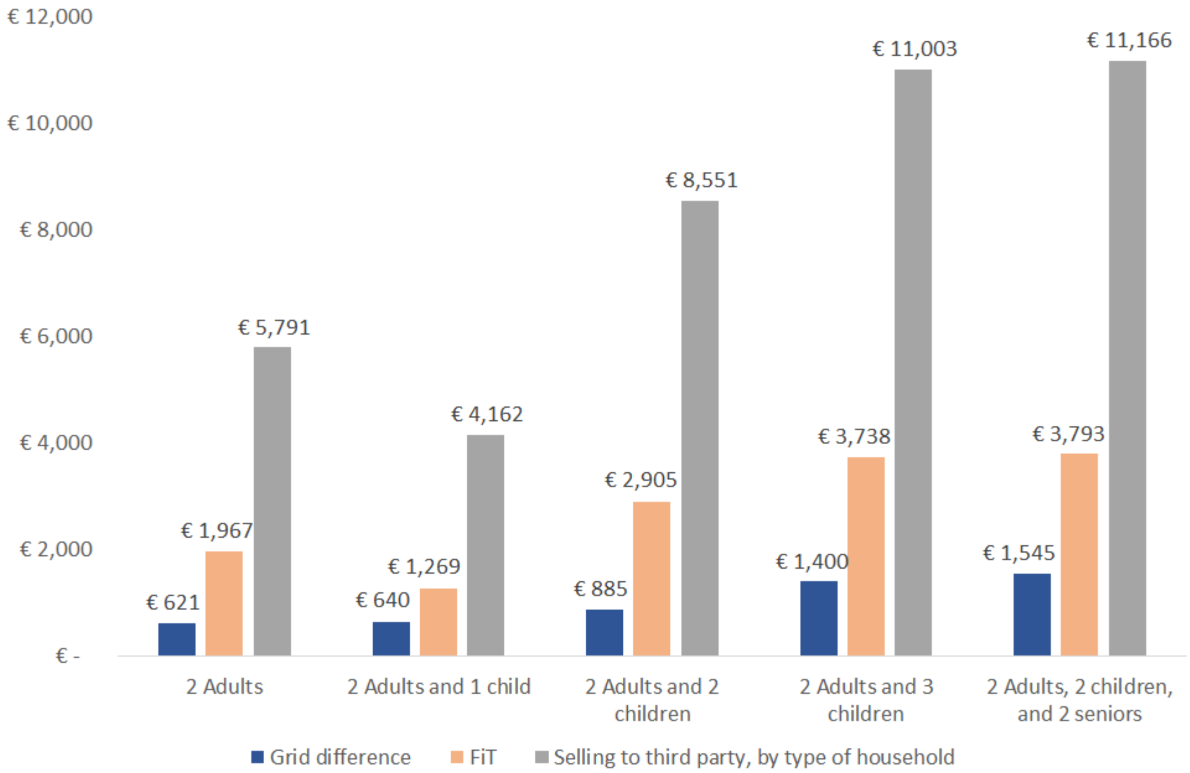


FIGURE 6
*Different sources of revenue for excess energy, by type of household*

To this end, we bring together the different sources of revenues and what else we are considering in this analysis. The grid difference remains the same for both scenarios since the house replaces the grid electricity price for the self-generated LCOE. The FiT is replaced by a third party, showing how the profitability of these systems could be reverted if the electricity surplus is sold to an interested party, such as neighbors or commercial entities (e.g., offices). The difference is almost three times higher since this is the same difference between FiT and grid tariffs. The new NPV for all systems is shown in Figure 7.

With the new destination for the excess energy, all projects reverted the negative results and are now positive and feasible. However, the household with 2 adults and 1 child has a lower revenue level because its required system is smaller, providing lower levels of excess energy and lower revenues from selling it to the grid.

It is important to note that no other costs involving investment or maintenance were considered, which is highly unlikely to happen in reality. However, given the positive values for all cases, we can conclude that this business model is still viable even taking into account profit share between many participants, for instance, a private household could keep just a small fraction of the remuneration without negatively affecting the economic viability of the autark system in a significant manner. Currently, predicting the

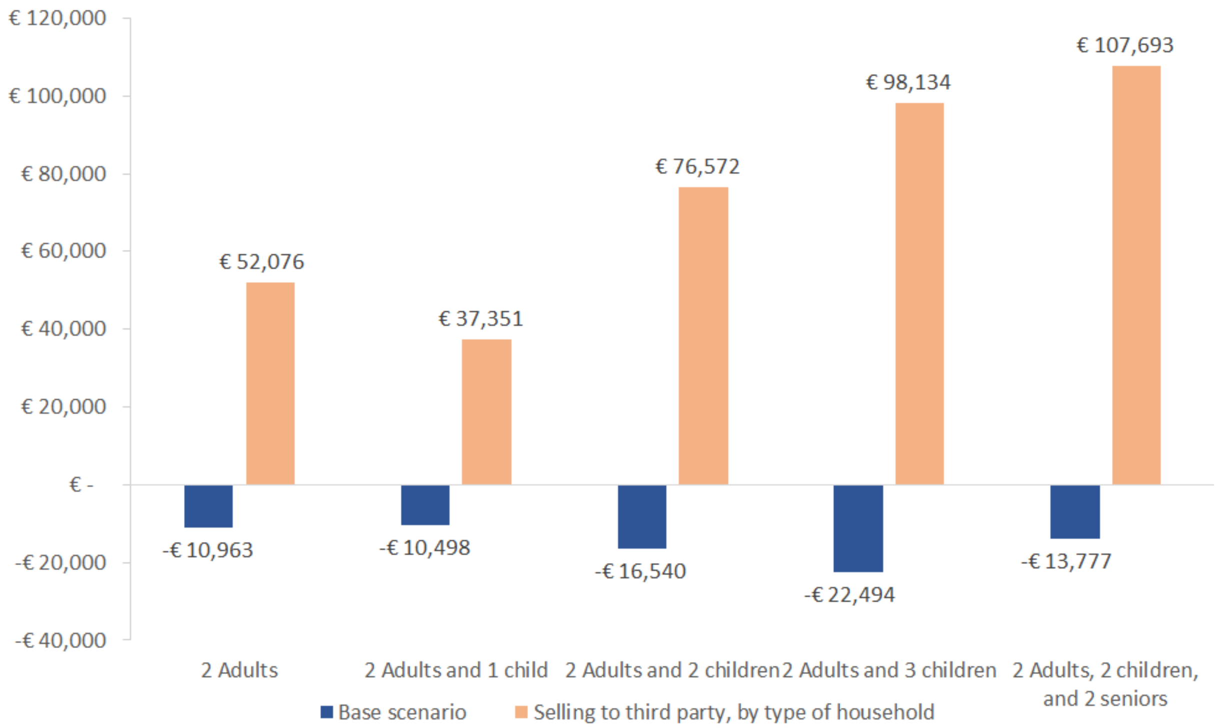


FIGURE 7
*Sensitivity analysis of selling energy to a third party as revenue as a replacement for FiT, by type of household*

future of new utility business models is challenging, but literature has pointed out how distributed renewable energy (DRE), especially solar PV, will change the utility business model [74–76]. Distributed solar PV generation is positioned on the consumer side of the utility chain, creating a new market that the utilities have yet to address. However, it is quite obvious that distributed electricity generation has already become too important to ignore, so at some point new market entrants will try to implement their business models and make profits.

Furthermore, we expect that the already existing market design, such as P2P [19] could develop faster in the future to connect consumers with an excess of electricity and consumers willing to buy cleaner and cheaper energy. Such concepts were already analyzed in other studies, such as cloud energy storage [77], VPP, and microgrids, but new business models need to emerge in order to connect prosumers and consumers [77, 78].

#### 4.3.2 Different levels of autarky

As demonstrated before, an independent system requires a very large investment in order to cover 100% TSL. Since the other important variable affecting system feasibility is the high investment costs to provide electricity 100% of the time, we now analyze different levels of grid independence time. Figure 8 provides the results obtained for levels of 99%, 95%, and 90% of self-generating hours, respectively (i.e. of various, but all positive levels of self-generation).

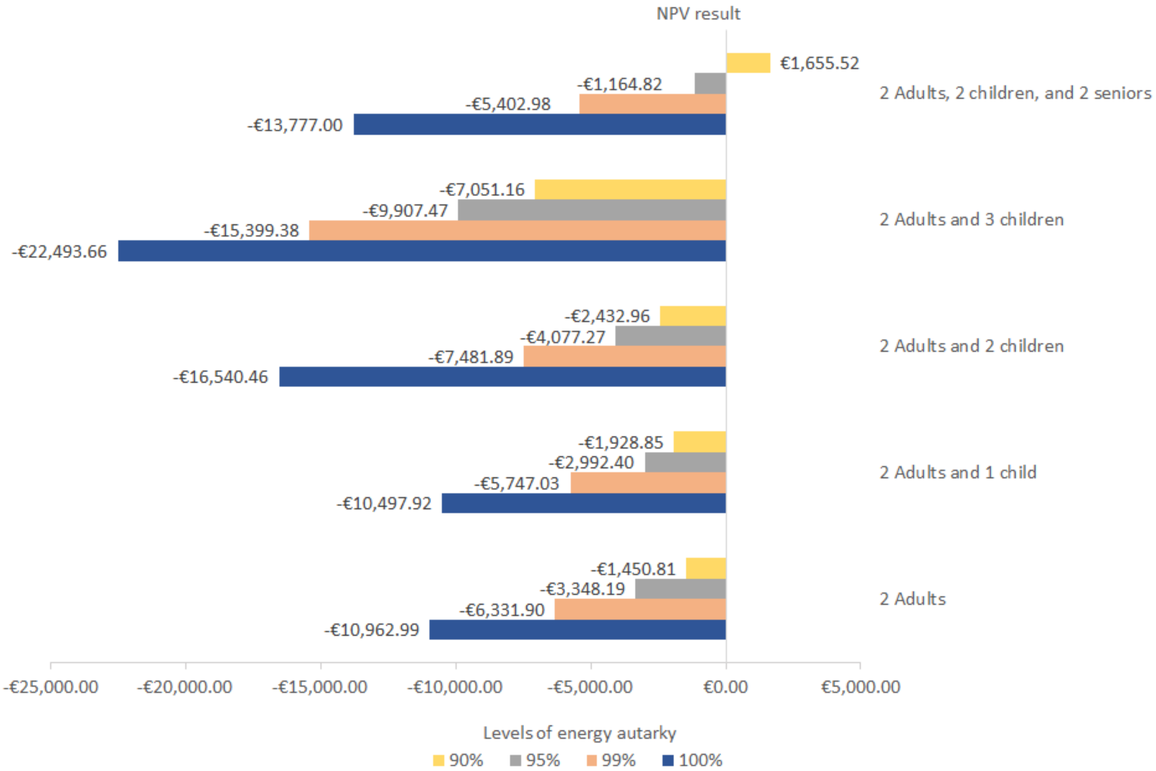


FIGURE 8

*Different levels of energy autarky and corresponding NPV, by type of household*

One can see for the 100% autarky level that the peak demand hours require a larger share of investments and that the marginal efficiency of the investment is considerably lower to cover the final percentage of hours. The final NPV result, as displayed before, is negative for all five types of household.

For the next steps, we decrease the level of autarky by some degrees and calculate the NPV again. The 99% autarky level gives a view of the core marginal dilemma of an off-grid system. Due to some electricity peaks during the year, the system must be very large and thus entails huge investment costs. These costs will be so high that even with a low LCOE, it is impossible to recover the investment. However, if we decrease the marginal self-sufficiency level by 1%, our financial result will be affected positively, reducing the financial loss.

Concerning other autarky levels, the results show the same non-linear behavior, with financial results being more affected than the reduced autarky level. However, even for 10% reduction in the autarky level, the system was economically viable in just one type of household, with 2 adults, 2 children, and 2 seniors.

### 4.3.3 Feasible levels of autarky

In the previous subsection , we found that reducing the autarky level to 90% is not enough to bring positive NPV results to all projects, although it reduce losses significantly.

Therefore, two different questions are posed next: (1) What is the maximum feasible level of autarky for each household? (2) At what levels do we find the maximum independence from the grid with a non-negative return?

For this step, we used the same model as in section 3. However, instead of aiming at the 100% TSL regardless of the financial results, the model picks the higher TSL only in the case of positive financial returns. Since the focus is on maximizing grid independence, the number of hours disconnected is more important than a higher NPV. Table 4 depicts the results for all types of households studied.

TABLE 4
*Optimized financial results with minimum number of blackout hours, by type of household*

| Household type | PV size ($kW_p$) | Battery size (energy capacity) (kWh) | Grid dependency hours (h) | LCOE (€-ct/kWh) | NPV (€) | TSL (%) |
|---|---|---|---|---|---|---|
| 2 Adults | 24 | 3 | 2080 | 4.61 | 10.51 | 76.26 |
| 2 Adults and 1 child | 17 | 3 | 3064 | 4.79 | 69.43 | 65.02 |
| 2 Adults and 2 children | 30 | 5 | 1962 | 4.81 | 10.88 | 77.60 |
| 2 Adults and 3 children | 28 | 3 | 4172 | 4.36 | 10.65 | 52.37 |
| 2 Adults, 2 children, and 2 seniors | 60 | 11 | 588 | 4.92 | 101.24 | 93.29 |

Since the pre-condition of all households is to have positive returns, we can analyze other variables as well. First, there is a significant reduction in the required sizes and how the project's profit is affected. Second, the LCOE also varies depending on each house compared to the initial scenario, but it remains below the FiT value. Finally, in the TSL column, we can observe how many hours were compromised to achieve a positive NPV and what maximum level of energy autarky is profitable for a private household in Germany.

Results show that, on average, a household can self-provide from 60% to 80% of its electricity with positive, but almost zero financial returns, which is close to other studies (e.g. [30, 79]. Although the households do not face negative results, we find that the NPV is close-to-zero. We conclude that in a real-life situation, and non-rational behavior apart, no household will be willing to invest a large amount of money to have a close to zero financial return. However, some households can be expected to want to generate their electrical power themselves for reducing their reliance on grid supply, and thus reap benefits other than simply financial ones [80, 81].

# 5 Conclusion

In this paper, the economic viability of off-grid households in Germany was analyzed. To this end, a NPV model used to investigate the possibilities for five different household configurations, with a diverse number of household members and different electricity consumption patterns was applied.

We find for all types of households studied that the LCOE of self-generation is lower than the national average residential electricity price for the case of Germany. However, for all types of households, we found large amounts of excess energy, around 45%, during some periods of the year, even for the case of larger battery storage units. Important to highlight that the excess energy, although significant, occurs just in the summer months as a result of higher generation due to more solar irradiation. During the wintertime, the excess energy is almost zero since the PV-battery size is optimized.

This is mainly due to the massive battery size necessary to generate sufficient amounts of electricity during the wintertime when solar irradiation is typically much lower than during the summer. Besides that, given the current battery prices, it is economically more viable to waste the excess energy than to install additional energy storage capacity in order to reduce the amount of excess energy.

We also found that a 100% autark household would need two sources of revenue for the vast amount of excess energy: either derived from selling the excess energy to the grid (remunerated under the FiT scheme) or from the difference in electricity prices between the house LCOE and the electricity price paid for electricity from the grid. The first one, due to the high amount of excess electricity, is the more significant.

Despite a lower LCOE, when analyzing the profitability of the projects, no type of household showed a positive NPV. So besides the high investment costs, the projects also showed negative project values even at a favorable (sunny) location in Germany, such as Munich. Regarding potential areas, the irradiation index reveals that the most profitable locations are in the south of Germany, and challenging locations in the northern parts of Germany because of lower levels of solar irradiation. Important differences are depending on weather conditions, and this affects the economic viability of different projects.

After the negative results from the NPV analysis, we also conducted a sensitivity analysis with a possible business solution to improve the financial results of the projects. The first option chosen was to find the use of the excess electricity not sold under the FiT scheme but among regular consumers. In this situation, the NPV values inverted from negative to significantly higher positive values for all types of households. Therefore, we can conclude that this business model is very attractive between energy sellers and other consumers seeking a renewable (green) and cheaper source of electricity.

Another sensitivity analysis conducted was to consider whether lower levels of energy autarky do decrease the investment needed for a 100% autark system. The outcomes reveal a remarkable decrease in the investments and an improvement regarding the NPV; however, even at the lowest autarky level considered (90%), the system remains unprofitable. Furthermore, the investments needed show that the marginal investment costs increase too much regarding the peak hours of the system, suggesting a higher investment to cover just a few hours.

As a final step in our sensitivity analysis, we showed at what levels it is possible to maximize the independent hours from the grid. All houses present a lower LCOE than the grid's energy tariff and, depending on each scenario, a household can self-provide between 60% to 80% of its electricity. Although those results are important, they seem somewhat unrealistic since the required investments for each project would be excessive, and the NPV is close to zero.

This study implies that leaving the grid is not yet an economically feasible option in Germany, given the current situation, even in the most favorable locations. Moreover, our analysis shows that for all system sizes investigated the necessary investment are very high and may constitute a major financial barrier to private households. Besides that, even with sufficient funding of the investment, the excess energy from all systems is substantial, and the revenue originating from FiT is not high enough to generate a sufficient annual cash flow for the payback of the investment.

We can conclude that the solution to this problem is to find a proper destination for the excess energy. Here we have proposed that the excess electricity generated could be sold peer-to-peer (P2P) to another consumer through a smart grid solution, such as a micro-grid or virtual power plant, or P2P platforms, in this case, all households could enjoy a positive NPV. It might also be more beneficial to maintain the connection to the grid but to minimize the electricity required from the grid by installing a smaller system.

In terms of limitations and future research, this study found for some types households, space constraint is decisive, and that depending on the size of the solar PV, it will not be possible to install such systems on urban residential building rooftop, which is a limitation not considered in most of the work in this area. Future research could also explore the economical autarky levels achievable with different technologies, and explore the autarky options there are for small- and medium-sized as well as industrial and/or, specifically rural areas. It is also possible to investigate additional options concerning self-sufficiency in terms of heating since that was not approached in the present study either. With more investigation in other countries, our study can serve as a basis for future research in this field.

Overall, we can conclude that, as a policy implication, defecting from the grid is not possible on a large scale due to the barrier of high investment costs and because no household type and system showed positive NPV. The best solution to revert the negative results is a future bidirectional grid of prosumers connected with consumers willing to buy their excess energy. If the prosumers had to pay for the smart grid technology investment themselves, that would decrease the profitability. If the government had to bear the costs, we would need more studies to check whether or not the amount of uses justifies the investment. Policies could focus specifically on helping small-scale prosumer contracts by facilitating smart mechanisms and connecting prosumers directly with consumers.

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# List of the latest FCN Working Papers

## 2020

Klie L., Madlener R. (2020). Optimal Configuration and Diversification of Wind Turbines: A Hybrid Approach to Improve the Penetration of Wind Power, FCN Working Paper No. 1/2020, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, January.

Klie L., Madlener R. (2020). Concentration Versus Diversification: A Spatial Deployment Approach to Improve the Economics of Wind Power, FCN Working Paper No. 2/2020, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, February.

Madlener R. (2020). Small is Sometimes Beautiful: Techno-Economic Aspects of Distributed Power Generation, FCN Working Paper No. 3/2020, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, March.

Madlener R. (2020). Demand Response and Smart Grid Technologies. FCN Working Paper No. 4/2020, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, March.

Vartak S., Madlener R. (2020). On the Optimal Level of Microgrid Resilience from an Economic Perspective, FCN Working Paper No. 5/2020, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, April.

Hellwig R., Atasoy A.T., Madlener R. (2020). The Impact of Social Preferences and Information on the Willingness to Pay for Fairtrade Products, FCN Working Paper No. 6/2020, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, May.

Atasoy A.T., Madlener R. (2020). Default vs. Active Choices: An Experiment on Electricity Tariff Switching, FCN Working Paper No. 7/2020, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, May.

Sheykhha S., Madlener R. (2020). The Role of Flexibility in the European Electricity Market: Insights from a System Dynamics Perspective, FCN Working Paper No. 8/2020, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, June.

Wolff S., Madlener R. (2020). Willing to Pay? Spatial Heterogeneity of e-Vehicle Charging Preferences in Germany, FCN Working Paper No. 9/2020, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, June.

Priesmann J., Spiegelburg, Madlener R., Praktiknjo A. (2020). Energy Transition and Social Justice: Allocation of Renewable Energy Support Levies Among Residential Consumers in Germany, FCN Working Paper No. 10/2020, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, July.

Sabadini F., Madlener R. (2020). The Economic Potential of Grid Defection of Energy Prosumer Households in Germany, FCN Working Paper No. 11/2020, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, August (revised October 2021).

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Specht J.M., Madlener R. (2019). Mitigation and Valuation of the Investment Risk in Engineered Geothermal Systems: A Real Options Analysis, FCN Working Paper No. 1/2019, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, January.

Hackstein F., Madlener R. (2019). Sustainable Operation of Geothermal Power Plants: Why Economics Matters, FCN Working Paper No. 2/2019, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, February.

Wolff S., Madlener R. (2019). Charged up? Preferences for Electric Vehicle Charging and Implications for Charging Infrastructure Planning, FCN Working Paper No. 3/2019, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, March.

Höfer T., von Nitzsch R., Madlener R. (2019). Using Value-Focused Thinking and Multi-Criteria Group Decision-Making to Evaluate Energy Transition Alternatives, FCN Working Paper No. 4/2019, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, April.

Glensk B., Madlener (2019). *Energiewende @ Risk*: On the Continuation of Renewable Power Generation at the End of Public Policy Support, FCN Working Paper No. 5/2019, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, May.

Höfer T., Madlener R. (2019). A Participatory Stakeholder Process for Evaluating Sustainable Energy Transition Scenarios, FCN Working Paper No. 6/2019, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, May.

Gimpel-Henning J., Madlener R. (2019). Synthetic Low-Voltage Grid Replication Using Spatial Information and Private Customer Load Profiles, FCN Working Paper No. 7/2019, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, June.

Gimpel-Henning J., Madlener R. (2019). Large-Scale Grid Clustering to Predict Future Electricity Grid Extension Costs, FCN Working Paper No. 8/2019, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, June

Gimpel-Henning J., Madlener R. (2019). Analyzing Actual Low-Voltage Grid Overloads Due to the Diffusion of Electric Vehicles, FCN Working Paper No. 9/2019, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, July.

Schreiner L., Madlener R. (2019). A Pathway to Green Growth? Macroeconomic Impacts of Power Grid Infrastructure Investments in Germany, FCN Working Paper No. 10/2019, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, August.

Schreiner L., Madlener R. (2019). Investing in Power Grid Infrastructure as a Flexibility Option: A DSGE Assessment for Germany, FCN Working Paper No. 11/2019, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, August.

Wintgens L., Madlener R. (2019). Multi-Criteria Decision Analysis of Technological Alternatives to Conventional Expansion of the German Electricity Grid, FCN Working Paper No. 12/2019, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, August.

Schultes G., Madlener R. (2019). Investment Under Uncertainty in a Power-to-Gas Plant in Germany: A Real Options Analysis, FCN Working Paper No. 13/2019, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, September.

Karami M., Madlener R. (2019). Smart Predictive Maintenance Strategy Based on Cyber-Physical Systems for Centrifugal Pumps: A Bearing Vibration Analysis, FCN Working Paper No. 14/2019, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, September.

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Liu X., Madlener R. (2019). The Sky is the Limit: Assessing Aircraft Market Diffusion with Agent-Based Modeling, FCN Working Paper No. 16/2019, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, October.

Fabianek P., Will C., Wolff S., Madlener R. (2019). Green and Regional? A Multi-Criteria Assessment Framework for the Provision of Green Electricity for Electric Vehicles in Germany, FCN Working Paper No. 17/2019, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, October.

Welsch M., Madlener R. (2019). Household Customers' Willingness to Cooperate in Smart Meter Services: A Survey-Based Regression Analysis, FCN Working Paper No. 18/2019, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November.

Von Bargen C., Madlener R. (2019). Economically Optimized Dispatch of Decentralized Power Plants and Storage Units in the Day-Ahead and Intraday Markets, FCN Working Paper No. 19/2019, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November.

Specht J.M., Madlener R. (2019). Quantifying Value Pools for Distributed Flexible Energy Assets: A Mixed Integer Linear Optimization Approach, FCN Working Paper No. 20/2019, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November.

Bruderhofer T., Madlener R., Horta F. (2019). Solar PV-Based Minigrids in Rural Areas of Developing Countries: An Economic Analysis, FCN Working Paper No. 21/2019, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, December.

Sheykhha S., Borggrefe F., Madlener R. (2019). A Counterfactual Analysis of Regional Renewable Energy Auctions Taking the Spatial Dimension into Account, FCN Working Paper No. 22/2019, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, December.

Sheykhha S., Madlener R. (2019). HECTOR – A Dynamic Dispatch and Investment Model for Electricity Markets in Europe, FCN Working Paper No. 23/2019, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, December.

Bayansalduz M., Knoeri C., Madlener R. (2019). Technical Potential and Market Diffusion of Smart Energy Hubs: An Agent-Based Modeling Approach, FCN Working Paper No. 24/2019, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, December.

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Crump R., Madlener R. (2019). Modeling Grid-Friendly Clean Energy Communities and Induced Intra-Community Cash Flows, FCN Working Paper No. 26/2019, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, December.

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