ECONOMICS OF RESIDENTIAL PV BATTERY SYSTEMS IN THE SELF-CONSUMPTION AGE

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ABSTRACT: This paper investigates the profitability of PV battery systems that aim to reduce the electricity purchased from the grid of households. The economic feasibility is assessed based on the approach of calculating the mean electricity cost of the household equipped with a PV battery system. The study focuses on the main question: What is the break-even point of the battery system price at which residential PV battery systems become economically viable in Germany? This is analyzed by determining the limit of profitability in terms of required battery system price, which makes the investment in a PV battery system under given circumstances profitable. The impact of different economic input parameters on the required battery system price was studied for a defined reference case. The results reveal that the major factor is the interest rate, followed by the PV system price, retail electricity price and feed-in tariff. Nevertheless, several uncertainties with regard to the economic assessment exist. However, assuming that the calculated required battery prices will be achieved in the future; investing in a PV battery system is financially more attractive than purchasing the entire electricity demand from the grid.
Keywords: PV Battery Systems, Battery Storage, Economical Analysis, Self-Consumption

1 MOTIVATION

In the recent years, a tipping point related to the usage of photovoltaic (PV) generated electricity has been reached in Germany. Whereas in the past grid-connected PV systems were mainly installed to feed the generated electricity into the electricity grid, now using the PV energy on-site to reduce the grid procurement is becoming more attractive than selling PV electricity to the grid. The reasons for that are the considerable changes in the cost situation with regard to the cost of PV and grid electricity, which happened not only in Germany, but also in other countries [1]. In 2008, the grid feed-in of PV systems below 10 kWp was remunerated by the EEG (German Renewable Energy Act) with a feed-in tariff more than twice as high as the retail electricity price for residential customers at that time (see Figure 1).

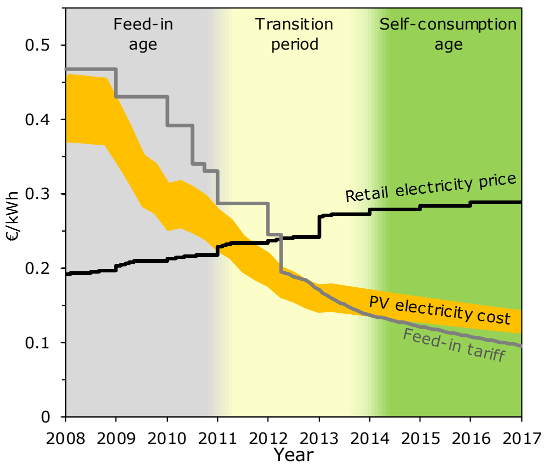

Figure 1: Previous and projected development of the cost of PV generated electricity, the feed-in tariff and the retail electricity price in Germany which indicate the transition from the feed-in to the self-consumption age (Data: Destatis, BNetzA, BSW, HTW; calculation of the PV electricity cost: annual PV yield between 850 and 1050 kWh/kWp, interest rate 4%, annual operational cost 1.5%, period 20 years)

On the one hand, due to enormous PV system price reductions, the cost of PV generated electricity and the feed-in tariffs have been declining strongly. On the other hand, the price of retail electricity for household customers has been steadily increasing at the same time, levelized cost of PV generated electricity crossed the retail electricity price in Germany around 2011. Besides that, a further momentous event has been occurring more recently: The feed-in tariffs for newly installed PV systems have undercut the generation cost for typical PV applications on residential roof-tops, considering characteristic yields and interest rates. From this intersection onwards the self-consumption of PV energy is becoming an essential prerequisite for the profitable operation. As a consequence, installing a PV system and feeding the overall produced energy into the grid is no longer economically viable. Therefore, this can be regarded as the introduction of a new era in the utilization of solar energy: The age of self-consumption.

Today, electricity from the grid is almost twice as expensive as the PV electricity cost. Hence, using PV electricity in private households simultaneously to substitute electricity purchased from the grid is becoming more attractive than selling it to the grid. This results in the situation that residential PV installations are increasingly refinanced by the savings in grid electricity costs. Consequently, the future development of the grid electricity price likely affects the economics of residential PV systems more strongly than the feed-in remuneration. From a historical point of view, this evolution can be considered as a complete turnaround in terms of the economics of PV systems in Germany within less than one decade.

It can be expected that the feed-in tariff will shrink much faster than the PV electricity cost in the foreseeable future. Therefore it is anticipated that the feed-in tariff will reach a level which is sufficiently lower than the cost of PV electricity in the long term. Nevertheless, with an increasing gap between these values, a higher share of the PV energy has to be self-consumed, in order to realize cost effectiveness (see Figure 2). This goes along with the assumption that the cost-optimal PV system size will shrink in the future, as higher self-consumption rates can be realized by smaller-sized PV systems [2].

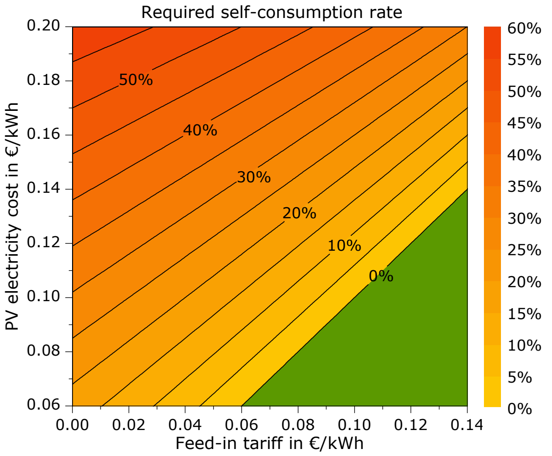

Figure 2: Required self-consumption rate of PV systems without batteries to preserve profitability as a function of the feed-in tariff and PV electricity cost (Assumption: 0.34 €/kWh of mean retail electricity price over 20 years)

Besides that, also energy storage could be a solution to increase the self-consumption without reducing the PV system size. This can be realized by storing surplus PV energy in batteries during the day and using it later at night. This allows the home owner to reduce the electricity purchased from the grid further and to realize the aim of becoming more independent from the utility. With this, several questions regarding the energetic and economic benefit of combining residential PV applications with batteries arise, which will be addressed in the following sections.

2 ENERGETIC BENEFIT OF PV BATTERY SYSTEMS

To assess a PV battery system from the energetic point of view, a deeper look into the possible energy flows is needed. Figure 3 illustrates the most important energy flows of homes equipped with grid-connected PV battery systems. The electricity generated from the PV system can be used in different ways. Preferably it is directly used to supply the electrical demand. The direct use of PV energy results from the simultaneity of the PV production and load demand. When the current PV power output exceeds the load, surplus PV power can be stored in the battery system for later consumption. If the battery is fully charged, the remaining excess PV power will be injected into the grid.

The loads of the household can be supplied through different sources and are preferably covered by the instantaneous use of PV energy. The battery starts to discharge when the PV output is insufficient to satisfy the electrical demand of the consumers. As soon as the battery is completely discharged, the residual load demand is covered by electricity drawn from the grid. Charging the battery by the grid or discharging the battery into the grid is not taken into account in this study. Therefore also the standby consumption of the PV battery system covered by the grid is neglected.

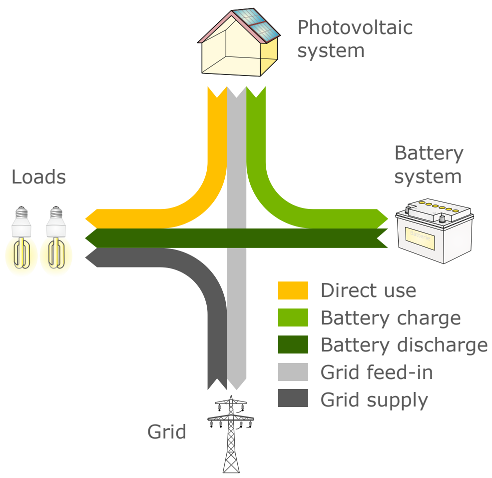

Figure 3: Energy flows of homes equipped with grid-connected PV battery systems

To evaluate the energy flows and moreover the energy balance over a whole year, two important assessment criteria should be defined. The first one is the self-consumption rate, which is equal to the share of PV generated electricity E_{PV} that is either directly used E_{DU} or stored in the battery E_{BC}.

$$s = \frac{E_{DU} + E_{BC}}{E_{PV}} \tag{1}$$

The second evaluation parameter is the degree of self-sufficiency, which specifies the fraction of the total load demand covered by the PV battery system. The degree of self-sufficiency d is obtained by dividing the sum of the directly used PV energy E_{DU} and the energy discharged from the battery E_{BD} by the load demand E_L.

$$d = \frac{E_{DU} + E_{BD}}{E_L} \tag{2}$$

Both assessment criteria vary with a number of parameters. The impact of the PV and battery size on these assessment criteria was analyzed by simulations of a PV system in conjunction with a lithium-ion based battery system using minutely resolved time series of the load demand and meteorological data over a time period of one year [2]. Figure 4 and Figure 5 show the simulation results with respect to the annual average values of the self-consumption rate and degree of self-sufficiency as a function of the size of the PV battery system. Additionally the rated PV power and usable battery capacity are normalized to the annual load demand, to draw conclusions widely independent from the total consumption.

Considering a PV system without a battery, the self-consumption rate is decreased with an increasing rated PV power, due to higher surplus PV energy that cannot be consumed concurrently (see Figure 4). Also the degree of self-sufficiency is increased, but starts to saturate with increasing size of the PV system (see Figure 5). With 1 kWp/MWh of rated PV power (e.g. 5 kWp in a household with an annual load demand of 5 MWh) the degree of self-sufficiency and the self-consumption rate are in the same order of magnitude of 30%. By adding a battery system with 1 kWh/MWh of usable capacity to the same PV system size, the attainable self-consumption rate and degree of self-sufficiency are increased to 59% and 56%, respectively.

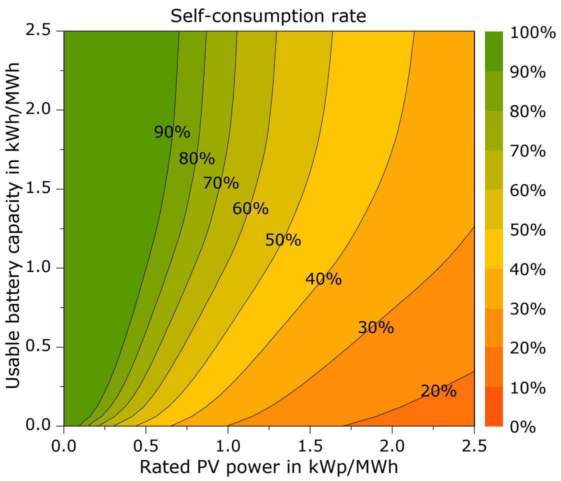

Figure 4: Annual mean of the self-consumption rate in dependency of the PV system and battery size, which are normalized to the annual electricity demand in MWh.

Nevertheless, increasing the battery capacity further and keeping the PV system size constant results only in a small increase in the amount of self-consumed PV energy. Hence, to realize a high degree of self-sufficiency, both the rated PV power and usable battery capacity have to be increased. It can be observed that a ratio between the battery size and the PV system size of 1 kWh/kWp is suitable to achieve high values of the degree of self-sufficiency. It has to be noted, that not the entire electricity demand can be covered instantaneously by the PV battery system due to the limited concurrency of the PV generation and load demand, especially in winter months. Hence, adjusting the size of the PV battery system in line with the demand is necessary. From the energetic point of view, an appropriate compromise to realize high values of the degree of self-sufficiency as well as self-consumption rate is to install 1 kWp/MWh of rated PV power and 1 kWh/MWh of usable battery capacity [2]. Besides the system configuration, further influence factors like the seasonal and diurnal distribution of the load demand exist. Nevertheless, it could be proven that these simulation results are characteristic for residential households in Germany [3].

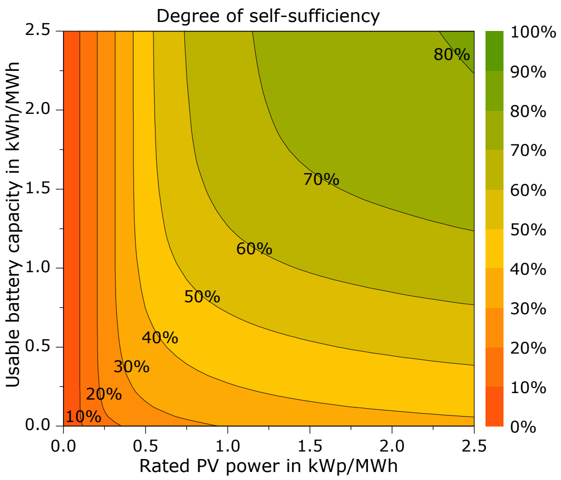

Figure 5: Annual mean of the degree of self-sufficiency in dependency of the PV system and battery size, which are normalized to the annual electricity demand in MWh.

3 ECONOMIC BENEFIT OF PV BATTERY SYSTEMS

Based on the aforementioned simulation results, the economic feasibility of PV battery systems is assessed in this section. For that reason, a cost-benefit analysis has been carried out by calculating the annuity of all accumulated revenues and expenses within the lifespan of the system. This allows determining the mean electricity cost for the home owner, which is directly comparable with the average retail price in the same period of time [4]. The mean electricity cost c_{EL} is obtained by dividing the sum of the annuity of all costs C and revenues R during the useful life by the annual demand E_L.

$$c_{EL} = \frac{C_{PV} + C_B + C_{GS} - R_{GF}}{E_L} \tag{3}$$

For both the PV system and battery storage the annuity C can be determined by the specific investment costs I, the size in terms of rated PV power P_{PV} and usable battery capacity E_{BU}, the annuity factor a and annual operational costs o.

$$C_{PV} = I_{PV} \cdot P_{PV} \cdot (a_{PV} + o_{PV}) \tag{4}$$

$$C_B = I_B \cdot E_{BU} \cdot (a_B + o_B) \tag{5}$$

The annuity factor is obtained based on the interest rate and the specific useful life of each system component. For simplicity, it is assumed that the useful life of the battery is restricted either by reaching the cycle lifetime or by the calendar lifetime, as described in more detail in [2]. Hence, the superposition of cycle and calendar aging is neglected.

In addition to the annual costs for the PV battery system also the expenses for purchasing electricity from the grid have to be taken into account. The annual grid electricity costs C_{GS} depend on the mean retail electricity price p_{GS}, the annual load demand E_L and the degree of self-sufficiency d.

$$C_{GS} = p_{GS} \cdot E_L \cdot (1 - d) \tag{6}$$

Additionally, the financial incomes from the grid feed-in have to be considered. This is done by calculating the annual revenues from the feed-in R_{GF} based on the feed-in tariff p_{GF}, the annual PV energy output E_{PV} and the self-consumption rate s.

$$R_{GF} = p_{GF} \cdot E_{PV} \cdot (1 - s) \tag{7}$$

The calculation of the mean electricity cost reveals that the profitability is sensitive to a variety of input parameters, summarized in Figure 6. Apart from the technological and economic ones, also energetic factors like changes in the load pattern affect the profitability. Furthermore, the expected interest rate of the home owner who decides to invest is a not negligible parameter. Additionally, possible investment grants provided by a funding scheme or taxes for self-consumed electricity have a positive or negative impact, which are not investigated in this work, though. As the German government has introduced the EEG surcharge for self-consumed electricity for PV systems greater than 10 kWp [5], the subsequently presented results are only applicable for residential PV systems below this threshold.

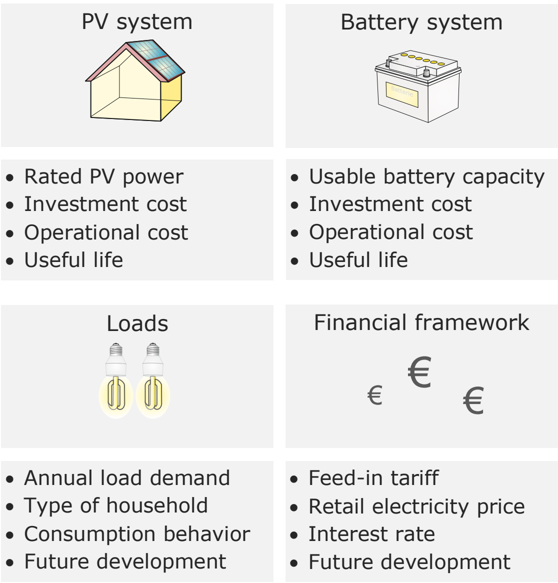

Figure 6: Most important factors of influence on the profitability of a PV battery system

Due to the fact that the feasibility of PV battery systems is strongly dependent on the input parameters, all assumptions should be defined first. The useful life of the PV system is limited to 20 years, which can be considered as a conservative assumption [6]. The annual operational costs of both the PV system and battery storage are set to 1.5% of the respective investment costs. The cycle life of the lithium-ion based battery system is limited to 5000 cycles and the calendar lifetime is assumed to be 20 years.

In this study, the economic impact of variations in the feed-in tariff, retail electricity price, interest rate and PV battery system price is studied in more detail. Hence, for these parameters a reference case is defined, summarized in Table I. In this case it is assumed that the grid feed-in is remunerated with a feed-in tariff of 0.12 €/kWh paid for 20 years. Furthermore, a mean grid electricity price of 0.34 €/kWh over a period of 20 years is presumed. This value results from the assumption that the current retail electricity price including value added tax (VAT) of 0.28 ct/kWh increases by 2% yearly, e.g. caused by inflation. Furthermore, an interest rate of 4% is considered in the reference case.

The investment costs including VAT of the PV and battery system are assumed with 1500 €/kWp and 1500 €/kWh, respectively. For simplicity the dependence of the specific investment costs on the size of the PV battery system is neglected. The specific battery system price is referred to the usable battery capacity. The considered system price can be expected in the short-term [2]. By summing up, the reference case can be considered as a possible cost situation in the foreseeable future.

Table I: Assumptions of the reference case

	Reference case
Feed-in tariff	0.12 €/kWh
Mean retail price incl. VAT	0.34 €/kWh
Interest rate	4%
PV system price incl. VAT	1500 €/kWp
Battery system price incl. VAT	1500 €/kWh
Rated PV power	1 kWp/MWh
Usable battery capacity	1 kWh/MWh

Based on the described assumptions, the economics of PV battery systems is assessed by calculating the mean electricity cost in the following. Figure 7 depicts the respective components that contribute to the mean electricity cost in the reference case for varying PV system sizes up to 2.5 kWp/MWh of rated power. It is obvious that with increasing size of the PV system, their contribution also rises proportionally. As the battery capacity is fixed to 1 kWh/MWh, the battery share is constant, too. As an increase in the rated PV power results in a higher degree of self-sufficiency (see Figure 5), a lower part of the load demand has to be covered by electricity purchased from the grid.

Figure 7 also reveals that the larger the PV system, the higher the incomes from the grid feed-in. By subtracting the expenses from selling electricity to the grid from the total costs, the mean electricity cost is determined. It can be seen that with increasing PV system size the mean electricity cost starts to decrease, but it does not go below a lower limit. This is the case in which the PV electricity cost is in the range of the feed-in tariffs. That means additional costs due to a higher PV system size can be compensated trough the additional incomes from the grid feed-in. Nevertheless, under the circumstances of the reference case considering 1 kWh/MWh of battery size the mean electricity cost cannot compete with the average price of purchased retail electricity.

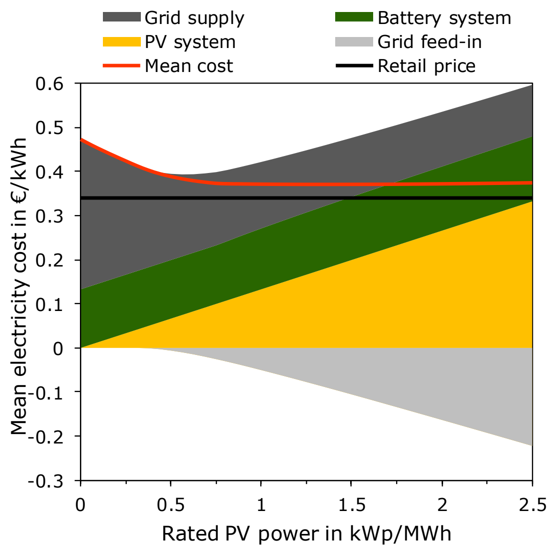

Figure 7: Components of the mean electricity cost in the reference case as a function of the rated PV power considering a fixed battery capacity of 1 kWh/MWh.

In Figure 8, the impact of varying the battery size on the mean electricity cost is illustrated. Opposed to Figure 7, the share of the mean electricity cost caused by the PV system remains constant and the share caused by the battery system is proportional to its size. The increase of the battery capacity results in lower expenses for purchased electricity as well as lower incomes from the grid feed-in. This results in the situation that the mean electricity cost rises almost constantly with the battery size.

By comparing Figure 7 and Figure 8 it can be observed that in the reference case changing the battery size has a larger impact on the mean electricity cost than changing the PV system size. The increase in the mean electricity cost is mainly because of the constantly rising battery costs at higher capacities. Hence, in the reference case only battery capacities below 0.6 kWh/MWh result in a mean electricity cost that is equal to or below the retail price, which the PV battery system competes with. The limit of profitability is the point of intersection of the curves of the retail price and mean electricity cost. That means, investing in a PV battery system is profitable as soon as the mean electricity cost is below the retail price. In the case in which the mean electricity cost undercuts the limit of profitability, the electricity costs for a household equipped with a PV battery system are lower than the household that covers its entire demand by purchasing electricity from the grid.

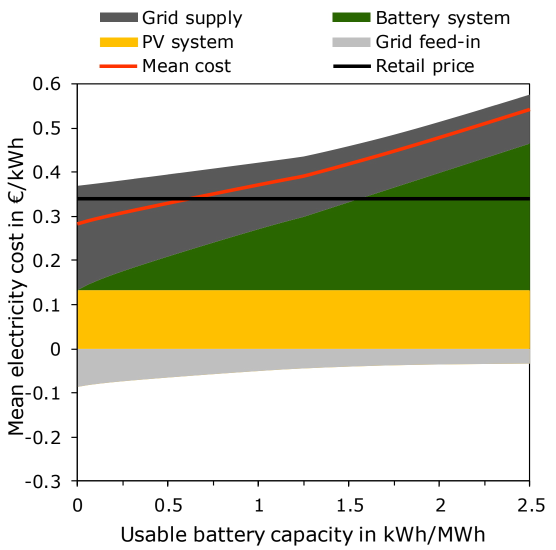

Figure 8: Components of the mean electricity cost in the reference case as function of the usable battery capacity considering a fixed rated PV power of 1 kWp/MWh.

In the following the profitability is analyzed for the reference system configuration with 1 kWp/MWh of rated PV power and 1 kWh/MWh of usable capacity in the case in which the system prices differ from the assumptions in the reference case according to Table I. To identify the impact of the investment costs on the profitability, a sensitivity analysis was conducted varying the costs of the PV system and battery storage (see Figure 9). The investment costs are constrained to 1000 and 2000 €/kWp for the PV system and to 500 and 2500 €/kWh for the battery system. The limit of profitability, which coincides with the mean retail electricity price, is indicated by the black line in Figure 9.

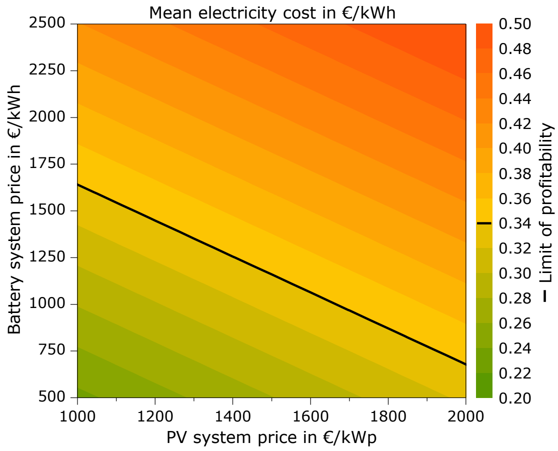

Figure 9: Mean electricity cost for varying PV and battery system prices in the reference case.

As could be expected, with falling system price, the mean electricity cost also decreases. Considering 1500 €/kWp of PV system price in the near future, investing in PV battery systems will become economically interesting at battery system price below 1160 €/kWh in the case of the reference system and scenario. Nevertheless, when the PV system price drops to 1200 €/kWp much faster than expected, 1500 €/kWh of battery price are sufficient for a profitable operation. As a consequence, the profitability of the battery system depends also on the PV system price. The limit of profitability can also be interpreted as the required battery system prices, which have to be reached in order to achieve a profitable operation of a PV battery system under given circumstances.

Determining the limit of profitability allows deriving the required battery system prices as a function of different impact factors. The impact of various feed-in tariffs on the required battery system price is shown in Figure 10 depending on the PV system price. The black dotted line corresponds to the limit of profitability in terms of required battery system price in the reference case.

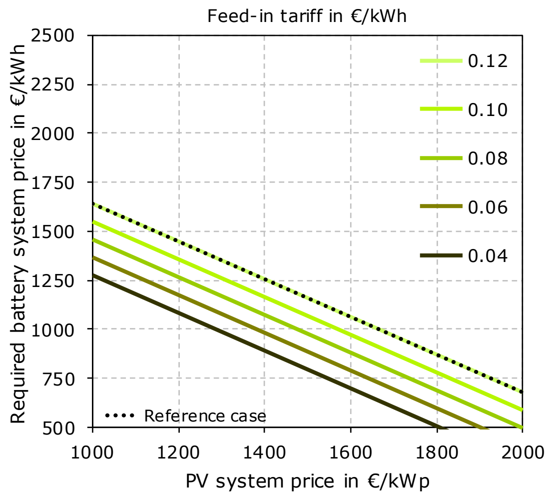

Figure 10: Required battery system price in the reference case in dependency of the PV system price for varying feed-in tariffs.

It is evident that with a decreasing feed-in tariff the limit of profitability drops. That means, lower battery system prices are needed to realize a profitable operation. In the case in which the feed-in tariff is dropped to 0.04 €/kWh, the required battery system price is lowered by 365 €/kWh compared to the reference case. Hence, the home owner has to pay less than 795 €/kWh for the battery system to make the investment profitable under these circumstances.

Apart from the feed-in tariff, the retail electricity price also affects the profitability and therefore the required battery system price. For the purpose of identifying the impact of the retail electricity price, further parameter variations have been carried out, assuming that the feed-in tariff and other parameters remain constant. The results are depicted in Figure 11 for retail electricity prices between 0.30 and 0.38 €/kWh on average during the useful life. As expected, the greater the retail price, the higher the battery system price can be. To realize a profitable operation considering that the mean retail electricity price is only 0.30 €/kWh, battery prices below 920 €/kWh are needed. Conversely, an increase of the retail price of 0.04 ct/kWh compared to the reference case makes battery systems up to 1400 €/kWh profitable. Hence, an increasing retail price is beneficial for the investment in a PV battery system from the economic perspective.

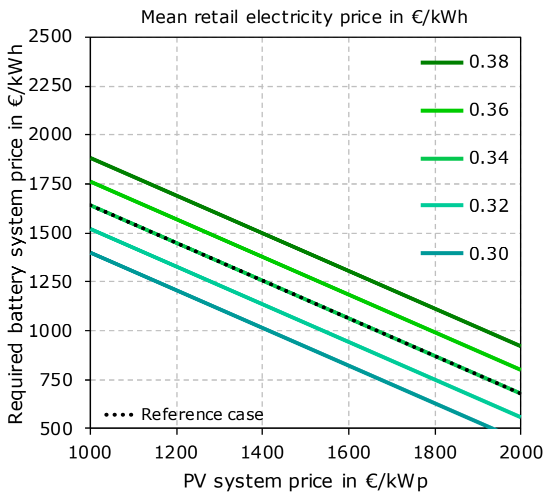

Figure 11: Required battery system price in the reference case in dependency of the PV system price for varying average retail electricity prices.

The results presented before are obtained considering a constant interest rate of 4%. Therefore, the impact of varying the interest rate between 0% and 8% is shown in Figure 12. Compared to Figure 10 and Figure 11, the required battery system prices differ over a larger range. The results reveal that the interest rate is a non-negligible factor. If the investor in a PV battery system is pleased without any expected financial benefit, investing could be profitable in the reference case at battery system prices as high as 2070 €/kWh. In this case incomes from the grid feed-in are indirectly used to partially refinance the battery system. Hence, a low interest expectation of the investor results in higher required battery system price. Conversely, low battery system prices are needed to accomplish higher expected interest rates.

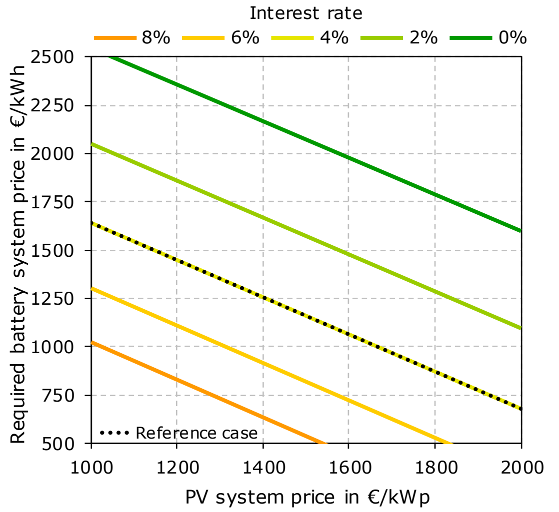

Figure 12: Required battery system price in the reference case in dependency of the PV system price varying the interest rate

Finally, the results of the sensitivity analysis are summarized in Figure 13. The range of the required battery system price is indicated by bars, considering the respective upper and lower bounds. The dotted black line represents the results of the reference case. It can be concluded that the interest rate has the greatest impact on the profitability and therefore on the required battery system price. This is in accordance with the results presented in [7]. The second most important factor is the price of the PV system. Hence, it can be concluded that the deployment of battery systems is also affected by the further cost reductions of the PV systems in the future. It can further be derived that an increase of the retail electricity price of 0.08 €/kWh has larger impact than a decrease of the feed-in tariff by the same magnitude. Hence, the future development of the retail electricity prices will likely has a larger impact on the profitability of PV battery systems than the development of the feed-in tariffs.

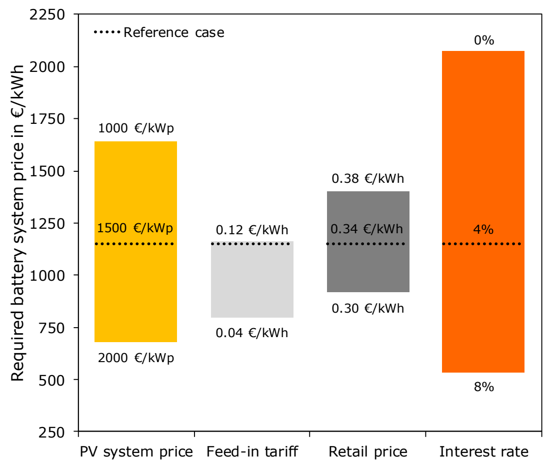

Figure 13: Impact of different factors on the limit of profitability in terms of required battery system price compared to the reference case.

4 DISCUSSION

Assuming that the determined required battery system price can be achieved in future; investing in a PV battery system will become more attractive than purchasing the entire electricity demand from the grid. Nevertheless, the aforementioned results reveal that the profitability is subjected to a variety of impact parameters. There are several factors which cannot be foreseen exactly and can only be estimated at the time of the investment. Among these are the annual load demand of the household and their temporal distribution within the lifespan of the PV battery system. Changes in consumption behavior can either increase or decrease the degree of self-sufficiency and therefore they also affect the profitability.

From the economic point of view, the future development of the grid electricity costs is also quite uncertain and cannot be predicted precisely. As the investment in a PV battery system competes with the retail electricity price, the introduction of time-of-use tariffs may affect the profitability positively or negatively as well, depending on their characteristics. Furthermore, the extension of the EEG surcharge for self-consumed PV electricity for PV systems below the current threshold of 10 kWp would burden the economics and therefore the deployment of residential PV battery systems.

Given the number of economic input parameters that cannot be projected exactly, the economic assessment is quite uncertain. Considering these facts makes the economic assessment of PV battery systems less reliable compared to the assessment of only grid-feeding PV systems, which were remunerated with predefined feed-in tariffs. However, other business models exist, e.g. participating at the wholesale or balancing power market, which can increase the economic value of a PV battery system [8]. Nevertheless, it remains uncertain to what extent home owners would be willing to allow third parties to control their battery systems.

Apart from the financial motivation to invest in PV battery systems, there are several other reasons for people to be increasingly interested in installing PV battery systems. Especially the aim of being self-sufficient and using self-generated electricity is one main driver making PV battery systems more attractive to customers [9]. Therefore it can be expected that some home owners will invest in PV battery systems, ignoring the cost issue.

5 CONCLUSIONS

This paper investigates the economics of residential PV battery systems with the business case of substituting grid electricity costs. The impact of different economic input parameters on the required battery system price were studied for a defined reference case. The results reveal that the major factor is the interest rate, followed by the PV system price, retail electricity price and feed-in tariff. Assuming that the calculated required battery system prices in the range of about 500–2000 €/kWh will be achieved in the future; investing in a PV battery system is financially more attractive than purchasing the entire electricity demand from the grid. Therefore it can be expected that most of the residential PV systems will be equipped with storage batteries in the future, which allows to implement additional functionalities to boost the further development of the PV expansion.

ACKNOWLEDGEMENT

The authors thank the Senate Department for Urban Development and the Environment of the state of Berlin for the support in the framework of the project “PVprog”. The project is funded by the Environmental Relief Program (UEP II) and is co-financed by the European Union through the European Regional Development Fund (ERDF) and the state of Berlin (Senate Department for Urban Development and the Environment).

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