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Authors' addresses:

Silvia Vonsien
RWTH Aachen University
Templergraben 55
52056 Aachen, Germany
E-Mail: silvia@vonsien.de

Reinhard Madlener
Institute for Future Energy Consumer Needs and Behavior (FCN)
School of Business and Economics / E.ON Energy Research Center
RWTH Aachen University
Mathieustrasse 10
52074 Aachen, Germany
E-Mail: RMadlener@eonerc.rwth-aachen.de

Publisher: Prof. Dr. Reinhard Madlener
Chair of Energy Economics and Management
Director, Institute for Future Energy Consumer Needs and Behavior (FCN)
E.ON Energy Research Center (E.ON ERC)
RWTH Aachen University
Mathieustrasse 10, 52074 Aachen, Germany
Phone: +49 (0) 241-80 49820
Fax: +49 (0) 241-80 49829
Web: www.fcn.eonerc.rwth-aachen.de
E-mail: post_fcn@eonerc.rwth-aachen.de

Cost-Effectiveness of Li-Ion Battery Storage with a Special Focus on Photovoltaic Systems in Private Households[1]

Silvia Vonsien[a] and Reinhard Madlener[b,*]

RWTH Aachen University, Templergraben 55, 52056 Aachen, Germany

Institute for Future Energy Consumer Needs and Behavior (FCN), School of Business and Economics / E.ON Energy Research Center, RWTH Aachen University, Mathieustrasse 10, 52074 Aachen, Germany

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Abstract

Using a self-developed economic model with a technical battery aging component, this paper provides a new approach to evaluating the economic efficiency of Li-ion battery storage. We use our model to quantify the increase in self-consumption of electricity from a solar photovoltaic system by means of a home battery storage system. Regarding battery aging, we find that the longest battery lifetimes can be achieved with the highest state-of-charge limit, which is, however, not economically efficient due to limited self-consumption. Although one of the three battery pooling concepts was identified as not being economically efficient, namely the case of *Sonnen*, our evaluation shows that economic efficiency can, in principle, be achieved with home battery pooling concepts. In future research, the model-based impacts on self-consumption and batteryaging found here ought to be validated by using real world data from the systems analyzed.

Keywords: Solar photovoltaics; Battery storage; Battery aging; Home battery pooling; Cost effectiveness

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[*] Corresponding author. Tel. +49 241 80 49 820, e-mail: RMadlener@eonerc.rwth-aachen.de (R. Madlener)

Nomenclature:		
BDEW	=	German Association of Energy and Water Industries (*Bundesverband der Energie- und Wasserwirtschaft e.V.*)
BESS	=	Battery energy storage system
BMWi	=	Federal Ministry for Economic Affairs and Energy (*Bundesministerium für Wirtschaft und Energie*)
C, C_{nom}	=	Capacity, nominal capacity
capex	=	Capital expenditure
DOD	=	Depth of discharge
EEG	=	German Renewable Energy Sources Act (*Erneuerbare Energien Gesetz*)
EOL	=	End of life
ESS	=	Energy storage system
EV	=	Electric vehicle
IRR	=	Internal rate of return
KfW	=	German Reconstruction Loan Corporation (*Kreditanstalt für Wiederaufbau*), a special purpose bank
KPI	=	Key performance indicator
kWh, kWh/a	=	Kilowatt hour, Kilowattatt hour per annum
kW_p	=	Kilowattatt peak
LCOS	=	Levelized cost of storage
Li-ion	=	Lithium-ion
max., min.	=	Maximum, minimum
NPV	=	Net present value
O&M	=	Operating and maintenance
opex	=	Operational expenditure
prod	=	Production
PV	=	Photovoltaics
ROI	=	Return on investment
SEI	=	Solid electrolyte interface
SOC	=	State of charge
VAT	=	Value added tax
VDI	=	Association of German Engineers (*Verein Deutscher Ingenieure*)

1 Introduction

Around the world, the trend in energy supply towards renewable sources is gaining increasing significance. Germany has been playing a leading role in this development, especially since the Fukushima accident [1]. Apart from phasing out nuclear power, the country's target is to increase the amount of renewable electricity from 32% at present to between 40 and 45% by 2025 and to between 55 and 60% by 2035 [2]. Battery storage is able to integrate a high amount of electricity from solar photovoltaics (PV) into the local grid, so that the conventional power plant output can be reduced [1].

By 2012, local PV electricity self-consumption had reached grid parity, meaning that self-consumption is more economical than grid feed-in. The three main reasons for this are falling PV system prices, falling feed-in tariffs and increased retail electricity prices. Installing a battery storage system—which becomes increasingly attractive with steadily falling battery prices—helps to increase the amount of self-consumption (cf. [3]: 68). Furthermore, the demand to increase the self-produced renewable electricity and the desire to raise the degree of self-sufficiency—especially in an environment of increasing retail electricity prices—can be met with a residential battery storage system [4].

The greatest challenge to the increased use of renewable energy is that of fluctuation. Since PV production and consumption profiles diverge, it is necessary to store the PV-produced electricity temporarily in order to enable a higher degree of self-consumption. Battery storage can time-shift the production by approximately four hours. If sufficient battery capacity and sunshine duration are available, it is possible to supply the electricity demand of a building self-sufficiently [1]. Besides the increased self-consumption, battery storage “can also help relieve local grid capacity constraints” and thus support the system operator [5].

In an economic context, the question emerges of whether local battery storage represents an economically efficient alternative to the grid supply and the sale of excess production to the grid, which in Germany is subsidized. A battery allows increased self-consumption of PV-produced electricity. Therefore, it is important to evaluate whether the benefit of increased self-consumption can exceed the high investment costs.

There exist several approaches for modeling the economic efficiency of energy storage. Besides the value of increased self-consumption, there is a relatively new concept of pooling batteries with the intention of providing services to the grid. The three battery storage manufacturers *Caterva*, *Sonnen,* and *Fenecon* are pioneers in offering a service for marketing both the (aggregated) stored electricity and the spare storage capacity in residential battery storage systems on the reserve energy market. With the pooling of small battery storage systems, a virtual large-scale storage unit is created, which meets the requirements for participating in the reserve energy or the ancillary services market [6]. The aim of our study is to analyze the economic efficiency of a residential hybrid Li-ion battery storage /solar PV system by taking the economics of battery aging explicitly into account.

This paper presents a novel approach for evaluating the economic efficiency of a Li-ion battery storage with the help of a self-developed economic model in association with a technical battery-aging model. The model is used to identify the increase in self-consumption which can be achieved with a battery storage system.

As indicated above, rapid advances in the Li-ion battery technology development can be observed. This study concentrates on the specific requirements of a battery storage system attached to a PV system for a residential use case. Contrary to the electric vehicle (EV) sector, where high energy density and high performance are the crucial factors, in a stationary use case the requirements focus on lifetime and costs (cf. [7]: 27). In this context, the aspect of battery aging plays an important role. In comparison to other storage technologies, chemical batteries suffer from aging effects. These effects lead to a capacity and performance decrease over a battery's lifetime (cf. [8: 20]). To evaluate the economic efficiency of the battery system, the impacts of aging are taken into account.

Besides the value of increased self-consumption, the further potential of enlarging the economic efficiency of a battery investment can be analyzed. The relatively new concept of pooling batteries with the intention of providing services to the grid is examined (cf. [6]: 61f.).

A comprehensive economic analysis requires well-founded research on the input parameters and on the environment. First of all, the costs of a battery investment need to be identified and determined. These include the costs for the battery itself, the costs for the inverter to connect the system to the PV system, the installation costs, and operation and maintenance (O&M) costs. Furthermore, the costs for electricity purchase from the grid and the future development need to be considered.

Also, all benefits connected to the battery investment need to be examined. One obvious benefit is the increase in self-consumption. The indirect increasing of retail prices increases the value of self-consumption. Besides self-consumption, the non-conventional revenue option of pooling concepts is reviewed.

An analysis of the environment is essential. Falling system prices for the battery investment have a strong impact on economic efficiency. Another aspect is that of falling remunerations for grid feed-in (cf. [9]: 2019f.).

Battery aging also has an impact on the economic performance of battery storage concepts, and thus needs to be examined as well. Therefore, it is important to gain knowledge of battery parameters that influence the aging process. One of our objectives is thus to derive an indication of how the operation of a battery influences battery aging and to identify the impacts on the economic viability of the battery investment.

Due to the wide range of applications of Li-ion batteries, all with various requirements, our study is restricted to the usage of battery storage for photovoltaic systems in private households. "*Lead-acid and lithium-ion (Li-ion) systems are the most commonly used battery in combination with PV systems in residential buildings*" ([9]: 2020). The Li-Ion technology is rather expensive compared to the conventional lead-acid batteries, but regarding the costs per cycle the Li-ion technology shows lower costs, due to longer lifetimes (cf. [5]: 28).

The advantages of Li-ion batteries are high specific energy density and high specific power. For stationary use cases, the specific energy density might hold less importance, but all the more important is that the stored power can be retrieved within a short time. Further advantages include the high charge and discharge efficiencies and a low self-discharge. The storage efficiency can be higher than 95% (cf. [7]: 386; cf. [1]: 15). Compared to other chemical battery storage technologies, the Li-ion technology shows a better performance (cf. [7]: 389), higher battery lifetimes, and a better cycling capability (cf. [7]: 419).

Requirements of a stationary PV battery storage are a high lifetime expectancy (calendar life and cycle life), just as the battery price and the energy efficiency. The requirements of a high lifetime and energy efficiency are fulfilled by the Li-ion technology (cf. [1]: 421). The costs are analyzed in detail in this study.

Germany was chosen as the location for the PV battery investment. PV power production plays a substantial role in Germany's reaching its ambitious Renewable Energy Sources Act (EEG) targets (cf. [10]: 5). PV systems with a maximum 10kWp enjoy the benefit of being exempted from the EEG apportionment (cf. [11] EEG Art. 61a (4)). Therefore, only households with PV systems below 10kWp power are considered here. Furthermore, it is assumed that the owner of the PV system is a prosumer, which means that she also has the intention of consuming the produced electricity rather than only supplying the PV production to the grid. In this study, it is expected that a PV system is already installed, which means that the economic viability of the investment in a PV system is not examined.

The theory of battery aging and the resulting impact on economic efficiency is regarded in detail, although for the simulation a technical model from the Institute for Power Electronics and Electrical Devices (ISEA) at RWTH Aachen University is used.

Our analysis is based on assumptions from a number of recent studies. The literature review was based on the Cooper method, as applied on a larger scale in [12]. For the economic calculation, the net present value (NPV) method is used to calculate the NPV of battery investment by regarding the discounted cash flows (cf. [4]: 78). Additionally, the break-even costs, i.e. the investment costs that would lead to an NPV of zero, are calculated. The NPV approach is the most commonly applied method for investment calculations. Furthermore, the levelized cost of storage (LCOS) is calculated, which represents the costs to charge and to discharge one kWh to and from the battery, respectively (cf. [13]: 4).

2 Methodology

2.1 Net present value (NPV) method

The net present value (NPV) approach allows an investment to be evaluated regarding its discounted net present value. This discounted cash flow method assumes a perfect capital market with a constant interest rate over the investment horizon studied [4]. The NPV is calculated by summing up the discounted gains (revenues) and losses (costs) for every period of the investment case, using a constant discount rate, to the date when the investment decision is made, i.e.

$$NPV = \frac{\sum_{t=0}^{n}(G_t - L_t)}{(1+\mathrm{i})^t}, \tag{1}$$

where *n* denotes the project lifetime; *t* is time [a]; *G* the gains; *L* the losses; *i* the interest rate; and $(1+i)^{-t}$ the discount factor. The assumed project lifetime depends on the useful life of the asset considered. In the initial periods of the investment, the accumulated cash flows are negative due to the initial investment costs. The time resolution typically assumed for the investment in a perennial project is yearly.

2.2 Discount rate

The interest rate in the discount factor is interpreted as the missed opportunity which could be achieved alternatively if the money for the investment were used for an investment case with an equivalent risk [6]. The next-best alternative to a battery investment could be a low-risk investment/asset such as a bank deposit, which in Germany has seen historically low interest rates in recent years. The current interest rate for a bank deposit in Germany is around 0.03%/a and for an overnight deposit it is around 0.05%/a [14].

The investment costs – also known as ‘capital expenditures’ (capex) – are to be paid in the first period. All running costs –also known as ‘operational expenditures’ (opex), such as maintenance and other operational costs, are assumed to be equal for each period. There might be periods where higher opex costs occur than in other periods, although over the lifetime they should level out. The further periodical calculation of the gains and losses in the hybrid solar PV–battery investment case is based on the self-consumed electricity. On the one hand, increased self-consumption avoids expensive electricity supply from the grid. On the other hand, implicit costs need to be considered. In this case, the implicit costs are the forgone feed-in remuneration that the household could alternatively receive for the electricity that is not self-consumed.

2.3 Taxation of PV systems

In Germany, the operator of a PV system has to take the decision of whether to use the advantage of input tax deduction and pay 19% VAT on each self-consumed kWh [15]. There are several options for the assessment basis for self-consumed electricity. One option is to calculate the self-consumption based on the production costs including operational and maintenance (O&M) costs, depreciation rates, and interest rates. If the operator registers the system as a small business, the input tax deduction advantage is lost, but no VAT has to be paid for self-consumption. In this case, the operator has to prove that the system is part of a business and that at least 10% of the electricity is fed into the grid [15].

2.4 Key performance indicators (KPIs)

Key performance indicators (KPIs) are used to better understand the quantitative facts of the investment in a meaningful way. KPIs improve the comparability of different projects and different cases within a project. In the following paragraph, all relevant KPIs that are later applied for the interpretation of the results of the economic model are defined.

NPV and break-even costs. The NPV is the sum of all discounted net cash flows that are related to the investigated investment [4]. If the NPV is greater than zero, not only do the (discounted) revenues cover the investment costs and the desired capital return rate, but also the investment is profitable. If the NPV is zero, the (discounted) revenues merely cover the expenses, which is known as “breaking even”. The corresponding investment costs for a zero NPV are the break-even costs. In the worst case, the NPV is negative. In this case, the investment costs and the capital return cannot be compensated by the revenues, and a loss occurs [16].

LCOS. The levelized cost of storage (LCOS) “is the (fictitious) average ‘net’ price that must be received per unit of output (effectively kWh or MWh) as payment for storing and discharging power in order to reach a specified financial return” [13]. This financial measure reflects the revenues that the battery storage investment needs to produce in order to reach the financial break-even over the entire lifetime, including all costs, i.e. both the initial investment costs and the O&M costs. Because the LCOS is calculated as the levelized per unit of output, it is often used in the scientific literature to compare the relative cost effectiveness of different storage technologies [13].

IRR. The internal rate of return (IRR) reflects the interest rate “which leads to a net present value of €0 and is a measure to quantify the profitability” [18]. Excel® enables the IRR to be calculated for a cashflow of several periods by using an estimated value (in our case, 10%). The IRR is then determined by using the iterative Newton approximation method [19].

Discounted payback year. The year in which the accumulated NPV turns into a positive number is called the ‘discounted payback year’. In other words, the discounted payback year reflects how many years the project needs until amortization. If the discounted NPV does not turn into a positive value over the lifetime of the project, the investment is not expected to pay off [19].

2.5 Sensitivity analysis

A sensitivity analysis is a useful addition to the initial base case of the investment calculation. The base case requires certain assumptions regarding the input parameters, which have an impact on the result. In reality, these parameters can fluctuate. Therefore, in the sensitivity analysis, each input parameter is varied in a separate calculation and allows the impact on the result to be examined. By doing so, parameters can be identified that have a substantial impact on the economic efficiency of an investment [19].

3 Literature review

All of the studies reviewed here use certain variables and parameters; see Table 1.

Table 1: Comparison of variable parameters

Reference	Cycles	Battery size	Load profile	Electricity price	Capital costs	DOD	c-rate
Jülch [20]	x						
Linssen et al. [9]		x					
Moshövel et al. [21]			x				
Parra and Patel [22]		x					
Naumann et al. [23]		x		x			
Lazard [24]					x		
Weniger et al. [25]				x			
Pawel [26]						x	x

Source: Own compilation, based on a literature research

Five of these studies perform an additional sensitivity analysis to consolidate the sensitivity to the result when certain parameter values change (for details on the chosen variables for the sensitivity analysis, see Table A.1). A common procedure is to vary the values of interest by 30%, and to examine the impact on the economic viability, as described in [22].

In terms of viability, only two of the nine sources reported in Table 1 and Tables A.1-A.6 in the Appendix, respectively, find Li-ion battery storage units economically viable at present. Weniger et al. [25] find economic operation at a battery price < 2,000 €/kWh, which is feasible with today's battery system prices on the German market. The *Fenecon* economic model 2017, on which their webinar is based upon [27], predicts economic viability for a fictitious household, but should be regarded with caution, given that non-financial revenue streams are taken into consideration as well. Two further studies expect economic efficiency in the future. Jülch (2016) calculates a LCOS of 0.17 €/kWh in 2030, which is below the forecasted retail energy price for households in 2030 of 0.284 €/kWh (cf. [17]: 227). Naumann et al. [23] include one viable scenario for 2018, with a strong decrease in battery system prices to a price below 450 €/kWh and an increase in retail electricity prices. Another three studies predict economic viability under certain circumstances. According to Linssen et al. [9], a battery system can be economically operated at battery prices (costs) of 1,200 €/kWh if subsidies are taken into consideration. In contrast, Moshövel et al. [21] – whose model also takes government support into account – see a possibility of economical operation at prices below 500 €/kWh, and only partly economical operation at prices between 500-700 €/kWh. Parra and Patel [22] find a positive IRR for battery sizes with a capacity of 10-14 kW in Germany. The remaining two studies do not allow a positive interpretation of the economic efficiency of Li-ion battery storage for residential use cases. Pawel [26] concludes that economic viability is only given at battery prices < 300 €/kWh. The LCOS calculated in Lazard [24] far exceeds the retail electricity price, even with the predicted 47% price decrease for the 5-year period from 2015 to 2020.

Regarding the assumed costs in all studies, the battery investment is the main component. As mentioned, all of the studies concur on a sharp future decrease in battery investment costs. Table A.2 provides an overview of the initial battery cost assumptions of the various studies. Note that [26] is excluded from the comparison of initial battery costs in that table due to the large-scale use case, which is not appropriate for a residential sector analysis.

It is challenging to compare the battery costs in the literature, as frequently no detailed information on the individual cost elements is provided. Furthermore, it is unclear whether the investment is calculated with or without VAT. Regarding the overview, the initial battery prices in 2015/2016 (i.e. when we conducted our study) varied on average from 719–1,570 €/kWh (mean value: 1,466 €/kWh). In addition to the reviewed literature, the study of Sauer et al. [28] is taken into account for evaluating the battery costs. The mean value derived from the literature is about 50% higher than the higher limit in Sauer et al. (2013), who show a range of 150-200 €/kW for the inverter and 300-800 €/kWh for the energy-related investment costs, which for the total investment costs indicates a range of 450-1,000 €/kWh (cf. [28]: 8).

According to the future outlook in five of the studies, an annual cost decrease of between 3% and 9.4% is expected. In contrast, [28] shows a decrease of 10%/a of the energy-related investment costs and a decrease of 5%/a of the inverter costs, overall showing a stronger decrease than the average of our literature review. The lowest estimated future value was found in the study of [23] in 2034 with 220 €/kWh. Besides the initial battery costs, the studies reviewed here also take further costs into consideration (for details, see Table A.3).

The electricity price in [22] for Switzerland [25] (where an average electricity price over 20 years was calculated), and the one in Fenecon [29] (not a literature-based reference) are excluded from the calculation of the average price. Furthermore, in seven of the nine references taken into consideration overall, the future retail electricity price increase will play an important role for the battery's economic efficiency. The mean average electricity [price] increase assumed is 2.5%/a, whereas the lowest (highest) value is 2%/a (3.58%/a). The mean average electricity retail price from the 2015 and 2016 literature covered is 0.295 €/kWh. During the lifetime of the battery system, O&M costs were considered in all studies; the mean value is 1.8%/a of the initial investment.

On the revenue side, six studies consider self-consumption or self-sufficiency as being revenue-increasing. Five studies take governmental support in the form of the German EEG feed-in tariff into account. Most of the studies calculate with 0.12 €/kWh (see also Table 3). Moshövel et al. [21] is the only study that considers the future decrease of the feed-in tariff in Germany. For the interest rate, five studies – i.e. the vast majority – calculate with 4%/a. It is uncertain whether a private household will finance a battery storage system with debt or equity capital. Two studies – Pawel [26] and Jülch [20] – use the WACC in their calculations. Inflation was only taken into consideration (with 2%/a) in Naumann et al. [23].

In terms of battery parameters, the values in the studies vary widely. All chosen values are based on Li-ion technology. The battery lifetimes in the reviewed literature range between 5-22 a, but four out of the six studies assume a lifetime of 20 years or more (see Table A.4). The calculated mean average battery lifetime is 16 years, with an upper (lower) weighted mean of 17 (15) a. The battery lifetime has to be further consolidated with market guarantees of battery manufacturers. Table A.5 provides an overview of the specific battery characteristics DOD, SOC, c-rate, and battery aging of the individual studies.

Regarding the specific battery characteristics, we checked whether battery aging was considered and whether parameters were influenced to prevent aging. The full range of the DOD is limited to 80% in [20], whereas [26] considered three different DODs: 100%, 75%, and 50%. The SOC is limited in [22] such that the upper and the lower 10% of the SOC range were not used. Furthermore, [22] set a limit to the c-rate of $3*C_{nom}$ for the charge and discharge rate. The calendric losses are calculated with the Wöhler formula, a fundamental equation for durability computations. Naumann et al. [23] refer to the Wöhler curve when it comes to battery aging, showing that smaller cycles cause lower degradation to the battery compared to larger cycles. Another way to include battery aging is to use a general degradation percentage rate in the calculations, as is done in Linssen et al. [9] (0.5%/a) and Pawel [26] (1%/a), respectively.

Another aging-relevant parameter is the c-rate. If the speed of loading and discharging the battery is increased, a higher throughput can be achieved and thus the economic efficiency of the battery can temporarily be increased. However, aging effects occur faster when the manufacturer's specifications are exceeded and hence the battery lifetime is reduced, causing a negative impact on economic efficiency. Moshövel et al. ([21]: 1641) limit the c-rate to 0.5*C for charging, and to 1*C for the discharge process, compared to the limits stipulated by the battery manufacturers.

Battery efficiency, considered in six of the reviewed studies, is another essential parameter for economic efficiency. A commonly used assumption for the efficiency of Li-ion batteries is 95% (see Table A.6); the mean value is at 91%. Efficiencies of Li-ion batteries of 95% and higher are also reported in Korthauer ([1]: 16). Therefore, an efficiency of 95% will be used as the base case assumption in our economic model.

Most of the studies reviewed find the self-discharge of Li-ion batteries negligible, as it is much smaller compared to that of other battery technologies (cf. [24]: 4) only two out of six references have taken it into account ([20]: 1%/m; [23]: 6%/m). Compared to [29], with a self-discharge range of 3-5%/m today, a mean average of 3.75%/m can be calculated. Sauer et al. [29] further predict a decrease of the self-discharge rate after 2023 to < 3%/m.

In order to finalize the interpretation of the evidence, we compare the project-specific data of the different studies. Eight of the use cases have a residential context, whereas the use case in [26] is not specified but can be assumed to be a large-scale business context due to other parameters. Projects mentioned here are located either in Germany or Switzerland. The battery size is either a decision variable (as in [9]; [22]), calculated based on optimality considerations (as in [21]), or determined by a 1:1 ratio (PV system size : battery size), the latter approach proposed e.g. in Waffenschmidt [30]: 97) and used in [23] and [25]. Regarding the optimum ratio calculated in [21] of a 7 kWh battery size for a consumption of 4,500 kWh/a, this gives a ratio of 1.55:1. For the other studies, it is not clear which rules were followed for the choice of battery size. The assumed yearly electricity consumption is found to be between 3,400-8,000 kWh/a, depending on the respective study's underlying load profile.

Considering the load profiles used in the reviewed studies, different approaches were chosen. Standard load profiles, such as H0 or VDI, are used. H0 was created by the German Association of Energy and Water Industries (BDEW) to map the load demand of private households and, where appropriate, also small industrial entities (cf. [31]). Either real-life measures are taken or an exemplary real-life measurement as in [22]. Linssen et al. [9] additionally consulted a load profile generator from Chemnitz University of Technology to create a user load profile for the study-specific requirements. If specified, as is the case in five studies, the solar irradiation data are based on real measured data from existing solar PV panels. As the battery cost data vary among the studies, a market data analysis on today's market prices provides profound knowledge about the current prices for the economic model used in our analysis.

3.1 Market review

The literature review reflects the cost assumptions for Li-ion batteries found in the literature. The market review examines the current market prices for Li-ion batteries as published in [32] and derived from battery manufacturers' information. Furthermore, the revenue for the economic efficiency calculation in the literature review is mainly based on an increase in the level of self-consumption. In the second part of the market review, pooling concepts offered by battery manufacturers are investigated. The market review yields some additional input for the economic model.

3.1.1 Battery manufacturers and prices

CARMEN [32] includes the systems of 33 manufacturers with 270 systems. All data were collected via request to the manufacturer, although not all manufacturers revealed their retail prices. The prices include VAT. The following summary concentrates on battery systems that are based on lithium technology and have a usable capacity of approx. 5 kWh. If a manufacturer offers multiple systems in the 5 kWh range, the cheapest and the most expensive system were chosen in order to examine the price spread (cf. [32]). Table 2 summarizes the market review. This review shows that even the lowest retail price for the chosen battery type is slightly above 1,000 €/kWh. All manufacturers provide a guarantee of 10 years.

Table 2: Overview of battery manufacturers and prices 2017

Manufacturer	Product	Usable capacity [kWh]	Guaranteed lifetime [a]	Retail price [€]	Retail price [€/kWh]
Akasol GmbH	neeoRack *	5	10	7256	1451
	neeoSystem Typ1*	5	10	9683	1937
Alpha ESS Europe GmbH	Storion-Eco S3	5.4	10	5690	1054
	Storion-T5	5.4	10	7270	1346
Energy Depot Deutschland GmbH	ESS PILUM 6.0	5.4	10	8898	1648
	ESS OPTIO 6.0	5.4	10	10888	2016
Fenecon	Mini 3-6	6	10	7200	1200
	B-Box 5.0*	4.9	10	5175	1056
	GW-Box 4-3-5	4.9	10	6000	1224
IBC Solar AG	IBC Solstore 6.5 Li	4.7	10	6800	1447
Q3 Energy GmbH &Co. KG	QBATT5/8	5.4	10	9982	1849
SHARP Electronics GmbH	Smart Chap BMZ	5.4	10	6660	1233

* Price for one accumulator; a mean inverter cost of €175 (cf. Sauer et al. 2013:8) was added to the costs

Source: CARMEN (2017)

3.1.2 Pooling concepts

Pooling of battery capacities is a relatively new business concept and hence future market developments are very difficult to predict. Our analysis reflects the current status, even though there might be changes to the concepts, because they need to be proven first. Given that pooling is novel, the scientific literature is still scarce, and hence recent trade journals and internet sites were reviewed.

The battery storage manufacturers *Caterva*, *Sonnen,* and *Fenecon* are pioneers in offering a service for marketing both stored electricity and spare storage capacity in residential battery storage systems on the reserve market by pooling a larger number of home battery storage systems. Their concepts are reviewed in the following. By pooling several small battery storage systems, a large virtual large storage system is created, which achieves the necessary controlling power and fulfils regulatory requirements for participating in the control storage market (cf. [6]: 61f.). This new concept offers an additional revenue opportunity for residential battery storage system owners besides the common revenue factor of increasing the self-consumption rate. Market access and pooling expenses of the service provider and the impact on the self-consumption rate need to be taken into account, as these are additional expenses for pre-qualification (cf. [6]: 62).

Economic efficiency depends on the future price development of control power, which can change if a major part of the control power is provided by battery storage facilities. Another important factor for economic viability is the legal situation: Whereas in Switzerland this marketing model is already being implemented, Germany has a special legal situation due to its Renewable Energies Act (EEG). It has to be clarified whether an EEG apportionment needs to be paid for self-consumption from a virtual storage unit. Therefore, it needs to be defined who the storage operator in the legal sense is: the control power marketer or the battery owner? (cf. [6]: 61f.).

In general, to be part of a pooling system as a residential battery energy storage system (BESS) owner, it is essential to buy a storage system from a pooling concept marketer. The pooling service suppliers claim that this concept provides higher benefits to the customers than the regular EEG feed-in remuneration, which continues to decrease over time. All regarded battery storage systems are based on the Li-ion technology.

Caterva. Caterva – based in Munich – was founded in 2013 as a Siemens spin-off (cf. [33]). The corporate vision of Caterva is to facilitate 100% self-consumption for their customers via a “Caterva Sun” at their homes, which is Caterva’s battery storage system. The concept is based on a free electricity supply for the Caterva battery storage owner from the Caterva electricity storage pool for a lifetime of 20 years. Furthermore, a premium from grid stabilization services and electricity trading can be granted if customers agree to Caterva having free access to their battery storage system. A PV system of up to 10 kW_p is a prerequisite. The maximum amount of free electricity is 10 kWh/a (cf. [34]).

Caterva provides two different battery storage sizes. The smaller size ('Caterva-Sonne neo') is dimensioned for a single-family home (electricity demand 7,500 kWh/a max, capacity of 12.8 kWh). In combination with a Caterva maintenance contract, a 20-year lifetime of the battery system is guaranteed. However this guarantee covers only 70% of the initial battery capacity (cf. [35]). Regarding the 20-year lifetime, it should be noted that Caterva sets the EOL of the BESS to 70% of the initial capacity and not to 80%, which is the common EOL in the literature. The costs for a Caterva Sonne neo are €17,450 (1,363 €/kWh) (cf. [36]). 7,500 kWh of free electricity is guaranteed and a revenue of approximately 200 €/a when taking part in the pooling concept (cf. [37]). No information on the price for the maintenance contract was found in our literature review. According to Caterva, these costs are compensated by the revenue for the pooling (cf. [34]) and thus should be below 200 €/a.

Sonnen. The pooling concept of Sonnen rests on the "sonnenCommunity". Membership in this community costs 19.99 €/month. Anyone can join and profit from the low electricity costs (cf. [38]). When purchasing electricity from the community, the costs are 0.23 €/kWh (cf. [38]), which nowadays is a saving of 0.0616 €/kWh regarding an average electricity price of 0.2916 €/kWh in 2017 (cf. [39]: 3). Membership additionally comes with a discount of €1,875 (gross) on the "sonnenBatterie", the battery storage system of Sonnen. Members who do not produce their own electricity with a PV system can also purchase the battery. The batteries serve as temporary storage units for the electricity marketing, although the current review concentrates on those customers with their own PV systems (cf. [38]).

The technical datasheet recommends the "eco 8/6" battery (capacity: 6 kWh) for an electricity consumption of up to 4,400 kWh/a. The battery lifetime is designed for 20 a, although only ten years and 10,000 cycles are guaranteed (cf. [40]). We found no further information on the EOL criteria.

The price of the "eco 8/6" is €10,990, and €9,115 (1,519 €/kWh) for community members (cf. [41]) Community members with a battery storage unit from Sonnen can book an electricity flat-rate tariff called "sonnenFlat". For the "eco 8/6" with a capacity of 6 kWh, the tariff "sonne Flat 4250" can be booked, which includes a maximum annual free electricity supply of 4,250 kWh. The 4,250 kWh/a includes direct PV self-consumption and electricity consumed from the battery storage (cf. [42]. With this concept, the storage owner has no negative impact from cuts in self-consumption, while Sonnen applies the storage capacity for marketing and trading (cf. [6]: 62).

Fenecon. The Fenecon concept (called “Energy Pool”) is based on 1,000 kWh/a of free electricity, which is credited to the battery storage customer with the year-end invoice. According to Fenecon, this 1,000 kWh/a closes the gap between self-consumption of the PV electricity (from the PV device directly and the battery storage) and the total annual electricity consumption needs. Additionally, customers have access to free electricity at times when the market shows negative electricity prices via a specific app (cf. [43]).

Fenecon states that there is only a slight impact on the self-consumption rate for customers taking part in the battery storage pooling (cf. [6]: 62). Fenecon has calculated a benefit of €194 for 2015 for a residential battery storage owner, with the optimistic assumption that control energy can be marketed permanently. This is said to be six times the benefit that is achievable with increased self-consumption only (cf. [6]: 62).

For residential electricity storage, Fenecon offers the ‘Fenecon Mini’ battery storage system with a storage capacity of 3 kWh (expandable to 6 kWh). This size is recommended for an electricity consumption of < 5,000 kWh/a. A 12-year lifetime or 6,000 cycles are guaranteed until 70% of the initial capacity remains. If the customer makes use of KfW funding, the customer gets a 10-year guarantee for 80% of the initial capacity (cf. [44]). The price of the 6 kWh capacity version is €7,200 (1,200 €/kWh) (cf. [32]).

The pooling concept is rather new to the market; therefore, no empirical data are available to evaluate the effect on the battery and the self-consumption. It depends on how often the service provider makes use of the battery. The effect on battery aging due to the additional cycling also needs to be taken into consideration. Theoretically, these effects should be balanced off by some financial compensation or free electricity supply. In the case of Caterva, the manufacturer’s guarantee can be extended to 20 years by means of a maintenance contract, which can be regarded as a guarantee that the influence on aging is not accelerated by the additional use of the pooling service. In the economic model, an assumption is made regarding the additional load and discharge activities that the pooling service has on the battery (cf. section 4.1). Compared to the preceding market review, the retail battery prices per kWh are in line with the rest of the market. The economic efficiency of the battery systems and the offered pooling services are analyzed separately in our economic analysis.

4 Economic Model

The economic calculation is based on the NPV method. Our model is built upon three pillars: (a) battery simulation; (b) technical battery-aging; and (c) economic calculation. The calculation does not originate from real-life measurements but is rather a theoretical approach based on a number of assumptions. All input data, calculations, and results can be obtained from the authors upon request. In the following, we first explain the assumptions made for the model inputs.

4.1 Assumptions

We decided to focus on the economics of the electricity storage in a battery only, assuming that the PV systems are pre-installed, because solar PV in Germany already reached grid parity in 2012 (cf. [1]: 68). The economic calculation considers the benefit of the additional self-consumption that can be gained with battery storage. Direct consumption from the PV system and selling electricity to the grid are revenues related to the PV system that are excluded from calculating the economic efficiency of battery storage.

The battery operator considered is an average private household located in Munich, Germany. The operational start of the battery investment is assumed to be January 2018. The PV power production derives from the online PV power production creator PVWatts, which is available on an hourly frequency for a whole year (cf. [45]). The yearly values were linearly interpolated to a 15-minute frequency (see Table A.7 for detailed information on the underlying PV system).

PV systems in Germany are mainly located on 1- or 2-family houses [46]. The most common PV system size in Germany is 5 kW_p (cf. [47]: 6). A survey conducted in 2009 by market research company forsa verified an average annual electricity consumption of a household in a 1- or 2-family detached home to be 3,483 kWh ([48]: 6) a value adopted for our economic analysis. The user load profile was designed by using the levelized H0 standard load profile (i.e. an average household user profile), which is available in 15-min time steps for a whole year (cf. [31]). The available data for 2017 were chosen and perpetuated for the following project years.

The optimum size of a battery storage system depends on the size of the PV-coupled system. A rule of thumb found in the literature is the simple 1:1 ratio of the PV system size in kW_p and the battery storage in $kW_{p,}$ which was proposed by Waffenschmidt ([30]: 97) and also used by [23] and [25]. Regarding the rule of thumb, the assumed battery size in this model is dimensioned to a 5 kWh capacity. The annual consumption and the battery size are part of a later sensitivity analysis aimed at analyzing the impact of changes in the consumption behavior and the battery size.

Following the MAX_SOC strategy of Angenendt et al. [18], an SOC restriction of 67% is chosen for the *base case* to increase the battery lifetime and thus to increase the economic efficiency (cf. [18]: 87). One sensitivity case is considering 100% and another case was created to analyze the impact when the range is limited to 67%, although cycling around the 50% mark, which means a lower SOC limit of 17% and an upper SOC limit of 84%. Battery replacement during the project life is not considered. The EOL of the battery is calculated with the technical aging model of the ISEA Institute at RWTH Aachen University. Therefore, the EOL in years is used as the project lifetime for the economic calculation, and not as the final number of full cycles.

Further battery parameters are defined as follows. The overall efficiency of the battery for charging and discharging is assumed to be 95% for the *base case*. A mean average value of battery self-discharge over time of 0.0025%/h is considered in the battery simulation (based on an average value of 3.75%/m from our literature review). The c-rate for the *base case* with a charge limit of 0.5*C and a discharge limit of 1*C was chosen following Moshövel et al. ([21]: 1641) For the battery efficiency as well as a lower c-rate, several cases for the sensitivity analysis are specified.

The battery costs for the *base case* are assumed at 1,000 €/kWh. The market review represents prices above the 1,000 €/kWh marker, with the lowest price being 1,054 €/kWh. With the forecasted price decrease of 3-9%/a from the literature review, 1,000 €/kWh is assumed to be realistic for a battery investment with an operational start in 2018. Besides the costs for the battery itself, additional investment costs for an inverter of €175 are used, following [28]. Installation costs of 5% of the battery investment are assumed, following [23]. Opex costs are calculated as a fraction of the investment costs at 1.8%/a (a mean value derived from the literature review).

We assume that the battery investment is entirely paid by equity capital, so that no debt financing is necessary. For the use of equity capital, we assume an alternative return rate of 0.5%/a, reflecting the opportunity of having the money in a bank deposit. The 0.5%/a are used as a discount rate for the NPV calculation as well as a yearly return for the LCOS calculation.

The KfW funding concept is not regarded in the economic calculation, as a payment from equity is assumed. The only remuneration taken into account is the feed-in remuneration. The size of the applicable remuneration depends on the date when the PV system was installed (see Table 3).

Regarding the constant decrease, the economic model calculates with the most conservative assumption that the PV system was installed in 2017 and thus calculates a remuneration of 0.1227 €/kWh. We assume further that the operator is not registered as a small business and thus has to pay 19% VAT for the self-consumed electricity, calculated after deducting the expenses for O&M and depreciation). As pooling concepts seem to bring additional revenue for the battery investment, three cases are specifed for the concepts of *Caterva*, *Sonnen*, and *Fenecon*, assuming the battery parameters and the revenue described above and an adjusted user load and PV production. For the simulation of the battery in our economic model, an assumption of lower self-consumption was made (for details, see section 4.3).

Table 3: Degression of average remuneration since August 2014

Year	Average remuneration [€/kWh]	Period
2014	0.1266	August to December
2015	0.1240	January to December
2016	0.1231	January to December
2017	0.1227	January to July

Source: [27]

4.2 Input parameters and cases

Following the previously described assumptions, we give an overview of the input parameters and the different cases for the sensitivity analysis. The parameters in the sensitivity analysis are generally varied by +/- 30%, following the approach of [22]. Table 4 reports on the different cases and input parameter variations.

The *base case* corresponds to the values described in the assumptions (section 4.1). Regarding the sensitivity analysis, the first varied parameter is the SOC. A range of different SOC assumptions were made in order to analyze the impact on battery aging and on economic efficiency. The first SOC case regards the full SOC range of 100%, whereas the second variation takes into account the 67% limit but examines the impact when cycling ranges between 17 and 84%. The other two SOC cases follow the +/-30% variety rule to the *base case* and are set with a SOC limit of 87% and 47%, respectively.

Further parameters varied by +/-30% relative to the *base case* are: battery size, yearly electricity consumption, and retail electricity price. Note that the variation of the retail electricity price is on top of the assumed increase of 2.5%/a. Regarding the battery costs, only a decrease of the costs of -30% is considered, as an increase would only reduce the economic efficiency. Furthermore, a mean case with 550 €/kWh and a low case with 300 €/kWh battery costs (reflecting the outcome of [28]) are observed in order to evaluate the impact on the price development in greater depth. An impact of the c-rate is examined, with one case assuming a 50% lower rate. A final parameter examined in the sensitivity analysis is the battery efficiency with a variance of +/-3%. Additionally, three cases for the pooling concepts of *Caterva*, *Sonnen* and *Fenecon* are evaluated.

Table 4: Input parameters

case	group	battery capacity	user load	size of PV system	PV production	battery cost	SOC	discharge rate	charge rate
		[kWh]	[kWh/a]	[kWp]	[kWh/a]	[€/kWh]	[%]	C	C
base case	base	5	3,483	5	4,477	1,000	67%	1	0.5
case 0	sensitivity	5	3,483	5	4,477	1,000	100%	1	0.5
case 17-84	sensitivity	5	3,483	5	4,477	1,000	17%-84%	1	0.5
case 87	sensitivity	5	3,483	5	4,477	1,000	87%	1	0.5
case 47	sensitivity	5	3,483	5	4,477	1,000	47%	1	0.5
c-rate-50%	sensitivity	5	3,483	5	4,477	1,000	67%	0.5	0.25
size of battery +30%	sensitivity	6.5	3,483	5	4,477	1,000	67%	1	0.5
size of battery -30%	sensitivity	3.5	3,483	5	4,477	1,000	67%	1	0.5
battery efficiency +3%	sensitivity	5	3,483	5	4,477	1,000	67%	1	0.5
battery efficiency -3%	sensitivity	5	3,483	5	4,477	1,000	67%	1	0.5
yearly consumption +30%	sensitivity	5	4,528	5	4,477	1,000	67%	1	0.5
yearly consumption -30%	sensitivity	5	2,438	5	4,477	1,000	67%	1	0.5
battery lifetime +30%	sensitivity	5	3,483	5	4,477	1,000	67%	1	0.5
battery lifetime -30%	sensitivity	5	3,483	5	4,477	1,000	67%	1	0.5
battery costs -30%	sensitivity	5	3,483	5	4,477	700	67%	1	0.5
low case 300€/kWh	sensitivity	5	3,483	5	4,477	300	67%	1	0.5
mean case 550€/kWh	sensitivity	5	3,483	5	4,477	550	67%	1	0.5
retail electricity price +30%	sensitivity	5	3,483	5	4,477	1,000	67%	1	0.5
retail electricity price -30%	sensitivity	5	3,483	5	4,477	1,000	67%	1	0.5
Caterva	pooling	12	7,500	12	10,744	1,363	67%	0.75	0.75
Sonnen	pooling	6	4250	6	5372	1519	67%	0.5	0.5
Fenecon	pooling	6	4250	6	5372	1200	67%	0.5	0.5

4.3 Battery simulation

The battery simulation represents the first pillar of the model. It serves the purpose of ascertaining how much the self-consumption of PV-produced electricity can be increased by using the battery storage, but also enables the changing SOC when charging and discharging the battery to be simulated. This is needed as an input for the technical aging simulation.

PV production and the user load profile are the inputs to the battery simulation. Assuming that PV production is directly self-consumed where possible, the remaining production can be saved for later consumption; alternatively, if the storage capacity is at the upper limit, production is sold to the grid. Braun et al. (2009) inspire the energy management strategy of the battery as follows. “*In case of PV surplus the additional energy is stored in the battery cells […]. If load demand exceeds the energy provided by the PV installation, the battery will be* *discharged. This functionality is limited by the storage capacity. In the afternoon, when the battery is fully charged, the PV energy has to be injected directly into the grid. This energy is lost for local consumption. Late at night the battery is fully discharged and the consumed electricity is provided by the public grid"* ([49]: 4). This strategy corresponds with the MAX_SOC strategy followed in [18], although the battery SOC should be limited to 67% in order to prevent accelerated battery aging. Figure 1 illustrates the daily course of PV generation and user load demand, representing the above-described energy management strategy.

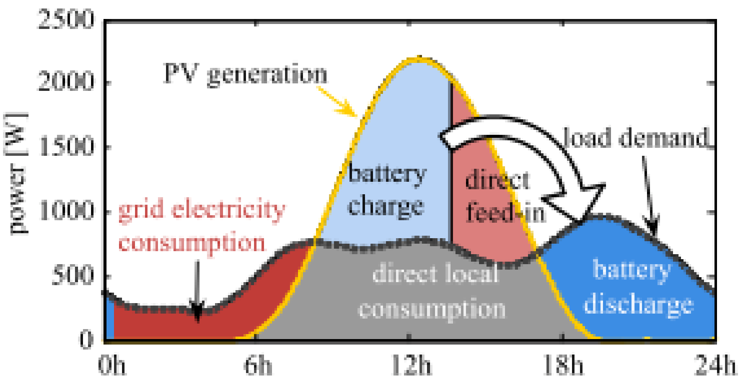

Figure 1: Energy Management Strategy (stylized)

Source: ([49]: 5)

The battery simulation is conducted in a separate Excel-based spreadsheet calculation. It is assumed that it is not possible to charge and discharge the battery at the same time (the algorithm used is shown in the flow chart in Figure 2).

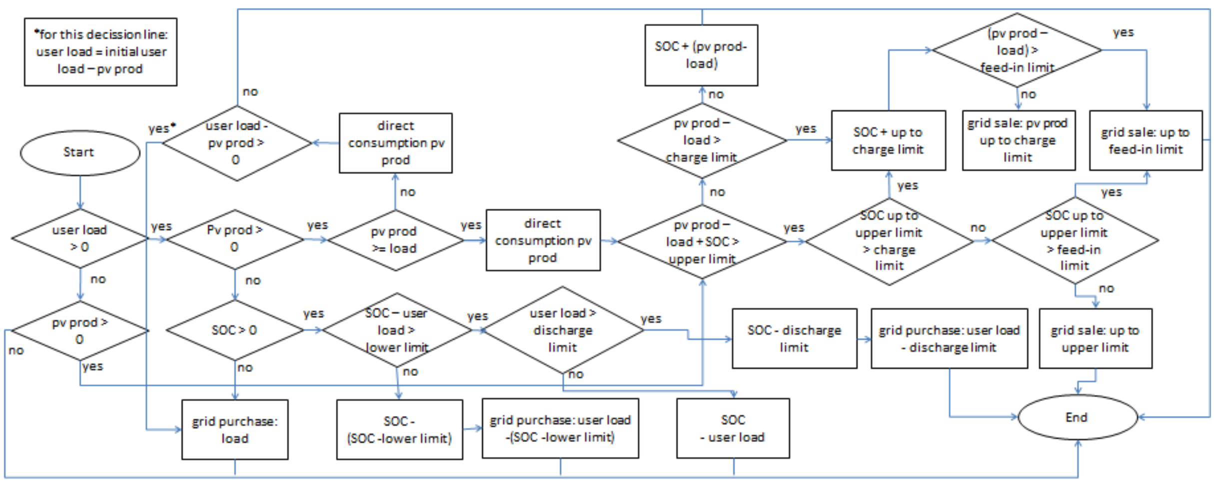

Figure 2: Flow chart battery simulation

Further research is needed to evaluate the impact of the pooling service on self-consumption and on battery life. To date, no empirical values are available. For the three cases, we made an additional assumption to simulate the impact on the battery use. In times when the user load is above the yearly average user load, we assume that the pooling provider refers to the battery and demands a load that is > 1.25 times the average load at that time. In times when the PV production is above the yearly average PV production, it is assumed that the energy supplier adds a load to the storage that is above the average PV production at that time to the battery storage. In times when both user load and PV production are above the annual average, only the difference is taken into account. We assume further that the pooling provider only refers to the storage if the capacity demanded is actually available.

Regarding battery aging (for details, see section 4.4) a loop is run for the battery simulation. First, the SOC output for one year of the battery simulation – assuming a constant battery capacity – was provided to ISEA, RWTH Aachen University. After ISEA had simulated the specific battery operation cases with their aging model, the capacity decrease outcome was included in the battery simulation. Finally, an output was delivered of self-consumption considering the capacity decrease over the whole battery lifetime until the EO. The increased self-consumption is then transferred to the economic calculation (described in section 4.5).

4.4 Technical battery-aging simulation

The battery aging was modeled with a technical battery-aging model of ISEA, RWTH Aachen University [49]. The battery simulation delivers the input for the aging simulation, which comprises the SOC, the load to the battery, and the discharge from the battery in 15-minute steps over the period of one year. The battery-aging model of ISEA covers the two dimensions of aging: calendric and cyclic aging. The former is mainly driven by the cell temperature and results in a decrease of active material, whereas the latter causes a growth of the solid electrolyte interface (SEI) layer. Hence, the resistance increases, which has a negative impact on the storage capacity (cf. [49]: 3). The impact of battery aging is expressed as a capacity decrease per hour, divided by cyclic aging and calendric aging, for the duration of the battery lifetime. The EOL is reached when only 80% of the original battery capacity is left.

Battery-aging simulation was conducted for the following six cases: *base case, case 0, case 17-84, case 87, case 47,* and *c-rate -50%*. The EOL for the remaining cases was calculated following the degradation of the *base case* aging simulation.

4.5 Economic calculations

The third pillar of the model is the calculation of the economic efficiency of the battery based on the NPV method. For every year of the project, the gains and losses are calculated and discounted to the decision year. In the first year of operation, the investment costs are due, representing the highest cost effect over the project's lifetime. All other gains and losses appear periodically year by year. On the revenue side, the project gain is the value of the increased self-consumption, calculated as the benefit of the avoided grid purchase and the opportunity costs for the grid feed-in remuneration. Due to the growing retail electricity prices and the constant remuneration based on the given feed-in tariff, the revenues rise over time. On the cost side, opex, depreciation and VAT occur periodically. Depreciation of the investment costs creates a tax advantage by lowering the revenue and thus the tax base. Adding up the yearly gains and losses delivers the annual cash flows, which are discounted with the assumed discount rate of 0.5%; the total of all discounted cash flows yields the project's NPV. Furthermore, the key performance indices IRR, discounted payback years, break-even costs, and LCOS are calculated in order to compare the different cases. The LCOS is calculated by summarizing the lifetime costs that consist of the initial battery investment and installation costs, the yearly opex costs, the yearly opportunity costs and an assumed year-on-year revenue of 0.5%/a. Thereafter, the lifetime costs are divided by the battery discharge over the lifetime.

5 Results

Table 5 presents the results of the battery simulation and the outcome of the aging simulation for each case considered. Based on the output of the battery simulation and the aging simulation, the NPV results were determined by cumulating the discounted cash flows of each year. In Table A.8, the economic KPIs of each sensitivity case are illustrated. In Figure 3, it can be seen that most of the cases yield a negative NPV, which clearly indicates that the assumed unit base price of 1,000 €/kWh for the battery investment is not economically viable for the base case and most of the sensitivity cases. This is confirmed by the calculated break-even costs illustrated in Figure 2 as well, which are only above 1000 €/kWh in the case of a retail electricity price increase of 30% on top of the assumed general increase of 2.5%/a. In contrast, the two cases that assume a lower battery investment cost of 550 €/kWh and 300 €/kWh, respectively, result in a positive NPV. Regarding the LCOS, all cases except one show a higher value than the assumed retail electricity price in 2018 of 0.30 €/kWh. This one case is the low case 300 €/kWh, assuming a battery investment cost of 300 €/kWh.

Table 5: Results of physical battery simulation (incl. battery aging)

Case	Battery discharge	Direct PV consumption	Grid el. purchase	Grid el. sale	Battery use	Lifetime
	[kWh/a]	[kWh/a]	[kWh/a]	[kWh/a]	[%]	[a]
base case	967	1384	1133	2069	28	21.55*
case 0	1115	1384	985	1913	32	11.58*
case 17-84	967	1384	1133	2070	28	15.48*
case 87	1083	1384	1016	1953	31	15.52*
case 47	750	1384	1349	2286	22	26.52*
c-rate-50%	965	1384	1134	2071	28	21.63*
size of battery +30%	2339	2779	2519	5193	30	25.00
size of battery -30%	1241	1433	1714	2594	28	19.47
battery efficiency +3%	1229	1433	1726	2527	28	21.44
battery efficiency -3%	1083	1384	1016	1946	31	21.67
yearly consumption +30%	749	1384	1350	2298	22	22.30
yearly consumption -30%	971	1384	1128	2100	28	23.43
battery lifetime +30%	961	1384	1138	2034	28	28.02
battery lifetime -30%	934	1709	1884	1778	21	16.91
battery costs -30%	889	1020	529	2513	36	21.55
low case 300€/kWh	967	1384	1133	2069	28	21.55
mean case 550€/kWh	967	1384	1133	2069	28	21.55
retail electricity price +30%	967	1384	1133	2069	28	21.55
retail electricity price -30%	967	1384	1133	2069	28	21.55
Caterva	967	1384	1133	2069	28	21.38
Sonnen	967	1384	1133	2069	28	20.15
Fenecon	967	1384	1133	2069	28	20.34

* Output of technical aging simulation by ISEA, RWTH Aachen University
Battery use [%] is defined as the share of the battery discharge to the total user load.
The battery discharge, grid purchase, and grid sale results are related to the first year of operation.

Two of the three pooling concepts show a positive NPV (see Figure 3). The Caterva case yields the highest NPV and an IRR of 4.5%. Break-even is reached after 14 years. The Fenecon case also shows a positive NPV, with an IRR of 1.7%. The break-even in year 16 is slightly later than in the Caterva case. Sonnen is the only case that shows a negative NPV in this assumed framework. Figure 4 illustrates the NPVs and break-even cost outcomes of the three home battery pooling concepts analyzed.

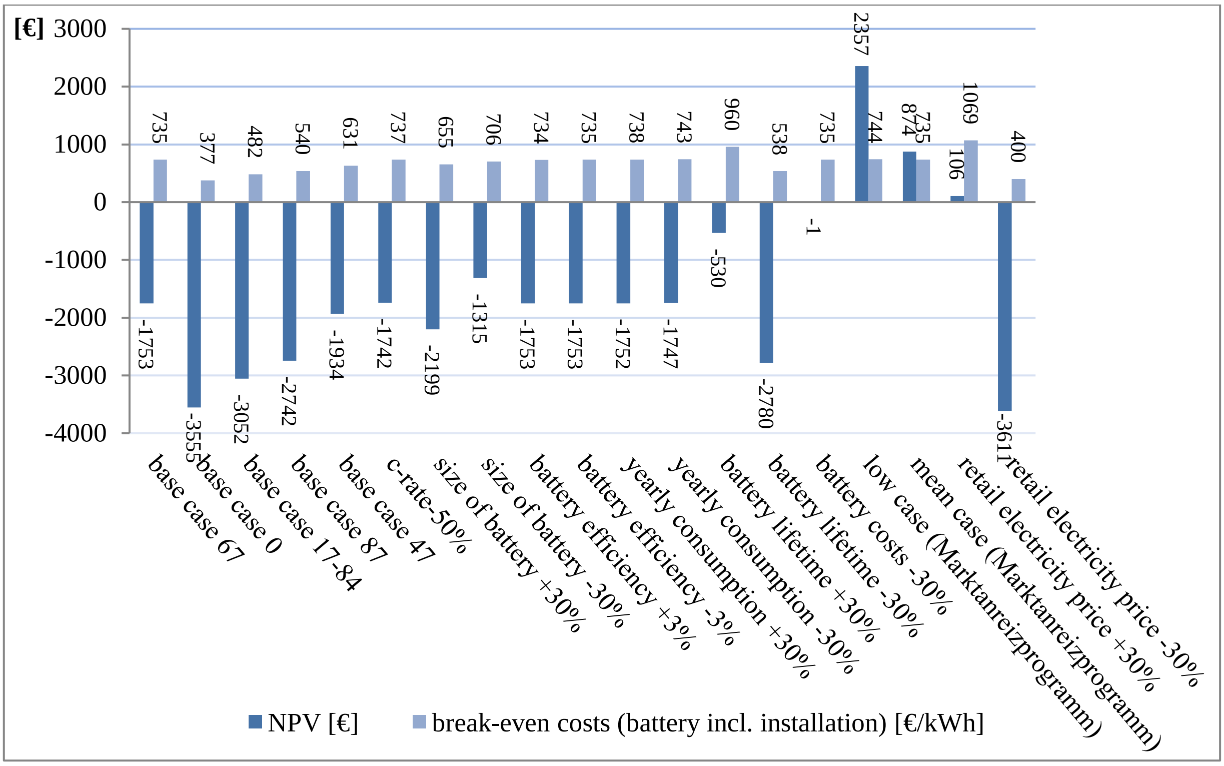

Figure 3: NPV and break-even cost results (sensitivity analysis)

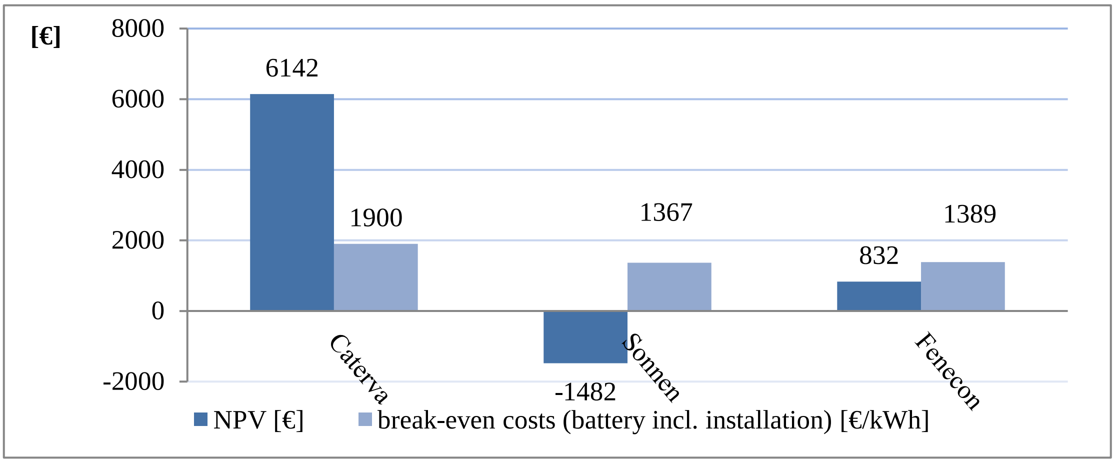

Figure 4: NPV and break-even costs of the battery pooling concepts considered

Because the results show mainly negative NPVs, the break-even costs are a more appropriate KPI for comparing the economic viability of the cases. Note that the break-even costs include the aging impact, as the project lifetime was set to the investigated EOL of each case. The NPV strongly depends on the battery investment costs. The break-even costs represent the battery investment costs (incl. installation) leading to an NPV of zero. Figure 5 shows the break-even cost ranges for the different sensitivity categories compared to the base case. The upper bar represents the high end, the lower bar the low end for each category.

The base case break-even costs are 735 €/kWh. This states that the battery investment and the corresponding installation costs per kWh of storage capacity can cost a max. of €735; otherwise, the investment is not economically efficient. The first sensitivity analysis addresses the SOC. Table 6 shows the details of the SOC cases arranged by a descending SOC range.

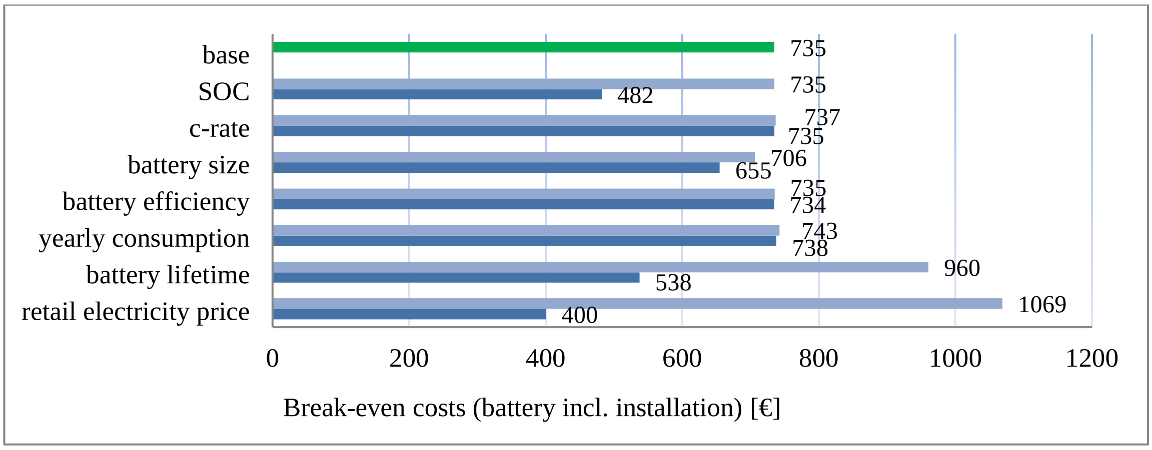

Figure 5: Sensitivity analysis for impacts of key parameters on the break-even costs range

Table 6: Impact of SOC on economic efficiency indicators

Case	NPV [€]	IRR [%]	Discounted payback [a]	Break-even costs* [€/kWh]	LCOS* [€/kWh]	Lifetime [a]	SOC [%]
case 0	-3555	-15	no	377	0.6676	11.58	100
case 87	-2742	-7	no	540	0.5626	15.52	87
base case	-1753	-3	no	735	0.5110	21.55	67
case 17-84	-3052	-9	no	482	0.6127	15.48	67
case 47	-1934	-2	no	631	0.5614	26.52	47

* Break-even costs for battery incl. installation

Regarding the lifetime, the highest EOL value was achieved with an SOC limit of 47%, which is represented by ‘case 47’. This confirms the statement that the lower the SOC, the higher the lifetime of the battery is. Nevertheless, the limited SOC reduces the possibility of self-consumption and thus the break-even costs are below those of the base case. A limitation of the SOC to 67% in comparison shows a shorter lifetime, but the highest break-even costs. The lifetime of 21.6 years exceeds the assumption of a battery lifetime of 20 years, which is a common assumption in the literature. Comparing the base case to ‘case 17-84’ – which also features a limited SOC range of 67% but cycles of between 17% and 84% – shows a remarkable negative impact on the lifetime. The same effect can be observed in ‘case 87’. This can be explained by the battery-aging theory, which states that storing the battery at a higher SOC causes higher aging effects on the battery [13]. This happens in ‘case 17-84’, as well as in ‘case 87’, where the average SOC storage level is higher over the whole battery lifetime. The lowest lifetime and the lowest break-even costs are achieved by fully utilizing the SOC range, as shown in ‘case 0’.

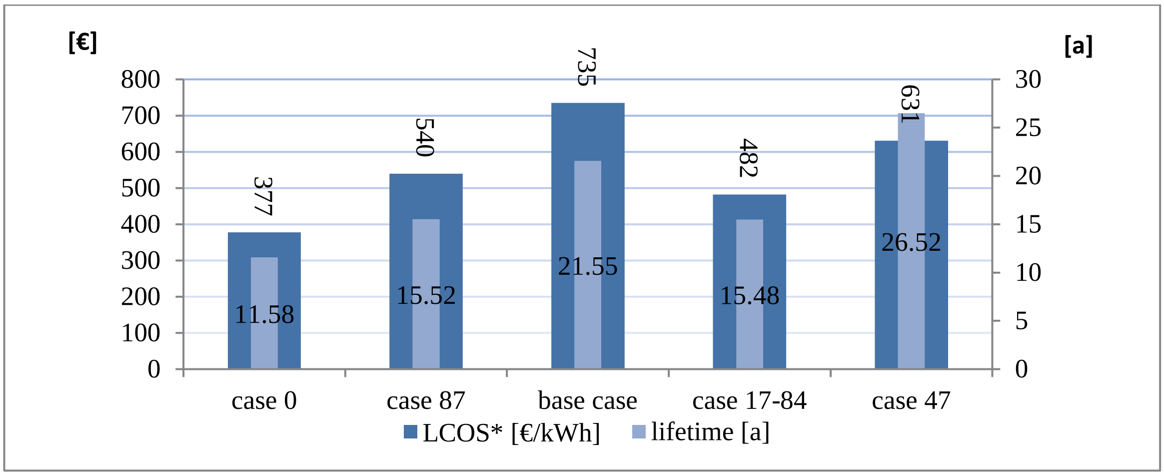

Figure 6: Impact of SOC on break-even costs and battery lifetime

Figure 6 represents the lifetime dependency of the break-even costs for the different SOC cases investigated. The outcome confirms the prior-gained knowledge about battery aging and the impact on the SOC balance. Based on the results of the model, it is recommended to limit the SOC to 67% in order to maximize the economic efficiency of the battery investment. Full use of the SOC should be avoided, as it leads to the lowest economic output. Furthermore, from an aging perspective, it is not recommended to cycle the battery around a 50% SOC, but rather to keep the SOC low by limiting the upper range. A much higher limitation than 67% for increasing the battery lifetime is not economically sensible, as the negative impact of reduced self-consumption cannot be compensated by the longer lifetime. This statement is proven by the lower break-even costs of ‘case 47’. Notice that in order to determine a precise turning point, more intermediate steps between the SOC limitation of 47% and 67% are necessary.

The variance of the battery size shows a smaller impact on the battery lifetime. A 30% decrease in battery size leads to a shorter lifetime of two years compared to the base case, whereas an increase of the battery size of 30% increases the lifetime by approximately 3.5 years. Regarding the break-even costs, changes in both directions lead to a decrease compared to the base case. On the one hand, a smaller battery reduces the option of higher self-consumption, whereas, on the other hand, an excessively large battery has not only higher costs but is also oversized with respect to the limited load demand of an average German household. This evaluation shows that maximizing economic efficiency requires that the choice of the battery size is aligned with a household’s electricity demand.

The variance of the yearly consumption by +/-30% shows higher break-even costs in both directions. This higher value is achieved by longer lifetimes. In the case ‘yearly consumption +30%’ the battery is used less, because with the increased load demand a higher direct PV consumption is possible. This leads to an increase in lifetime and in this case is even more economically efficient than the base case. In the ‘yearly consumption -30%’ case, the battery is used even less. Therefore, a lifetime extension can be achieved. The higher break-even costs arise, on the one hand, from the higher lifetime and,; on the other hand, from the more efficient use of the available battery capacity compared to the yearly consumption. The battery use for the ‘yearly consumption -30%’ case is 36%. The base case shows a battery use of only 28%. This observation leads to the conclusion that the optimum balance of yearly consumption and the battery size is essential for a long battery lifetime and thus economic efficiency.

A variance in the battery lifetime significantly influences the break-even costs. The longer that a project yields revenues, the higher is its economic efficiency. A shorter lifetime shows an even higher negative NPV compared to the base case, but also the increased lifetime to 28 a in the ‘battery lifetime +30%’ case does not lead to a positive NPV. In the literature, a lifetime of 20 years is typically assumed, which is far exceeded in this case, but still no positive return for a battery investment of 1000 €/kWh can be achieved.

Regarding the varied retail electricity costs, an increase leads to a higher economic efficiency of the battery investment. The opportunity costs for feeding the electricity into the grid are stable and thus do not reduce the increasing savings. The variance in the electricity price shows the greatest impact on the break-even costs compared to the base case. The variation of the c-rate and battery efficiency shows no significant impact on the economic efficiency and thus is not discussed any further.

Besides the sensitivity cases, the expected development of the battery costs was considered as well. A decrease of the base case assumption of a battery investment of 1000 €/kWh to 700 €/kWh leads to the project break-even. Regarding a cost decrease of 5%/a, a price of 700 €/kWh will be achieved in six years in 2023. The break-even costs for the case ‘battery costs -30%’ are 735 €/kWh. The installation costs are included in the break-even costs. Furthermore, following Sauer et al. [28], two cases with the battery cost assumptions of 300 €/kWh and 550 €/kWh were simulated. These costs are below the calculated break-even costs and thus return a positive NPV. The low case 300 €/kWh shows a significant IRR of 10%, whereas the mean case 550 €/kWh shows a 3% IRR. Following the approach of a battery cost decrease of 5%/a, battery costs of 550 €/kWh could be realized in nine years and battery costs of 300 €/kWh in 14 years from now.

The last KPI calculated is the LCOS. Figure 7 shows the results of each case compared to the electricity price assumed in 2018, 2028, and 2038, with an annual increase of 2.5%. The first three bars represent the electricity price increase in ten-year steps. The low case 300 €/kWh is the only case that is above grid parity in 2018, although this low price is assumed to be unrealistic before the year 2032. This observation corresponds to the statement of Pawel [26] that the investment is only economically viable for system prices below 300 €/kWh. In the year 2023, the electricity price is assumed to be 0.34 €/kWh. At that point, the mean case 550 €/kWh will reach grid parity. However, the price reduction to 550 €/kWh is not assumed before 2027. The cases ‘battery costs -30%’ with 700 €/kWh and ‘battery lifetime +30%’ reach grid parity after the year 2028. All other sensitivity cases are far beyond grid parity according to the calculated LCOS.

In the following, the outcome for the pooling concepts is reported. Comparing the results with the base case assumption, the additional values of free electricity supply and the remuneration of 200 €/a in the Caterva case lead to the break-even of the battery investment. In the case of Caterva and Sonnen, the free electricity supply covers the total electricity demand from the grid. The Fenecon case provides 1,000 kWh/a of free electricity supply. That does not cover the whole electricity demand from the grid for one year, but is sufficient for a positive NPV outcome. Even though the Sonnen case includes a cost-free electricity supply of 4,250 kWh/a that covers the yearly grid electricity demand the case shows a negative NPV. This can be explained by the costs for the monthly membership, which are not fully compensated by the positive effects of free electricity supply from the grid.

The LCOS calculation shows values of above 0.60 €/kWh for all three pooling cases, which is far beyond grid parity at the current electricity prices. This shows that the battery storage itself is not economically efficient, because the costs of charge and discharge for one kWh are high. It is the revenue gained from the cost-free electricity supply and the remuneration in the Caterva and the Fenecon cases that lead to a positive NPV.

The Caterva case shows the highest NPV, although a battery size of 12 kWh is required for the pooling concept. For the economic model, a PV system with a size of 12 kW_p was assumed, which exceeds the EEG levy exemption. The payment of an EEG levy is not considered in the model and has a negative impact on the economic efficiency. Furthermore, the assumed 7,500 kWh/a electricity demand is overrated for a private household. The Fenecon case better fits the requirements of a private household.

In the Fenecon webinar [29], an online tool for computing the economic benefit of battery pooling concepts, further benefits besides the pooling revenue were attributed to the battery investment. On the one hand, the reliability of electricity supply with 0.5 €/d (183 €/a) is calculated as an additional benefit. On the other hand, an electric vehicle that is connected to the stationary battery as well is regarded. Therefore, a benefit of 400 €/a was assumed. Further investigation is needed to verify whether the reliability of the electricity supply is really worth 0.5 €/d to prosumers. The same applies to the benefit of connecting an electric vehicle (EV) to the battery. However, this is only a benefit for households owning an EV.

The calculated lifetimes for all pooling scenarios is above 20 years, as shown in Table 5. Caterva offers a guarantee of 20 a in combination with a maintenance contract; however, only on 70% of the initial battery capacity. Sonnen offers only ten years. Fenecon provides a guarantee of twelve years, but only on 70% of the initial battery capacity. The results from the aging simulation suggest a significantly longer lifetime, which, however, is not reflected in the manufacturers' guarantees.

Comparing the LCOS results with one of the studies from the literature review, we find that Jülch (2016) reports an LCOS value of 0.34 €/kWh, which is equivalent to our *mean case 550 €/kWh* value. Note, however, that this comparison must be made with caution, as in Jülch [20] the LCOS were calculated for the pure battery costs only, i.e. ignoring installation costs.

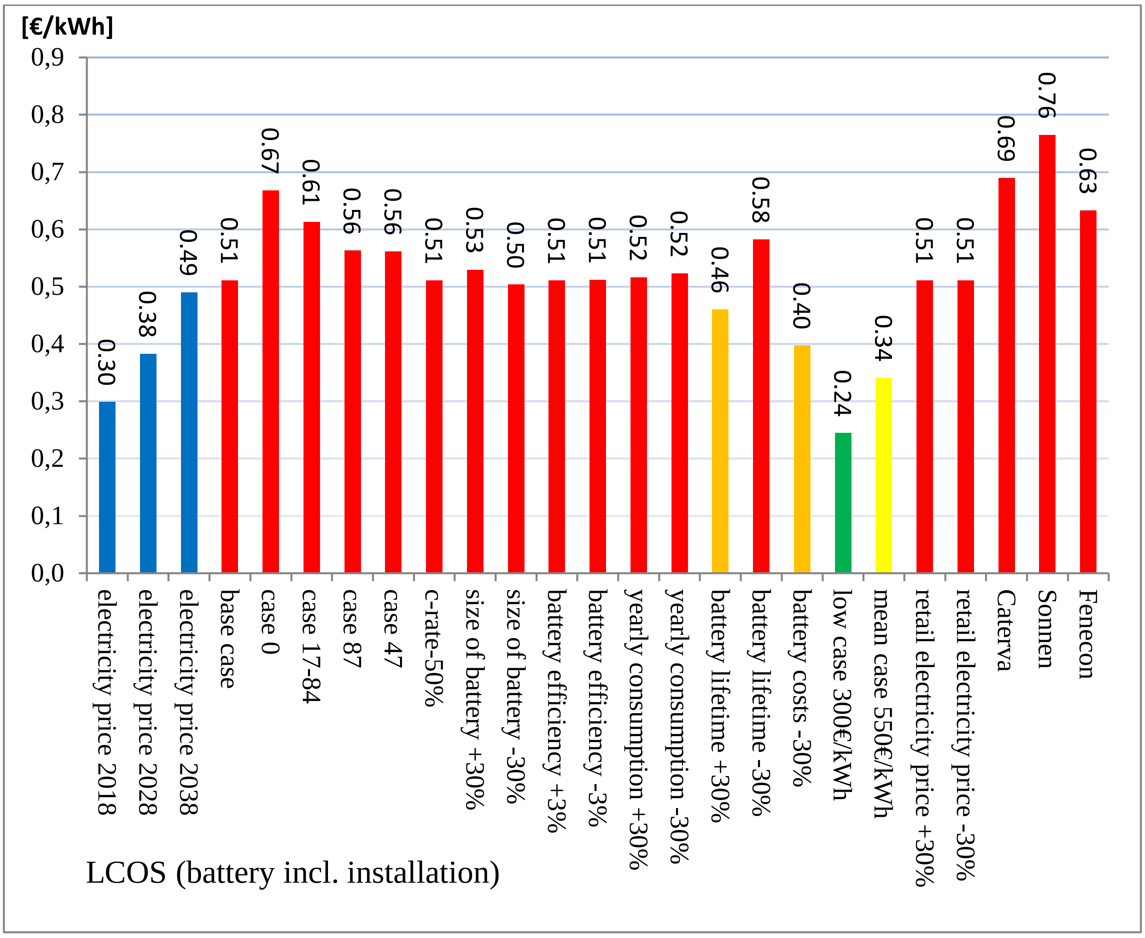

Figure 7: Levelized cost of storage (LCOS) compared to electricity price

6 Discussion

The developed model serves the purpose of this study well, although it clearly has its limitations. Accordingly, there is clearly potential to develop the model further for additional analysis. In this case, the economic calculations and the battery simulation were performed in MS Excel®. For the economic calculations, it is the best choice and delivers all necessary functions. On the other hand, for the battery simulation, Excel reached its boundaries when handling big data volumes in 15-minute steps for several years. Hence it would be more convenient and time-saving to reprogram the algorithm with a simulation software, such as Matlab®.

The EOL of six of the 22 cases was simulated with the aging model. Due to the time-consuming and elaborate process, the effort of simulating the aging impact was limited to six cases. All SOC sensitivity cases are included in these six cases. The EOL for the remaining cases was calculated following the degradation of the base case aging simulation. To substantiate the results, all cases should be simulated with the aging model. Furthermore, to define precise turning points of the economic efficiency regarding the SOC, cases with incremental SOC steps around the SOC limit of 67% need to be regarded as well.

Moreover, concepts for tax savings and investment funding should be analyzed in more detail. The German tax law offers possibilities for prosumers to avoid the VAT payment for self-consumption, which can be advantageous but cost savings nevertheless need to be assessed in each individual case. Another expandable topic is financing. The model assumes that the battery storage is financed with equity capital, whereas the results show that this is hardly economical today. Whether financing on a bank credit can be efficient needs to be analyzed again in each individual case. Regarding the financing aspect, the German special purpose bank KfW offers favorable loan conditions, and a part of the credit raised for the battery storage investment is funded by KfW [49]. Whether the KfW financing is economically efficient with the limiting conditions needs to be analyzed further.

7 Conclusion

The aim of this study was to evaluate the economic efficiency of a Li-ion battery storage unit attached to a PV system in a residential context with regard to the impact of battery aging on economic efficiency. The battery-aging output provided by ISEA, RWTH Aachen University, contributes to the evaluation of aging impacts on the economic efficiency of a battery investment.

Economic efficiency of a Li-ion battery storage investment attached to a PV system in a private household can be determined only under certain circumstances. For the base case, assuming a battery investment of 1000 €/kWh, the battery investment turned out to be uneconomical. Even though the base case assumes a battery lifetime of 21.6 a, which exceeds the standard assumption in the literature of 20 a. The only case not related to battery price assumptions that shows a positive NPV is the 'retail electricity price +30%' case. The development of the retail electricity price is difficult to predict and depends on many factors. Regarding the battery prices, costs of 700 €/kWh could be identified as being economically efficient for the base case lifetime of 21.6 a. Assuming an average decrease of the battery costs for stationary Li-Ion batteries, a price of 700 €/kWh will be reached in 2023.

Regarding battery-aging, the highest expected battery lifetimes could be achieved with the highest SOC limit, which is not economically efficient due to the limited self-consumption. From the results of the model, the recommendation can be derived to limit the SOC to 67% in order to both extend the battery lifetime and maximize the economic efficiency of the battery investment. Incremental SOC cases need to be investigated to derive an accurate function that allows the influence of aging on the economic efficiency to be determined.

Furthermore, the impacts of battery pooling concepts on the economic efficiency were analyzed. Two out of three concepts were identified as being economically efficient, namely the cases of Caterva and Fenecon. However, the battery of Caterva is oversized for a private household use case, although the evaluation shows that economic efficiency can be achieved with pooling concepts in principle. Nonetheless, the negative impact on self-consumption and battery-aging needs to be further analyzed for real world cases, as the calculations in this study are mainly based on assumptions and average values. Actual values and developments in the actual market environment may vary. Therefore, a monitoring of actual revenues and costs of the investment needs to be conducted in order to corroborate our findings on the economic efficiency.

Following the conclusion and summary of this study, a future outlook is presented. In our investigation, a residential battery storage in a private household use case was examined. With the increasing number of EVs, battery manufacturers offer to integrate the EV into the PV battery system. Fenecon shows this as revenue in its webinar. This concept is called 'vehicle-to-home'. On this occasion, the EV battery can be used additionally to the stationary battery storage in order to store the PV electricity in times of surplus production and when the EV can be loaded with the stationary battery. Further research should be conducted regarding the economic efficiency of this concept and the impact on battery-aging when the stationary battery is exposed to the use of the EV.

Regarding the pooling concepts, further developments are expected. Following the concept of Sonnen, entire communities can be built that consume high shares of renewables. The coming years will show whether such concepts and their offered benefits of cost-free electricity and remunerations can actually be realized on a large scale. Another aspect that needs further investigation is the acceptance of pooling concepts by the battery owners if service providers have unlimited access to battery storage units.

On the internet platform 'batteryuniversity', we can read that the ongoing research on batteries is clearly an indicator that the perfect battery has not yet been developed [17]. This study is based on the assumption that the Li-ion battery technology will be the future technology in the EV and the stationary sector. The results of this study show that a Li-ion battery investment today is only economically efficient under certain circumstances. As the battery price is the main driver of the economic efficiency, future developments will show whether Li-ion battery prices will decrease as expected, or whether another, lower-priced technology will take over.

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Appendix

Table A.1: Comparison parameters for sensitivity analysis

Reference	Capex	Opex	WACC / interest rate	Efficiency	Full-load hours	Electricity price	Battery size	Aging behavior	Remuneration
Jülch [20]	x	x	x	x	x				
Linssen et al. [9]						x	x		
Parra and Patel [22]	x					x			
Naumann et al. [23]	x					x	x	x	
Weniger et al. [25]	x		x			x			x

Source: Own compilation, based on literature research

Table A.2: Overview of battery cost assumptions

	Present battery costs [€]			Future outlook	
Author	**Low**	**High**	**Mean**	**Mean decrease**	**Further initial costs**
Jülch [20]	680	1,130	905	3.5%/a until 2030	x
Linssen et al. [9]			1,000		x
Moshövel et al. [21]			1,670	8%/a until 2020 and 4%/a until 2030	x
Parra and Patel [22]			1,945		€1485 for the inverter
Naumann et al. [23]	758	2330	1544	5%/a until 2034	Installation cost rate: 5% of invest. costs
Lazard [24]	718	1251	985	9.4%/a until 2020	Initial other costs: €131-232
Weniger et al. [25]			1,500	High potential for battery cost decrease	
Pawel [26]					x
Fenecon webinar [29]			1,200		Installation costs: €3500
Calculated average	**719**	**1,570**	**1,463**		

Source: Own compilation, based on literature research

Table A.3: Overview of further cost assumptions

	Electricity price			
Reference	**Present level [€/kWh]**	**Increase [%/a]**	**O&M costs [%/a of investment costs[a]]**	**Tax on self-consumption**
Jülch [20]		2	2% of capex	x
Linssen et al. [9]	0.29	2.5	Operation: 1.5%/a, Maintenance: 10 €/kW$_p$/a (~1%/a of invest. costs)	x
Moshövel et al. [21]	0.29	2	Maintenance 110 €/a (approx. 1.5%/a of invest. costs)	x
Parra and Patel [22]	0.20	5.7	Considered but no value mentioned	x
Naumann et al. [23]	0.30	3.58	1.5	x
Lazard [24]			O&M €122 to €142 (~2.5%/a of invest. costs)	€104 to €164
Weniger et al. [25]	0.34		1.5	x
Pawel [26]	0.30	2	1	Considered but no value mentioned
Fenecon webinar [29]	0.25	3	x	x
Calculated average from literature review				
High	0.30	3.58	2.5	
Mean	0.295	2.5	1.8	
Low	0.29	2	1	

Source: Own compilation, based on literature research; [a] unless stated otherwise

Table A.4: Overview of project and battery lifetimes

Reference	Project lifetime [a]	Battery lifetime [a]	Cycles [-]
Jülch [20]	20	20	7,000
Linssen et al. [9]	20		6,200
Moshövel et al. [21]	20	20	
Parra and Patel [22]		max. 22	4,000
Naumann et al. [23]	20	12.5 to 15	3,000 to 6,000
Lazard [24]	10	5 to 15	3,000
Weniger et al. [25]	20	10 to 20	3,000 to 10,000
Pawel [26]	25	7	2,555
Fenecon webinar [29]	20	20 (12)	
Calculated average			
Highest	25	22	10,000
Lowest	10	5	2,555
Mean	18	14	6,278
Weighted mean	19	16	4,822
Lower bound		15	4,108
Upper bound		17	5,536

Source: Own compilation, based on literature research

Table A.5: Overview battery parameters

Reference	DOD	SOC	c-rate	Battery-aging
Jülch [20]	80%	x	x	x
Linssen et al. [9]	100%	x	x	Battery degradation: 0.5%/a
Moshövel et al. [21]	x	x	Limited charge rate of 0.5 C and discharge rate of 1C	Battery-aging considered, but not specified
Parra and Patel [22]	x	80% (max. 90%; min. 10%)	Max. charge rate: 3 x C_{nom}; Max. discharge rate: 3 x C_{nom}	Cyclic losses and calendric losses (0.07%/month) considered
Naumann et al. [23]	x	x	x	Considered
Lazard [24]	100%	x	x	x
Weniger et al. [25]	x	x	x	Considered
Pawel [26]	100%/ 75%/50%	100%	20 to 100%	Battery degradation: 2%/a

Source: Own compilation, based on literature research

Table A.6: Overview battery efficiency

Reference	Efficiency [%]
Jülch [20]	95
Linssen et al. [9]	95
Naumann et al. [23]	95
Lazard [24]	89 to 92
Weniger et al. [25]	85 to 95
Pawel [26]	80
Calculated average	
High	95
Mean	91
Low	80

Source: Own compilation, based on literature research

Table A.7: PV system details

Location and Station Identification	
Requested Location	Munich
Weather Data Source	(INTL) MUNICH, GERMANY 5.7 mi
Latitude	48.13° N
Longitude	11.7° E
PV System Specifications *(Residential)*	
DC System Size	5 kW
Module Type	Standard
Array Type	Fixed (open rack)
Array Tilt	20°
Array Azimuth	180°
System Losses	14%
Inverter Efficiency	96%
DC to AC Size Ratio	1.1
Economics	
Average Cost of Electricity Purchased from Utility	0.33 $/kWh
Performance Metrics	
Capacity Factor	11.4%

Source: [44]

Table A.8: Results of economic calculation for sensitivity cases

Case	NPV	IRR	Discounted payback	Break-even costs**	LCOS**	Lifetime
	[€]	[%]	[a]	[€/kWh]	[€/kWh]	[a]
base case	-1753	-3	no	735	0.5110	21.55*
case 0	-3555	-15	no	377	0.6676	11.58*
case 17-84	-3052	-9	no	482	0.6127	15.48*
case 87	-2742	-7	no	540	0.5626	15.52*
case 47	-1934	-2	no	631	0.5614	26.52*
c-rate-50%	-1742	-3	no	737	0.5105	21.63*
size of battery +30%	-2199	-2	no	655	0.5291	25.00
size of battery -30%	-1315	-3	no	706	0.5035	19.47
battery efficiency +3%	-1753	-3	no	734	0.5103	21.44
battery efficiency -3%	-1753	-3	no	735	0.5117	21.67
yearly consumption +30%	-1752	-3	no	738	0.5156	22.30
yearly consumption -30%	-1747	-2	no	743	0.5225	23.43
battery lifetime +30%	-530	0	no	960	0.4601	28.02
battery lifetime -30%	-2780	-7	no	538	0.5822	16.91
battery costs -30%	-1	0	(22)***	735	0.3975	21.55

low case 300€/kWh	2357	10	11	744	0.2446	21.55
mean case 550€/kWh	874	3	17	735	0.3407	21.55
retail electricity price +30%	106	1	21	1069	0.5110	21.55
retail electricity price -30%	-3611	-8	no	400	0.5110	21.55
Caterva	6142	4	14	1900	0.6891	21.38
Sonnen	-1482	-1	no	1367	0.7647	20.15
Fenecon	832	2	16	1389	0.6324	20.34

* Output of technical aging simulation by ISEA, RWTH Aachen University
** Break-even costs /LCOS for battery incl. installation costs
*** Payout slightly after EOL

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