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Optimization of PV Battery Systems Using Genetic Algorithms

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Abstract

A modular simulation model of a PV battery system has been developed and integrated into a genetic algorithm framework in order to evaluate optimal sizing of such systems under various boundary conditions. The presented paper describes the simulation assumptions and presents optimization results for a PV battery system having a DC topology, comparing current economic scenarios with and without KfW funding. Sensitivity analyses provide information on critical boundaries to reach economic operation. The fitness of a system is evaluated based on the levelized cost of electricity (LCOE) defining the average cost – including all investment and operation cost over the system lifetime – per kWh supplied to the load.

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Keywords: PV, battery system, grid-connected, optimization, genetic algorithm, levelized cost of electricity

1. Introduction

PV battery systems gain increasing interest due to rising electricity cost and decreasing feed-in tariffs. Nevertheless, at the moment an economic operation of such systems is not possible when relying on self-consumption. Due to significantly decreasing installation cost, an optimally sized system can come close to economic operation when considering funding by the German market incentive program.

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Nomenclature

β	Tilt angle of the PV generator (Degree)
Δ_{Az}	Azimuth angle of the PV generator (Degree; zero towards south, pos. values towards west)
η	Efficiency (%)
A	Annuity (€)
c_{Bat}	Initial specific battery cost (€/kWh)
c_{el}	Initial electricity price (€/kWh)
c_{fi}	Feed-in tariff (€/kWh)
c_{PV}	Initial specific PV generator cost (€/kW)
Cap_{cell}	Battery capacity per cell (Ah)
d_{Bat}	Price degression of battery (%/a)
$E_{k,el}$	Electric energy purchased from the grid in year k (kWh)
$E_{k,fi}$	Energy fed to the grid in year k (kWh)
E_{load}	Annual energy demand of the household (kWh)
i	Interest rate (%/a)
i_{el}	Increase of electricity price (%/a)
I_{out}	Converter output current (A)
j	Index referring to a respective number of replacement of a component
k	Index referring to a respective year under consideration
l_{Bat}	Lifetime of battery (a)
l_{PE}	Lifetime of power electronics (a)
l_{PV}	Lifetime of PV generator (a)
$LCOE$	Levelized cost of electricity (€/kWh)
NPV	Net present value (€)
p	Proportionality factor for maintenance cost; same for all components (%)
$P_{bat\ conv}$	Nominal power of the battery converter (kW)
P_{in}	Converter input power (kW)
$P_{Inverter}$	Nominal power of the inverter (kW)
P_{loss}	Converter power losses
P_{MPP}	Nominal power of the MPP tracker (kW)
P_{out}	Converter output power (kW)
P_{PV}	Nominal power of the PV generator (kW)
R_{loss}	Ohmic term of converter power losses (Ω)
T_X	Residual value of component X
SoC_{Min}	Minimum state of charge of the battery (%)
SoC_{Max}	Maximum state of charge of the battery (%)
t_{ref}	Reference time frame for cost calculation (a)
V_{loss}	Voltage term of converter power losses (V)
X	Index referring to a respective component of the system

The economic balance of system operation is strongly dependent on the given load profile and an appropriately matched system design with respect to battery and converter sizes, PV generator size and orientation but also the operation strategy of the system. On the other hand, for an appropriate system design the economic boundary conditions like capital cost, electricity price and feed-in tariff, investment cost for the system components but also funding schemes like the German market incentive program initiated by the German federal government and the KfW banking group, play a major role. An additional degree of freedom to influence the economics of PV battery systems is the operation strategy with respect to the battery, offering the potential to prolong battery lifetime.

Various works have been addressing this topic. In [1] and [2] the optimum sizing can be evaluated based on previously performed scenario simulations. Where in the first case the sizing is limited to battery capacity, in the second approach the PV generator size is part of the sizing recommendation and multiple load profiles are used to evaluate the optimum. Both approaches are limited to previously simulated generation and load profiles as well as the assumed operation strategy. The goal of the proposed method is to provide a universal tool that is able to consider various system topologies, different locations as well as different operating strategies and that can therefore be used to analyze interdependencies and sensitivities of system design.

2. Methodology

2.1. Simulation Model:

The simulation model has been developed in the software environment MATLAB®/Simulink in a modular way, so that it is easily possible to compose and analyze various system topologies.

The **PV generator** model allows calculating the expected power output of an arbitrarily oriented PV generator as a function of time series data of direct and diffuse irradiation on a horizontal surface and ambient temperature. It is assumed that the PV generator is at any time operated in the maximum power point (MPP). The calculation of global irradiation on an arbitrarily oriented generator surface from data on a horizontal surface is based on the method described in [3]. The output power calculation for MPP operation based on global irradiation and ambient temperature follows the approach proposed in [4]. The input data for the presented results are taken from the Baseline Surface Radiation Network (BSRN) for the location of Lindenberg, Germany for the year 2006 [5]. The data is available with 60 s temporal resolution.

All **converters** in the simulation model are based on a generic approach also presented in [4]. Here the efficiency η, given as ratio between output power P_{out} and input power P_{in} of the converter, is determined by the power losses P_{loss} reducing the input power:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{out}}{P_{out} + P_{loss}}$$

The power losses are described as polynomial of order 2 composed of power independent idling losses P_{self}, a voltage term V_{loss} scaling linearly with the output current I_{out} and an ohmic term R_{loss}, scaling quadratically with the output current:

$$P_{loss} = P_{self} + V_{loss} \cdot I_{out} + R_{loss} \cdot I_{out}^2$$

To be able to also cover voltage dependent efficiencies of the converters (e.g. the battery converter efficiency depending on battery voltage) the model has been extended by this functionality as described in [6].

The **battery** model follows an impedance based approach with a coupled aging model. Due to the time resolution of the simulations of > 1 s, the highly dynamic components of the electric battery model are neglected and the focus is laid on the diffusion behavior and relaxation effects. The aging model considers cyclic as well as calendar aging. The parameterization of the model for both, electrical and aging behavior is based on measurements of the SAFT VL45E cell. As cell configuration, a series connection of 56 cells is assumed. With a nominal cell voltage of 3.6 V this corresponds to a nominal battery voltage of 201.6 V.

The household **load profile** is fed to the model as a time series of active power values representing the sum of all three phases. It is possible to use any arbitrary time series with constant sample rate. For the present paper a dataset presented in [7] and provided by the Institute for Ecological Economy Research (IÖW) has been used. The load profile is synthesized from measured load profiles and has a 60 s temporal resolution. Similar to standard load profiles, weekdays and weekend as well as seasonal effects are considered. The annual energy demand of the profile is 4,500 kWh.

The electricity grid typically absorbs all surplus energy that is not stored to the battery or consumed by the household. On the other hand, potential shortcomings of energy from the PV battery system are provided by the distribution grid. The grid can also be applied with a maximum feed-in capacity to represent weak grids. This functionality can also be used to represent the 60 % feed-in limit required by the KfW market incentive program [8]. In this case the limit is used by the energy management system to control the feed-in power. Power exceeding the limit is curtailed.

The energy management system (EMS) decides, based on the implemented energy management strategy and the current state of the system, how the energy flows should be distributed between the different potential paths. For the following results the energy management strategy is assumed to maximize the self-consumption of the household. This means, that the battery is charged with maximum available power as soon as there is a surplus of PV generation and as long as the battery has not reached its maximum state of charge (SoC_{Max}). Following this strategy, the battery is discharged, as soon as there is a lack in PV generation and as long as the battery has not reached its minimum state of charge (SoC_{Min}).

The analyses in this paper are based on the so called DC-Topology shown in Figure 1, where the battery is connected to the DC link of a modified PV inverter via an additional DC/DC converter.

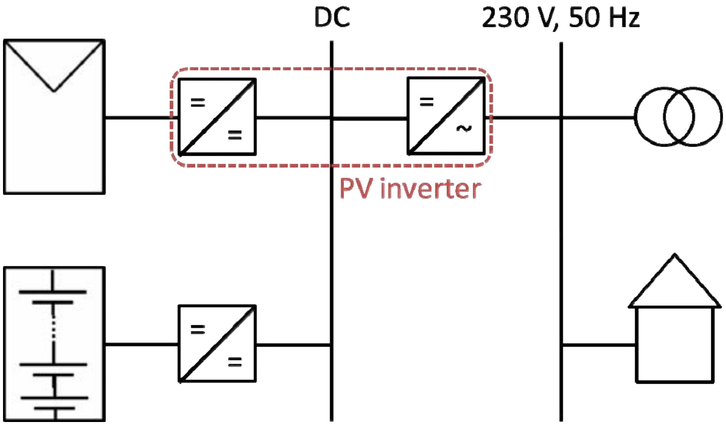

Figure 1: PV battery system having a DC topology. The system consists of a PV generator, three converters (MPP tracker, battery DC/DC converter and joint inverter stage), and a battery.

2.2. Cost Calculation:

In order to optimize the parameters of the PV battery system, a measure to compare different configurations needs to be defined. For a PV battery system, an appropriate measure is the levelized cost of electricity (LCOE), relating the overall cost (including investment as well as fixed and variable operating cost) to the overall amount of electricity provided by the system. As reference time frame t_{ref} for cost calculation, 20 years have been chosen.

The net present value of investment cost of a component X, is composed of an initial investment with cost $C_{0,X}$, replacement cost $C_{l_X,X}$ after the respective component lifetime l_X (multiple times if necessary) as well as a residual value T_X considering linear depreciation. All cash flows after $t = t_0$ have to be discounted with the interest rate i. Furthermore, all reinvestments are subject to cost degression d_X (given in percent per year), which can be specific for each component.

The net present value of investments for component X can therefore be written as:

$$NPV_X = C_{0,X} + \frac{C_{1\cdot l_X,X}}{(1+i)^{l_X}} + \cdots + \frac{C_{n\cdot l_X,X}}{(1+i)^{n\cdot l_X}} - T_X \cdot \frac{(1-d_X)^{t_{ref}}}{(1+i)^{t_{ref}}} \quad (1)$$

where

$$C_{j\cdot l_X,X} = C_{0,X} \cdot (1-d_X)^{j\cdot l_X},$$

$$n \cdot l_X \leq t_{ref},$$

and

$$T_X = \frac{l_X - mod(t_{ref}, l_X)}{l_X} \cdot C_{0,X}$$

Fixed operational cost are restricted to maintenance cost. It is assumed that the annual maintenance cost are proportional (with factor p_X) to the initial cost of the respective component. So the annuity of the fixed operational cost for component X is:

$$A_{M,X} = C_{0,X} \cdot p_X$$

The corresponding present value can therefore be calculated as:

$$NPV_{M,X} = A_{M,X} \cdot \frac{(1+i)^{t_{ref}} - 1}{(1+i)^{t_{ref}} \cdot i}$$

Variable operational cost are resulting from electricity purchase and reimbursement for feed-in. The net present value of electricity purchase is calculated similar to equation (1) as sum over all annual cost

$$NPV_{el} = c_{1,el} \cdot E_{1,el} + \frac{c_{2,el} \cdot E_{2,el}}{(1+i)^1} + \cdots + \frac{c_{t_{ref},el} \cdot E_{t_{ref},el}}{(1+i)^{(t_{ref}-1)}}$$

where the initial electricity cost $c_{1,el}$ are also subject to an annual increase i_{el} and therefore the resulting electricity cost for year k are calculated as

$$c_{k,el} = c_{1,el} \cdot (1 - i_{el})^{(k-1)}$$

The amount of electricity purchased from the public grid can vary over lifetime and therefore is referred to as $E_{k,el}$ for any year k.

The reimbursement for feed-in is based on a constant feed-in tariff c_{fi} over the full 20 years. In contrast to all other cost components, the reimbursements are negative cost:

$$NPV_{fi} = -\left(c_{fi} \cdot E_{1,el} + \frac{c_{fi} \cdot E_{2,fi}}{(1+i)^1} + \dots + \frac{c_{fi} \cdot E_{t_{ref},fi}}{(1+i)^{(t_{ref}-1)}}\right)$$

The cash flows finally sum up to a net present value of

$$NPV_{sum} = \sum_x \left(NPV_x + NPV_{M,x}\right) + NPV_{el} + NPV_{fi}$$

The LCOE are then calculated based on the corresponding annuity divided by the annual load demand E_{load}:

$$LCOE = \frac{NPV_{sum} \cdot \frac{(1+i)^{t_{ref}} \cdot i}{(1+i)^{t_{ref}} - 1}}{E_{load}}$$

where it is assumed that the annual load demand is constant for each year.

2.3. Optimization Framework:

The simulation model is embedded into an optimization framework using the MATLAB® genetic algorithm implementation. As fitness function the above described LCOE is used in order to find the optimum system configuration. The free parameters of the optimization as well as their assumed limits are listed in Table 1. To reduce computational effort, all parameters are restricted to a certain increment, which is also given in the table (column “Incr.”).

The battery capacity is given in Ah per cell. Based on the assumed series connection of 56 cells and nominal cell voltage of 3.6 V (see section 2.1 **battery**), this corresponds to an incremental change in energy capacity of 201.6 Wh.

Table 1: Free parameters of the optimization

Parameter	Description	Unit	Min	Max	Incr.	Opt.
β	Tilt angle of the PV generator	°	0	+90	5	30
Δ_{Az}	Azimuth angle of the PV generator; zero towards south, pos. values towards west	°	-90	+90	5	-5
P_{PV}	Nominal power of the PV generator	kW	0	10	0.1	10
P_{MPP}	Nominal power of the MPP tracker	kW	0	10	0.1	7.4
$P_{inverter}$	Nominal power of the inverter	kW	0	10	0.1	7.2
$P_{bat\ conv}$	Nominal power of the battery converter	kW	0	10	0.1	2.1
Cap_{cell}	Battery capacity per cell	Ah	0	100	1	23
SoC_{Min}	Minimum state of charge of the battery	%	0	100	1	0
SoC_{Max}	Maximum state of charge of the battery	%	0	100	1	99

3. Results

The optimization has been done using the set of economical parameters given in Table 2. Based on the assumption that power electronic cost scale significantly with the component size, a market survey on PV inverters has been made in 2014. It has been found, that the specific initial power electronic cost can be assumed to be

$$c_{PE} = max\left(1000, \frac{970.3 \cdot P_{nom}^{-1.887} + 304.5}{2}\right)$$

This formula is based on the assumption that 50 % of the cost for a standard two stage PV inverter can be assigned to the MPP tracker and 50 % to the inverter stage. For a 5 kW PV inverter the specific cost result in 173 €/kW per stage or 346 €/kW for the full inverter.

Table 2: Economic parameters used for the optimization

Parameter	Description	Value	Unit
c_{Bat}	Initial specific battery cost	550	€/kWh
c_{PV}	Initial specific PV generator cost	1,170	€/kWp
c_{el}	Initial electricity price	0.2913	€/kWh
c_{fi}	Feed-in tariff	0.1288	€/kWh
l_{PE}	Lifetime of power electronics	20	a
l_{PV}	Lifetime of PV generator	20	a
d_{Bat}	Price degression of battery	7	%/a
i_{el}	Increase of electricity price	1.85	%/a
i	Interest rate	1.3	%/a
p	Proportionality factor for maintenance cost; same for all components	1.5	%

The battery lifetime l_{Bat} is determined dynamically based on the battery aging model and depending on the operation scenario. As the lifetimes of power electronics and PV generator are assumed to be 20 years, the corresponding degression factors can be neglected.

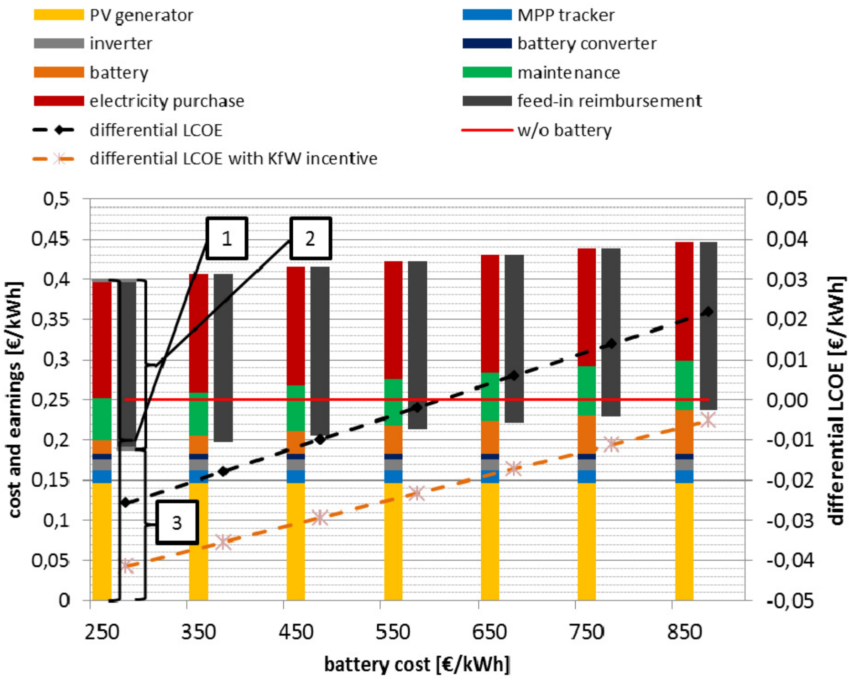

Figure 2: Composition of the levelized cost of electricity based on the optimization results (550 €/kWh) and sensitivity vs. battery cost (bar plots). Differential LCOE vs. the case without battery are shown on the secondary y-axis without (black) and with (orange) KfW incentive (line plots).

The optimum set of parameters found by the genetic algorithm is given in (Table 1 column “Opt.”). The corresponding LCOE are 0.2132 €/kWh. Figure 2 shows the composition of the cost (bar plots) for a variation of battery cost. The optimization result corresponds to the case at 550 €/kWh battery cost. Cost components are added in the first bar (marked with 1) earnings are subtracted in the second bar (marked with 2). The resulting LCOE are the difference between the latter two (marked with 3). On the secondary y-axis, the differential LCOE compared to the case without battery are shown (line plots). The reference case without battery results in LCOE of 0.2152 €/kWh. Without KfW incentive, battery costs of 550 €/kWh are just on the edge to a profitable operation. Considering the incentive a benefit vs. battery-less operation can already be gained with battery cost above 850 €/kWh. It has to be mentioned that the presented line shows the ideal boundary for the case, that no energy is dismissed due to the feed-in limit of 60 % of the nominal PV power required by the KfW program.

4. Discussion

The optimization result shows, that under the assumed conditions, a PV battery system can be operated beneficially if an optimum system design is chosen. It has to be stated that battery cost on battery system level (including housing, battery management system, cell connectors etc.) of 550 €/kWh today are hardly available.

Nevertheless, the described reduction potential of LCOE by the KfW incentive can almost be achieved, when using an intelligent operating strategy based on forecast, which reduces curtailment of PV power feed-in [9]. This can reduce LCOE by 0.027 €/kWh for battery cost of 850 €/kWh, leading to beneficial operation even in this case. However, those results were not based on an optimized system design. Compared to the optimized setup, such a setup not subject to optimization allows distributing the full PV power via all possible paths in the system (meaning all converters having a size of approx. 9 kW for a 10 kWp PV generator). If the same can be achieved with the system configuration provided by the optimization has not been analyzed, yet.

Based on the described cost structure a not optimized system design as described above would lead to investment cost of approx. 18,740 € (incl. PV generator) compared to approx. 17,150 € for the optimized system design, meaning approx. 0.245 €/kWh vs. 0.2152 €/kWh in terms of LCOE.

5. Conclusion

In this paper a tool for PV battery system design optimization has been presented, which is able to consider many economic parameters and boundary conditions. Due to the modular approach it is easily possible to analyze different system topologies or operating strategies. The system optimization is done based on time series simulation over 20 years considering degradation of battery performance.

As the system design is always depending on the load profile and user behavior, an optimization result is always very specific for the used data. Due to the – depending on temporal resolution – very time consuming optimization process, the tool is mainly suitable to analyze general correlations of PV battery system design rather than optimizing individual systems.

The presented results have to be considered exemplary as the use of only one load profile is not representative. Furthermore, as mentioned above, battery costs of 550 €/kWh are rather optimistic. In particular, the used battery model for the simulations is based on a very long lasting cell which is not available at that low cost. Finally, additional cost components adding up on retail prices like development cost and margins are not considered in the calculations, as those are hard to estimate. Based on [10] and assuming the median (as cost for DC systems are tending to be higher than those for AC systems) current cost for a 5 kWh system are approx. 9,500 €. Based on the described cost assumptions with 850 €/kWh battery cost the system cost for the optimized configuration (also 5 kWh) would sum up to only 7,100 €. Therefore current retail prices do not allow for a profitable operation even when considering the KfW incentive.

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