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Adaptive Control Strategy for Stationary Electric Battery Storage Systems with Reliable Peak Load Limitation at Maximum Self-Consumption of Locally Generated Energy

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Abstract: Nowadays, stationary battery storage systems are generally used to optimize the self-consumption of electricity generated locally or to limit the peak load of the local grid connection. Self-consumption optimization aims to achieve economic benefits by using more of the self-generated electricity within the local grid. Batteries used for the optimization of self-consumption tend to present low states of charge and, therefore, normally do not contribute to peak load limitation. Peak load limitation is used to minimize the grid connection power to enable more cost-efficient grid connections. However, this function can only be achieved year-round if there is sufficient surplus electricity production or if the battery can be charged from the grid. In the latter case, the batteries are often fully charged and do not significantly optimize the self-consumption. This study presents a new operating strategy that combines all the advantages of the previous operating modes with none of the disadvantages. This can be accomplished by combining the operation modes depending on the particular situation, together with a variable battery charging process. Furthermore, a simulation-based optimization procedure is introduced for the optimal configuration of the parameters. The potential of this operating strategy is demonstrated based on application examples. As a result, the operating strategy enables reliable peak load limitation all year round while simultaneously optimizing self-consumption. The operating strategy can easily be adapted to meet changing requirements such as the increasing charging power demands of electric vehicles. Thanks to a simple process based on common measured variables, the operating strategy can be integrated smoothly into practical applications.

Keywords: stationary battery; BESS; control strategy; self-consumption; peak-shaving; peak load limitation; economic optimization; energy management; charge management

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1. Introduction

Solar photovoltaics (PV) is a renewable energy technology that is highly suitable for micro-scale electricity production, for example, in residential buildings. Due to sinking technology costs and rising electricity prices, the adoption of PV systems has been large, even in countries with moderate solar irradiation. For the vast majority of households, the decision to invest in a PV system, or any other technology for micro-scale production, is primarily driven by the expected economic performance [1–3]. The economic performance is mainly determined by the system costs, end-consumer electricity prices, insolation, and the ratio of the on-site consumed electricity, so-called self-consumption [4]. In countries with high electricity prices, it is found that, in particular, the ratio of self-consumption has a significant effect on the economics of residential PV systems. The potentially large margin for self-consumed electricity even leaves room to increase the amount of self-consumed electricity by installing stationary battery storage [5,6].

Increasing self-generation and self-consumption is not the only development in the residential sector; with the uptake of electric mobility, the number of electric vehicles increases. The charging of these electric vehicles can increase the electricity demand of households to more than double [7]. The potential contribution of electric vehicles to increase self-consumption is discussed in recent studies; however, the potential is found to be limited, due to the low match between PV production and charging patterns of electric vehicles [8]. Quite the contrary, the charging of electric vehicles, usually in the late afternoon after returning from work, can lead to high local peak loads that strain the public electricity grid and potentially increase costs for electricity consumers [9,10]. This is particularly relevant for multi-family homes with many electric vehicles and limited grid connection capacities [9], and also for companies, whose electricity tariffs are often load dependent [11]. Additional costs can be incurred for the expansion of the grid connections if required, due to the additional loads resulting from electric vehicles. Stationary battery systems have the potential to reduce load peaks and take stress from the public grid [12], which is, therefore, a competing optimization goal besides the increase in self-consumption in local energy systems.

1.1. Background of Battery Control Strategies

To analyze the potential conflict of different use cases for stationary batteries, the corresponding battery control strategies need to be discussed in more detail. In this study, we distinguish between strategies that aim to optimize self-consumption and strategies that limit load peaks.

Operated according to the "**optimizing self-consumption**" strategy, battery systems are charged using surplus electricity from the pv system, and electricity is discharged from the battery (instead of being drawn from the grid) if the pv system does not produce enough to meet the on-site demand. this minimizes both the grid feed-in and the grid consumption and thus increases the rate of self-consumption, which is potentially more cost-efficient than operations without a battery system [13–15]. alternatively, battery systems can be implemented to limit the grid connecting power using the "**limiting peak load**" operating strategy. this means that the battery is discharged when a specific power (peak load limit) has been exceeded and limits the power load at the connection to the public grid [12]. to ensure its peak load-limiting function, the battery must always be sufficiently charged. The battery can be charged using surplus production of the local PV system, or with electricity from the grid in times with low load levels and, therefore, available grid capacity.

As stated earlier, if electricity is produced on-site, the "Optimizing self-consumption" operating strategy generally offers a cost-efficient form of operation for a battery. However, with this operation strategy, it is not generally possible to ensure an additional year-round reliable peak load limitation [10]. Particularly in the case of PV battery systems, lower levels of production in winter can cause batteries to fully discharge, making further peak load limitation effectively impossible (Figure 1a).

With the "Limiting peak load" operating strategy, the battery is used considerably less than with self-consumption optimization. Nevertheless, even in this case the battery can run empty and prevent further peak load limitation if it is not sufficiently charged between peak load limitation events, e.g., if the peak load has been exceeded frequently or for long durations and/or there is insufficient surplus electricity production for charging (Figure 1b). The same happens if the battery is too small. For peak load limitation to work, the battery's electricity—when sufficiently charged—must meet the requirements in terms of capacity and power when the peak load is exceeded. Extreme load peaks are normally quite rare. Thus, the electricity consumption from the battery is relatively low and it often remains fully charged. From an economic perspective, this means that the (expensive) battery capacity is not used well and, in addition, the high state of charge (SOC) has a negative effect on battery degradation [16–18]. This effect is more pronounced if, for example, the battery is being charged using grid power (Figure 1c). Moreover, in the case of a local electricity production, the economically more advantageous self-consumption is hardly increased when operating with the "Limiting peak load" strategy. With this in mind, the question arises if it is possible to combine the discussed operating and charging strategies to enable reliable peak load limitation and benefit from the economic advantages of self-consumption optimization at the same time.

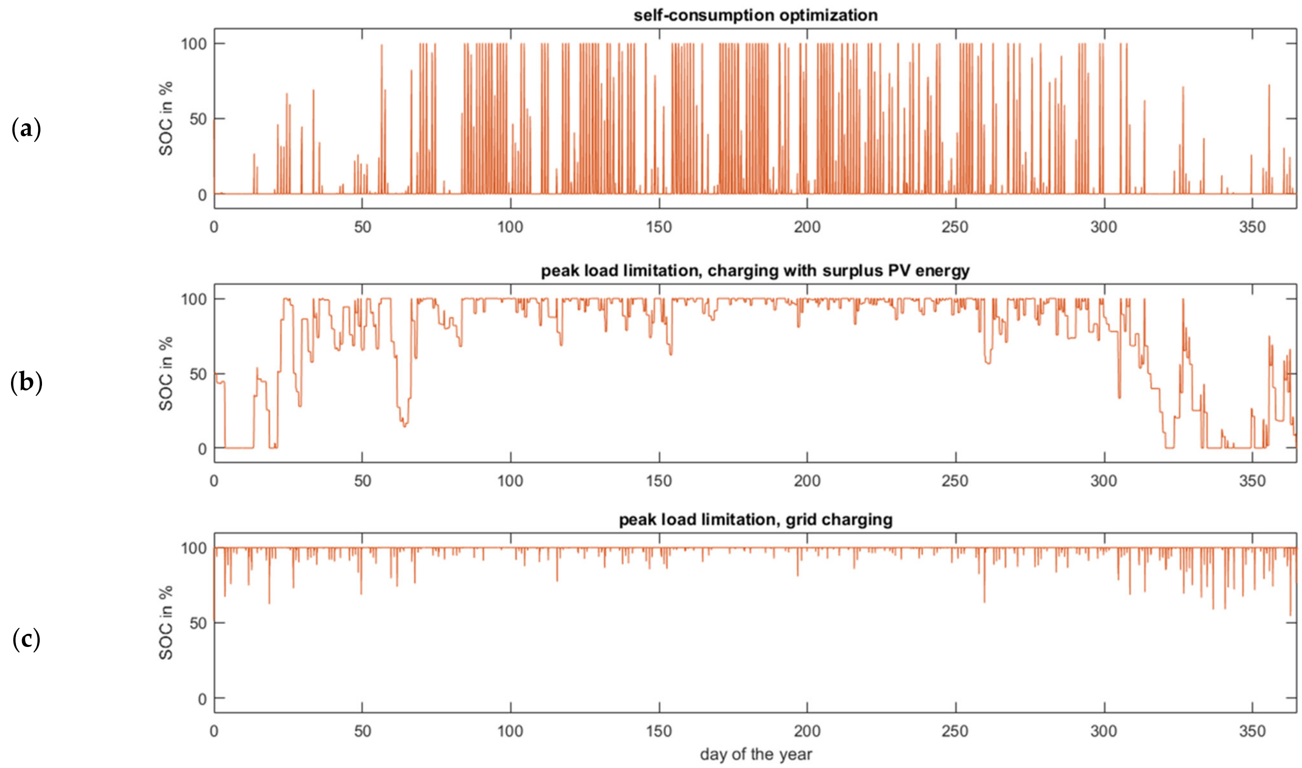

Figure 1. Sample battery states of charge (SOC) over one year for self-consumption optimization resp. peak load limitation for a residential neighborhood with charging infrastructure, PV system, and battery storage system (simulation results, see application example 1 in Section 2.3). (**a**) Self-consumption optimization; (**b**) peak load limitation—charging with surplus PV production; (**c**) grid charging. Surplus PV production is not sufficient for year-round peak load limitation. When charging from the grid, the battery is usually fully charged and not used to capacity. Furthermore, peak load limitation is also not ensured during self-consumption optimization.

1.2. Research Objective

As introduced above, both "Optimizing self-consumption" and "Limiting peak load" operating strategies have been analyzed and discussed separately in numerous different studies. Wagner and Stiller show that the increased use of PV systems can sometimes lead to grid instabilities [19]. Batteries can counteract this tendency and increase the self-consumption of local PV production. Luthander et al. showed in their review paper that batteries have a higher potential for optimizing self-consumption in buildings with PV systems than demand-side management [6]. Both flexibility options are also considered in Lorenzi et al. for households in the residential sector [20]. They show a better performance for the battery regarding self-consumption; however, to compete economically with demand-side management a strong cost reduction in batteries is necessary. Merei et al. analyze the potential for PV battery systems in a commercial building (supermarket) to optimize self-consumption [13]. For an economical scenario, they quantified the battery cost limit to a maximum of 200 EUR/kWh. Lehmann et al. describe both self-consumption and peak-shaving applications in an industrial environment (a company in the metalworking industry) and performed a techno-economical assessment [11]. As a result, they found economically feasible scenarios with smaller batteries for both use cases, but with only minor effects on self-consumption or peak load limitation.

Rana et al. analyze the benefits of peak-shaving in microgrid systems and examine the technological, economic, and environmental advantages in a review paper [21]. One fundamental challenge for the application of a battery system is the optimal size of the storage. They conclude that high capital costs make that application impractical to employ and further investigation is needed in that context. In the review of Uddin et al. different peak-shaving strategies have been analyzed, including the use of batteries [12]. Besides the potential benefits of the use case, they also identify significant challenges caused by high capital costs and the optimal size of the batteries. Further, the scheduling of the batteries for optimal operation was highlighted as another challenge. They suggest further research with the aim to develop an algorithm based on variable load limits, which will overcome the limitation of scheduling the batteries. Schram et al. have demonstrated the potential of distributed battery systems for local self-consumption to limit peak loads in a residential district [15]. They show that the neighborhood peak demand can be reduced significantly; however, the effects on the self-consumption rates of the individual battery systems are neglected.

High peak loads occur, in particular, at charging infrastructure sites with high individual charging power and/or a high number of charging stations. This applies, e.g., for electric trucks and for urban fast charging parks for electric vehicles [22,23]. In the latter, it was shown that stationary batteries have the potential to reduce peak loads without restrictions for mobility. The optimal sizing of batteries for urban charging parks is challenging due to the expected dynamic increase in the number of electric vehicles in contrast to a static estimation for sizing the energy infrastructure. Another challenge, in this case, is to guarantee a reliable peak load limitation all year long, while using only surplus energy from a given PV system.

In summary, we find that the efficient usage of battery systems by combining different control strategies should be investigated further to overcome existing difficult economic conditions for power storage. We, therefore, aim to contribute to this research field by developing a new operating strategy for stationary battery systems that enables a reliable peak load limitation even with restricted battery capacities and enhances the self-consumption of given PV battery systems at the same time, especially considering the special challenges posed by electric vehicles. Compared to the current state-of-the-art, the new operating strategy should achieve the following advantages:

- Batteries for self-consumption optimization, achieve additional peak load limitation and consequently operation with lower grid connection power, with almost consistent self-consumption rates.
- Batteries for peak load limitation achieve additional self-consumption and consequently, a more cost-efficient operation is made possible, while maintaining the load limit.
- With Batteries for peak load limitation with limited PV generation or with batteries that are too small, the load limit can be reliably maintained all year round.
- The batteries can be operated at a more favorable state of charge in terms of lifetime.
- The operating strategy is based exclusively on the status and measurement data of the battery. No external data or forecasts are required during operation. The associated parameters can be adaptively adjusted to the application and the respective boundary conditions.

The remainder of this study is structured as follows: First, we present the developed strategy and show how it enables switches between different discharging options (“Optimizing self-consumption” or “Limiting peak load”) and/or charging options (with local surplus production, total local production, or grid charging) depending on the battery’s state of charge. Therefore, it enables reliable peak load limitation which works all year round and at the same time maximizes self-consumption of locally produced electricity (Section 2.1). The ideal states of charge, which trigger a change in operating strategy, are determined in advance for each specific system using an optimization algorithm based on historical load and production data. The parameters can optionally be adjusted at regular intervals or adaptively (Section 2.2). The potential of the new operating strategy is demonstrated using two application examples (Section 2.3). In the following, the optimization strategy is applied and compared to a conventional approach to battery operation.

The results are presented in Section 3. Finally, the operation strategy is critically reflected (Section 4) and conclusions are drawn (Section 5).

2. Materials and Methods

The developed methodology includes both the new operating strategy for stationary battery systems themselves (Section 2.1) as well as the determination and optimization of the underlying parameters (Section 2.2). The operating strategy's main control parameter is the current state of charge of the battery SOC(t) at time t. The following factors have been assumed for the operating strategy: prioritized local electricity production (e.g., a photovoltaic (PV) system in this study), a local grid connection to the public electrical grid, and a local consumption load (e.g., household load and charging stations for electric vehicles).

2.1. Operating Strategy

The following processes are considered for **charging the battery**:

- *Surplus charging*: The battery is charged when the electricity production of the PV system P_{prod} exceeds the local consumption P_{load}. The charging power P_{charge} corresponds to the surplus production (or the maximum possible battery charging power P_{batt_max}).

$$P_{charge} = \begin{cases} min\left(P_{prod} - P_{load},\ P_{batt\_max}\right) & \forall\ P_{prod} > P_{load} \\ 0 & else \end{cases} \tag{1}$$

- *Local charging*: The battery is charged by the entire energy produced by the PV system, provided that the maximum grid reference power P_{grid_max} is not exceeded by the consumers as a result. The charging power corresponds to the production or the available production proportion, which is not needed for peak load limitation (or the maximum possible battery charging power). P_{res} is the power needed to comply with the grid limit.

$$P_{charge} = \begin{cases} min\left(P_{prod} - P_{res}\ ,\ P_{batt\_max}\right) & \forall\ P_{prod} > P_{res} \\ 0 & else \end{cases} \tag{2}$$

$$P_{res} = max\left(P_{load} - P_{grid\_max}\ ,\ 0\right) \tag{3}$$

- *Grid charging*: If there is free capacity, the battery is charged using the local grid connection with corresponding power (or the maximum possible battery charging power).

$$P_{charge} = \begin{cases} min\left(P_{grid\_max} - P_{load}\ ,\ P_{batt\_max}\right) & \forall\ P_{load} < P_{grid\_max} \\ 0 & else \end{cases} \tag{4}$$

The following processes are considered for **discharging the battery**:

- *Optimizing self-consumption*: The battery is discharged when the local consumption exceeds the local production. The discharge power $P_{discharge}$ corresponds to the power difference between consumption and production (or the maximum possible battery discharge power). For the purposes of this study, self-consumption optimization always assumes surplus charging.

$$P_{discharge} = \begin{cases} min\left(P_{load} - P_{prod}\ ,\ P_{batt\_max}\right) & \forall\ P_{load} > P_{prod} \\ 0 & else \end{cases} \tag{5}$$

- *Limiting peak load*: The battery is discharged when the local consumption, minus any local production, exceeds a defined maximum power. The discharge power corresponds to the power difference between (net) consumption and maximum power. This maximum power is described below as the *peak load limit* and is equated with the connected load of the local grid connection P_{grid_max}.

$$P_{discharge} = \begin{cases} min\left(P_{load} - P_{prod} - P_{grid\_max}\ ,\ P_{batt\_max}\right) & \forall\ (P_{load} - P_{prod}) > P_{grid\_max} \\ 0 & else \end{cases} \quad (6)$$

When applying the new operating strategy, both the discharging and charging processes can be changed depending on the SOC of the battery (Figure 2). Different SOC limit values are defined for these operating changes. If these are exceeded or undershot, the operation in question is changed. These limit values are referred to below as **Change SOCs a, x and y** (in % SOC) and feature the following characteristics:

- Change from "Optimizing self-consumption" to "Limiting peak load" when SOC(t) < a and vice versa
- Change from "Surplus charging" to "Local charging" when SOC(t) < x and vice versa
- Change from "Local charging" to "Grid charging" when SOC(t) < y and vice versa

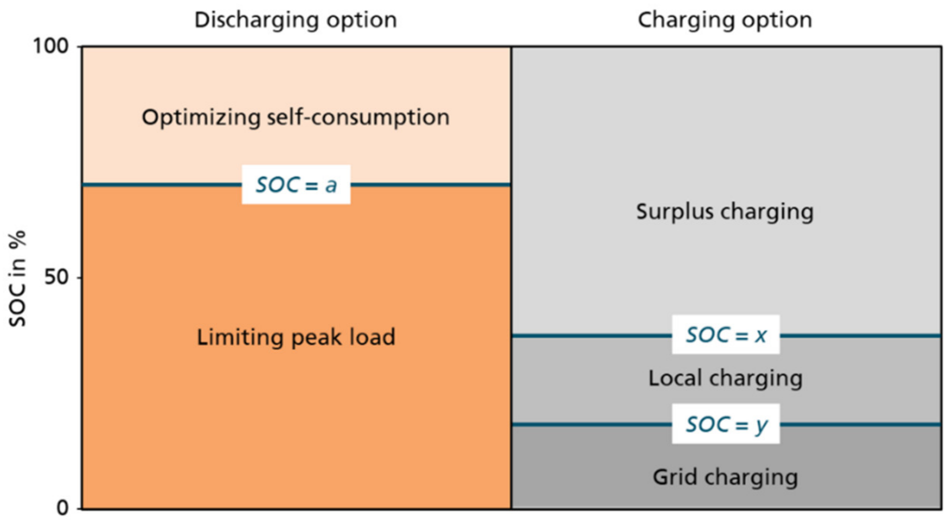

Figure 2. Schematic illustration of the SOC-dependent change of the charging and discharging options regarding the parameters a, x, and y.

Depending on the system configuration and optimization goal, one or more of these parameters are used. Depending on the application, it would be possible to implement additional hysteresis and control damping to prevent frequent changes and oscillations in the system. However, this study does not consider such options.

The new operating strategy can be applied in several different variants, depending on the initial situation. The behavior of each of these variants is described in the following. The ideal value for each of the specified parameters a, x, and y can be determined by optimization, which is described in Section 2.2.

2.1.1. Scenarios A, B, and C—State of the Art

Scenario A represents a basic scenario of the energy system without a battery and serves only for comparison purposes for the example applications presented below. Furthermore, it is possible to map the state-of-the-art operating strategies "Optimizing self-consumption" (scenario B) and "Limiting peak load" (scenario C). For these cases, parameter a has the value 0% or 100%. For peak load limitation, the charging process can also be set to any fixed option using parameters x and y and by setting the values to 0% or 100%.

2.1.2. Scenario D—Self-Consumption Optimization with Functioning Peak Load Limitation

Scenario D optimizes the self-consumption of a functioning peak load limitation. The prerequisite is that the peak load limitation (scenario C) functions on a permanent basis for a given peak load limit. Parameter a is used to define an alternating SOC between 0% and 100% (0% < a < 100%) to switch from peak load limitation to self-consumption optimization in the case of higher SOCs. The ideal parameter is selected if the peak load limitation remains ensured on a permanent basis and a is as small as possible. The charging process for peak load limitation can be predefined (e.g., using settings x = a, y = 0 for local charging or x = y = a for grid charging). Partial operation during self-consumption optimization for SOC > a increases the self-consumption rate, thereby making it more economically viable.

2.1.3. Scenario E—Peak Load Limitation with Optimized Charging Process

Scenario E improves the peak load limitation (scenario C) by optimizing the charging process in terms of reliability. The starting point is a peak load limitation with a defined peak load limit in combination with surplus charging (optional: local charging) which does not work on a permanent basis as the battery discharges completely every so often. Optimum reliability is achieved by permanently switching the charging process to grid charging (x = y = 100%, a = 100%). Ideally, the peak load limitation would then function on a permanent basis and could be optimized further with scenario E to minimize grid consumption and increase the degree of self-sufficiency and self-consumption (scenario F). This is generally also accompanied by an improvement in economic viability. Alternatively, grid consumption can also be excluded (y = 0%), if this is not an option for the application in question (e.g., due to state subsidy regulations for the system). The consideration then refers only to a change from surplus charging to local charging. In scenario E, parameters x and y are set between 0% and 100% (0% $\leq$ y $\leq$ x $\leq$ 100%, a = 100%). Thus, the charging variant is changed from surplus charging to local charging and finally to grid charging for certain states of charge. When y = x, it is also possible to switch directly from surplus charging to grid charging. The ideal parameters are selected if the peak load limitation remains ensured on a permanent basis and the values are as small as possible (lowest grid consumption). Depending on the application, directly changing to grid charging at a higher SOC may be more favorable than changing in steps at a lower SOC.

2.1.4. Scenario F—Self-Consumption Optimization with Optimized Charging Process

Scenario F combines scenarios E and D. As presented in scenario E, a reliable peak load limitation can be achieved on a permanent basis by optimizing the charging process. This can be further improved by optimizing self-consumption (as in scenario D) to increase the self-consumption rate of locally produced energy. For this purpose—in addition to the x and y values specified in scenario E—parameter a is set between x and 100% (x $\leq$ a $\leq$ 100%). The ideal value for a is selected if the peak load limitation remains ensured on a permanent basis and a is as small as possible.

2.2. Determining and Optimizing Parameters a, x and y

When applying the new operating strategy, parameters a, x, and y required in each case must be defined at least once in advance. The parameters can then be recalculated regularly during operation if required (based on current measurement data, if applicable; manually or automated). This is useful, for example, if the energy system's configuration or its utilization changes over time (e.g., if the local production or storage capacities are expanded, more electric vehicles are in use or there are new consumers). It also enables the parameters to be fine-tuned according to the seasons.

An optimization algorithm is run to determine the ideal values for a, x, and y in each case. In principle, the parameters can also be set arbitrarily (e.g., with empirical values). However, the operating strategy's potential is only fully exploited in terms of reliability and economic viability when the ideal parameter values are set. Therefore, we present here a simple algorithm (Figure 3), which is well suited for a practical implementation. The ideal parameter values are set specifically for each system. This means that they depend, for example, on the battery design, the grid connection, and the local consumption and production load profiles.

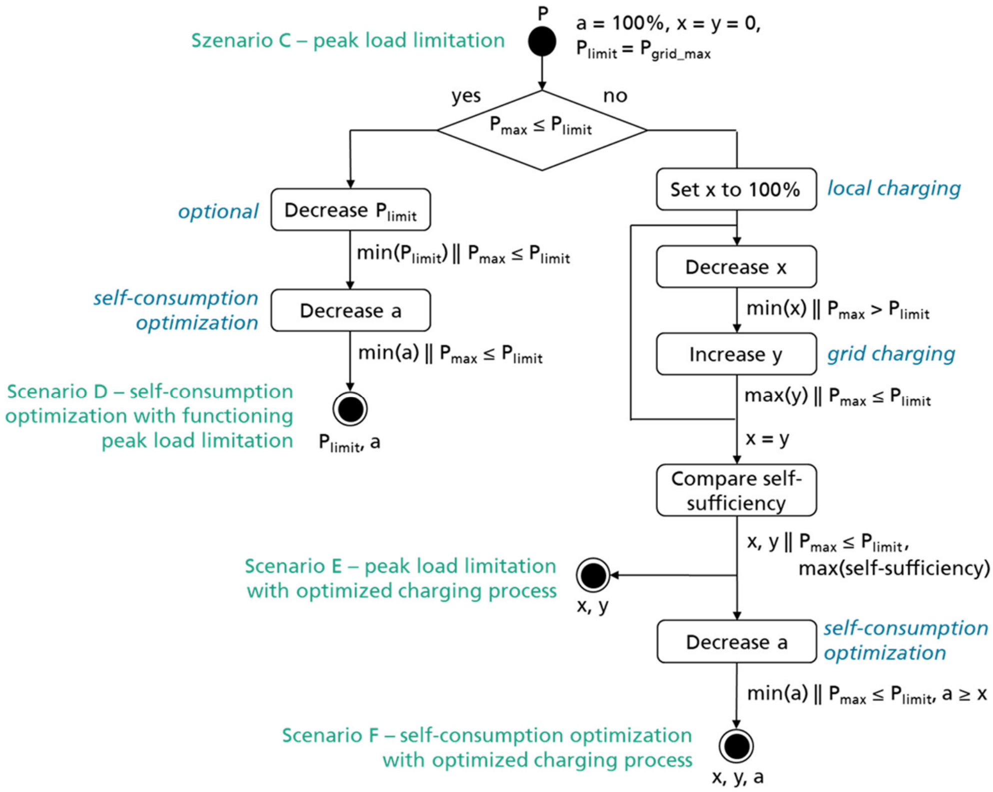

Figure 3. Illustration of the optimization algorithm to determine the parameters a, x, and y of the new operating strategy. The calculation is based on the (net) load profile P(t) at the grid connection point during a reference period.

2.2.1. Input Data

Optimization is performed based on a *reference period* that is to be defined for the system operation in question. The following section is based on the example of one year, where seasonal effects (e.g., PV systems producing energy) are taken into account. For the optimization process, the system's electrical load profiles during the reference period are used as input data. These power values may include measurement data from an existing system or simulated or predicted values. It is also possible to use a combination of these options. The higher the temporal resolution of the values, the more accurate the optimization results will be, as shorter load peaks are also resolved (e.g., minute values).

The following minimal dataset of power values must be available for the reference period with sufficient temporal resolution:

- *Production power*: aggregated production load profile of all electricity generators of the system under review, e.g., the output power of a PV system.
- *Consumption power*: aggregated consumption load profile of all consumers of the system under review, e.g., residential or commercial load profiles and charging load profiles of electric vehicles. (Alternatively, the load at the grid connection point can be used, for example, to calculate the consumption with production power.)

Other essential boundary conditions include the technical data of the battery used (capacity and power), as well as the maximum load specified for the grid connection or the peak load limit. Additional parameters, such as the battery system's efficiency curve, can be used as an option to increase the optimization accuracy.

2.2.2. Optimization Goals

Depending on the application, one or more of the following optimization goals can be used to determine parameters a, x, and y:

- *Complying with the peak load limit*: the grid-connected load or peak load limit should not be exceeded at any time during the reference period
- *Maximizing the self-consumption*: maximum possible self-consumption of the energy produced locally
- *Maximizing the degree of self-sufficiency*: the battery should be charged as little as possible from the grid

Alternatively, related or derived optimization goals can be used to achieve optimization—for example, maximizing economic viability instead of self-consumption, or grid consumption instead of the degree of self-sufficiency.

2.2.3. Simulation Model

A battery simulation model is used for optimization (see Section 2.3.1). In the simulation, the battery is controlled by the operating strategy variants described in Section 2.1 with adjustable parameters a, x, and y. Then, based on the input data and the boundary conditions affecting the reference period, the battery's charging and discharging power is calculated in the simulation for each time step. The resulting load at the grid connection point can be determined using the predefined production and consumption load profiles. By extension, the grid consumption, peak load, the proportion of self-consumption, the degree of self-sufficiency, and other aspects can be determined. The battery model provides information on the SOC and the number of full cycles performed.

2.2.4. Optimization Sequence

When using the simulation model, the variables defined in the optimization goals are obtained as functions of the parameters a, x, and y. Determining the ideal values for a, x, and y with regard to the optimization goals is therefore considered to be a minimization or maximization task, under the constraint that the peak load limit is met. These tasks can be solved using common methods—if necessary, even directly in the simulation model. The following example illustrates how a simple numerical method is used to determine a, x, and y for the different variants of the new operating strategy from Section 2.1. A simplified overview of the algorithm is shown in Figure 3.

Scenario C

The simulation is performed with a pure peak load limitation (a = 100%). Surplus charging has been assumed as the charging method (x = y = 0%). If peak load limitation is possible on a permanent basis for the reference period, the peak load limit can optionally be decreased in discrete increments (e.g., in −10 kW increments) in further cycles. With the smallest peak load limit, which still allows a permanently reliable peak load limitation, the sequence moves on to scenario D. If there is no reliable peak load limitation on a permanent basis, scenario E is deployed.

Scenario D

The simulation from scenario C is executed several times, with the value for a decreasing discretely from 100% (e.g., in −10% increments) until the peak load limitation is no longer reliably maintained on a permanent basis. The previous value for a is the ideal parameter value, whereas the x and y values remain at 0%.

Scenario E

Starting from scenario C, the values for x and y are varied in discrete increments (e.g., in ±10% increments) as follows and a simulation is performed in each case: When y = 0%, x is gradually decreased from 100% until the peak load limitation is no longer reliably maintained on a permanent basis. This x value is used to gradually increase y until the peak load limit is maintained once more. Once this y value is reached, the x value decreases even more. This sequence continues until x = y. All value pairs which cause the peak load to be exceeded are discarded. One of the remaining x and y pairs leading to the highest degree of self-sufficiency represents the optimum for this scenario. The value for a remains at 100%. Optionally, scenario E can be executed without grid charging (y = 0% on a permanent basis) or starting with local charging in scenario C. If a functioning peak load limitation is achieved, self-consumption can be optimized as described as follows in scenario F.

Scenario F

The simulation from scenario E which provided the ideal pair of x and y values is further optimized in scenario F with regard to self-consumption. For this purpose, the simulation is executed several times, with the values decreasing discretely from 100% (e.g., in −10% increments) until the peak load limitation is no longer reliably maintained on a permanent basis or until a = x. The previous value for a or the last value where a = x is taken as the ideal parameter value.

2.3. Application Examples

2.3.1. Example 1: New Operating Strategy Applied in a Residential Neighborhood

This scenario describes a residential neighborhood with 30 residential units and a shared underground garage (Figure 4). PV systems for local use are installed on the residential buildings. These systems are operated in combination with a common battery storage system. The neighborhood has a common grid connection which defines the maximum reference power. The underground garage is equipped with a charging infrastructure for electric vehicles. The load profiles of all components were simulated in one-minute resolution with MATLAB/Simulink 2015b over the course of a year. The basic simulation methodology is described in more detail by Göhler et al. [10].

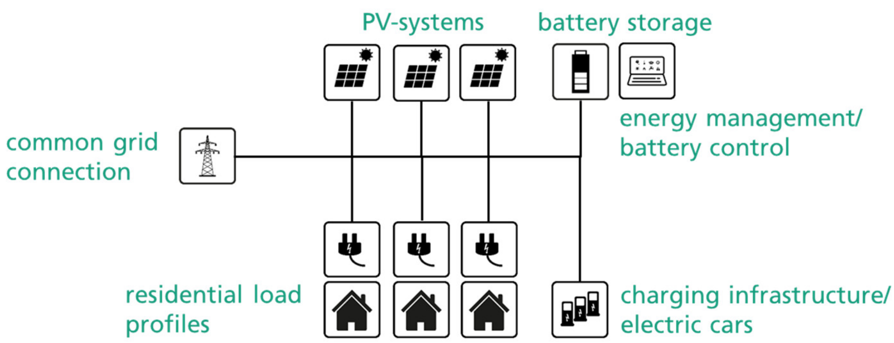

Figure 4. Schematic illustration of the residential neighborhood simulated in application example 1.

For the residential electricity consumption, HTW Berlin University of Applied Sciences provides 72 annual load profiles in kW in one-minute resolution [24]. These have been created using measurement data to also include short-term load fluctuations compared to standard load profiles. The example used profiles 1 to 30, which, for equal weighting, were standardized to an average annual consumption of 3500 kWh per residential unit [25,26]. The common grid connection was restricted to 60 kW to ensure that the residential loads were covered in any case without a charging infrastructure.

Using a load profile generator from the University of Stuttgart, load profiles in kW in 5 min resolution based on the realistic and mixed mobility behavior of electric vehicles were generated for the charging infrastructure [27]. For the vehicles, the study assumed a constant charging power of 11 kW, a battery capacity of 40 kWh, a consumption of 18 kWh/100 km, and a charging efficiency factor of 95%. 10 or 30 electric vehicles were used for the evaluation.

Based on standard weather data provided by the Deutscher Wetterdienst (German Meteorological Service), the energy generated by the PV systems (installed with a 30° incline and facing the south) was simulated in one-hour resolution and interpolated [28]. The power values in kW were converted from the weather data according to Quaschning using the Perez model [29]. The simulation includes the use of an inverter with a maximum efficiency of 98% and a corresponding characteristic efficiency curve [30]. The complete system features a peak output of 40 kW_p.

Moreover, a usable energy capacity of 50 kWh and a discharge/charge power of 60 kW are assumed for the battery storage. Provided that the state of charge is sufficient, the battery capacity is able to cover the maximum total peak load together with the grid connection. A characteristic efficiency curve with a maximum efficiency of 97% has also been assumed for the inverter. A constant efficiency of 99% has been assumed for the battery. This results in a maximum system efficiency of 92% for a full cycle (charging and discharging). The battery is operated using both the conventional operating strategies ("Optimizing self-consumption", "Limiting peak load") and the new strategy with optimized parameters a, x, and y.

2.3.2. Example 2: Using the New Operating Strategy in the "Fraunhofer IAO Micro Smart Grid"

The "Fraunhofer IAO Micro Smart Grid", a real facility at the Fraunhofer Institute Center Stuttgart, hosts a PV system that generates energy with a peak output of 30 kW_p. This is used to charge up to 30 electric vehicles (company cars, commuter cars, research cars) with a charging power ranging between 3.6 and 22 kW [31]. In addition, a battery storage system with an energy content of 100 kWh and an output of 60 kW is available, which is charged with PV generation surpluses. An initial estimate of 80 kW was adopted for the available grid-connected load. Using the same methodology as in example 1, a battery simulation was used to optimize parameters a, x, and y and to evaluate the new operating strategy. Measurement data in kW for the production power and the consumption loads from the previous year in the one-minute resolution were used as input data.

3. Results

3.1. Evaluation of Example 1: New Operating Strategy Applied in a Residential Neighborhood

3.1.1. Result of Simulation with 30 Households, 30 × 11 kW Electric Vehicles and 40 kW_p PV Power

Due to the high number of electric vehicles, the assumed grid-connected load of 60 kW is not always sufficient to cover the total load of all consumers, which is up to 117 kW during the reference year (Table 1). Even with the "Limiting peak load" operating strategy applied to the battery, this situation cannot be permanently prevented (scenario C). In winter in particular, when PV production is lower, the battery is often fully discharged and is no longer available for peak load limitation (Figure 5a). The grid connection is still significantly overloaded by up to 107 kW. The new operating strategy uses adaptive adjustment of charging at the SOC limits of 50% (local charging) and 10% (grid charging) to enable reliable peak load limitation throughout the year (scenario E). The degree of self-sufficiency remains virtually unchanged, as only a very limited amount (0.1%) of additional energy needs to be drawn from the grid for battery charging. By further optimizing the discharging strategy, self-consumption can be increased by 4% compared to peak load limitation alone, without affecting functional reliability (scenario F). At an average of 76%, the SOC is usually in a more favorable range in terms of battery degradation (Figure 5b).

Table 1. Results for example 1 with 30 electric vehicles: the degree of self-consumption and self-sufficiency was increased with the new operating strategy and peak load limitation was enabled all year long.

Battery Control Strategy	Base	Self-Consumption Optimization	Peak Load Limitation	C, with Optimized Charging	E, with Optimized Charging and Discharging
Scenario	**A**	**B**	**C**	**E**	**F**
Load limit (grid connection) (kW)	60	60	60	60	60
Battery charge power (kW)		60	60	60	60
Battery energy capacity (kWh)		50	50	50	50
Peak load from grid (kW)	**117**	**117**	**107**	**60**	**60**
Degree of self-consumption	**0.75**	**0.93**	**0.77**	**0.77**	**0.80**
Degree of self-sufficiency	0.20	0.27	0.21	0.21	0.22
Full cycles		166	22	28	56
Change-SOC a (%)					90
Change-SOC x (%)				50	50
Change-SOC y (%)				10	10
Charge mode		surplus charging	surplus charging	adaptive	adaptive

(**a**) (**b**)

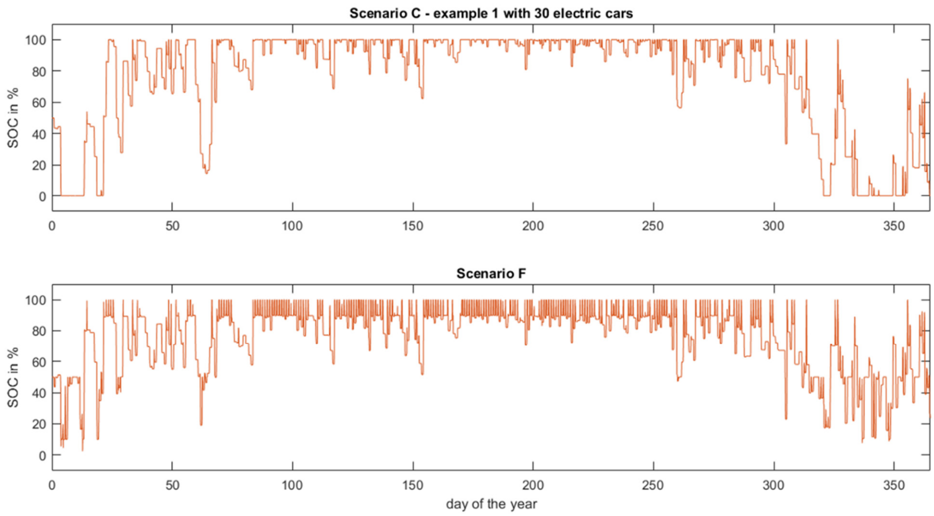

Figure 5. Evaluation of example 1 with 30 electric vehicles: The new operating strategy allowed peak load limitation to be achieved throughout the year with minimal grid consumption. The average state of charge of the battery moved into a more favorable range in terms of service life. (**a**) Peak load limitation, (**b**) optimized control strategy.

3.1.2. Result of Simulation with 30 Households, 10 × 11 kW Electric Vehicles and 40 kW_p PV Power

Due to the lower number of electric vehicles, peak load limitation with the battery can be guaranteed throughout the year even with a 17% reduction in the grid connection (Table 2). As high load peaks occur only rarely, the states of charge of the battery remain very high even in winter with the "Limiting peak load" operating strategy (scenario C, Figure 6a). Despite the starting value of 50%, the average SOC is over 97%. With just two full cycles a year, the battery is not used anywhere near its full capacity. With the new operating strategy, the battery can primarily be used for self-consumption optimization (scenario D, Figure 6b). This enables the degree of self-consumption to be increased by 25% to 0.85, placing it just slightly below the figure for the "Optimizing self-consumption" operating strategy but with reliable peak load limitation.

Table 2. Results for example 1 with 10 electric vehicles: the new operating strategy significantly improved the degree of self-consumption and self-sufficiency, almost reaching the values for self-consumption optimization alone.

Battery Control Strategy	Base	Self-Consumption Optimization	Peak Load Limitation	C, with Optimized Discharging
Scenario	**A**	**B**	**C**	**D**
Load limit (grid connection) (kW)	60	60	50	50
Battery charge power (kW)		60	60	60
Battery energy capacity (kWh)		50	50	50
Peak load from grid (kW)	**75**	**75**	**50**	**50**
Degree of self-consumption	**0.68**	**0.88**	**0.68**	**0.85**
Degree of self-sufficiency	**0.25**	**0.36**	**0.25**	**0.35**
Full cycles		181	2	154
Change-SOC a (%)				20
Charge mode		surplus charging	surplus charging	surplus charging

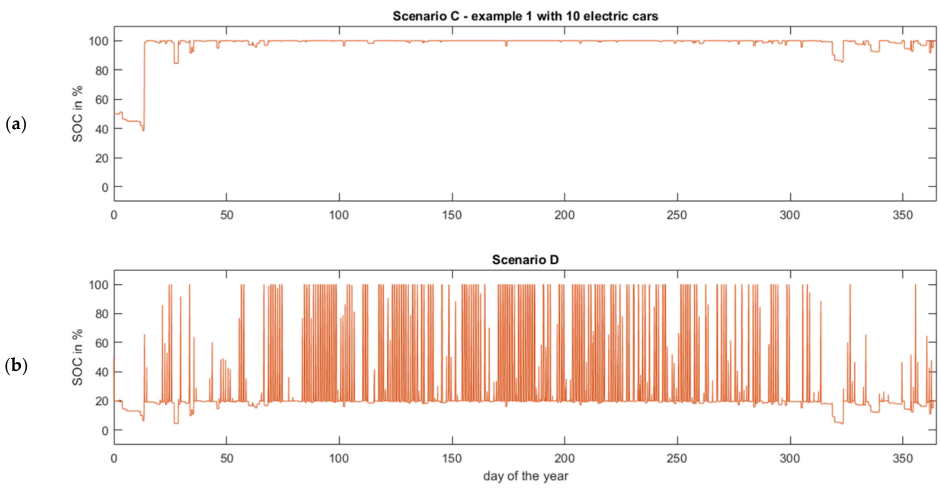

Figure 6. Evaluation of example 1 with 10 electric vehicles: Peak load limitation can already be achieved throughout the year, even with a reduced peak load limit. The average state of charge of the battery moved into a much more favorable range in terms of service life. (**a**) Peak load limitation, (**b**) Optimized control strategy.

3.2. Evaluation of Example 2: Using the Operating Strategy in the "Fraunhofer IAO Micro Smart Grid"

The grid reference power in the reference period is up to 69 kW without a battery, with a maximum consumption load of 79 kW. The grid feed-in is up to 27 kW, with a maximum PV system production power of 31 kW (scenario A). The total consumption was 38,153 kWh, comprised of 24,400 kWh for the charging infrastructure and 13,753 kWh for the other consumers. The PV system generated 27,559 kWh. The peak load limit was complied with even in the basic scenario (Table 3).

Table 3. Results for example 2: the new operating strategy significantly improved the degree of self-consumption and self-sufficiency and the peak load limit could be significantly reduced.

Battery Control Strategy	Base	Self-Consumption Optimization	Peak Load Limitation	C, with Optimized Discharging
Scenario	**A**	**B**	**C**	**D**
Load limit (grid connection) (kW)	80	80	20	20
Battery charge power (kW)		60	60	60
Battery energy capacity (kWh)		100	100	100
Peak load from grid (kW)	**69**	**64**	**20**	**20**
Degree of self-consumption	**0.47**	**0.84**	**0.49**	**0.67**
Degree of self-sufficiency	**0.34**	**0.66**	**0.37**	**0.53**
Full cycles		97	6	52
Change-SOC a (%)				80
Charge mode		surplus charging	surplus charging	surplus charging

With the "Optimizing self-consumption" operating strategy, the battery storage system increases the degree of self-consumption from 0.47 to 0.84 and the degree of self-sufficiency from 0.34 to 0.66 (scenario B). The peak load on the grid connection is slightly lower than the starting value in this scenario. With the "Limiting peak load" operating strategy, the peak load limit can be reduced to as low as 20 kW throughout the year (scenario C). The degree of self-consumption and self-sufficiency in this scenario is only slightly higher than that of the scenario without a battery.

By applying the new operating strategy with optimized parameters, the battery is switched from "Limiting peak load" to "Optimizing self-consumption" at a SOC > 80% (scenario D). The minimum peak load limit of 20 kW is still maintained throughout the year. Compared to scenario C, which uses peak load limitation only, the degree of self-consumption is increased by 37% to 0.67; the degree of self-sufficiency is increased by 43% to 0.53. In scenario C, the average SOC is 96% (Figure 7a). In scenario D, the optimization reduces this value to 80%, which is in a more favorable range in terms of battery degradation (Figure 7b).

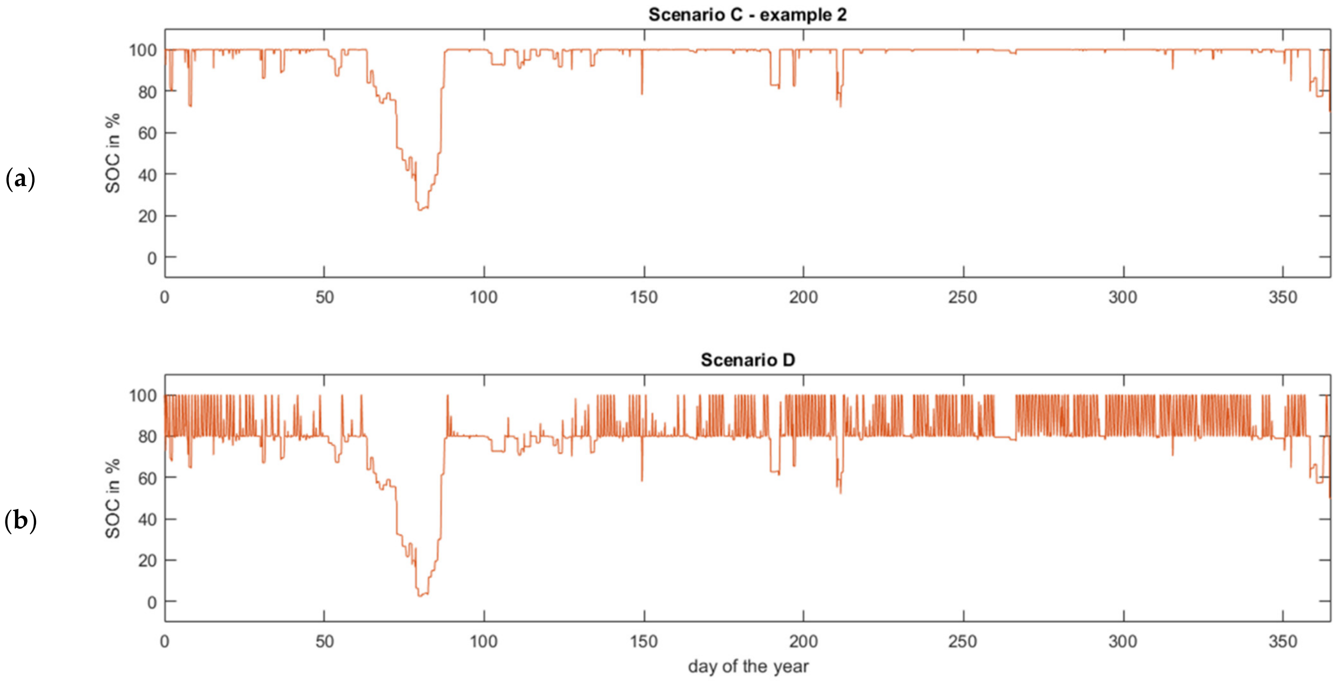

Figure 7. Evaluation of example 2: Peak load limitation can already be achieved throughout the year, even with a significantly reduced peak load limit. The average state of charge of the battery moved into a more favorable range in terms of service life. (**a**) Peak load limitation, (**b**) optimized control strategy.

As the grid feed-in of up to 27 kW is above the new peak load limit for grid consumption, the evaluation was also performed with an assumed peak load limit of 30 kW. In this scenario, the switch between "Limiting peak load" and "Optimizing self-consumption" takes place at a SOC of 20% (scenario D). This means that the degree of self-consumption can be increased by 73% compared to peak load limitation (scenario C), from 0.48 to 0.83, bringing it close to the level achieved with self-consumption optimization (scenario B), which is 0.84. In this case, too, the peak load limit is maintained throughout the year.

4. Discussion

The evaluation of the two application examples demonstrates the potential of the new operating strategy in several ways: By optimizing battery charging, it is possible to limit the peak load, which cannot always be permanently achieved using surplus charging with locally produced electricity alone. Compared to grid charging alone, this solution enables greater use of local resources and minimizes consumption from external sources. By optimizing the battery discharge process using a hybrid model of peak load limitation and self-consumption optimization, it is possible to increase self-consumption across the entire system without restricting the peak load limitation. At the same time, the state of charge of the battery moves into a range associated with lower levels of degradation. This is particularly true in comparison with the SOCs associated with peak load limitation alone; these figures are usually very high, particularly in conjunction with grid charging.

Other parameters that influence the battery life are the number of full cycles and the depth of discharge (DoD) during operation. The number of cycles is higher if the battery is applied for self-consumption optimization than with peak load limitation due to the higher energy turnover. With the proposed operating strategy that combines the two application purposes, the number of cycles is in between (see Tables 1–3). Modern battery systems largely allow cycle numbers in the range of 3500 to 10,000 full cycles [32] and are designed for self-consumption optimization with regard to their service life. The application of the new operating strategy is therefore not expected to have any significant disadvantages in this respect. However, the new operating strategy can change the depth of discharge, which can have a positive effect compared to self-consumption optimization, and a negative effect compared to peak load limitation. Future work should investigate this aspect in more detail. A method for accounting for the effects of different DoD on the service life of a battery was presented by Yan et al. [33]. An additional optimization objective regarding the minimization of degradation could thus be included in the operational strategy, e.g., by further restricting the SOC ranges and charge/discharge powers during self-consumption optimization. Models for this were introduced by Scarabaggio et al. [34] in the context of grid services through electric vehicles.

The proposed procedure regarding the new operating strategy could be used during the planning and realization of local energy systems, as well as to improve the efficiency and cost-effectiveness of existing systems. In particular, integrating electromobility and the associated charging infrastructure into local energy systems could cause peak loads at grid connection points to increase significantly in the future. Battery storage systems allow energy systems to operate with restricted or smaller—and therefore more cost-effective—grid connections, without mobility being affected by any charging restrictions. The increase in electromobility is a dynamic scenario, but energy systems and battery storage systems are being designed based on a static estimation of demand. In practice, this means that battery capacity will initially be far greater than required but will begin to reach its limits as vehicle electrification becomes more common (see application example 1 with 10 and 30 electric vehicles). Using the new operating strategy enables the battery to be used more efficiently throughout its life cycle. Initially, the focus can be on self-consumption optimization; as utilization increases, it can shift to guaranteeing peak load limitation. The optimum parameters for the operating strategy at any given time can be determined during the planning phase based on simulated requirements, and then adjusted during operation based on up-to-date load profile measurements. The simple process requires only common measured variables, with no additional external data or forecasting needed.

The optimal parameters for the operating strategy can be regularly adjusted as framework conditions change. For example, adjustment can take place manually once a year based on the load profile measurements taken over the past year, or it could be scheduled automatically at more frequent intervals. Shorter reference periods can also be selected to account for factors such as seasonal fluctuations in surplus production. This enables the degree of self-consumption to be increased even further. As battery suppliers acquire more experience, they can develop default settings specific to each application. This would eliminate the need to conduct a simulation for parameter optimization.

The new operating strategy has so far been designed for stand-alone battery storage applications. Future work should investigate possible extensions with regard to external services, such as energy marketing [35] or grid services [33]. For this purpose, it is necessary to define suitable criteria for prioritizing the applications and to optimize the operation economically. In contrast to the simple stand-alone application, however, this significantly increases the complexity of the operating strategy. To ensure the reliability of all operational objectives, forecasting methods should be used for generation, loads, and external demands. Forecasting techniques could also further increase the efficiency of the new operation strategy in the stand-alone application, by adaptively adjusting the parameters, for example daily, based on the respective forecast for generation and load.

The analysis of the application examples indicates the maximum potential of the new operating strategy in each case, as the evaluation is based on the dataset used for optimization. In practice, additional reserves or backup strategies required for operation would also need to be considered. There are several ways to achieve this. Firstly, the analyses assumed highly restrictive grid-connected loads; in practice, these values would be higher to account for the relevant reserves, including for residential loads. Irrespective of this, a slightly higher assumed peak load limit allows the degree of self-consumption to be increased further (see application example 2 with 20 kW and 30 kW peak load limit). Secondly, the battery capacity can be slightly higher than in the optimization. Thirdly, there is the option of adding restrictions to the charging infrastructure (charge management), to act as a backup on the rare occasion that extreme circumstances arise. This step is highly recommended anyway to absorb any battery maintenance and downtime. Future research should consider bidirectional charging of electric vehicles which also has the potential to avoid peak loads and, therefore, could support the battery system in critical situations.

The new operating strategy was implemented in the control system for the live "Fraunhofer IAO Micro Smart Grid" system (see application example 2). However, it was not possible to carry out a practical validation of the simulation results as part of this study, as on-site vehicle charging ceased almost completely a few weeks after commencing the evaluation due to the coronavirus pandemic. This radical change to the framework conditions because of the pandemic highlights how susceptible optimizations based on historical data are to extreme scenarios. In the future, appropriate resilience strategies will need to be developed to counteract this challenge.

5. Conclusions

This study presented a new operating strategy for stationary battery systems in local energy systems and introduced a process for optimizing the associated parameters. By applying the new operating strategy, it was possible to achieve the following improvements compared to current technology:

- Using battery systems solely for peak load limitation with local production the degree of self-consumption and therefore cost-effectiveness can be increased.
- With the given battery systems without functional peak load limitation, permanent and reliable peak load limitation can be achieved without permanent grid charging. The degree of self-sufficiency can be improved.
- Peak load limitation can also be guaranteed using adaptive optimization as conditions in electrical systems evolve (as electric mobility becomes more widespread, for example).
- The operating strategy keeps the state of charge of the battery in a more favorable range in terms of degradation, which extends the service life of the storage system.

The potential of these characteristics has been analyzed and demonstrated based on several application examples. In future studies, the new operating strategy will be tested and validated in live systems.

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References

1. Claudy, M.; O'Driscoll, A.; Duffy, A. *'Home Owners' Attitudes, Perceptions and Willingness to Pay for Microgeneration Technologies*; Dublin Istitute of Technology & Dublin Energy Lab.: Dublin, Ireland, 2010.
2. Peter, R.; Ramaseshan, B.; Nayar, C. Conceptual model for marketing solar based technology to developing countries. *Renew. Energy* **2002**, *25*, 511–524. [CrossRef]
3. Scarpa, R.; Willis, K. Willingness-to-pay for renewable energy: Primary and discretionary choise of British households' for micro-generation technologies. *Energy Econ.* **2010**, *32*, 129–136. [CrossRef]
4. Rickerson, W.; Couture, T.; Barbose, G.; Jacobs, D.; Parkinson, G.; Chessin, E.; Belden, A.; Wilson, H.; Barret, H. *Residential Prosumers: Drivers and Policy Options (Re-Prosumers)*; International Energy Agency (IEA): Paris, France, 2014.

5. Klingler, A.-L. Self-consumption with PV+Battery systems: A market diffusion model considering individual consumer behaviour and preferences. *Appl. Energy* **2017**, *205*, 1560–1570. [CrossRef]
6. Luthander, R.; Widén, J.; Nilsson, D.; Palm, J. Photovoltaic self-consumption in buildings: A review. *Appl. Energy* **2015**, *142*, 80–94. [CrossRef]
7. VBEW. Doppelter Haushaltsstromverbrauch mit Elektroauto. 1 February 2021. Available online: https://www.vbew.de/energie/presseinfos-energie/news/doppelter-haushaltsstromverbrauch-mit-elektroauto (accessed on 9 February 2023).
8. Murkhammar, J.; Grahn, P.; Widén, J. Quantifying self-consumption of on-site photovoltaic power generation in households with electric vehicle home charging. *Sol. Energy* **2013**, *97*, 208–216. [CrossRef]
9. Klausmann, F.; Göhler, G.; Endriss, F. *Leitfaden zur Implementierung Intelligenter Energiesysteme in Wohnquartieren*; Universität Stuttgart, Institut für Arbeitswissenschaft und Technologiemanagement: Stuttgart, Germany, 2019. [CrossRef]
10. Göhler, G.; Klingler, A.-L.; Klausmann, F.; Spath, D. Integrated Modelling of Decentralised Energy Supply in Combination with Electric Vehicle Charging in a Real-Life Case Study. *Energies* **2021**, *14*, 6874. [CrossRef]
11. Lehmann, C.; Weeber, M.; Böhner, J.; Steinhilper, R. Techno-economical Analysis of Photovoltaic-battery Storage Systems for Peak-shaving Applications and Self-consumption Optimization in Existing Production Plants. *Procedia CIRP* **2016**, *48*, 313–318. [CrossRef]
12. Uddin, M.; Romlie, M.F.; Abdullah, M.F.; Halim, S.A.; Bakar, A.H.A.; Kwang, T.C. A review on peak load shaving strategies. *Renew. Sustain. Energy Rev.* **2018**, *82*, 3323–3332. [CrossRef]
13. Merei, G.; Moshövel, J.; Magnor, D.; Sauer, D.U. Optimization of self-consumption and techno-economic analysis of PV-battery systems in commercial applications. *Appl. Energy* **2016**, *168*, 171–178. [CrossRef]
14. Johann, A.; Madlener, R. Profitability of Energy Storage for Raising Self-consumption of Solar Power: Analysis of Different Household Types in Germany. *Energy Procedia* **2014**, *61*, 2206–2210. [CrossRef]
15. Schram, W.L.; Lampropoulos, I.; van Sark, W.G. Photovoltaic systems coupled with batteries that are optimally sized for household self-consumption: Assessment of peak shaving potential. *Appl. Energy* **2018**, *223*, 69–81. [CrossRef]
16. Lee, M.; Park, J.; Na, S.-I.; Choi, H.S.; Bu, B.-S.; Kim, J. An Analysis of Battery Degradation in the Integrated Energy Storage System with Solar Photovoltaic Generation. *Electronics* **2020**, *9*, 701. [CrossRef]
17. Ecker, M.; Nieto, N.; Käbitz, S.; Schmalstieg, L.; Blanke, H.; Warnecke, A.; Sauer, D. Calendar and cycle life study of Li(NiMnCo)O_2-based 18650 lithium ion batteries. *J. Power Sources* **2014**, *248*, 839–851. [CrossRef]
18. Schmalstieg, J.; Käbitz, S.; Ecker, M.; Sauer, D. A holistic aging model for Li(NiMnCo)O_2 based 18650 lithium-ion batteries. *J. Power Sources* **2014**, *257*, 325–334. [CrossRef]
19. Wagner, R.; Siller, M. Zwischenspeicherung von Solarenergie durch Batterien zur Eigenverbrauchserhöhung und Netzstabilisierung. *uwf UmweltWirtschaftsForum* **2013**, *21*, 251–259. [CrossRef]
20. Lorenzi, G.; Silva, C.A.S. Comparing demand response and battery storage to optimize self-consumption in PV systems. *Appl. Energy* **2016**, *180*, 524–535. [CrossRef]
21. Rana, M.; Atef, M.; Sarkar, M.; Uddin, M.; Shafiullah, G.A. A Review on Peak Load Shaving in Microgrid—Potential Benefits, Challenges, and Future Trend. *Energies* **2022**, *15*, 2278. [CrossRef]
22. Klausmann, F.; Mauch, L.; Klingler, A.-L.; Röckle, F.; Wohlhüter, M. *Anforderungen an Eine Elektrische Lade- und Wasserstoffinfrastruktur für Gewerbliche Nutzfahrzeuge mit dem Zeithorizont 2030*; FAT: Berlin, Germany, 2021.
23. Klausmann, F. *Schnellladen in der Stadt 2—Bedarfe, Anforderungen und Potenziale für Urbane DC-Ladeparks*; Fraunhofer IAO: Stuttgart, Germany, 2023. [CrossRef]
24. Tjaden, T.; Bergner, J.; Weniger, J.; Quaschning, V. *Repräsentative Elektrische Lastprofile für Wohngebäude in Deutschland auf 1-Sekündiger Datenbasis*; HTW Berlin—University of Applied Sciences: Berlin, Germany, 2015. [CrossRef]
25. Durchschnittlicher Stromverbrauch in Deutschland und Europa in Zahlen. 2021. Available online: https://www.stromvergleich.de/durchschnittlicher-stromverbrauch (accessed on 30 May 2022).
26. Zahl der Privathaushalte und Durchschnittliche Haushaltsgröße in Deutschland (1871–2018). Bundesinstitut für Bevölkerungsforschung. 2022. Available online: https://www.bib.bund.de/DE/Fakten/Fakt/L49-Privathaushalte-Haushaltsgroesse-ab-1871.html (accessed on 30 May 2022).
27. Göhler, G.; Otteny, F.; Triebke, H.; Reiser, M. Load Profile Generator for Electric Vehicle Home Charging. In Proceedings of the 32nd Electric Vehicle Symposium & Exhibition (EVS32), Lyon, France, 19–22 May 2019.
28. Testreferenzjahre (TRY). Deutscher Wetterdienst. 2015. Available online: https://www.dwd.de/DE/klimaumwelt/klimaforschung/spez_themen/try/try_node.html (accessed on 30 May 2022).
29. Quaschning, V. *Regenerative Energiesysteme*, 9th ed.; Carl Hanser Verlag München: München, Germany, 2015.
30. Datenblatt Powador 12-20 TL3, Kaco New Energy. 2022. Available online: https://www.pvxchange.com/mediafiles/pvxchange/attachments/DTS_PW_12-20_TL3_de.pdf (accessed on 6 May 2023).
31. Klausmann, F. *Fraunhofer IAO Micro Smart Grid—Dezentrale Energiesysteme in der Praxis*; Fraunhofer IAO: Stuttgart, Germany, 2022. Available online: www.microsmartgrid.de (accessed on 30 May 2022).
32. Centrales Agrar-Rohstoff Marketing- und Energie-Netzwerk e.V. Marktübersicht Batteriespeicher 2022. Centrales Agrar-Rohstoff Marketing- und Energie-Netzwerk e.V.: Straubing, Germany, 2023.
33. Yan, G.; Liu, D.; Li, J.; Mu, G. A cost accounting method of the Li-ion battery energy storage system for frequency regulation considering the effect of life degradation. *Prot. Control Mod. Power Syst.* **2018**, *3*, 4. [CrossRef]

34. Scarabaggio, P.; Carli, R.; Cavone, G.; Dotoli, M. Smart Control Strategies for Primary Frequency Regulation through Electric Vehicles: A Battery Degradation Perspective. *Energies* **2020**, *13*, 4586. [CrossRef]
35. Mignoni, N.; Scarabaggio, P.; Carli, R.; Dotoli, M. Control frameworks for transactive energy storage services in energy communities. *Control Eng. Pract.* **2023**, *130*, 105364. [CrossRef]