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Economic Viability of Second-Life Electric Vehicle Batteries for Energy Storage in Private Households

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Economic viability of second-life electric vehicle batteries for energy storage in private households

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Abstract

We examine the economic viability of second-life batteries from electric vehicles for load shifting and peak shaving in residential applications. We further investigate the expected impact of a growing number of residential storage systems on the electricity market. For the analysis a simulation model of a private household with integrated PV-storage system is used that is parametrized for an electricity demand of three people and a location in southern Germany. The conditions for which investments in second use batteries are profitable are examined for three scenarios. The central scenario S2 tackles an expected net increase in the electricity price by 4% per year. Upward and downward deviations from this price trajectory are covered by scenarios S1 and S3. For scenario S1, we find that investments in storage systems are profitable for all Li-ion battery costs assumed. In scenario S2, the breakeven battery price is found to be 107 € kWh^{-1}, whereas in scenario S3 with the lowest electricity price growth the battery price has to be equal or lower than 73 € kWh^{-1} to maintain economic viability.

Keywords: E-vehicle, Residential electricity, Battery storage, Load shifting, Peak shaving

1. Introduction

Renewable energy technologies are a promising way to mitigate the consequences of climate change and the finiteness of fossil fuels. However, the intermittent electricity output from technologies like solar photovoltaic systems is volatile and depends on daytimes or local weather conditions. Energy storage technologies can help to match supply and demand. Reused batteries from (hybrid) electric vehicles may provide a storage technology with environmental

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and economic benefits to utilities, companies and homeowners. In the upcoming years the global society is confronted with a variety of challenges. Climate change and fossil fuel resource depletion are some challenges the energy economy has to find solutions for. Renewable energy technologies will play a significant role in mitigating the consequences of these challenges [1]. Governments of many countries have passed laws to support the transition to sustainable energy generation. In Germany policy makers decided to foster the development of renewable energy technologies through the provision of guaranteed feed-in tariffs. This funding made rooftop photovoltaic (PV) systems attractive to private homeowners. However, the energy generation from PV systems strongly depends on time of day and local weather conditions and brings an element of uncertainty to the power grid [2]. Furthermore, the peak in energy generation around noon produces a mismatch in demand and supply and is a threat to the stability of the electricity system [3].

A feasible way to compensate for this mismatch is to adjust the energy supply by using conventional power plants (like modern gas-fired power plants) which can be modulated relatively quickly. But with limited capacities and an increasing amount of energy fed in by renewables, other options have to be considered. The mismatch exists because the power supply generated by PV systems is highest during the day with a peak around noon, whereas power demand is low during the day and increases in the evening hours. The use of storage technologies and smart grid technologies represents a promising way to shift energy demand from the evening hours to the hours with a surplus of renewable energy generation.

In battery storage systems the electricity is stored through an electro-chemical process. Due to decreasing battery costs they have become a potentially important alternative to other storage technologies and several pilot projects have been started in recent years. Although battery costs have declined, [4]-[6] could not find evidence that investments in battery storage were profitable under present conditions. The costs per kWh decrease further if used battery storage units are taken into consideration. In this case, the benefits from lower costs have to be balanced with the downsides (e.g., lower capacity and efficiency, earlier replacement need of used battery systems).

In the automotive industry the “second life” of retired batteries from electric vehicles is a much debated issue, and nearly all of the major car manufacturers are currently determining possible applications for their batteries after they have reached a capacity between 70-80% through aging during their “first life” in the vehicle. Most industry experts expect them to be used as stationary storage for renewable energy production, since they still retain significant capacity. In recent years, several projects were implemented in order to gather knowledge about the feasibility and the capabilities of the second life usage. For instance, Nissan and Green Charge Networks, a large provider of commercial energy storage, have embarked on a partnership for the commercial use of the retired batteries from the Nissan Leaf, which is one of the world's top-selling electric vehicle [7]. Toyota started a partnership with the Yellowstone National Park and provides a ranger station and education center with power from a hybrid PV-battery system [8]. General Motors has tested their batteries from the Chevrolet Volt to provide solar and wind power to their new IT center in Milford, Michigan. However, the projects of Toyota and General Motors are mostly isolated applications, whereas in Germany grid-connected solutions by Daimler and BMW are explored. A cooperation between Daimler, The Mobility House, GETEC and REMONDIS provides a 13 MWh energy storage unit to balance the energy in the electricity grid [9] and BMW, Bosch and Vattenfall operate a battery pack as part of a virtual power plant in Hamburg [10]. The discussion shows the relevance of using batteries as energy storage systems, and the importance of taking a closer look at the requirements for a successful implementation, the consequences, and the resulting implications.

The question arises concerning the conditions under which the economic viability of the residential PV-storage system is given. The purchase and maintenance not only of the battery but of the other system components, like the inverter, has to provide a benefit to the decision maker, in this case the homeowner. Possible benefits for other involved parties, like the grid operators, may be shared with the decision maker in order to positively influence economic viability. In addition to that, policy makers may foster the spread of the storage technology through various incentives like credits at reduced interest rates. Further, it is important to estimate what impact a growing number of residential battery storage systems has on the market, the electricity sector, and policy-making. Finally, there is the question concerning which implications and guidance can be derived from the results for energy companies, grid operators, car manufactures, and policy makers.

The research objective is to determine the economic viability of the implementation of a used battery from an electric (EV) or hybrid electric vehicle (HEV) in a residential application for load-shifting and peak-shaving. Precisely, a household with a PV generation system is considered and the benefit of combining it with a battery storage system is examined. The battery technology is limited to lithium-ion as it is the dominant technology for EVs and HEVs today.

The economic viability is evaluated based on literature research and a precise and time-dependent calculation of the cash flows and the resulting net present value. The research issues described can be examined using different approaches. Battke et al. [11] examined lifecycle costs using Monte Carlo simulations and also conducted some expert interviews. Pawel [12] showed how to calculate the levelized cost of energy (LCoE) for battery storage combined with PV systems. They revealed the dependency of LCoE for storage due to a variation of the economic parameters. In this paper, a techno-economic simulation model is used to examine the economic value of integrating a second-use storage to a residential PV system and to show the dependency from economic as well as from technological parameters. Similar approaches are used in [1] and [13] for new battery packs. To examine the economic viability of a second-use battery, the technical aspects are as important as the economic ones. The degradation of the state of health is crucial to the economic value, especially for a used battery, and has to be considered. In our study, a simulation tool has been developed that includes a detailed degradation calculation through a decrease of capacity and an increase of the inner resistance. It reflects the state of charge as well as the power generation over time and can be used for revenue calculation in various scenarios.

2. Modeling approach and data

2.1 Introduction

In order to investigate the economic viability of an integrated PV-storage system using a second-life battery a simulation model for a private household is developed. Figure 1 depicts the general system layout adopted for the analysis. The model uses technological and economic parameters as an input for the calculation model, programmed in the simulation environment MATLAB/Simulink. The simulation model calculates the time-dependent PV power generation, battery state, load profile, and resulting cash flows. The model output enables to make a statement regarding the viability of the battery integration, the optimal storage size and some of the resulting implications for the parties involved.

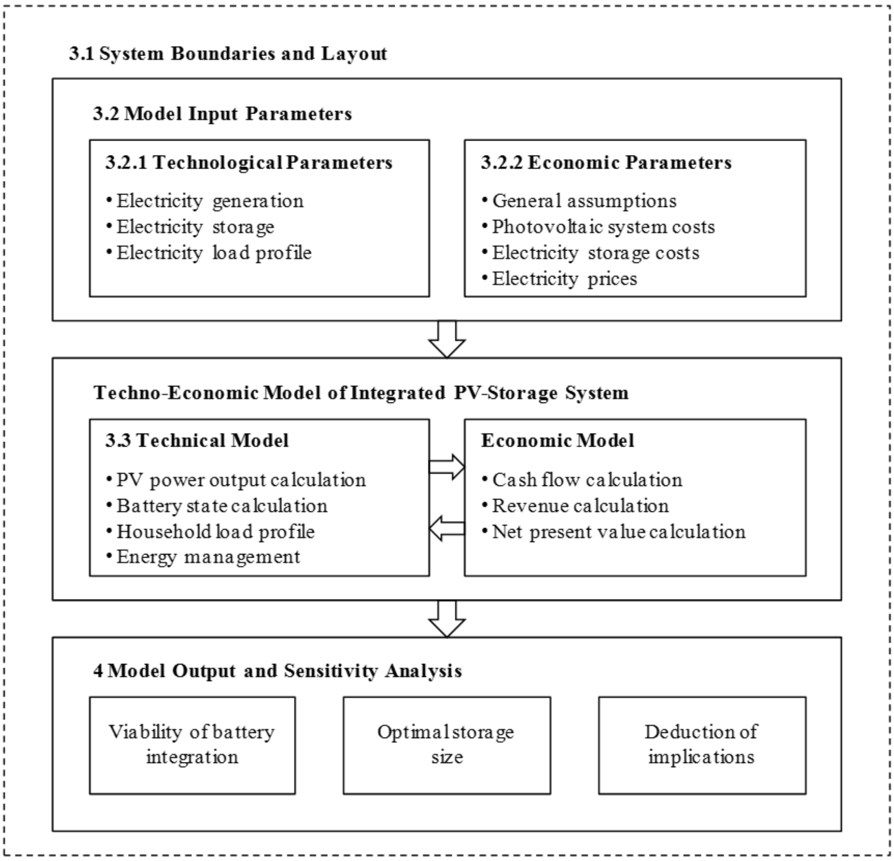

Fig. 1. System architecture. *Source:* adopted from [1], p.7.

2.2 Model input parameters

The developed simulation model is independent of prescribed scenarios and can be used to examine a variety of different cases by parameterization. In this case the parameters are defined for a three-person household in the area of Stuttgart, Germany, in order to make it comparable to similar studies by Bost et al. [4] or Braun et al. [5]. Also the German electricity market has a large share of PV generation and the resulting intermittency may make Germany an important lead market for second-use battery storage systems. Furthermore, a large share of the German PV market consists of residential small-scale systems which could profit from a storage system [15].

2.2.1 Technological parameters

The technological input parameters can be grouped into the parameters concerning the electricity generation, the electric load and the electricity storage.

Electricity Generation. The electricity generation depends on exogenous data like the available solar irradiation and the air temperature as well as on variable parameters like the amount of installed modules, the mounting or the tilt of the modules. Model inputs are the irradiation data and the air temperature. This information is taken from a database provided by the DWD (*Deutscher Wetterdienst*) [16] for a measuring station near Stuttgart, Germany. The data consists of the global solar irradiation and the diffuse solar irradiation. For the year 2014 the solar irradiation is presented in Figure 2.

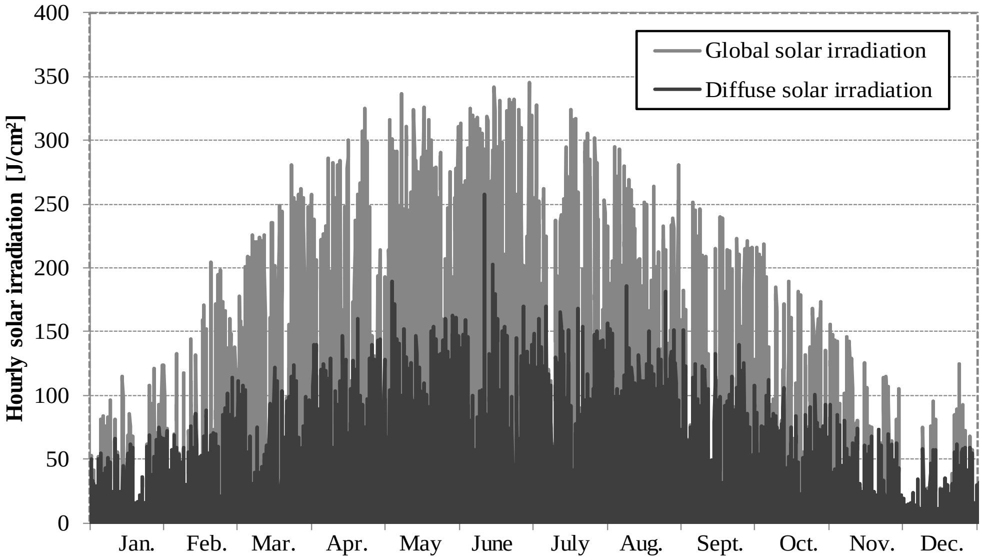

Fig. 2. Solar irradiation data in 2014.

The irradiation data has to be converted in order to calculate the power generation of the PV system. This will be discussed later in subsection 2.3.1. The second input is the air temperature. Be-cause the electricity generation depends on the module temperature the ambient temperature has to be known. The ambient air temperature is shown in Figure 3. Crystalline silicon has been chosen as the PV technology and an installed PV system with a power of 5 kW_p.

Electric Load. The electric load profile is based on the standard load profile from BDEW (*Bundesverband der Energie- und Wasserwirtschaft*) [17]. It is separately defined for weekdays, Saturdays and Sundays as well as for summer, winter and transitional periods. The data is available in 15-minute steps and has to be multiplied with the day-specific dynamic modification factor. Figure 4 shows the electric load profiles for the different days in the transitional period.

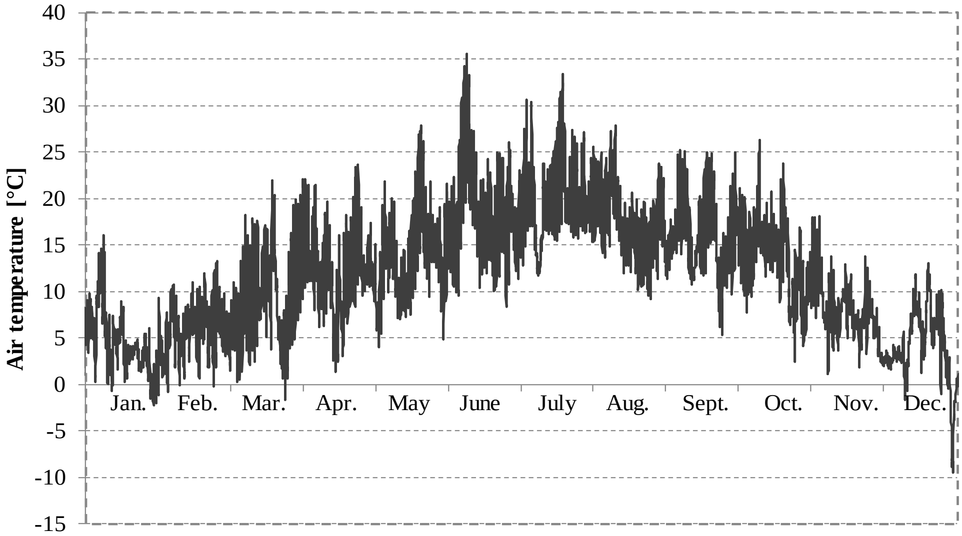

Fig. 3. Ambient air temperature in 2014.

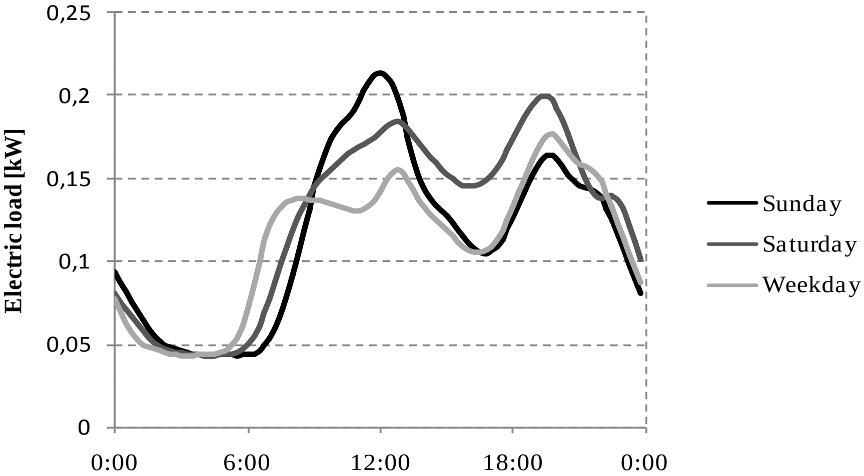

Fig. 4. Electric load profiles for the transitional period.

It is apparent that for weekdays and Saturdays the energy demand in the evening hours is higher than over the rest of the day. Only on Sundays the peak around noon is higher than in the evening. While the peak of the solar irradiation and therefore the PV electricity generation occurs during noon the electricity is needed in the evening hours. This mismatch can be solved with a battery storage. The data is scaled for a 3-person household with an annual electricity consumption of 3892 kWh [4].

Electricity Storage. For the electricity storage a lithium-ion battery is chosen as the technology is dominant in automotive applications as a traction battery for EV and HEV. For the analysis, the size of the battery storage is varied between 4 kWh and 8 kWh BOL (beginning of life) with a capacity of 80% at the start of the second life [18].

2.2.2 Economic parameters

The economic input parameters can be divided into general assumptions and the parameters concerning the electricity generation, the electricity market and the electricity storage.

General Assumptions. As the model is parameterized for a household in Germany, the currency is Euro and the inflation is set to 1.74% (mean value from 2004 to 2015 for the Euro area [19]). In the past years the inflation has fallen to values around zero. The dependency from the inflation rate will be examined in a sensitivity analysis. For the nominal discount rate a value of 4% chosen in line with previous other studies.

Electricity Generation. In order to estimate the value of adding a battery storage to a PV system, the differential investment between the option to invest in a battery storage or not is examined. The cost of the PV system is not regarded in this case as the net cash flows are the same for both options.

Electricity Market. In order to calculate the electricity costs, scenarios for the future development of the electricity tariffs had to be created. For defining electricity price scenarios the retail price of the period from 2008 to 2015 is regarded. The mean rate of increase in this period is about 4% (including the inflation). It is assumed that the rate of increase in the next ten years is in the corridor of 2 to 6%. This is reflected by the scenarios S1 (low: increase of 2% per year), S2 (medium: increase of 4% per year) and S3 (high: increase of 6% per year). Figure 5 shows the electricity price trajectories and the scenarios investigated.

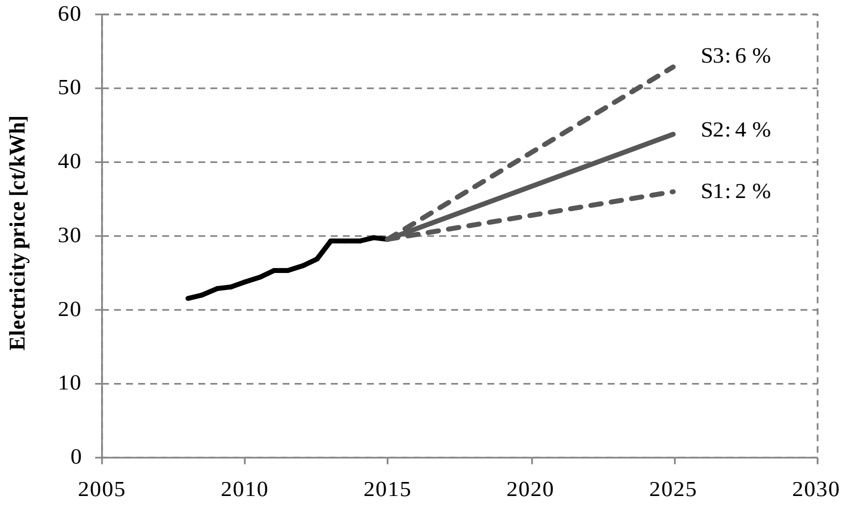

Fig. 5. Retail electricity price in Germany.

Due to the German EEG (*Erneuerbare Energien Gesetz*) the feed-in tariffs are guaranteed over the period of 20 years. For residential roof-mounted PV systems with a peak power of less than 10 kW_p the feed-in tariff is about 12.31 €-ct/kWh (January 1, 2016) [20]. The dependency of the feed-in tariff will be discussed in subsection 3.2.2 further below.

Electricity Storage. Due to the fact that today only a few electric vehicles are being retired, there exists no real market for the second-use batteries yet. Neubauer et al. [21] estimated a value for refurbished electric vehicle batteries by calculating the maximum selling price assuming that the refurbished batteries compete with new batteries and have to be cost-competitive. They estimate a re-purposed battery selling price between 38 US$/kWh and 132 US$/kWh (34 €/kWh to 117 €/kWh) and end-user system costs of 100 US$/kW (89 €/kW) for power conditioning, controls and interfaces. The installation and startup costs are assumed to be 52 US$/kWh (46 €/kWh). For the maintenance costs, different studies vary between 1.5% and 6% of the investment costs; for our analysis a value of 3% is chosen. The economic parameter values used are reported in Table 1.

Table 1 Input parameters for the economic model

Location: Stuttgart, Germany	Value	[Unit]
Installed PV peak power	5	[kW_p]
Annual electricity consumption	3892	[kWh]
Battery size	4–8	[kWh BOL]
Battery capacity at the beginning of the second life	80	[%]
Inflation p.a.	1.74	[%]
Nominal discount rate	4	[%]
Feed-in tariff	12.31	[€-ct kWh^{-1}]
Battery selling price	34–117	[€ kWh^{-1}]
Battery power conditioning, controls and interface	89	[€ kW^{-1}]
Battery installation and startup costs	46	[€ kWh^{-1}]
Battery maintenance costs (% of investment costs)	3	[%]

2.3 Technical approach and modeling

The question which components and which level of detail are necessary to be modeled can only be answered considering the specific research issue. In this case the time-dependent amount of generated electricity and the battery state are crucial. The modeling was done in MATLAB/Simulink which is a graphical programming environment for modeling, simulating and analyzing multi-domain dynamic systems. The layout of the integrated PV-storage system considered is shown in Figure 6.

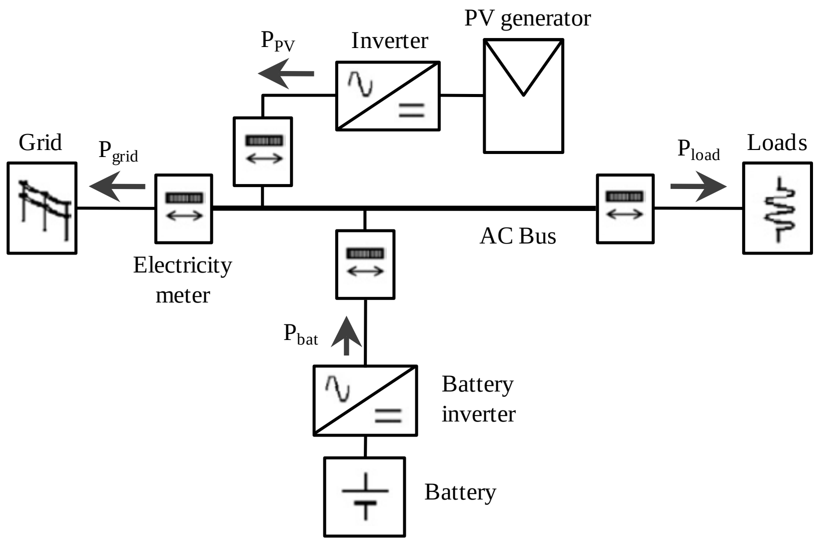

Fig. 6. Topology of integrated PV-storage system [22].

The PV generator provides electricity which will be transformed from DC (direct current) to AC (alternating current) and partially or completely consumed by the electric load. If there is a surplus of generated electricity it can be fed into the grid or stored in the battery if the battery is not fully charged. In the second case, it has to be transformed into DC again before it can be stored. Every transformation results in an energy loss that has to be taken into account.

If the electricity demand excels the generated electricity the difference can be provided by the grid or the battery storage if the SOC (state of charge) is above the lower limit. In order to be economically as well as technically efficient this system topology is the most widely used in the literature for residential applications [1].

2.3.1 Power generation

The performance of the PV modules depends not only on the solar irradiation, but is also affected by a number of other important effects [23]: (1) The temperature of the PV module; (2) Nonlinearities of the conversion efficiency dependent on the irradiance level and module temperature; (3) The reflection on the module surface; and (4) The spectral sensitivity of the module type.

In this paper, the performance is calculated according to a mathematical approach presented by Huld et. al. [24] concerning the irradiation and the temperature of the module. The mathematical function was fitted with measured data and the parameters were developed for the crystalline silicon and the thin-film technology. Because of the dominant market share in existent applications (about 90% in 2013) [15], the dominant market share in the global production (above 90% in 2014) [24] and according to previous studies, crystalline silicon has been chosen as PV technology. The input parameters of the model are the in-plane irradiance G and the module temperature T_{mod}. With P_{STC} as the power at standard test conditions (STC) of $G_{STC} = 1000$ W⁄m^2 and $T_{(mod\_STC)} = 25$ °C the power output is given by:

$$P(G,T_{mod}) = P_{STC} \cdot G/G_{STC} \cdot \eta_{rel}\,(G', T') \tag{2}$$

The instantaneous relative efficiency η_{rel} depends on six parameters k_1 to k_6 which are fitted to experimental data. The solar irradiation data as well as the ambient temperature was obtained from a database provided by the DWD (*Deutscher Wetterdienst*) for Stuttgart (station no. 04928) [16]. For use in the model, the dataset has to be transformed in two ways. The solar irradiation has to be projected onto the plane of the PV module and the ambient temperature has to be converted to the module temperature. The adjustment of the temperature can be made by the coefficient c_T [23] as follows:

$$T_{mod} = T_{amb} + c_T \cdot G. \tag{3}$$

The coefficient c_T describes the modules' temperature difference to the ambient temperature due to solar irradiation and is primarily dependent on the way the module is mounted. For rooftop-integrated PV modules, a value of (0.05 °C)⁄(W m^2) is chosen [25].

In order to project the solar irradiation onto the plane of the PV module the actual position of the sun has to be known. The position is described by the azimuth and the altitude (or elevation angle) and is shown in Figure 7. In our analysis, it has been calculated according to the approach suggested in Reda et al. [26] for the latitude of Stuttgart, and corrected by the difference between solar apparent and mean time using the equation of time [26].

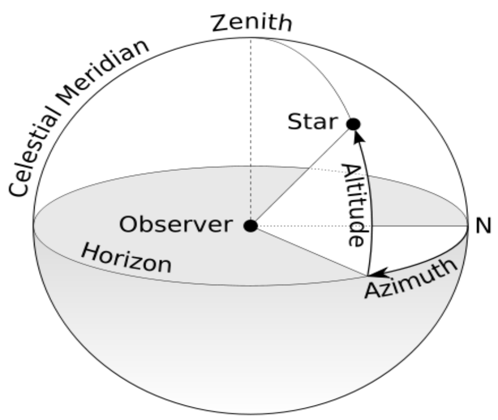

Fig. 7. Coherences between altitude, azimuth and the position.

Now the position of the sun is known at every time step of the simulation, and the actual in-plane irradiation is then calculated with the geometrical relations. For the location of Stuttgart, a tilt of 30° and a southward orientation has been chosen. Depending on the installed capacity, the annual power generation is about 980 kWh/kW_p for an average year. This of course depends on the actual solar irradiation as well. The efficiency of the inverter has been assumed at 98%, according to several other studies. The parameter values used for the simulated PV system are reported in Table 2 (left-hand side).

Table 2 Input parameters for the technical model (left two columns: PV system, right two columns: battery storage system)

Technology	Crystalline silicon	Technology	Lithium-ion
Installation	Rooftop-integrated	Heat capacity	900 J $(kg\cdot°C)^{-1}$ [29]
Location	Stuttgart, Germany	Heat transfer coefficient	10 W $(m^2\cdot K)^{-1}$ [30]
Latitude	48.8282° N	Specific energy	120 Wh kg^{-1} [31]
Longitude	9.2000° E	Energy density	230 Wh l^{-1} [31]
Tilt	30°	Ambient temperature	13°C [32]
Orientation	Southward	Technology	Lithium-ion
Annual electricity generation	~980 kWh $(kW_p)^{-1}$	Heat capacity	900 J $(kg\cdot°C)^{-1}$
Efficiency of the inverter	98%	Heat transfer coefficient	10 W $(m^2\cdot K)^{-1}$

2.3.2 Energy storage

In order to estimate the economic viability of a repurposed second-life battery in residential applications the prediction of degradation and aging of the battery is a crucial element of the simulation. There are many individual effects and mechanisms that, in combination, lead to aging of the battery pack. While electrolyte decomposition (capacity loss) and the formation of a solid electrolyte interphase (SEI, increase of inner resistance) are mostly the dominant aging processes, further mechanisms are described by Vetter et al. [27]. Physical-chemical simulation approaches try to focus on a single mechanism and describe its impact while other approaches focus on the measured aging under real operating conditions isolated from single mechanisms and try to predict the aging in total. Due to the fact that tests under real operating conditions are quite expensive and time-consuming, most models use data from accelerated aging tests and try to adjust the results to the real operating conditions. In our study, an approach by Ecker et al. [28] is chosen to predict the loss of capacity and the increase of the inner resistance leading to a decrease of the efficiency. The following equation was used to describe the evolution of capacity and inner resistance and it can be derived to fit the data from accelerated aging tests:

$$L(t,T,V) = L(t_0,T,V)\cdot[1+B(T,V)\cdot F(t)] \quad (4)$$

In this approach, the time dependency is described by the term

$$F(t) = c_a \cdot t^{\beta} \tag{5}$$

where c_a describes the rate of aging at reference conditions (T_0,V_0) and β becomes 0.5 under the assumption that electrolyte composition and the correspondent SEI formation are the dominant aging processes. $B(T,V)$ describes the temperature and potential dependency according to:

$$B(T,V) = c_T^{((T - T_0)/\Delta T)} \cdot c_V^{((V - V_0)/\Delta V)} \tag{6}$$

The two factors describe the impact of a temperature and potential increase on the aging process, meaning that an increase of ΔT leads to an increase of c_T compared to the reference conditions set to T_0 = 25 ℃ and V_0=3.5 V. ΔT was chosen at 10 °C and ΔV at 0.1 V. The parameters c_a, c_T and c_V have been fitted so the equation minimizes the deviation to the measured data.

The actual temperature of the battery pack was estimated with a simple thermal model using one thermal mass and heat transfer by natural convection. The power loss in the battery causes a heat input and thereby an increase of the temperature according to the heat capacity of the battery pack. As there is a temperature gradient between the ambient temperature and the battery temperature a heat flow to the colder part occurs. The larger the temperature difference is the higher is the heat flow. In steady-state conditions the heat flow is equal to the power loss. Figure 8 shows the relations between the different parameters/quantities involved.

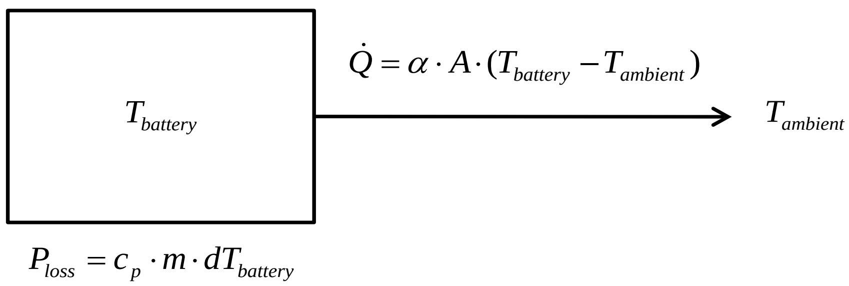

Fig. 81. Scheme of the thermal model.

In order to scale the size of the battery system the values of the area A and the mass m are defined by the energy density and the specific energy. To calculate the area a cubic form is assumed. The ambient temperature is chosen as an annual mean value for a basement, assuming that it will mostly be installed in there. The parameters used are depicted in Table 2 (right-hand side).

Three scenarios are considered for the development of the electricity retail price in Germany. We assume that prices escalate annually between 2-6% over the ten years from 2015-2025.

Specifically, Scenario S1 (low) assumes 2% p.a., S2 (medium) 4% p.a., and S3 (high) 6% p.a. of price escalation. In Germany, from 2008-2015 the price increased on average by about 4%.

3. Results

3.1 General model outputs

In this section we report on general model results, enabling to compare the model's behavior and results with those from other studies. Figure 9 shows the simulation output for PV electricity generation and electricity consumption over the time period of one year. Without an energy storage system there is a strong mismatch between energy generation and demand. Figure 10 depicts the behavior of battery capacity and inner resistance over the examined period of ten years. The capacity starts at 80% of its beginning of life (BOL) value, as this is the remaining capacity at the time the battery is replaced in the electric vehicle. Over the second life the available capacity decreases to roughly 60% of its original capacity. At the same time the inner resistance increases from 150% to 320% of its BOL value. The increasing inner resistance results in a decrease of the efficiency due to power losses.

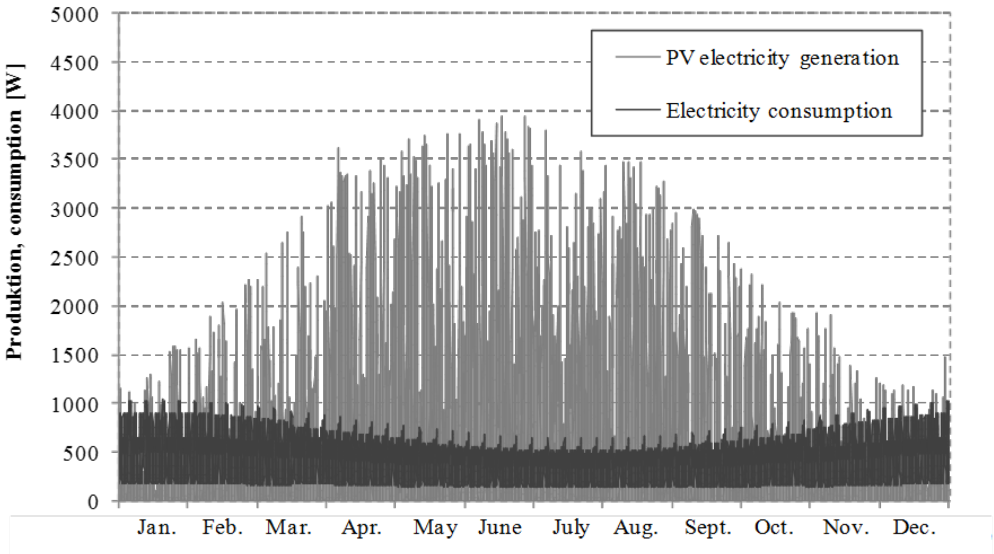

Fig.9. PV electricity generation and electricity consumption over the duration of one year.

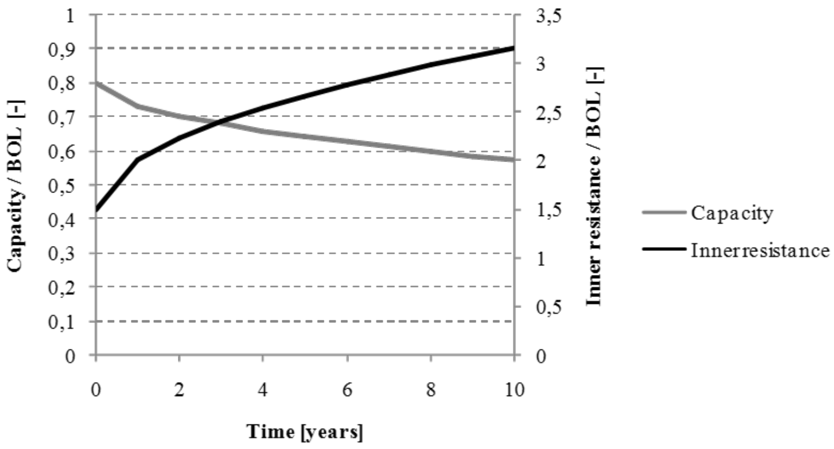

Fig. 20. Development of the battery capacity and inner resistance over the examined time period of 10 years.

3.2 Viability of second-life batteries

In this section the viability of investments in second-life batteries is discussed and the profitability evaluated. The input parameters create cash flows which are constantly discounted and added over time. The NPV is calculated for a time period of 10 years and results in values between €-326 and €825, depending on the chosen scenario and battery price. Figure 11 shows the NPV over the battery price per kWh. It is decreasing with increasing battery price and increasing with increasing net increase of the electricity price. The NPV in scenario S3, which represents a high net increase of the electricity price by 6% per year, is positive over the entire time span examined. Scenario S2 represents the expected net increase of the electricity price by 4% per year and the breakeven point is reached at a battery selling price of 107 €/kWh. For a net increase of the electricity price by 2% (S1) the breakeven point is reached at a battery price of 73 €/kWh. In Figure 13 the NPV is plotted against the installed storage capacity and the battery price. The installed PV peak power is about 5 kW_p. The maximum NPV is reached for an installed storage capacity of about 5.5 kWh BOL and a battery price of 117 €/kWh, rising to about 7 kWh BOL as the battery price decreases. This is in line with the existing literature, e.g. [13], which proposes the rule-of-thumb “1 kWh per 1 kW_p“ installed PV power. In the case of second-life batteries, however, the initial capacity loss has to be taken into account.

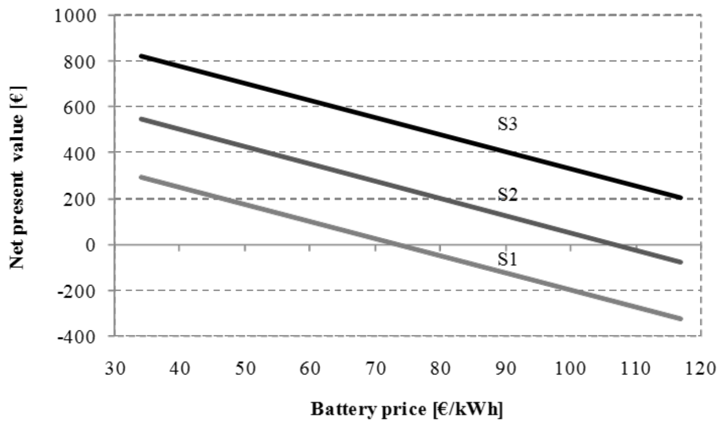

Fig. 31. Net present value for different scenarios and battery prices.

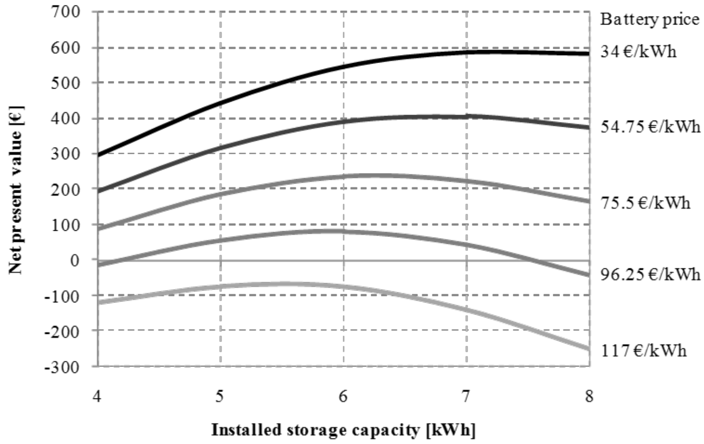

Fig. 12. Optimal storage size.

3.3 Sensitivity analysis

The sensitivity analysis illustrates how the NPV changes when varying the given parameters. It is important for estimating the influence of a certain parameter and can be used to identify crucial values. Figure 13 shows a tornado graph of the most important input parameters. The value of the feed-in tariff is the most influencing factor and thus has to be well estimated. This is not crucial though because the feed-in tariff is fixed for the duration of the investment.

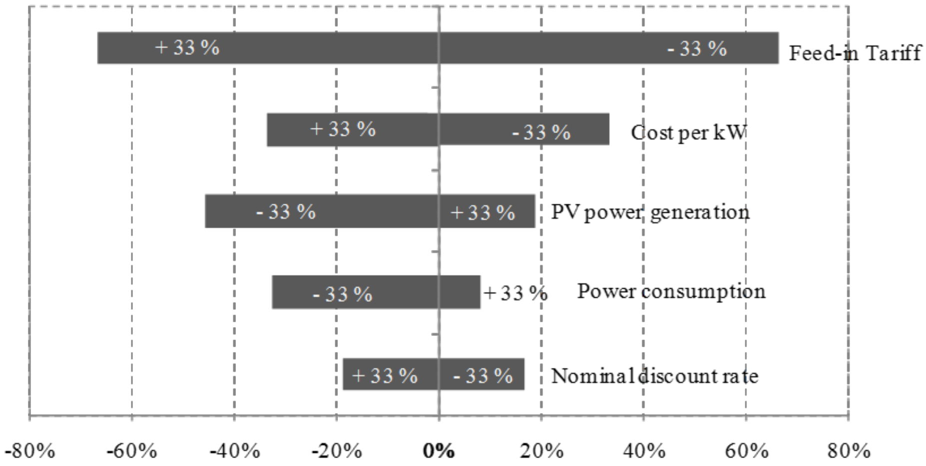

Fig. 13. Sensitivity analysis.

4. Discussion

4.1 Implications for homeowners

The presented results have shown that investments in second-use battery storage systems are profitable for the homeowner under certain circumstances. For an annual increase of the electricity tariff by and 6% (S3) an economic viability is found for all estimated battery costs. The NPV varies from about €800 to €200. For scenarios S1 and S2 the profitability depends on the actual battery selling price per kWh. In scenario S2 the breakeven point is reached at a battery selling price of 107 €/kWh, while in scenario S1 a price of 73 €/kWh is necessary. For future investments an expected decreasing guaranteed feed-in tariff will increase the viability of the storage. For the economic viability of the battery storage, the difference between the electricity price and the feed-in tariff is crucial. At the moment the private homeowner benefits from the exemption from electricity taxes, the EEG apportionment and grid fees for the self-consumed self-generated electricity, provided the PV systems size is smaller than 10 kW_p [15]. This puts an increasing burden on the other consumers and with an increasing number of PV systems this may change in the future. It has to be acknowledged that several differences may appear to the real operating conditions since for example the location and therefore the solar irradiation will vary. The electric load profile is a standardized demand pattern that will differ from the real demand. Furthermore, the operating strategy will mostly be different for optimizing the grid support and may influence the viability as well.

4.2 Implications for the environment

If electric vehicles and vehicles with internal combustion engine are compared, then from an environmental perspective both the initial material and energy investment have to be considered. For electric vehicles this applies especially for the production of large battery packs. In a lifecycle view the higher resource expense for electric vehicles in the beginning can be more than compensated over the time of use. After the use in the electric vehicle, the battery can be recycled or reused, and the automotive industry has shown high recycling rates for lead-acid batteries (although for Li-ion batteries recycling may be more restrictive). Further benefits are possible for a re-used battery after the life in the car and recycling is still possible after a second and even a third life. Ahmadi et al. [33] examined the possible CO_2 savings which result from a re-use of electric vehicle batteries. Challenges are of course the collection and the removal of the used batteries because of hazards through high voltage or the handling of liquid coolant. The collected batteries had to be disassembled and sorted by cell chemistry and type and then reassembled. However, the study showed a 56% reduction in life cycle CO_2 emissions by the use of refurbished electric vehicle batteries for peaking power applications [33].

4.3 Implications for the electricity sector

Due to the fact that the prospects regarding the economic viability of residential battery storage systems look very promising for various reasons, the number of installed units can be expected to increase further rapidly in the upcoming years. In addition, the share of renewables is very likely to continue to increase. This development certainly will have an impact on the electricity sector and some implications are presented in this section. Energy storage systems are expected to shave the peak that PV systems generated during the daytime and, as a result, decrease the burden for the electric grid. Whether a battery in a household accomplishes this goal or not is pretty much dependent on the operating strategy employed. For the rational homeowner, the strategy should be to maximize profit and to maximize the self-consumption rate. The conventional strategy is to charge the battery if the power generated by the PV system exceeds the load and to discharge the battery if the load exceeds the power generated by the PV system. Especially in the summer, the battery is likely to be fully charged before the highest peak arises around noon. In this case, the battery cannot fulfill its role of peak-shaving. Increasing the capacity of the installed battery may be a solution but leads to the problem that a complete discharge is mostly not possible in the summer. An operating strategy that is not grid-optimized is found to have no or near to no positive effects on the electric grid as it still has to be designed for the maximal annual peak [34]. A different approach is followed by the grid-optimized operating strategy. In this case, the battery is charged when the PV generation output is the highest in order to minimize the feed-in power peak. To generate the same profit for the homeowner, the self-consumption rate has to be as high as before. Because of the predictive character an accurate forecast of solar irradiation and the load has to be available. Since a perfect forecast is not available [34], the profit will be less than with the conventional operating strategy. The goal is to make the forecasts as accurate as possible and it may be thought about using incentives to run this strategy as well. Figure 14 illustrates the differences between the conventional and the grid-optimized strategies over the course of a day.

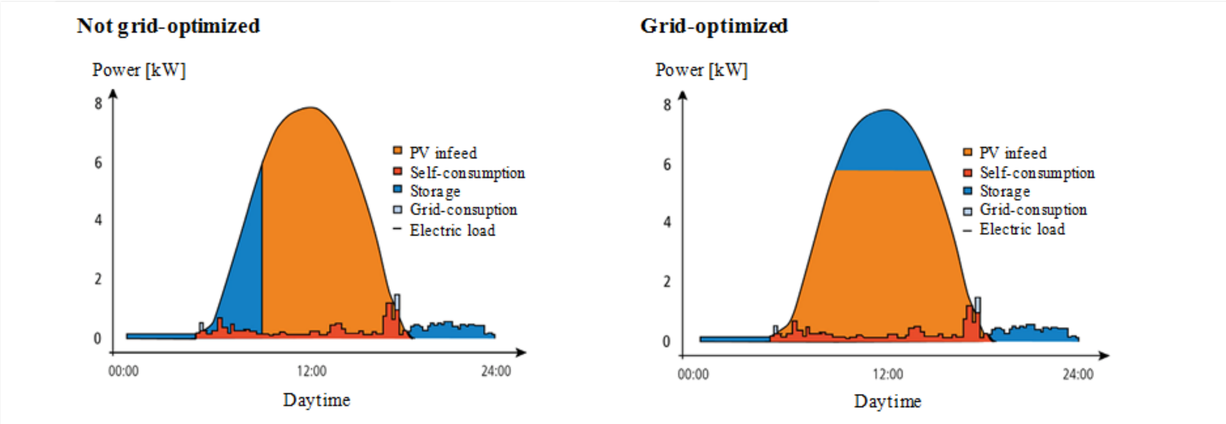

Fig. 44. Comparison of (a) non grid-optimized; and (b) grid-optimized battery operating strategies. *Source:* [34], p.4.

4.4 Implications for policy makers

For policy-making every action and measure has to serve a predefined goal. Battery storage systems by itself do not provide positive effects to the electricity market. By optimizing the operating strategy, however, they can help to relieve the electric grid and lower the peak from renewable energy sources. So policy makers have to ensure that a grid-optimized operating strategy is implemented in the funded storage system. The results of our study show that under certain circumstances the integration of used batteries in PV systems is profitable even without additional economic incentives. If the investment is currently not profitable, or if the development is found to be faster, policy makers can support the progress by several measures. All measures that raise the gap between retail price and feed-in tariff are expected to raise profitability. In this context raising the taxes and charges for self-consumed electricity will lower profitability but may be necessary as the number of residential PV systems rises. In Germany, the federal government fosters the use of stationary battery storage systems which are connected with a PV system by low-interest loan programs and repayment bonuses [35]. To receive the funding the PV system has to be smaller than 30 kW_p and be operated at least for five years. More importantly, the operating strategy is defined as well. The integrated PV-storage system has to ensure that only 50% of the installed PV power is fed into the grid and the inverter must have an open interface for remote control and parametrization. As it is implemented at the moment the program does not apply to used battery storage systems. It may be worth considering to extend that program onto repurposed batteries as well if the market has grown.

4.5 Implications for car manufacturers

The high cost of lithium-ion batteries is a major barrier for the political goal of one million electric vehicles in Germany until 2020 and the market growth of electric vehicles in itself. Establishing a market for second-use batteries could lower the battery costs and raise the market share of electric vehicles, although Neubauer et al. [21] found that battery second-use is unlikely to have a notable impact on today's battery prices [21]. Nevertheless, many automotive companies are starting projects to gather experience in second-use applications and found collaborations with battery manufacturers and electricity companies.

5. Conclusion

When traction batteries of electric or hybrid electric vehicles reach a capacity of 80% or lower they are often considered to have reached their end-of-life because of the limited range. Nevertheless, they retain a considerable amount of storage capacity which can be utilized in subsequent applications. A conceivable application for second-use batteries is residential load-shifting and peak-shaving in combination with a PV system. Previous studies examined the economic viability of new storage systems and lead-acid batteries in particular. Other studies evaluated the profitability of retired EV batteries but neglect the batteries' further degradation. We evaluate conditions under which investments in repurposed battery storage systems will become economically viable. Therefore, a simulation model of a household with an integrated PV-storage system has been developed and parameterized for the electricity demand of a typical three-person household and a location in Southern Germany. The conditions under which investments are profitable have been examined for three scenarios. Scenario S2 covers the expected net increase of the electricity price by 4% per year. Upward and downward deviations from scenario S2 are covered by scenario S1 and scenario S3. For the scenario with the highest increase of the electricity price investments in storage systems are found to be profitable for all expected battery cost levels. In scenario S2, the breakeven battery price is found to be 107 €/kWh and in the scenario with the lowest increase of the electricity price the battery price has to be equal to, or less than, 73 €/kWh. We also evaluate the optimal storage size, which is approximately the PV system's peak power in kWh (so the optimal storage size of the 5 kW_p PV system examined is about 5 kWh, and for the case of second-use batteries about 6 kWh BOL when compensating the initial capacity loss). The optimal storage size depends on the battery costs as well as on the costs for additional equipment and maintenance.

In order to give some guidance to involved parties, some implications were derived from the results. For homeowners, it is important to recognize that investments in second-use battery storage units can be profitable under certain conditions even without financial incentives. The environment will benefit as well from using batteries after the first life in the car instead of recycling. In other studies, it has been found in the literature that through the use of refurbished electric vehicle batteries a 56% reduction in lifecycle CO_2 emissions is possible. For the electricity sector the operating strategy of the integrated PV-storage system is a crucial part. Only with grid-optimized operating strategies positive effects on the electricity grid are achievable. The battery has to be charged at times when the power generation peak is highest in order to relieve the electric grid. Grid-optimized operating strategies require precise forecasts if they should be as profitable as operating strategies that are not grid-optimized. In order to foster only those storage systems supporting the electric grid the KfW program for PV-storage systems has included the grid-optimized operating strategy in its eligibility conditions. Finally, it should be noticed that the simulation model developed in our study is flexible regarding the input parameters and can be parameterized to examine a number of further research questions.

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