

Documentation

Performance Simulation Model for PV-Battery Systems (PerMod)

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1 Purpose of application

The open source *Performance Simulation Model for PV-Battery Systems (PerMod)* is developed to assess the energy efficiency of grid-connected PV-Battery systems for residential applications. The model can be used for power flow simulations of AC-, DC- and PV-coupled systems (see Figure 1) with a temporal resolution of one second over a period of one year. As a result, the overall efficiency of the three system topologies can be assessed with the System Performance Index (SPI). *PerMod* primarily focuses on the better comparability of the system efficiency of different products. In addition, *PerMod* can be used for detailed loss analyses and evaluation of different measures to optimize the overall system efficiency. Moreover, the model can be implemented in software applications for system design and component sizing purposes.

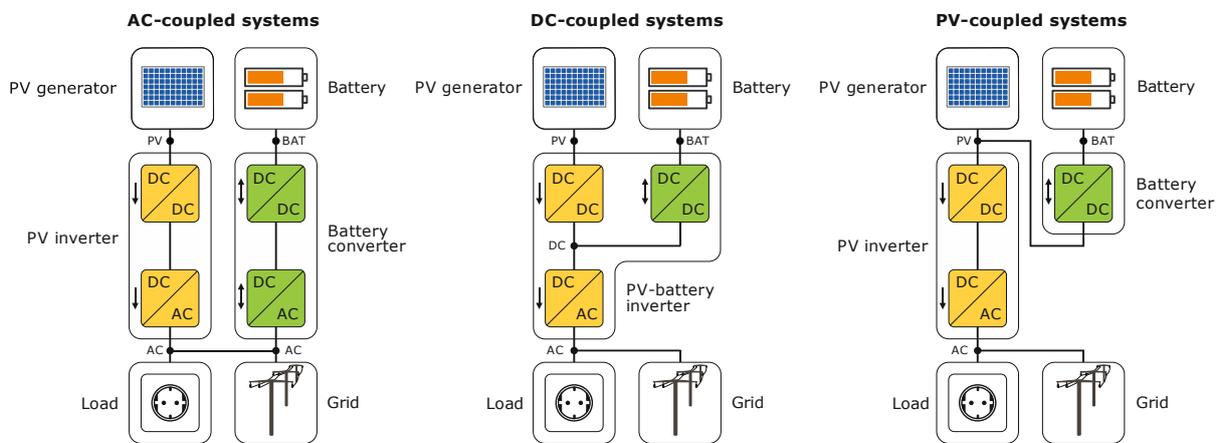


Figure 1 Schematic system configuration of AC-, DC- and PV-coupled PV-battery systems.

2 Provided files

PerMod is developed in the simulation environment MATLAB. Figure 2 shows the provided files and the schematic structure of *PerMod*. To parametrize the model, a test report of the system under study according to the "Efficiency guideline for PV storage systems" is required [1]. The summary of the test results has to be transferred to the Excel spreadsheet *PerModPAR.xlsx*.

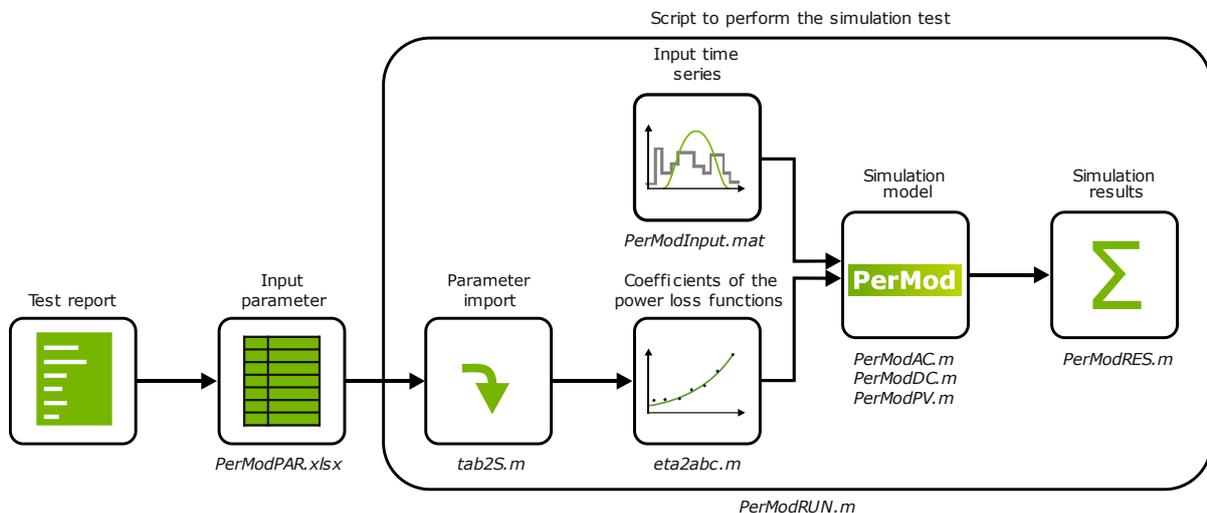


Figure 2 Schematic structure of *PerMod*.

The script *PerModRUN.m* performs the simulation test in MATLAB and executes *PerMod*. First, the model parameters from the spreadsheet are imported by the function *tab2S.m* to a structure array. Following this, the coefficients of the quadratic power loss functions from the path efficiency curves are calculated by the function *eta2abc.m*. The operating behavior of the PV-battery system is simulated using a data set of the PV power output and the electrical load demand included in the file *PerModInput.mat*. In a further step, the power flow simulation is performed by the function *PerModAC.m*, *PerModDC.m* or *PerModPV.m* depending on the system topology. Then the different energy sums are calculated by *PerModRES.m* and finally, the SPI can be determined based on the annual amount of energy exchanged with the grid. Table 1 gives an overview and a short description of the provided files of *PerMod*.

Table 1 Provided files of *PerMod*.

Filename	Description
<i>PerModRUN.m</i>	Script to perform the simulation test
<i>PerModInput.mat</i>	Input time series of the PV power output and the electrical load demand
<i>tab2S.m</i>	Function to import the model parameters from the spreadsheet
<i>eta2abc.m</i>	Function to calculate the coefficients of the quadratic power loss functions
<i>PerModAC.m</i>	Function to simulate AC-coupled PV-battery systems
<i>PerModDC.m</i>	Function to simulate DC-coupled PV-battery systems
<i>PerModPV.m</i>	Function to simulate PV-coupled PV-battery systems
<i>PerModRES.m</i>	Function to evaluate the simulation results
<i>PerModPAR.xls</i>	Spreadsheet with the system parameters

3 Input time series

To perform the simulation test under standardized conditions, the data set *PerModInput.mat* has to be used. It contains time series of the PV output power and the electrical load demand with a temporal resolution of one second over the period of one year. The power output of the PV generator is calculated using meteorological measurement data provided by the University of Oldenburg, Germany [2]. The irradiance on the plane of the PV array is calculated by means of geometric relations and the Klucher model [3]. The PV generator is oriented due south with a 35° tilt angle and the power output is determined using the empirical model of Beyer et al. [4]. The annual yield of the PV generator amounts to 1055 kWh/(kWp·a).

The electrical load profile is taken of an open data set which contains synthetically generated load profiles of residential buildings (profile no. 31 of [5]). It has an annual electrical load demand of 5010 kWh/a.

4 Modeled loss mechanisms

Several loss mechanisms affect the overall energy efficiency of grid-connected PV-battery systems, as shown in Figure 3. Sizing losses are caused by the power limitations of the system components. Moreover, conversion losses occur in the power electronics as well as in the battery storage. In addition, there are losses which can be attributed to the control unit and the energy management. The standby losses occur as a result of the power consumption of the system components during standby mode.

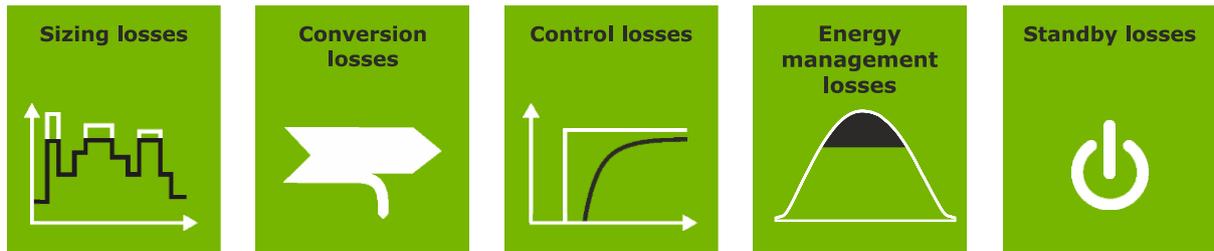


Figure 3 Efficiency-related loss mechanisms of PV-battery systems.

It must be noted that the level of detail of *PerMod* is limited to the test results according to the efficiency guideline. Consequently, not all system properties and loss factors are implemented within the simulation model. The model takes the most important losses into account which were described above. Table 2 gives an overview of the modeled loss mechanisms. Some loss mechanisms, such as the voltage dependency of the conversion efficiency, are neglected for reasons of simplification. Battery aging is not modeled in *PerMod* due to a lack of data.

5 Structure of the model

Figure 4 illustrates the simplified structure of the *PerModAC.m* function for AC-coupled PV-battery systems. The conversion losses of the PV inverter are calculated based on the DC power output of the PV generator. The AC power output of the PV system and the electrical load are used to determine the residual power which serves as a set point for the AC power of the battery system. Thereafter, the dead time and the stationary control deviation of the control unit are modeled. The AC power of the battery system is restricted to the nominal charging or nominal discharging power. In a further step, a first-order time delay element is implemented to depict the settling time of the control unit. Then the conversion losses of the battery converter as a function of the power throughput are calculated. The battery losses are considered by the mean battery efficiency. Finally, the energy content of the battery storage is adjusted, provided that the battery is neither fully charged nor completely discharged. During the standby mode of the battery system, the DC power demand of the battery converter is covered by discharging the battery storage and the AC power demand is supplied by the PV system or by the grid. It should be mentioned that the model approach for the DC- or PV-coupled systems differs from the one for AC-coupled systems. Validation results can be found in [6].

Table 2 Overview of the modeled and not considered efficiency losses.

Implemented factors of influence	Non-implemented factors of influence
Sizing losses	
<ul style="list-style-type: none"> Nominal power of the system components 	<ul style="list-style-type: none"> Short-term overload capability of the power electronics Voltage dependency of the nominal power
Conversion losses	
<ul style="list-style-type: none"> Power dependency of the conversion efficiency of the power electronics at nominal voltage Mean battery efficiency 	<ul style="list-style-type: none"> Voltage and temperature dependency of the conversion efficiency of the power electronics and battery Power dependency of the battery efficiency
Control losses	
<ul style="list-style-type: none"> Stationary efficiency of the maximum power point tracking (MPPT) Hysteresis of the charging control Mean stationary control deviation of the charging and discharging power Mean dead time and settling time of the charging and discharging power 	<ul style="list-style-type: none"> Dynamic efficiency of the maximum power point tracking (MPPT) Variable dead time and settling time of the charging and discharging power Trickle charging and cell balancing of the battery Reduced charging power during the final charging phase
Energy management losses	
<ul style="list-style-type: none"> Curtailment of the PV power (limitation of the feed-in power to 70% of the rated PV power) 	<ul style="list-style-type: none"> Predictive operating strategies Unbalanced load limit Provision of reactive power
Standby losses	
<ul style="list-style-type: none"> Power consumption of the power electronics during standby operation Power consumption of the peripheral components (e.g. AC power sensor, energy manager, etc.) 	<ul style="list-style-type: none"> Time dependent switchover conditions between the different modes of operation Self-discharging of the battery and power consumption of the battery management system (BMS) during standby operation

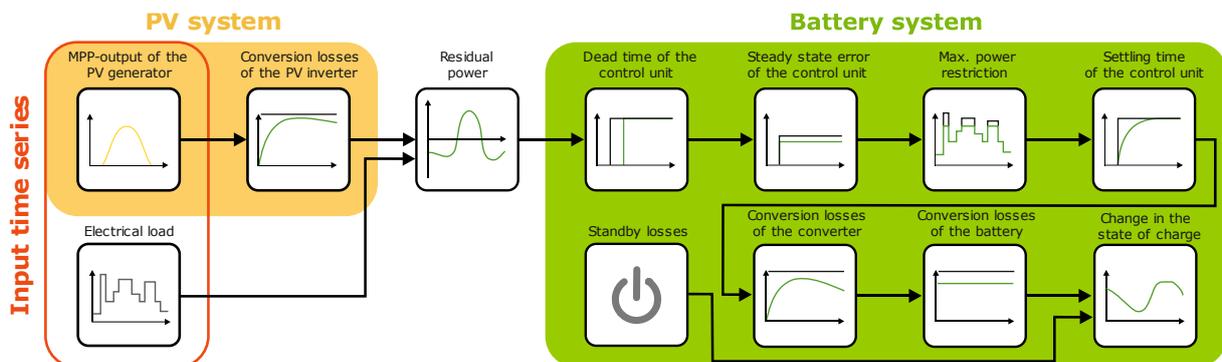


Figure 4 Simplified structure of PerModAC including the order of the modeled loss mechanisms.

6 System Performance Index (SPI)

The System Performance Index (SPI) has been introduced to compare the energy efficiency of PV-battery systems with different battery capacities and system topologies [7]. The SPI can be determined from the power flow simulation of the respective PV-battery system by analyzing the amount of energy exchanged between the building and the grid, as shown in Figure 5. The results of the real PV-battery system are compared with the results of an ideal PV-battery system without any losses. As the battery capacity is identical in both cases, the impact of the system losses on the energy flows can be determined. The overall losses of the real PV-battery system increase the energy supplied from the grid and reduce the energy fed into the grid.

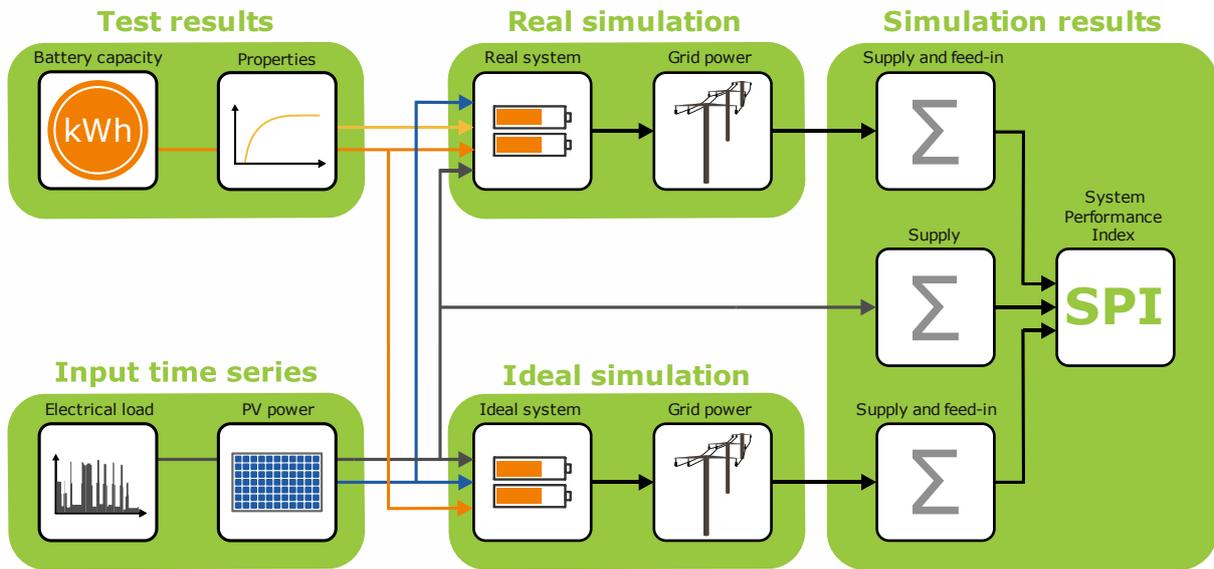


Figure 5 Simplified block diagram to calculate the System Performance Index (SPI) of a PV-battery system.

In a further step, the grid supply E_{G2AC} and grid feed-in E_{AC2G} are valued with the retail electricity price p_{G2AC} and feed-in tariff p_{AC2G} , respectively. The net grid electricity costs are determined by subtracting from the procurement costs for the grid supply the revenues from the grid feed-in. Afterwards the net grid electricity costs of the real and ideal PV-battery system are compared with the reference case without any PV-battery system. The SPI is defined as the ratio of the net grid electricity cost savings of the real PV-battery system to the grid electricity cost saving potential of the ideal PV-battery system:

$$SPI = \frac{E_{G2AC,REF} \cdot p_{G2AC} - E_{G2AC,REAL} \cdot p_{G2AC} + E_{AC2G,REAL} \cdot p_{AC2G}}{E_{G2AC,REF} \cdot p_{G2AC} - E_{G2AC,IDEAL} \cdot p_{G2AC} + E_{AC2G,IDEAL} \cdot p_{AC2G}} \quad (1)$$

The SPI can also be determined by the energy sums and the ratio p of the feed-in tariff p_{AC2G} to the retail electricity price p_{G2AC} :

$$SPI = \frac{E_{G2AC,REF} - E_{G2AC,REAL} + E_{AC2G,REAL} \cdot p}{E_{G2AC,REF} - E_{G2AC,IDEAL} + E_{AC2G,IDEAL} \cdot p} \quad \text{mit } p = \frac{p_{AC2G}}{p_{G2AC}} \quad (2)$$

In the reference case, the feed-in tariff is set to 0.12 €/kWh and the retail electricity price is valued at 0.3 €/kWh. It should be noted that the rated PV power and the battery capacity of the ideal and real PV-battery system remain unchanged.

7 Recommendations

The following chapter provide a guidance and useful hints to conduct the simulation test with *PerMod*. To run the simulation for the exemplary AC-coupled PV-battery system as specified in the spreadsheet *PerModPAR.xlsx*, open *PerModRUN.m* and execute the source code with Matlab. If a new PV-battery system should be analyzed, transfer the test results to column G (System ID 1) of the spreadsheet *PerModPAR.xlsx*. Then, change the variable *sys* in Section 1 of the script *PerModRUN.m* to "1" and execute the source code.

It must be noted that the energy efficiency of different PV-battery systems is **only comparable under identical test conditions using the provided input profiles**. This implies that the SPI has to be determined for the described reference case:

- Rated PV power 5 kWp
- Electrical load demand 5010 kWh/a
- Feed-in tariff 0.12 €/kWh
- Retail electricity price 0.3 €/kWh

If the system under study is not suited for this application, the system cannot be assessed with the SPI. Moreover, the AC- and PV-coupled systems should be assessed in combination with the reference PV inverter as specified in column J of the spreadsheet *PerModPAR.xlsx*. It also should be noted that the model is developed to conduct simulations with a temporal resolution of 1 s. The power flow variables are specified in *PerModRES.m*.

8 Download and licensing

The simulation model *PerMod* including the source code and required input time series is freely available at <https://pvspeicher.htw-berlin.de/permod>. This open source MATLAB simulation model is published under the MIT-License. Please read the file *License.txt* for more information.

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