

Documentation

Performance Simulation Model for PV-Battery Systems (PerMod)

Version: 2.2 (9/2023)

Johannes Weniger, Tjarko Tjaden, Nico Orth, Selina Meier
Research group Solar Storage Systems
University of Applied Sciences Berlin (HTW Berlin)

Content

Content 2

1 Purpose of application 3

2 Files provided with the model..... 3

3 Input time series..... 4

4 Modeled loss mechanisms 5

5 Structure of the model 6

6 Reference cases 7

7 System Performance Index (SPI)..... 8

8 Recommendations 9

9 Download and licensing 10

Acknowledgements 10

Literature 11

1 Purpose of application

The open source *Performance Simulation Model for PV-Battery Systems (PerMod)* was 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 the period of one year. As a result, the overall system efficiency of the three topologies can be assessed with the System Performance Index (SPI). Increasing the comparability of different products based on the SPI is the main task of *PerMod*. In addition, *PerMod* can be used for detailed loss analyses as well as evaluations of different measures to optimize the overall system efficiency. The model may also be implemented in software applications for system design and component sizing purposes.

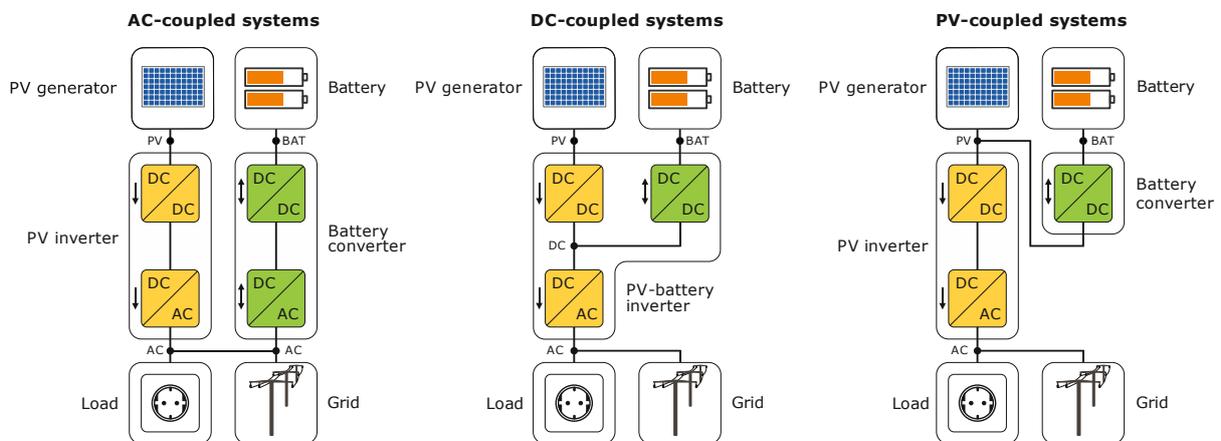


Figure 1 Schematic system configurations of AC-, DC- and PV-coupled PV-battery systems.

2 Files provided with the model

PerMod was 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 according to the “Efficiency guideline for PV storage systems” of the system under study is required [1]. The essential test results must then be transferred to the Excel spreadsheet *PerModPAR.xlsx*.

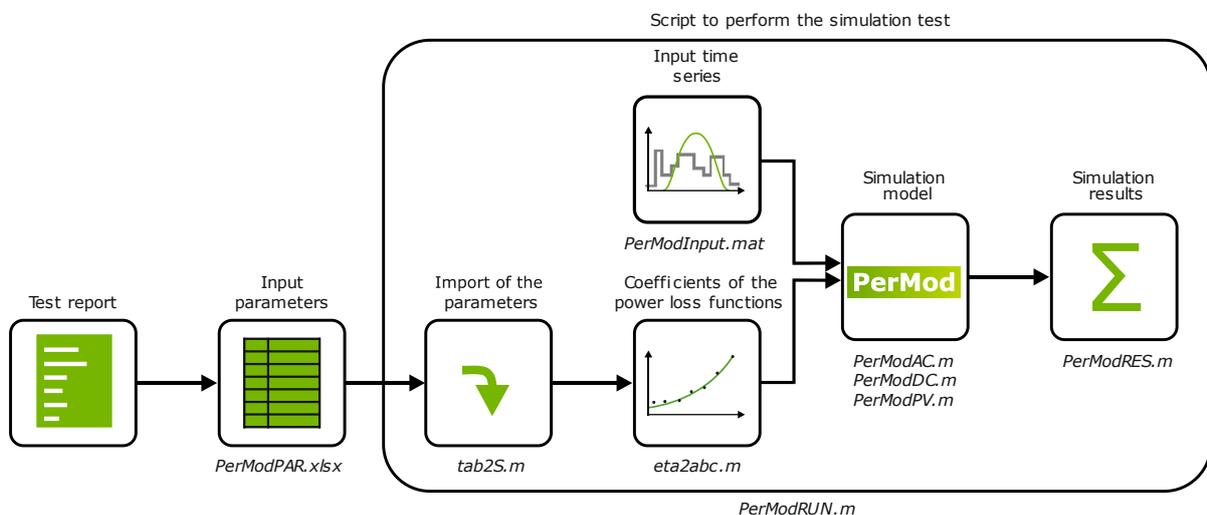


Figure 2 Schematic structure of *PerMod*.

In addition, it is necessary to define which of the two reference cases shall be used for the simulation (see Section 6). This is done by initially specifying it in row 160 and 161 of the spreadsheet *PerModPAR.xlsx*.

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

Table 1 Files provided with *PerMod*.

Filename	Description
<i>PerModRUN.m</i>	Script to perform the simulation test
<i>PerModInput.mat</i>	Input time series of the PV output power 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 model parameters

3 Input time series

In order to perform each simulation test under standardized conditions it is suggested to use the data set *PerModInput.mat*. It contains time series of the PV output power and the electrical load demand for the two different reference cases (see Section 6) 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 PV array is calculated by means of geometric relations and the Klucher model [3]. The PV generator is south-oriented at a tilt angle of 35° and the power output is determined using the empirical model of Beyer et al. [4]. The annual DC energy yield of the PV generator amounts to 1055 kWh/(kW·a). The rated PV power of the 1st reference case is set to 5 kW whereas that of the 2nd reference case amounts to 10 kW [5].

The electrical load profile is part of an open data set which contains synthetically generated load profiles of residential buildings (profile no. 31 out of [6]). The profile with an annual electrical load demand of 5010 kWh/a serves as the basis for the 1st reference case as described in Section 6. Measured load profiles of a heat pump and an electric vehicle are added for the 2nd reference case [7]. Thus, the electrical load demand of the 2nd reference case amounts to 9363 kWh/a. Figure 3 shows the power consumption of both reference cases sorted by height and displayed as annual load duration curves. Approximately half of the electric energy demand of the household appliances occurs at power values below 0.6 kW. The heat pump operates about 1450 h/a and the wall box of the electric vehicle shows a constant power consumption of 3.5 kW at about 500 h/a.

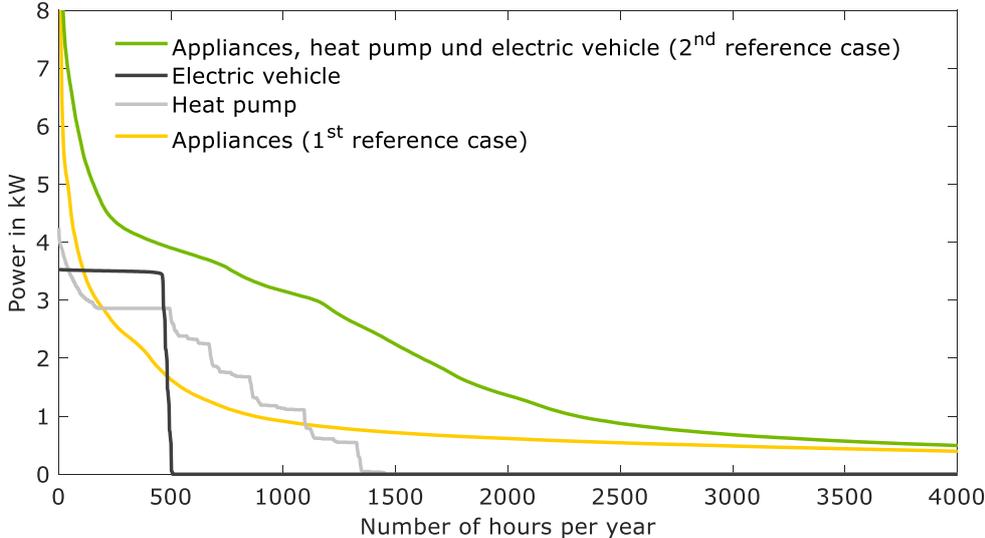


Figure 3 Load duration curves of the different load profiles.

4 Modeled loss mechanisms

Several loss mechanisms affect the overall energy efficiency of grid-connected PV-battery systems, as shown in Figure 4. Sizing losses are caused by the power limitations of the system components. Moreover, conversion losses occur in the power electronics as well as the battery. In addition, there are losses which can be attributed to the control unit. Standby losses are caused by the power consumption of the system components in standby mode.

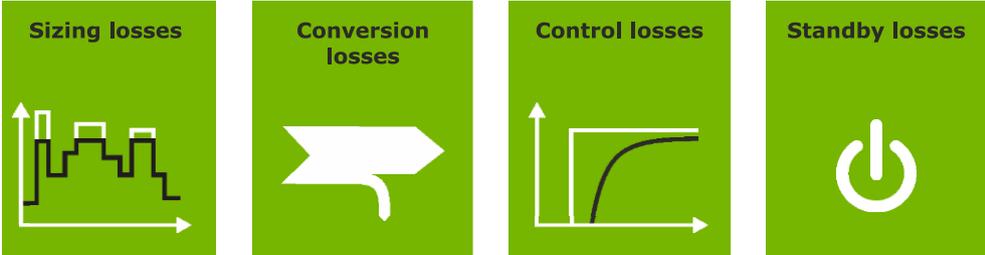


Figure 4 Efficiency-related loss mechanisms of PV-battery systems.

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

Table 2 Overview of the modeled as well as the not modeled efficiency losses within *PerMod*.

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 dependence of the nominal power
Conversion losses	
<ul style="list-style-type: none"> Power dependence of the conversion efficiency of the power electronics at nominal voltage Mean battery efficiency 	<ul style="list-style-type: none"> Voltage and temperature dependence of the conversion efficiency of the power electronics and battery Power dependence 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
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 different operation modes Self-discharging of the battery and power consumption of the battery management system (BMS) during standby operation

5 Structure of the model

Figure 5 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 discharging power. Further, a first-order time delay element is implemented to depict the settling time of the control unit. The conversion losses of the battery converter are then calculated as a function of the power throughput. The battery losses are derived from the mean battery efficiency. Finally, the energy content of the battery system is adjusted, provided that the battery is neither fully charged nor completely discharged. While the battery system is in standby mode, the DC power demand of the battery converter is covered by discharging the battery and the AC power demand is supplied by the PV system or by the grid. It should be mentioned that the model for DC- or PV-coupled systems differs from the one for AC-coupled systems. Validation results can be found in [8].

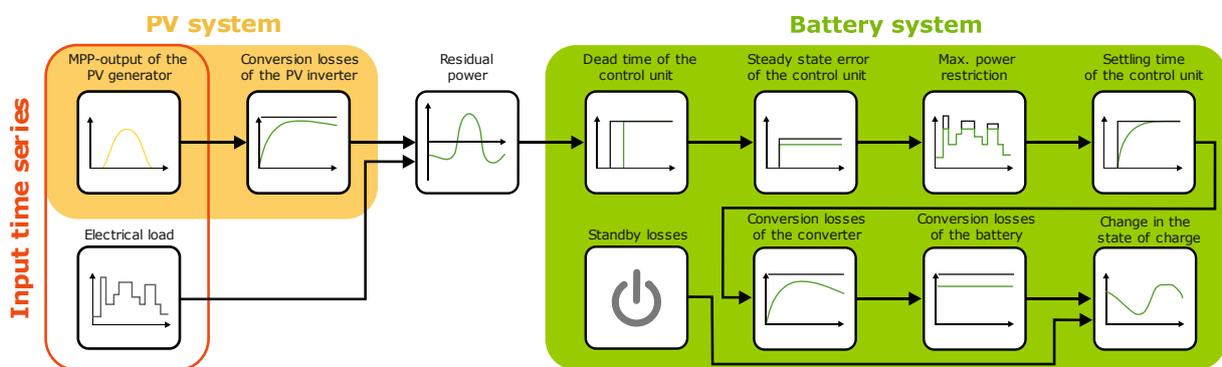


Figure 5 Simplified structure of *PerModAC* showing the order of the modeled loss mechanisms.

6 Reference cases

There are various PV-battery systems available on the market with different configurations in terms of battery capacity and nominal power of the power electronics. To account for the increasing number of diversely sized system configurations, two different reference cases have been defined [9]:

- 1st reference case for PV-battery systems with 5 kW rated PV power
- 2nd reference case for PV-battery systems with 10 kW rated PV power

Figure 6 illustrates the properties of the two reference cases which can be used to assess the energy efficiency of residential PV-battery systems. The appliances of the household in the 1st reference case cause an annual electrical load demand of 5010 kWh/a (see also Section 3). In the 2nd reference case, the household is additionally equipped with a heat pump and an electric vehicle. As a result, the annual electrical load demand amounts to 9363 kWh/a.

The choice of the reference case depends on the system properties and the system topology (see Figure 1). In theory, AC- and PV-coupled systems could be assessed with both reference cases, except when this is not possible for technical reasons. However, it should be noted that the combination of a 5 kW PV system and a battery system of more than 10 kWh is not advisable. Larger-sized battery systems should thus not be assessed with the 1st reference case.

In contrast, DC-coupled systems should be assessed with either the 1st or the 2nd reference case. DC-coupled systems with a nominal PV input power below 7.5 kW should be assigned to the 1st reference case, whereas DC-coupled systems with a

nominal PV input power above this threshold should be classified using the 2nd reference case. Nonetheless, the final decision is left to the user. The reference case can be set in row 160 and 161 of the spreadsheet *PerModPAR.xlsx*.

To be able to compare the results for different AC- and PV-coupled systems, each system should be assessed in combination with the default PV inverters as specified in the spreadsheet *PerModPAR.xlsx*.

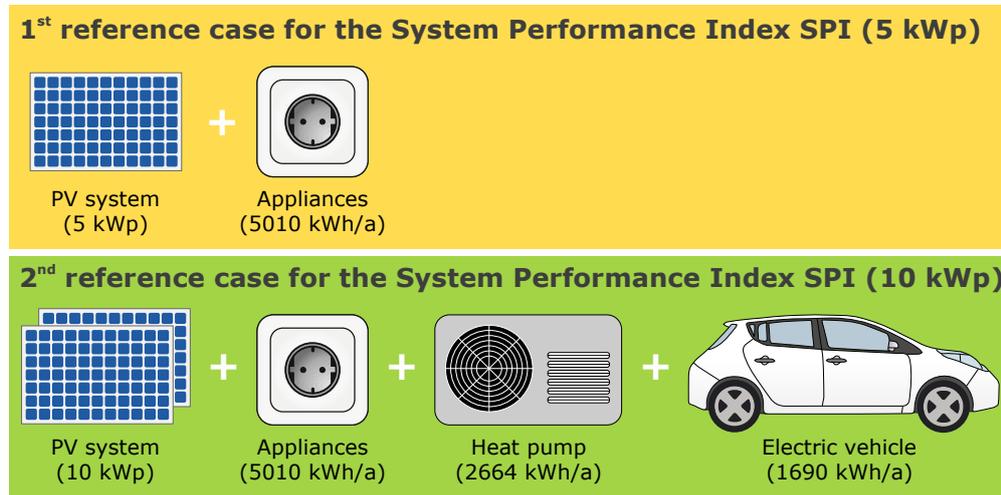


Figure 6 Framework conditions for the 1st and 2nd reference case, respectively.

7 System Performance Index (SPI)

The SPI was introduced to compare the energy efficiency of PV-battery systems with different battery capacities and system topologies [10]. The SPI can be determined by simulating the power flows of the tested PV-battery system and analyzing the amount of energy exchanged between the building and the grid, as shown in Figure 7. The results of the real PV-battery system are then compared with the results of an ideal, lossless PV-battery system of the same size. 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 by the grid and reduce the energy fed into the grid.

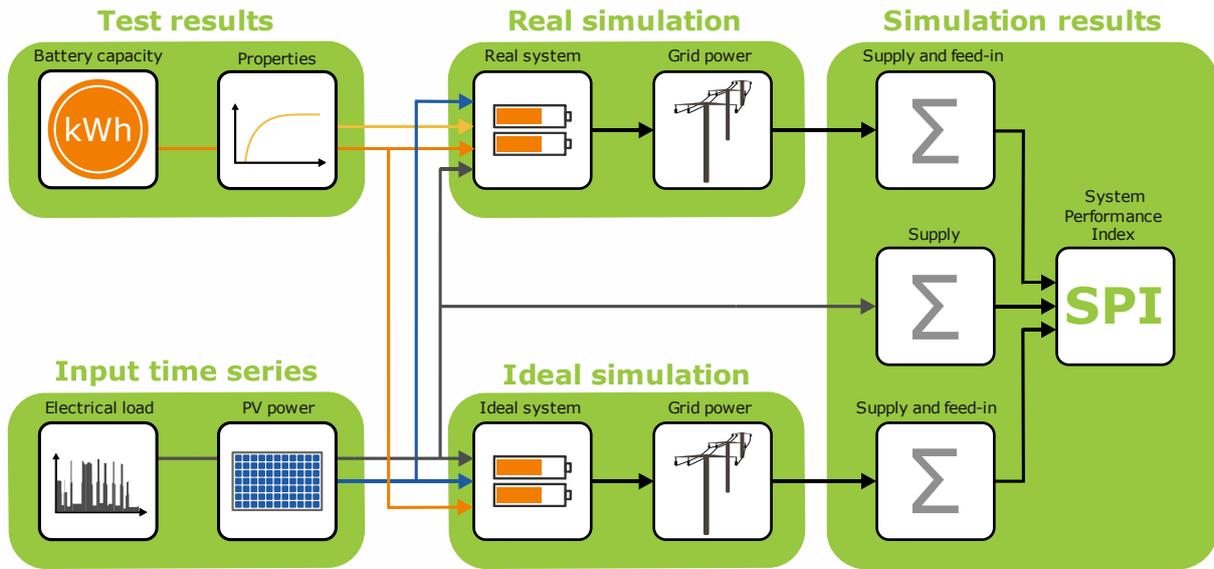


Figure 7 Simplified block diagram to explain how the System Performance Index (SPI) of a PV-battery system is calculated.

Further, the retail electricity price p_{G2AC} and feed-in tariff p_{AC2G} are applied to the grid supply E_{G2AC} and grid feed-in E_{AC2G} , respectively. The net grid electricity costs are determined by subtracting the revenues of the grid feed-in from the procurement costs for the grid supply. Afterwards, the net grid electricity costs of the real and ideal PV-battery system are compared with the initial situation without the 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 means of the energy sums and the ratio p of the feed-in tariff p_{AC2G} to the retail electricity price p_{G2AC} :

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

The feed-in tariff is set to 0.08 €/kWh and the retail electricity price is valued at 0.4 €/kWh, so that the ratio p is 0.2. The rated PV power and the battery capacity of the ideal and real PV-battery system remain unchanged. In order to be able to distinguish the results from the assessment with the two reference cases clearly, the SPI is referred as SPI (5 kW) or SPI (10 kW). Please note that SPI (5 kW) and SPI (10 kW) are not comparable due to the different conditions of the two reference cases (see Section 6).

8 Recommendations

This chapter provides guidance and useful hints to conduct the simulation test with *PerMod*. To run the simulation for one exemplary PV-battery system included in the spreadsheet *PerModPAR.xlsx*, open *PerModRUN.m* and execute the source code with MATLAB.

If you want to analyze a new PV-battery system, transfer the test results that were obtained in a laboratory test according to the efficiency guideline to column G (system ID 1) of the spreadsheet *PerModPAR.xlsx*. In addition, it is necessary to choose one or both of the reference cases in order to assess your system with the SPI. This is done by inserting "yes" or "no" into row 160 and 161 of the spreadsheet (further information see Section 6). Then, change the variable *sys* in Section 1 of the script *PerModRUN.m* to "1" and execute the source code.

Please note that the performance of different PV-battery systems is only comparable under identical test conditions. This implies that the SPI has to be calculated for one of the described reference cases using the provided input data sets. If the system under study is not suited for neither the 1st nor the 2nd reference case, the system cannot be assessed with the SPI.

In addition, the SPI assessment should be conducted using the defined ratio of the feed-in tariff to the retail electricity price of 0.2. Moreover, AC- and PV-coupled systems should be assessed in combination with one of the PV inverters specified in column L and M (depending on the reference case) of the spreadsheet *PerModPAR.xlsx*. It should also be noted that the model was developed to conduct simulations with a temporal resolution of one second. If desired, the function *PerModRES.m* provides the resulting power flow variables of the simulation.

9 Download and licensing

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

Copyright © 2023 Johannes Weniger, Tjarko Tjaden, Nico Orth, Selina Meier

Acknowledgements

This work was financially supported by the German Federal Environmental Foundation (Deutsche Bundesstiftung Umwelt DBU) within the project "EffiBat". The simulation model was validated with measurement data provided by several institutes. The authors thank the RWTH Aachen University Institute for Power Electronics and Electrical Drives, the Karlsruhe Institute of Technology (KIT) Battery Technical Center, the Austrian Institute of Technology (AIT), the Institute for Solar Energy Research Hamelin (ISFH) and the Technical University of Braunschweig Institute for High Voltage Technology and Electrical Power Systems (elenia) for their support.

sponsored by



Deutsche
Bundesstiftung Umwelt

www.dbu.de

Literature

- [1] Bundesverband Energiespeicher e.V. (BVES) and Bundesverband Solarwirtschaft (BSW), 'Efficiency guideline for PV storage systems 2.0', Berlin, Jul. 2019. [Online]. Available: https://www.bves.de/effizienzleitfaden_3_2019/.
- [2] J. Kalisch, T. Schmidt, D. Heinemann, and E. Lorenz, 'Continuous meteorological observations in high-resolution (1Hz) at University of Oldenburg in 2014'. PANGAEA - Data Publisher for Earth & Environmental Science, 2015, Accessed: Sep. 07, 2015. [Online]. Available: <http://dx.doi.org/10.1594/PANGAEA.847830>.
- [3] T. M. Klucher, 'Evaluation of models to predict insolation on tilted surfaces', *Solar Energy*, vol. 23, pp. 111–114, Jan. 1979, doi: 10.1016/0038-092X(79)90110-5.
- [4] H. G. Beyer, G. Heilscher, and S. Bofinger, 'Identification of a General Model for the MPP Performance of PV-Modules for the Application in a Procedure for the Performance Check of Grid Connected Systems', in *19th European Photovoltaic Solar Energy Conference*, Paris, 2004, pp. 3073–3076.
- [5] J. Weniger, S. Maier, N. Orth, and V. Quaschnig, 'Stromspeicher-Inspektion 2020', Hochschule für Technik und Wirtschaft Berlin, Berlin, 2020.
- [6] T. Tjaden, J. Bergner, J. Weniger, and V. Quaschnig, 'Representative electrical load profiles of residential buildings in Germany with a temporal resolution of one second', 2015. doi: 10.13140/RG.2.1.3713.1606.
- [7] SMA Solar Technology AG, 'Leistungsmessdaten von Wärmepumpen und Wandladestationen in Privathaushalten'. 2017.
- [8] S. Maier, J. Weniger, N. Böhme, and V. Quaschnig, 'Simulationsbasierte Effizienzanalyse von PV-Speichersystemen', in *PV-Symposium 2019*, Bad Staffelstein, Mar. 2019.
- [9] N. Orth *et al.*, 'Vergleich der Energieeffizienz verschiedener PV-Speichersystemkonzepte', in *PV-Symposium 2018*, Bad Staffelstein, Apr. 2018.
- [10] J. Weniger, T. Tjaden, and V. Quaschnig, 'Vergleich verschiedener Kennzahlen zur Bewertung der energetischen Performance von PV-Batteriesystemen', in *32. Symposium Photovoltaische Solarenergie*, Bad Staffelstein, Mar. 2017.