Bornholm lighthouse energy system models

WP4: Modelling, simulation, engineering and equipment development for the Lighthouse demonstration

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D4.10 Bornholm lighthouse energy system models

WP4 – Modelling, simulation, engineering and equipment development for the Lighthouse demonstration

INSULAE
Maximizing the impact of innovative energy approaches in the EU islands

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ABBREVIATIONS

BESS: Battery energy storage system

EV: Electric vehicles

PV: Photovoltaic

WT: Wind turbine

PWM: Pulse width modulation

DSL: Dynamic simulation language

MPPT: Maximum power point tracking

BMS: Battery management system

SOC: State of charge

VPP: Virtual power plant

CHP: Combined heat and power

EXECUTIVE SUMMARY

Deliverable 4.10 focuses on the development of the energy system models that will constitute the basis of the planned experimental validation of Use Cases 4 and 5. Use case 4 (UC4) aims at establishing a local DC bus with a battery backup. Use case 5 (UC5) aims at assessing integrated management of local bio-based economies supporting the electrical, thermal and transport systems.

With these objectives in mind, and considering that the main tools used for the simulations will be DIgSilent Powerfactory and Matlab-Simulink, four different models have been developed: two for UC 4 and two for UC5. While each model has its own distinctive feature, common elements in the methodological approach are maintained in order to set the basis for future improvements based on the foreseen results of the experimental investigation part of WP6 (demonstration in Bornholm).

The reader will find the key objectives and boundaries of each model in this document. A more extensive set of results will be made publicly available as part of D4.8 (Bornholm Lighthouse UC-4 report) and D4.9 (Bornholm Lighthouse UC-5 report). Publicly available early stage results are reported as part of three conference papers submitted to the UPEC 2020 conference.

The deliverable content and the models of D4.10 have been prepared by DTU with specific input from the Danish partners: BEOF, Fremsyn, and BRK. The four model files are uploaded as annex of D4.10 and their availability and usage is limited to the partners involved in the Bornholm demonstration.

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1 INTRODUCTION

Deliverable 4.10 includes the first versions of the models that prepare the simulation activities part of T4.3 (Bornholm Lighthouse demonstration preparatory activities). Task 4.3 started in June 2019 and will last until March 2021 (halfway through the project). Core activities of T4.3 are modelling and simulation, engineering and development of the use cases (UC 4 and UC 5) taking place in Bornholm.

The final models and consolidated results on the simulations will be included in D4.8 and D4.9 (due on March 2021). The final models will take into account the results from the tests carried out in the laboratory (where applicable) during the second year of the project as well as the demonstration activity part of WP6, which will last until the end of the project. Engineering specifications and development will be part of D4.11 (September 2020) and D4.12 (March 2021). The deliverable content and the models of D4.10 have been prepared by DTU with specific input from the Danish partners: BEOF, Fremsyn, and BRK.

Early stage results, along with a more extensive description of the models reported in this deliverable can be found in the following conference papers [1]-[3]. The papers, currently submitted and under review for the UPEC (University Power Engineering Conference) 2020, will be presented and made publicly available in September 2020.

Four models are described in the following chapters, two for each use case (UC4 and UC5). In short, each model has the following objectives:

1. DC microgrid (UC 4 model): The model aims at performing simulation studies on the operation and control of the DC microgrid to provide flexible operation of the grid components and support voltage and frequency balancing services to the external AC grid.
2. Reconfigurable stationary battery (UC 4 model): The model focuses on describing the characteristic behavior of a reconfigurable stationary battery, which is the type of electro-chemical storage that is going to be deployed on Bornholm.
3. Virtual power plant (UC 5 model): The model intends to assess the potential of the VPP linking different energy domains (electrical, thermal, transportation) for exploiting synergies between the different energy domains and supporting flexibility and ancillary service provision to the power system.
4. Biogas plant (UC 5 model): The model aims at simulating the internal processes of a biogas power plant, comprising the anaerobic digestion processes, the gas storage dynamics, and the combustion of biogas for generating combined heat and power, to assess the flexibility potential and the support towards a bio-based economy.

2 USE CASE 4 MODELS

2.1 DC microgrid

The model aims at performing simulation studies on the operation and control of the DC microgrid to provide flexible operation of the grid components and support voltage and frequency balancing services to the external AC grid. The model is a flexible platform and can be adapted for different system configurations in accordance with specific study objectives.

Figure 1 depicts the topology of the modelled DC microgrid. It integrates a photovoltaic system (PV), a battery energy storage system (BESS), consisting of three battery strings (String 1…3), a wind turbine (WT), and an electrical vehicle (EV) connected to a DC charger. A three-phase AC/DC inverter provides the interconnection between the AC grid and the DC side of the microgrid [1].

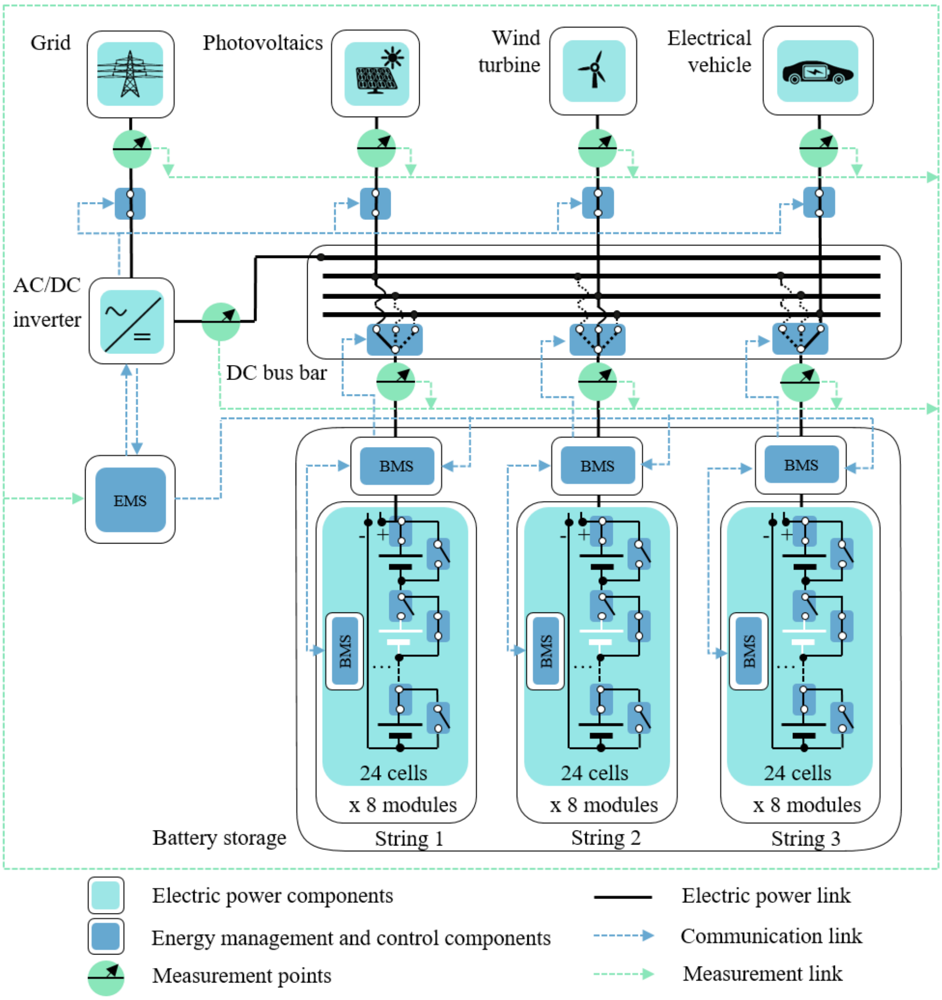

Figure 1. DC microgrid topology. Components, power connections, measurement and control signals are highlighted.

The model is developed in DIgSilent Powerfactory. In the current version of model, the AC grid is assumed to have an infinite generation capacity and modelled as an infinite bus. A voltage-sourced PWM converter represents the AC/DC inverter component. The PV facility and the WT are modelled as DC current sources, while the BESS and EV by DC voltage sources. At the same time, to reflect dynamic behavior of the battery components (BESS and EV), dynamic battery models are additionally being developed using dynamic simulation language (DSL) and embedded into the microgrid model.

The delivered version of the model is tailored to perform steady state analysis of the DC microgrid, the model is currently being upgraded to support dynamic studies. The dynamic active and reactive power (P/Q) control, frequency control and BESS charging control systems, represented in the system diagram by the inverter, EMS and BMS blocks, are being designed and implemented into the model. The control systems of the model will be suited for running the model in grid-connected and islanded operation modes [4], [5]. Next, the model will be tested towards a fast EV charging scenario based on a real charging profile for the 40 kWh battery from a 2018 Nissan Leaf. Then, the static components of the DC microgrid (PV and WT) will be supplemented by dynamic models. Thereafter, the following control strategies will be implemented and tested through the simulations:

- Maximum power point tracking (MPPT) of PV and WT.
- Power reference tracking at the grid connection point.
- Pure battery charging to follow frequency or voltage droop control characteristics (unidirectional EV charging).
- Battery charging/discharging to follow frequency or voltage droop control characteristics (bi-directional EV charging).

2.2 Reconfigurable stationary battery

The presented model focuses on describing the characteristic behaviour of a reconfigurable stationary battery, which is the type of electro-chemical storage that is going to be deployed on Bornholm. The idea behind this kind of battery technology is that the topology in which the cells are connected with each other can be changed in a real-time fashion [5]. This offers several advantages, such as an advanced battery management with the chance to improve the life-time, and the flexibility to follow a reference voltage without the need of power converters. The modelling of the battery system is realized in Matlab/Simulink [2].

In order to provide the voltage and current levels necessary for practical applications, stationary battery energy storage systems (BESS) reveal a modular and scalable design. Individual battery cells or blocks are electrically connected in series and/or parallel into modules, and several of these battery modules are integrated with required peripheral equipment into systems. The essential characteristic of a reconfigurable battery is that all cells can individually be connected or bypassed. This allows to control the output voltage by connecting the appropriate number of cells, without the need of any power converter. The battery device that is responsible for controlling the cell connection state is the battery management system (BMS). A BMS is responsible to ensure safety and increase reliability of a BESS as well as protect individual cells and modules inside the battery system. Furthermore, the BMS is used to improve energy efficiency of the battery system as well as prolong stability and durability of a BESS.

The modelled battery system includes 8 modules, each of them containing 24 battery cells that are arranged in a series connection. Since the BESS has a reconfigurable cell topology, cell states (e.g. SOC) may differ among the cells. Hence, each cell is modelled separately, which offers various options for analyzing the data acquired through the simulations. Figure 2 shows the view on the BESS when opening the model file. The part of the model with light red background is representing the physical properties of the battery including the effects of charging and discharging on the battery state. The part of the model with light blue background is the BMS containing the decision-making algorithm for connecting or bypassing the individual cells. The part of the model with white background is representing the data flow between BMS and the battery cells. Here, the data are clustered in order to avoid the use of too many connections within the model. Finally, the part of the model with light green background is assigned to the data analysis and simulation results.

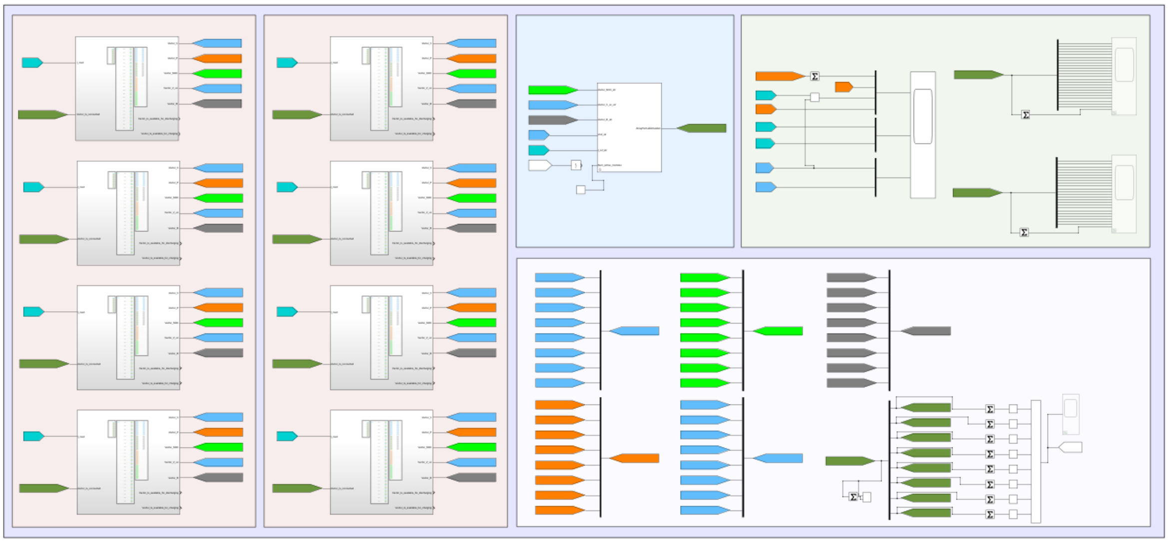

Figure 2. Battery model overview. Details are difficult to appreciate given the amount of blocks. The figure is intended only to give an overview.

One use-case for BESS is to provide the electric power for fast-charging of electric vehicles [7]. In the scenario that we are investigating, the BESS is directly connected with the EV, without any power converter interconnected between the two units. Hence, the modelling approach has two main objectives. First, the capability of the BESS to control the charging voltage according to the charging request of the EV can be evaluated. Second, the impact of the reconfigurable topology on the individual cells can be analysed.

The EV model is designed to behave like an EV while being connected to a fast-charging station [8], [9]. The EV model is also divided into a submodel representing the physical state of the battery and a submodel representing the BMS. During the charging process, the EV will send reference values for charging voltage and charging current to the BESS, according to the charging standard IEC 61851 [10]. Hence, the capability of the BESS to follow the charging request of the EV can be analyzed.

Figure 3 provides an overview of the connections between the two models. The model linkage is used to calculate the charging current resulting from the behavior of both units during the simulation. A description of the used variables is given in Table 1. To provide clarification, variables that refer to the BESS model have the superscript “BESS”, and variables that refer to the EV model have the superscript “EV”. If no superscript is given, the variable is a common representation that is applicable for both models.

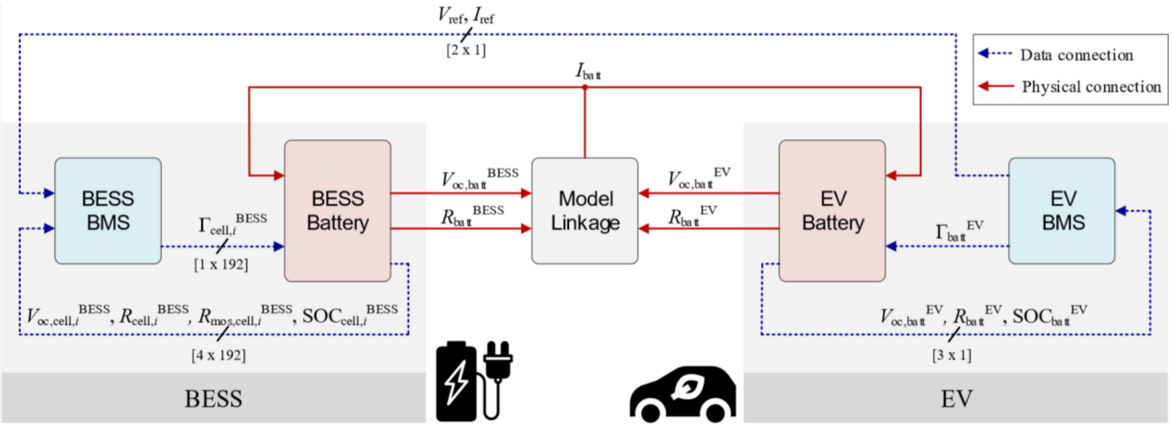

Figure 3. Overview of connections between BESS model and EV model.

Table 1. Variables used for model connection

Variable	Description
V_{ref}	Reference voltage sent by EV
I_{ref}	Reference current sent by EV
$V_{oc,batt}$	Battery open-circuit voltage
R_{batt}	Battery resistance
I_{batt}	Charging current
$V_{oc,cell,i}$	Individual open-circuit voltage of all cells
$R_{cell,i}$	Individual resistance of all cells
$R_{mos,cell,i}$	Individual resistance of the switches
$SOC_{cell,i}$	Individual cell state of charge
SOC_{batt}	Battery state of charge
$\Gamma_{cell,i}$	Individual connection state of all cells
Γ_{batt}	Connection state of the battery

3 USE CASE 5 MODELS

3.1 Virtual power plant

The model intends to assess the potential of the VPP linking different energy domains (electrical, thermal, transportation) for exploiting synergies between the different energy domains and supporting flexibility and ancillary service provision to the power system. Thanks to the implementation in DIgSilent PowerFactory, the model can be flexibly adapted for testing different system configurations and scenarios. The architecture of the VPP is based on the 60/10 kV Aakirkeby substation of the Bornholm's power energy system [11]. Figure 4 presents the single-line diagram of the modelled VPP [1].

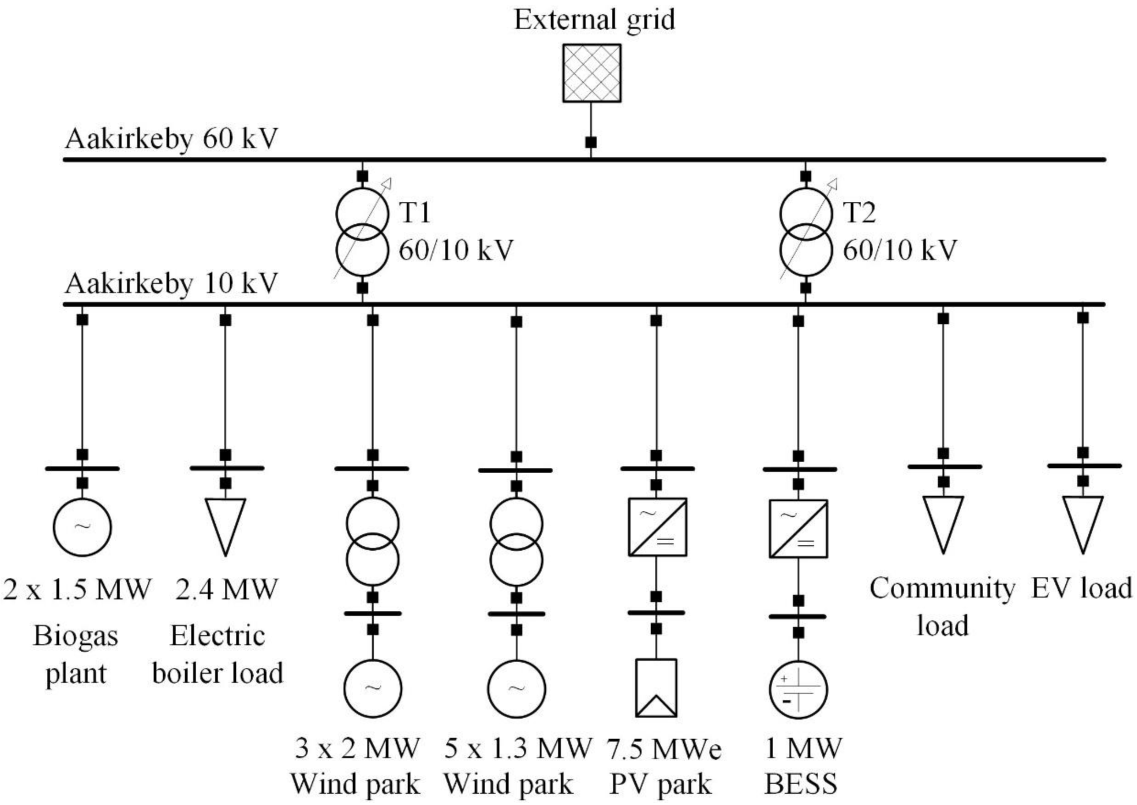

Figure 4. VPP single line diagram.

As it can be seen, it integrates a number of generation and consumption feeders, connected to the 10-kV bus of the substation. Among them are: a biogas cogeneration plant, two wind parks, a PV park, a 1-MW-MWh BESS, and a series of loads, such as a lumped Aakirkeby community load, an aggregated EV charging load, and a controllable load of the electric boiler of the Osterlars district heating plant. It has to be highlighted that while all the generation and consumption is currently present in the system and modelled based on historical data, the EV load represent a fictitious amount of EV charging which is likely to happen in the next 5-10 years. As such, EV charging profiles will be derived based on the data reported in this previous publication [12]. The 60-kV side of the substation and the 60-kV grid are currently considered as an infinite bus. Depending on the scope of the study, this can be adjusted by connecting the model to the existing model of the 60 kV grid of the Bornholm island.

The current version of the model is intended to perform dynamic studies of a hybrid wind-EV-oriented VPP [13], [14]. The remaining VPP elements are modelled via real generation or load behaviour profiles. An associated energy management and control system is being developed and integrated into the model [15]. The control system aims at compensating the fluctuations of wind generation by a bi-directional power exchange between the EV fleet and the grid via the V2G technology according to the wind turbine's production forecast.

Model inputs and outputs of the VPP model vary depending on the purpose of the study and on the VPP configuration. In the current version of model, the following input data with second-by-second time resolution are used:

- Power measurement profiles at the 10-kV sides of the 60/10 kV transformers.
- Power generation profiles of the wind park with controllable wind turbines (3 x 2 MW).
- Generation and consumption measurement for the rest of the feeders.
- EV load behaviour profile.

The developed VPP model will also provide input to BEOF for updating their energy simulation tool. Specifically, a new 'atom' called Power to X (P2X), for producing and store methane, from CO2 and H2 from electrolysis by wind and solar power.

3.2 Biogas plant

The model aims at simulating the internal processes of a biogas power plant, comprising the anaerobic digestion processes, the gas storage dynamics, and the combustion of biogas for generating combined heat and power (CHP), to assess the flexibility potential and the support towards a bio-based economy [3]. It can determine the electrical and thermal output of a biogas plant based on discrete feeding instances of animal manure or other biodegradable wastes. The model represents the relevant time constants of each of these three parts in order to evaluate the potential for flexibility as well as to analyze the interaction and mutual dependence of these coupled processes. The model is, in terms of size and parameterization, calibrated to Bornholm's Bioenergi biogas plant, and aims in its current form at reproducing the input-output relationship for the month of December 2018.

The model consists of three main parts constituting the (a) anaerobic digestion, (b) the gas storage, (c) the combined heat and power units. An overview is given in Figure 5.

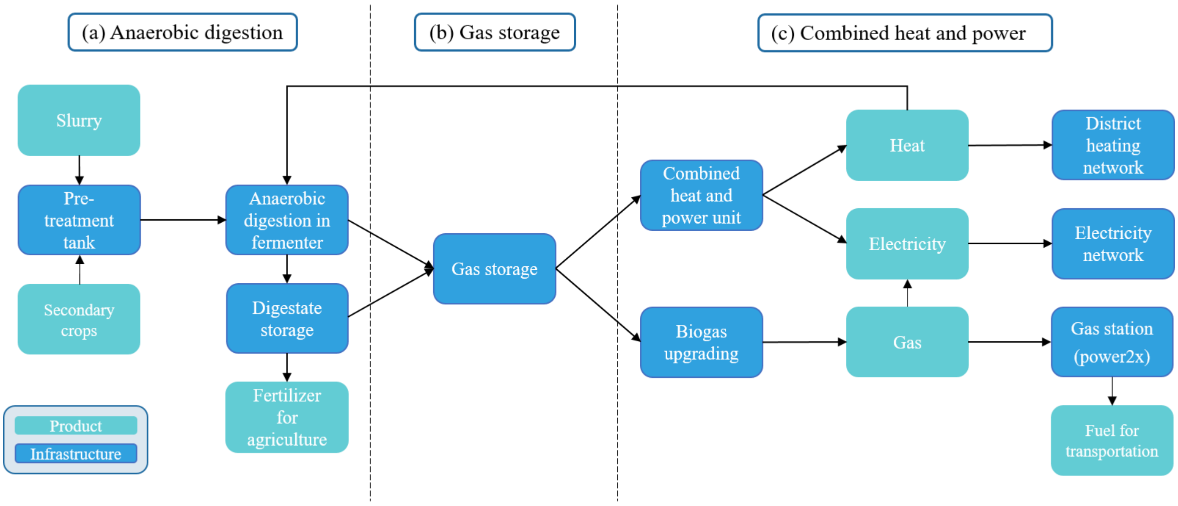

Figure 5. Biogas model overview.

The anaerobic digestion model simulates the biogas production of discrete daily feeding instances, which are based on historical data from the power plant. The model is structured with 15 indices (placeholders) which are used for separate biogas production from each feeding. This is due to the fact that the biogas is produced from one feed for at least 10-15 days, although feedings take place up to five times a week. For the first 15 feedings, one index after another is assigned with the relevant parameters. After that, the processes are replaced by the following algorithm: Once a new feeding is detected, the anaerobic digestion model assigns the new feeding mass and feeding time to the index with the lowest residual biogas production from the ongoing processes. The biogas yield of one specific feeding instance is implemented as a modified Gompertz function [16]. The total amount of biogas produced is consequently constituted of the sum of production of all the separated processes.

The gas storage of a biogas plant depicts the linking entity between the biogas production from the anaerobic digestion part and the burning of biogas for the generation of combined heat and power. The gas storage model takes as input the biogas influx from the anaerobic digestion model and the biogas outflow to the CHP units, and accumulates these flows. A protection system is in place to secure the upper and lower boundaries of the storage.

The two co-generation units considered in this study are of the kind Jenbacher JMS 420, manufactured by GE, each with a nominal electrical output of $\mathrm{P}_{el}^{max} = 1497\ \mathrm{kW}_{el}$ and thermal output of $\mathrm{P}_{th}^{max} = 1882\ \mathrm{kW}_{th}$. Under full load biogas operation of one generator, the electrical and thermal efficiencies amount to 42.3% and 53.2%, respectively. The part-load response of a generator is modelled with a decrease in electrical and a relative increase in thermal efficiency towards low loadings [17].

From an electrical point of view, the permanent utilization of pumps, mixing and stirring machines as well as the CHP control units amounts to a significant share of the own electricity production.

An electrical self-consumption of 13.36% of the own production was found to give accurate results. In terms of heat needed for pre-treatment and warming of the digestion tanks, a thermal energy self-consumption of the biogas complex of 45% is assumed [18].

The data set consists on the input side of the daily fed amount of manure, and hourly active power values from the biogas distribution network feeder, which are taken as reference for the electrical set point in the CHP unit. On the output side, the model retrieves secondly values for the produced amount of biogas, as well as generated electricity and heat. These results can subsequently be aggregated to daily values for a comparison with historical measurements.

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