Modelling of decentralised grid-connected electricity storage

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Abstract:

Decentralised energy storage is becoming a key element for deeper integration of distributed generation based on intermittent renewable energies and to improve price-competitiveness, efficiency and reliability of such electricity supply systems. Currently, different technologies for (indirect) electricity storage are available whereby their characteristics and possible application fields vary within a large range. For all potential applications, appropriate storage technology / system selection and dimensioning is crucial. In order to analyse the integration of energy storage systems in different reference application scenarios, modelling of energy storage can be deployed. For the purpose of conducting quantitative analyses including dimensioning of storage devices and simulating storage integration in different reference scenarios, a mathematical model for using Matlab/Simulink has been developed which can be specified and parameterized for individual application cases.

The underlying analyses are based on studies on implementation potentials of a small-scale hydro-pneumatic energy storage system currently being developed. As the storage system has been modelled to simulate storage implementation in several use cases, the model design has been extended in order to apply it to other forms of electrical energy storage as it is based on energy conversion and balance calculations. The model allows simulation of storage implementation in several application scenarios in order to derive figures of optimal storage parameters / seizing (required storage system input / output power, optimal storage capacity, required dynamic behaviour necessary storage charge / discharge duration, cycle rates etc.). Based on that, financial feasibility analyses for specific cases of application can be derived (as far as financial parameters like investment and operation costs of storage systems depending on calculated parameters/size, electricity prices/tariffs, etc. are known for the specific case.)

The developed STOR-E Library is an extension for Matlab/Simulink, organized in blocksets like the Simulink Library itself. The STOR-E blockset is a tool for analysing the commercial relevance of indirect electricity storage systems in the following reference applications:

- Load and energy management for industrial enterprises
- Optimization of on-site power supply / auxiliary power requirement based on photovoltaic electricity generation
- Optimization of energy feed-in into the public grid for a wind power plant

Keywords: Electrical energy storage, modelling, simulation, grid-connected, distributed generation

1 Introduction

Energy storage is considered to play an important role today but particularly for future energy supply systems with a growing share of renewable energy sources. Especially regarding the integration of intermittent renewables electricity storage devices can be applied to balance the supply and demand of energy as the electricity generation based on intermittent renewables is basically not demand-oriented. The increased use of renewable energy sources has implications for the structure of electricity supply systems. As electricity supply up to now was mainly based on large central power plants and distribution of electricity from the highest down to low voltage levels (unidirectional power flow), we now face a growing decentralization along with the integration of distributed generation in the smaller power range into existing power grids. As a consequence of increased feed-in on lower voltage / distribution grid level, reverse power flow more often occurs along with other potential negative impacts like voltage fluctuations, power fluctuations, fault currents, grounding issues etc. Existing grids are widely not designed for such operation conditions – transformers and cables may reach their loading limits, grid voltage may exceed permissible thresholds etc. – which may lead to the necessity of strengthening distributions networks in order to allow increased integration of distributed generation and feed-in. On the other hand, as the feed-in tariffs for electricity generated from solar and wind energy systems are intended to be reduced on medium to long term, operators of photovoltaic and other distributed generation devices are increasingly motivated to use the energy they have generated for themselves. To increase the capacity of such systems to enhance own consumption, storage of electrical energy is necessary.

Those developments lead to decentralised energy storage to become a key element for deeper integration of distributed generation based on intermittent renewable energies and to improve price-competitiveness, efficiency and reliability of such electricity supply systems. Currently, different technologies for (indirect) electricity storage are available whereby their characteristics and possible application fields vary within a large range. While some technologies are already used to a greater extent (pumped hydro storage on the larger range, different battery systems), others are still on development stage. For all potential application cases appropriate storage device selection and dimensioning is crucial.

The analyses of which this paper was derived from are based on studies on implementation potentials of a small-scale hydro-pneumatic energy storage system currently being developed. This technology targets indirect electrical energy storage via conversion of electrical energy to be stored in form of compressed air, basically in a power range of several kW_{el} to a few hundred kW_{el}. As the storage system has been modelled to simulate storage implementation in several use cases the model design has been extended in order to be able to apply it to other forms of electrical energy storage. As it is based on energy conversion and balance calculations it can principally be applied on several storage technologies by parameterisation.

Essentially, the model allows simulation of storage implementation in several application scenarios in order to derive figures of optimal storage parameters / seizing (required storage system input / output power, optimal storage capacity, required dynamic behaviour necessary storage charge / discharge duration, cycle rates etc.). Based on that, financial feasibility analyses for specific cases of application can be derived (as far as financial parameters like investment and operation costs of the storage system depending on calculated parameters/size, electricity prices/tariffs, etc. are known for the specific case.)

Within the scope of this paper, exemplary application scenarios are defined and analysed regarding the integration of electrical energy storage systems. The following reference applications are examined:

- Load and energy management (for exemplary load profiles of industrial enterprises): application of energy storage for reduction of peak load and utilization of time-variable power supply tariffs
- Optimisation of on-site power supply based on photovoltaic electricity generation
- Optimisation of energy feed-in for a wind power plant: application of energy storage for market integration of wind power

In order to analyse the integration of energy storage systems in different application scenarios, a general storage model for simulating (indirect) electricity storage implementation has been developed which can be specified and parameterized for individual application scenarios.

2 Overview of storage model and reference application scenarios

2.1 General storage model and mathematical basis

The mathematical basis used to develop this Matlab/Simulink tool is outlined in following figure 1 and figure 2 showing the schematic diagram and basic functions of general storage model.

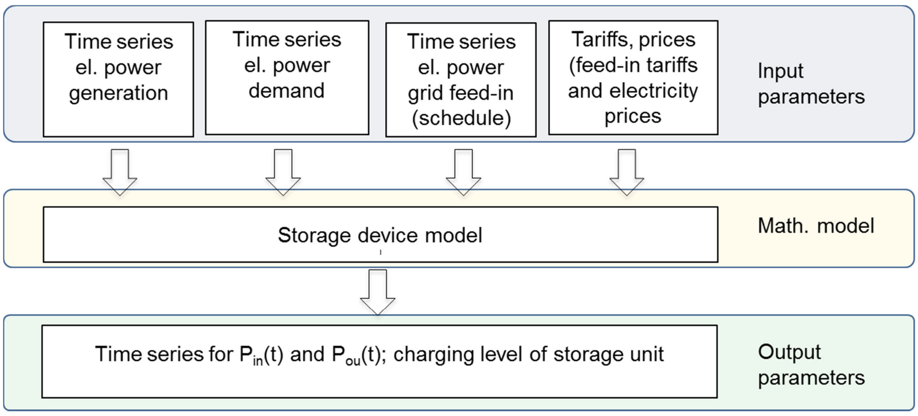

Figure 1 Schematic diagram of general storage model

The shown input and output parameter sets represent all options used within the scope of the model. For modelling and simulation of individual application cases the general storage model has to be specified and parameterized.

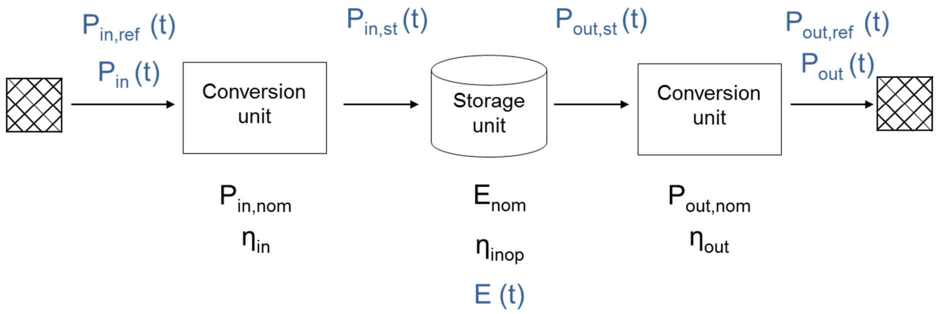

Figure 2 Basic functions of general storage model

Expl:	E_{nom}	Nominal storage capacity [kWh]
	$E(t)$	Storage charging level (energy level) at time t [kWh]
	$P_{in,nom}$	Nominal input power of conversion unit [kW]
	$P_{ouz,nom}$	Nominal output power of conversion unit [kW]
	$P_{in}(t)$	System input power [kW]
	$P_{out}(t)$	System output power [kW]
	$P_{in,st}(t)$	Input power into storage unit [kW]
	$P_{out,st}(t)$	Output power from storage unit [kW]
	$P_{in,ref}(t)$	Reference input power (into system) [kW]
	$P_{out,ref}(t)$	Reference output power (from system) [kW]
	η_{in}	Efficiency of input energy conversion [-]
	η_{out}	Efficiency of output energy conversion [-]
	η_{inop}	Storage efficiency of storage unit at storage (non-operating) state [-]
	T_{St}	Storage duration [h]

For this general model following relations and equations apply. The input power into the storage unit is defined by the system input power and the efficiency of input energy conversion (2.1).

$$P_{in,st}(t) = \eta_{ein} \cdot P_{in}(t) \tag{2.1}$$

$P_{in,st}(t)$	Input power into storage unit [kW]
$P_{in}(t)$	System input power [kW]
η_{in}	Efficiency of input energy conversion [-]

The efficiency of input energy conversion is a function of the system input power (2.2).

$$\eta_{in} = f\left(P_{in}(t)\right) \tag{2.2}$$

η_{in}	Efficiency of input energy conversion [-]
$P_{in}(t)$	System input power [kW]

The system output power at time t is dependent on output power from storage unit and efficiency of output energy conversion (2.3)

$$P_{out}(t) = \eta_{out} \cdot P_{out,st}(t) \tag{2.3}$$

$P_{out}(t)$	System output power [kW]
$P_{out,st}(t)$	Output power from storage unit [kW]
η_{out}	Efficiency of output energy conversion [-]

The efficiency of output energy conversion is a function of the system output power (2.4).

$$\eta_{out} = f\left(P_{out}(t)\right) \tag{2.4}$$

η_{out}	Efficiency of output energy conversion [-]
$P_{out}(t)$	System output power [kW]

The losses of the storage unit during storage (non-operation) state are covered by storage efficiency at storage state. This item is dependent on charging level (storage energy level) and storage duration (2.5).

$$\eta_{inop} = f\left(E(t), T_{st})\right) \tag{2.5}$$

η_{inop}	Storage efficiency of storage unit at storage (non-operating) state [-]
$E(t)$	Storage charging level (energy level) at time t [kWh]
T_{st}	Storage duration [h]

The charging level (stored energy level) at a time (t) can be expressed as function of energy level at (t-1) minus losses of the storage unit during storage state, storage input and output energy during (t-1) until t (2.6).

$$E(t) = \eta_{inop} \cdot E(t-1) + \int_{t-1}^{t} P_{in,st}(t)\, dt - \int_{t-1}^{t} P_{out,st}(t)\, dt \tag{2.6}$$

$E(t)$	Storage charging level (energy level) at point of time t [kWh]
η_{inop}	Storage efficiency of storage unit at storage (non-operating) state [-]
$P_{in,st}(t)$	Input power into storage unit [kW]
$P_{out,st}(t)$	Output power from storage unit [kW]

Furthermore, the reaction time of the storage unit during storage input and output process as well as the time delay with power modifications by given power gradients are to be considered. The requested input power is referred to as the reference input power. The actual input power at time t is a function of the reference input power and the input power delay function, see (2.7). Within that input power delay function, the time-dependent delay of actual input power compared to reference requested input power is summarized.

$$P_{ein}(t) = f\left(P_{ein,ref}(t), T_{V,ein}(t, P_{ein,ref}(t))\right) \quad (2.7)$$

$P_{ein}(t)$	System input power [kW]
$P_{ein,ref}(t)$	Reference input power [kW]
$T_{V,ein}(t, P_{ein,ref}(t))$	Input power delay function

By analogy, the requested output power is referred to as a reference output. Actual power output depends on the reference output power and the output power delay function, see (2.8). The time-dependent delay of the actual output power compared to the requested reference output is covered by that output power delay function.

$$P_{out}(t) = f\left(P_{out,ref}(t), T_{V,out}(t, P_{out,ref}(t))\right) \quad (2.8)$$

$P_{out}(t)$	System output power [kW]
$P_{out,ref}(t)$	Reference output power [kW]
$T_{V,out}(t, P_{out,ref}(t))$	Output power delay function

The outlined relations apply to the general storage model basically for all reference application scenarios. In order to conduct quantitative analyses and simulate storage integration in different scenarios, the general storage model has to be specified and parameterized for the individual application case.

2.2 Reference application scenarios

For the defined decentralised storage application fields of load and energy management as well optimisation of intermittent renewable based generation, reference application scenarios have been defined in order to analyse storage integration and conduct quantitative analyses. Out of these, requirements concerning storage system selection and configuration can be derived including calculation of optimal storage dimensioning. In the following section, required parameters for model application in each application field are defined.

In this regard, the reference application scenarios are characterised by properties of consumer/loads and generation. Load profiles as well as fluctuation and intermittence of generation related data are necessary. Furthermore, in case of power supply from the grid, supply tariffs can be characterised by tariffs and rates like time variable tariffs (high tariff HT and low tariff NT supply period) in combination with accounting periods, kilowatt-hour rates as well as peak power rates. In case of feed-in into the grid, tariffs or, more specifically, expected revenues (prices, corresponding times) are to be included. Out of the particular framework conditions, objectives for storage integration and operation can be derived. Subsequently, storage integration and operation in each application case is simulated using the storage model in order to deduce results/conclusions especially regarding requirements on the storage system and optimal storage parameters (capacity, power characteristics etc.) for each application case like:

- Required storage system input / output power

- Optimal storage capacity
- Required dynamic behaviour (dynamic charge/discharge properties, reaction time, power gradients)
- Necessary storage charge / discharge duration
- Cycle rates

Furthermore, it is possible to analyse financial feasibility of (optimal) storage system integration in a specific use case as far as financial parameters (investment and operation costs of storage system depending on calculated parameters/size, electricity prices/tariffs, etc.) are known for the specific case of application

2.2.1 Load and energy management

This scenario is designed for application of energy storage for reduction of peak load and utilization of time-variable power supply tariffs primarily for industrial enterprises. Energy storage application in that application field can be feasible especially if there are no other possibilities of load management or load shifting or if all potentials are already exhausted for the specific enterprise. By implementation of a storage system, electricity supply from the grid is to be optimised and therefore electricity costs can be minimised. Storage use is based on following objectives:

- Reduction of grid supplied peak load
- Utilization of time-variable power supply tariffs (time variant shifting of grid supply)

Storage system operation aims at optimising electricity supply from the grid in regards of reducing electricity supply costs compared to supply without storage implementation. Feasibility of storage implementation on that application scenario is dependent on payback period or resp. amortisation through savings from electricity supply costs.

2.2.2 Optimisation of on-site power supply based on photovoltaic generation

In this scenario, storage application is aiming at optimising electricity supply based on intermittent renewable sources. This scenario covers energy storage application to enhance own consumption of (intermittent) renewables based generation, especially from PV. As the feed-in tariffs for electricity generated from solar energy systems are intended to be reduced on medium term, operators of photovoltaic (and other distributed generation) devices are increasingly motivated to increase own use of energy storage systems allow increasing the capacity of such systems and to enhance own consumption.

Storage operation in this scenario targets to optimise self-consumption of PV based generation in terms of minimising costs for covering electricity demand. As photovoltaic generation is basically not demand-oriented, the storage system functions as buffer between (intermittent) generation and demand/load curve. The feasibility of a storage system in this application case is basically dependent on supply and feed-in tariffs / revenues in combination with storage system costs and its amortisation.

2.2.3 Optimization of energy feed-in into the public grid for a wind power plant

Storage application in this scenario is targeting (economic) optimisation of energy feed- in of wind power plants for market integration of wind power. The use of energy storage is based on time shift or "buffering" between fluctuating generation of wind turbines and power supply of the entire system (wind power plant combined with on-site storage) with the goal of electricity sales at market prices.

The use of energy storage in combination with electricity generation based on wind energy provides feed-in which is, to a certain degree, independent from current availability of the primary energy source (wind), and thus the production of a wind turbine. However, a controllable generation or feed-in is a prerequisite for participation in the electricity market. By steadying the feed-in of wind turbines by means of energy storage, it could be possible for example to participate in the day-ahead spot market, for which at least hourly constant power / feed-in is required. By using larger storage capacities, storage over several hours could be possible to feed-in / sell electricity in times of high spot market prices and thereby increase revenue. Thus, feed-in is also demand-driven, as supply / feed-in is displaced from low-load periods to peak load times.

As a precondition for selling electricity based on wind power combined with on-site storage on the electricity market, a day-ahead generation forecast and a deducted 24-hour timetable for grid-feed-in are required. Using the storage model for such an application case, optimal storage device parameters (necessary power, capacity etc.) in order to maximise revenues from market sales of electricity based on wind power can be derived.

3 Matlab/Simulink Storage Model

In order to conduct quantitative analyses including dimensioning the required storage unit scale for suitable application scenarios and simulate storage integration, a mathematical model using Matlab/Simulink has been created. The STOR-E Library is an extension for Matlab/Simulink. It is organized in blocksets like the Simulink Library itself so that the blocks can be handled in the same way as the Simulink blocks. The STOR-E blockset is a tool for analysing the commercial relevance of an energy storage system in the reference applications mentioned before. In figure 3 an exemplary load and energy management simulation is illustrated. This example can be found in the developed STOR-E Library.

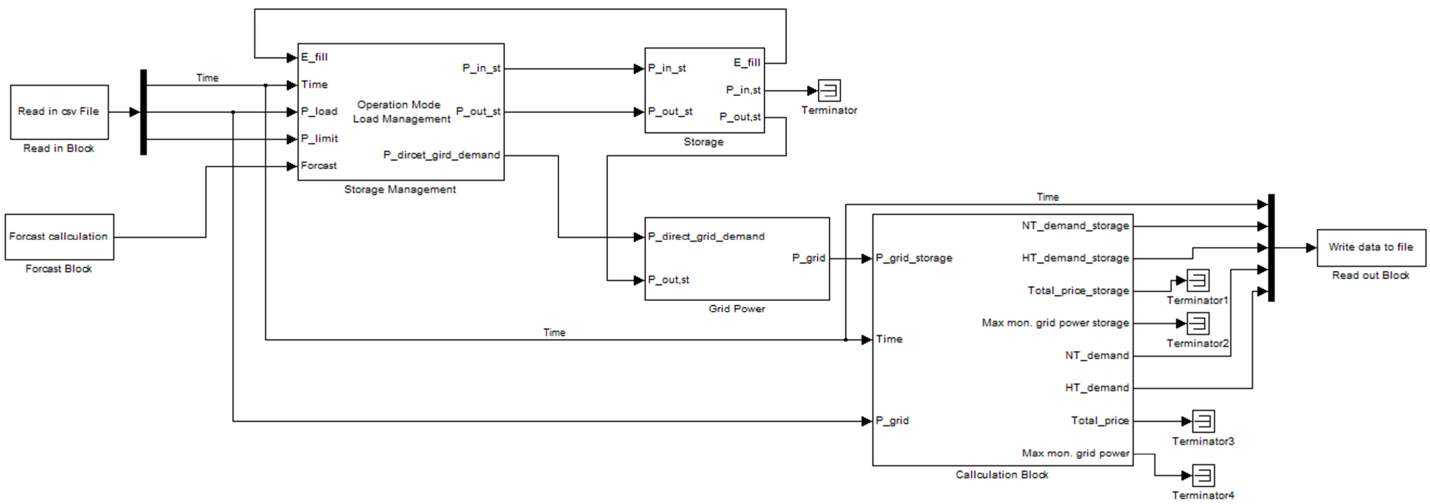

Figure 3: Example for a load management simulation

An outline of essential blocks and functions of the STOR-E Library comprises:

- Input / Read in block: to handle data input, in particular electrical load and generation data (real data / forecasts), which is to be read in from csv file format
- Storage management block: to manage the charge/discharge-process of the storage system. For the simulation of different application scenarios, three storage operation modes are available:
    - Load management: In this simulation mode an optimisation of load and energy management of a consumer load profile is implemented to reduce the total supply costs (energy and power costs). This means that load peaks are covered and power obtained from the grid is “shifted” from high to low tariff time by using a storage system. Data concerning tariffs and related tariff times have to be provided.
    - PV: In this operation mode the power generated from a PV system is “shifted” over time to maximise self-consumption. In this case, basically, excess generation from PV (generated power of the PV system higher than demand) is used for storage charging and demand is covered using the storage device to discharge if PV generation is lower than the load.
    - Wind power plant (WEA): This simulation mode serves to manage grid feed-in following a prior determined schedule depending on forecasted power generation.
- Storage block: to simulate energy storage (charge / discharge processes of the storage system). In particular, it calculated the charging (energy content) level, storage system input and output power stored for each simulation time step.
- Forecast block: to calculate schedules for grid-fed in and grid supply / time shifting schedules
- Calculation block: to actually run calculations for the simulation depending on selected simulation type and calculation mode. Concerning the different simulation modes, the following parameters are calculated:
    - Wind power plant: el. energy fed-in into the grid during scheduled hours; corresponding revenues
    - PV: max. grid power per month and corresponding tariffs; power obtained from the grid / fed-in during high and low tariff times and corresponding tariffs; total costs and savings
    - Load management: max. grid power per month and corresponding tariff; power obtained from the grid during high and low tariff times as well as corresponding tariffs; total costs and savings
- Output / Read out block: to output simulation results (in csv file format). The output contains charging (energy content) level and input / output power of the storage system over the simulated time period. Furthermore, depending on the selected simulation mode, the following figures are depicted:
    - Wind power plant: el. energy fed-in (following the defined schedule), total costs and revenues
    - PV: max. grid power per month and corresponding tariff, power obtained from the grid / fed-in during high and low tariff times, corresponding tariffs; total costs and revenues / savings

- Load Management: max. grid power per month and corresponding tariff; power obtained from the grid during high and low tariff times as well as corresponding tariffs; total costs and savings

4 Exemplary application

To illustrate a model application exemplarily, simulation results for a small industrial enterprise are shown in the following section. The application case is a company engaged in processing and trading in metals and furthermore operates a thinfilm PV system installed on the plant halls rooftops with nominal power of 200 kWp. A representative weekly load profile of that company is depicted in figure 4 in order to illustrate the fluctuation and spread of the load curve.

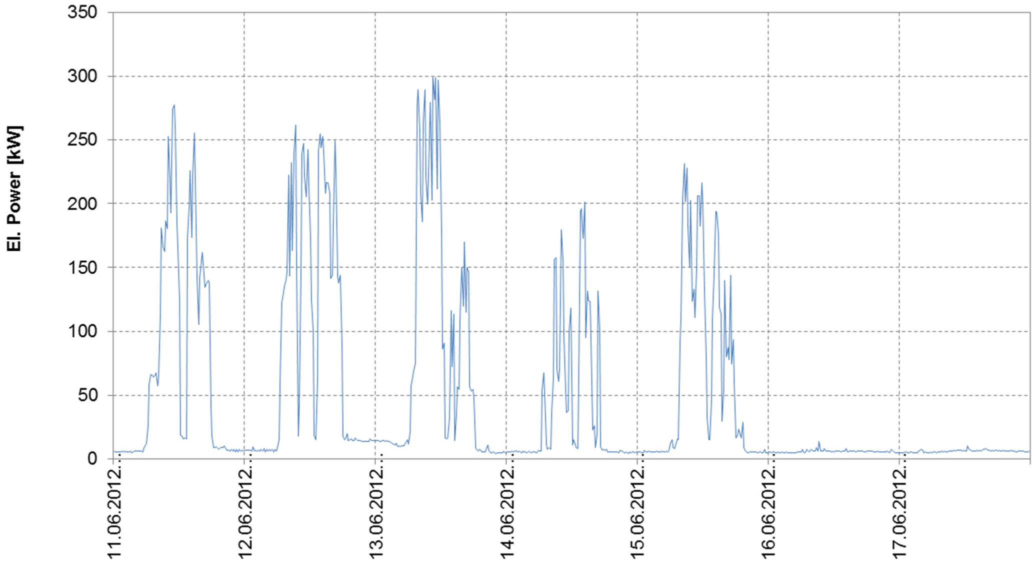

Figure 4: Weekly load profile of exemplary application enterprise

The Matlab/Simulink tool has been used to analyse the suitability of that plant site for storage implementation. The Matlab/Simulink STOR-E model has been run with available load curves and PV power output. With the targeted optimization of auxiliary power requirement based on photovoltaic electricity generation the following required storage device scale has been calculated.

- Max. storage input power: 160,33 kW_{el}
- Max. storage output power: 289,12 kW_{el}
- Max. charging level of storage device: 2929,35 kWh

The following weekly profile of simulated operation curves of a storage device (Figure 5) illustrates simulation results for the application field PV / balancing of on-site power and demand. For that kind of application case, PV generation is used directly for load coverage in case the load is lower than PV power output. Surpluses of the PV generation are therefore used to charge the storage device used as a buffer (depicted as storage input power curve). In case the load exceeds the photovoltaic power output, the storage device is being discharged to cover the load illustrated in figure 5.

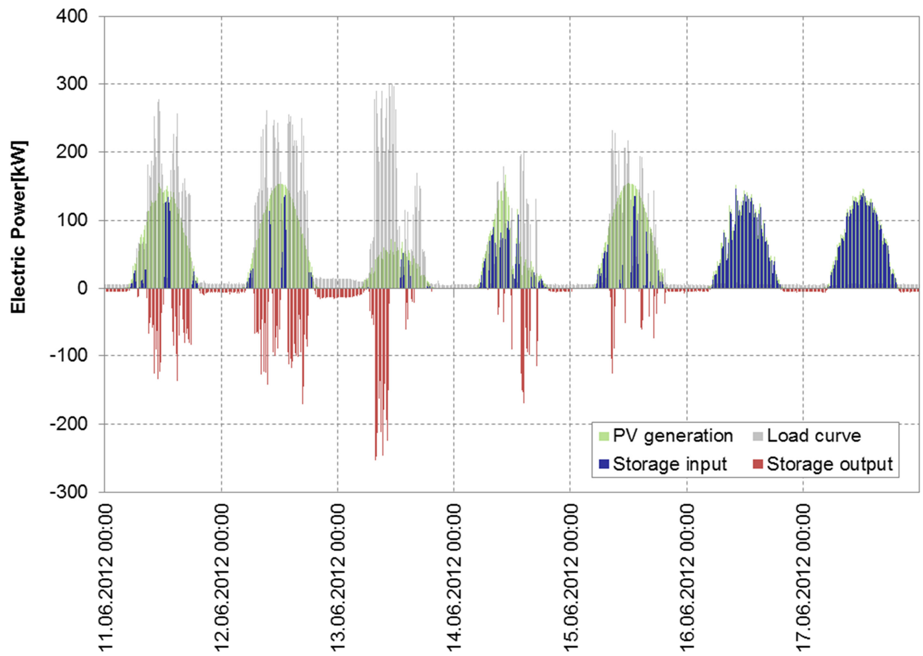

Figure 5: Weekly profile of simulated operation curves of storage device at potential application site with photovoltaic generation and exemplary load curve

5 Conclusions

Based on the simulation results of different storage implementation scenarios, the following conclusions concerning the developed storage model and its application can be drawn:

- Simulation of the depicted exemplary application case with real data shows a low utilization of the storage system with an integration of the entire PV generation. Feasibility of the storage system in that application case depends on how well the generation and load curves match.
- The developed model can be used to simulate storage integration of different storage system types in several application scenarios.
- The simulation model is suitable to calculate optimal storage seizing (in terms of economical optimal/feasible) for a particular electrical generation and demand situation.

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