SimBench - Documentation

Documentation Version EN-1.0.0

SimBench

Electrical Power System Benchmark Models

January 13, 2020

Authors

Energiemanagement und Betrieb elektrischer Netze

University of Kassel

M.Sc. Steffen Meinecke
Dr. Nils Bornhorst
Dr. Lars-Peter Lauven
M.Sc. Jan-Hendrik Menke
Prof. Dr.-Ing Martin Braun

Fraunhofer IEE

Fraunhofer IEE

M.Sc. Simon Drauz
Dr. Christian Spalthoff
M.Sc. Dennis Cronbach
Dr. Tanja Kneiske
Prof. Dr.-Ing Martin Braun

IAEW Institut für Elektrische Anlagen und Energiewirtschaft | RWTH AACHEN UNIVERSITY

RWTH Aachen University

M.Sc. Annika Klettke
M.Sc. Julian Sprey
Dr. Tobias van Leeuwen
Prof. Dr.-Ing Albert Moser

Institut für Energiesysteme, Energieeffizienz und Energiewirtschaft

TU Dortmund University

M.Sc. Džanan Sarajlić
M.Sc. Chris Kittl
Prof. Dr.-Ing Christian Rehtanz

Contents

1 Licence

2 Introduction

SimBench is a research project to create a "simulation database to allow comparing innovative solutions in the field of network analysis, network planning and operation". SimBench was conducted for three and a half years from 1.11.2015 to 30.04.2019. It was part of the German Federal Government's 6th Energy Research Program "Research for an Environmentally Friendly, Reliable and Affordable Energy Supply". The above mentioned authors of the University of Kassel, the Fraunhofer IEE, the RWTH Aachen University and the Technical University of Dortmund carried out the project. The project, coordinated by the University of Kassel, was supported by the professional advisory from six German distribution network operators: DREWAG NETZ GmbH, Energie Netz Mitte GmbH, ENSO NETZ GmbH, Netze BW GmbH, Syna GmbH and Westnetz GmbH.

2.1 Motivation

The development of new technology as well as legal and regulatory framework changes lead to continiously challenges in the field of electrical energy supply. In particular, the shift towards a sustainable energy economy with reduced greenhouse gas emissions cause changes. As a result, researchers and grid operators conduct several power flow based studies to improve the electrical energy supply. For simulations with power flow calculation programs (such as PowerFactory [1], Integral [2] or `pandapower` [3]) grid parameter data of the grid models are required. In a lot of cases, it's meaningful to use the real grid data. But there is also a variety of use cases where the usage of realistic grid data is sufficient. Publicly available grid data are helpful for research and to improve the electrical energy supply. They can accelerate research by reducing processes regarding discussion, authorization between partners and exchange of data, and also help deliver transparent and comprehensive results. Different approaches can be compared based on publicly available grid data and other work can thus be reproduced and verified. Simulations with publicly available grid data can fulfill the general requirements for scientific research purposes.

Due to the above-mentioned continuous change of real power systems, the suitability of unchanged grid data decreases over time. New or revised grid data becomes necessary. For instance, smart grid operation strategies with distributed energy resource (DER), controllable loads and energy storages cannot be efficiently developed, since these information do not occur in older grid dataset as they are nowadays or as expected in the future.

Benchmarking is defined as a process to measure the performance of a tool, software or business process under predefined or determined conditions, which enables comparing or evaluating [4]. Grid data, which are appropriate to serve as a data bases in order to compare different tools for grid operation, grid extension and grid simulation, are defined here as a benchmark grid. Benchmark data is of great interest for researchers, since they do not need to generate their own grid dataset and the results can be easily compared with other work using the same grid data. Grid data that is well thought out, properly selected and publicly available can save developers many efforts in compiling, customizing and improving the grid dataset.

2.2 State of the art

A large number of elaborated and useful grid datasets already exist. The grids can be distinguished from each other by different aspects. There are old and new, simple and extensive network models available. Likewise, grid data exist in all common voltage levels as well as for different regions or use cases. Therefore, in research project SimBench an overview of existing, publicly available grid data and time series is created and published online (↳Link). Despite the existing public grid data, there is a need for new, suitable benchmark grids due to the multitude of different properties and use cases as well as the continuous change of real power systems and requirements for grid datasets.

Existing grid data are sometimes published without mentioning the intended use cases or providing information about the origin of the data. Thus, available network data are repeatedly used for use cases for which they were not explicitly compiled [5]. A general methodology to meet the continuous need for new benchmark grid data is still missing.

Another point is that benchmark datasets designed to allow multi voltage-level simulations are rare. So far, different types of grids from different origins are often combined for cross voltage-level studies [6, 7]. Furthermore, because there are hardly any benchmark datasets with existing and assigned profiles of loads and generations, users must use third-party data [8, 9, 10]. This means that reproducability and comprehensibility can only be achieved with extra effort.

To simulate and analyze new solutions of grid planning and operation, it is crucial that underlying grid has an appropriate state. For example, investigations on the reduction of active power of renewables (peak shaving) and comparisons of operation strategies of DERs are only meaningful if the high infeed leads to voltage or loading violations. Another example is to determine an optimal switch configuration among a large set of possible combinations. For that, the grid cannot be in a state, that no combination can solve the operational violations in the grid. As a result, researchers are often forced to manipulate the grid data to reach a desired grid state.

2.3 Objectives and contributions

The objective of the research project SimBench is to develop a benchmark dataset to support research in grid planning and operation. The SimBench grids differ from other grids in the following key aspects:

- Consideration of a wide range of use cases during the development of the dataset
- Provision of grid data for low voltage (LV), medium voltage (MV), high voltage (HV), EHV as well as design of the dataset for a suitable interconnection of a grid among different voltage levels for cross-level simulations
- Grid data in three scenarios, i.e. variants, to provide today's grid states without voltage and current violations and future grid states with violations (grid extension measures are neglected)
- Ensuring high reproducibility and comparability by providing clearly assigned load and generation time series
- Validation of the suitability of the datasets by means of literature research, comparisons to real grid data, expert advice and simulation calculations

The focus of the dataset generation and validation is Germany. Nevertheless, the SimBench dataset can also be applied internationally if simulations are performed for comparable grids. As mentioned in Chapter 1, it is published under the ODbL license.

Grids that can be used, for example, to draw conclusions or extrapolate to real grid areas are not the goal of SimBench. It is also not the aim to create models of real existing grids. Such grids would be conceivable, but are not a prerequisite for appropriate benchmark datasets.

The objective of the project includes also the development of a methodology to create a benchmark grid.

2.4 Structure of this documentation

The aim of this documentation is to describe the developed and publicly available SimBench benchmark dataset (Chapter 4), to present the methodology to generate the data (Chapter 3) and to provide the user advices on the appropriate use of the data (Chapter 5 and appendix). An analysis whether other energy networks, such as gas and heat networks, can be modeled as benchmark network with a similar methodology was also carried out but is not covered in this documentation.

3 Methodology to generate the SimBench dataset

In the research project SimBench, a general methodology for a stepwise generating of benchmark grids is developed [11]. It enables developing benchmark grids for different use cases or voltage levels. The grid design can vary on the objectives and available information. First of all, the general methodology is explained using the MV as example. Then, the specifications of the application of the methodology on other voltage levels are presented.

3.1 A new general methodology to generate benchmark grids presented by the application to the medium voltage level

In this section, in addition to [11], MV examples are used to explain the methodology in SimBench. Development criteria are that the SimBench methodology should be appropriate, applicable, scientific and comprehensible. Besides the generation of the SimBench dataset, the objective of the methodology includes to allow updating SimBench properly. If the dataset is not sufficiently extensive for extra use cases, the user can apply the same, general methodology and extend the dataset comprehensively and transparently. The methodology is also intended as an example for other benchmark projects.

Figure 3.1 illustrates the flowchart of the methodology. The Steps 1-4 are designed to obtain a comprehensive information on suitable grid data. This should lead to a compilation of precise requests on the grid data and recommendations for the grid parameter selection. By going through these steps under common consideration of defined use cases, those with potentially conflicting parameter choices can be found and reconciled in the early phase. In Step 5, the grid will be created and then tested in Step 6. The iterative process of Step 5 and Step 6 is the key to ensure appropriateness, applicability and comparability of the dataset. For each of the four voltage levels (EHV, HV, MV and LV), the complete methodology is carried out separately. Finally, combinations of two voltage levels are validated, including all voltage levels, time series and development scenarios. A comprehensive iterative evaluation of additional combinations, as well as more than two voltage levels according to the loop of Step 5 and 6 was not conducted.

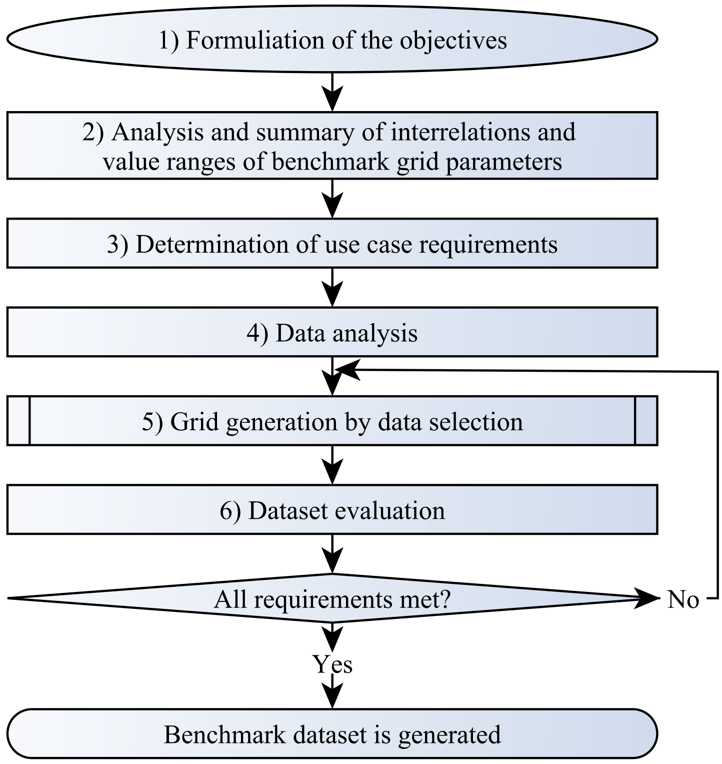


Figure 3.1: Flowchart of the benchmark generation methodology

3.1.1 Objectives and defined use cases

The objectives for the creation the SimBench dataset have already been introduced in Section 2.3 and remained unchanged for the MV grid. The addresses include all those, who conduct power grid studies on the basis of static power flow calculations, most notably in the German or European context as well as researchers and grid operators. The use cases, which are relevant to create the dataset and considered in our scope, are summarized in Table 3.2 and 3.3. An example calculation for the use case grid planning will be introduced in Chapter 5.

3.1.2 Analysis and summary of relevant interdependencies and value ranges of benchmark grid parameters

With this step, it should be estimated at an early stage in the dataset creation process, which sub-areas are relevant, which grid parameters have expected influences on the objective and the range of these grid parameters. The following influencing factors have been classified to be of high or very high relevance: grid topology (e.g. mesh grade, number of parallel lines and transformers, feeder lengths, number of branches), rated voltage, transformer model and parameterization, selection of cable or overhead line (OHL), line types, line lengths and distribution of generations and

Table 3.1: List of considered use cases in the filed of transmission system operations

Acronym	Mainly affected voltage levels	Use case
TSO1	EHV, HV	Retrieval and dimensioning of reactive power
TSO2	EHV	Retrieval and dimensioning of control power
TSO3	EHV, HV	Failure simulation
TSO4	EHV	High-voltage direct current transmission usage
TSO5	EHV, HV	Redispatch simulation
TSO6	EHV, HV	Simulation of grid restoration
TSO7	EHV, HV	Voltage and reactive power optimization
TSO8	EHV, HV	Voltage stability evaluation
TSO9	EHV, HV	Topology optimization

loads. Variables, whose importance depends heavily on the use case, are: switch and substation conceptions, energy storage and modeling of external grid. For the MV, the compensation system, due to their rare appearance, and the grounding treatments, due to the addressed use cases in SimBench, are classified as less relevant.

The results from data analysis in Step 4 of the characteristic and range of grid parameters will be compared and validated with those from literature. The found values of the variables “grid topology” and “cable-OHL ratio” will be briefly introduced here: The most widely used grid topologies in MV level are open-ended rings [12, 13, 14, 15]. In the books [16, 12], further popular and conceivable topologies, e.g. those with remote station, base station and triple ring system, are introduced. In a German distribution grid study [15], on MV level, 70 %-95 % share of cables were characteristic while only 40% for some rural areas can be observed. The German association of energy and water industries (BDEW) announced in 2013 a total 78.8 % of share of cable in Germany [17], while another study [18] claimed a median of 56.8 % with large deviation for Europa. Using the information determined in this way and the evaluations of Step 4 described below, MV grids with the various frequently occurring grid topologies and cabling degrees are created in Step 5.

In an extensive literature review, publications related to grid classification or clustering were analyzed for their classification and resulting classifications (MV: [15, 19, 20, 21, 22, 23, 24, 25], LV: [26, 14, 27, 28, 29, 30]). The five most commonly used criteria for grid classification are the power rating of transformer, total length of lines, total length of cables, total length of OHL and the total number of grid supply points. In addition, we attempted to summarize the identified grid classification and extract those, which were frequently referred to. These are categories, such as rural/village, semi-urban/urban/rural, urban/commercial and, when needed, their several subclasses. Due to different data sources from different countries for different types with energy supply, different standard voltage levels and different grid classifications, a direct comparison of resulted grid classification is hardly possible. Consequently, it is not possible to determine a

Table 3.2: List of considered use cases in the filed of distributed system operators

Acronym	Mainly affected voltage levels	Use case
DSO1	HV, MV	Reactive power supply of higher-level grid operators
DSO2	HV	Active power curtailment request of higher-level grid operators
DSO3	HV - LV	Voltage control
DSO4	HV, MV	Central reactive power control
DSO5	HV	Losses minimization
DSO6	HV, MV	Active power peak shaving in operation management
DSO7	MV	Foresighted operation management
DSO8	MV, LV	Grid automation with local or decentralized controllers
DSO9	MV, LV	Automated restoration of supply after failure
DSO10	MV, LV	Sectioning point optimization
DSO11	HV	Local congestion management
DSO12	HV, MV	Multi-voltage congestion management
DSO13	MV, LV	State Estimation in the distribution grid
DSO14	EHV, HV	Power flow control in the transmission and distribution grid
Plan1	MV, LV	Autonomous distribution grid operation/configuration
Plan2	HV, MV	Automated power system restauration
Plan3	HV - LV	Conventional network planning
Plan4	EHV, HV	Multi-voltage network planning
Plan5	HV - LV	Ancillary services from distribution grids
Plan6	EHV - LV	Time series based grid capacity analysis
Plan7	EHV - LV	Conventional network planning + SmartMarket + SmartGrid
Plan8	HV	High-voltage direct current line usage in distribution grids
Plan9	HV, MV	Topology optimization
Plan10	LV	Testing of application concepts for controllable MV-LV transformers

number of grid classes that are suitable for different grid areas. However, it can be stated that the four aforementioned classes are used very frequently, sometimes in slightly different variants. Furthermore the number of network classes is never less than four. This information on classification variables and resulting network classes is also used in Step 5.

3.1.3 Determination of use case requirements

An essential criterion to evaluate the quality of a benchmark dataset is the applicability for the intended use cases. The influencing factors relevant for studying the use case should be clearly defined by the dataset. Variables, which may be handled differently by algorithms and approaches, are not required, but can be added manually by the user. Besides the completeness of necessary data, suitable parameter selection is necessary for the simulation of use cases. In SimBench, possible control variables, output variables, input variables with big impact are determined for all addressed use cases in this step.

Table 3.3: List of considered use cases in the filed of network simulations

Acronym	Mainly affected voltage levels	Use case
Sim1	MV, LV	Development and testing of the integration of new plant and storage models
Sim2	EHV - LV	Network simulation with various software tools
Sim3	HV - LV	State Estimation
Sim4	EHV - LV	Probabilistic power flow analysis
Sim5	EHV - LV	Accelerated and modified power flow analysis

The number of available grids in SimBench is limited, so users can get a quick overview of all of them, which also ensures good comparability of results from SimBench grids. With similar but different grids for the same purpose, it can be expected that diverse users would develop and apply comparable algorithms on them, although from the same provider, which still makes the results incomparable. On the other hands, with the increasing number of grids with different configurations provided, the challenge in results delivery and visualization increased tremendously as well.

The variables required for the use cases listed in Table 3.2 are extensively summarized. In addition to the highly relevant variables from Step 2, extra variables such as generation, load and storage time series and the modeling of the voltage level transition of storage, heat pump (HP) and electromobility have to be considered. The required time series is marked as bus-specified (locationally) and has a resolution from minutes to quarters (timely). The high-voltage direct current (HVDC) lines are not a relevant quantity for MV. The literature review for elaborated, detailed model of information and communication technology (ICT) did not reveal any simple models to provide additional value for the development of a SimBench dataset. In the publications with the focus on ICT, different reality-close complex models are used, e.g. [31, 32]. As a result, SimBench does not contain data for ICT modeling.

Following are derived requirements for the MV grid data:

- Only typical voltage levels are allowed (20 kV or 10 kV)
- Different grid topology (and grid station planing) should be present to investigate differences, including radio grids, ring grids (opened, closed, tripled), grids with base station or remote station, respectively HVMV substation configuration like H-arrangement and busbar conception.
- The size (number of nodes) of the grids should be realistic. A supply of about 70-250 local grid stations is estimated to be realistic, with which the benchmark grid have realistic demands and the solution worked on this scaling best will be preferred.

- The usage of standard equipment types such as lines and transformers meets the requirements of the reality.
- Cable and OHL should be taken into account separately due to their different electrical behaviors.
- For the active and reactive power of loads as well as active power of generations, the yearly time profile should be clearly assigned, in order to get the results to be comparable with other studies based on yearly time series. Reactive power of generation is not required, since it is relevant to the user-defined operation strategy.
- To compare the conventional grid construction plan with other methods for grid congestion managements or time-series based grid construction planning, relevant load and generation development in the future should be considered.
- For different use cases, grid with and without operational limits are required. It should be the case that up-to-date and reality-close grid without limit violations as base version and also development variations with limit violations (Without any implemented grid reinforcement), e.g. Scenario 1: Future grid with normal increase of DERs, Scenario 2: Future grid with large increase of DERs and also warm pumps and electromobilities.
- In development scenarios, the voltage and operational limits violations with no or just simple operation are needed, so that development of solutions such as improved grid operation or grid reinforcement and expansion must be involved.
- In base grid (scenario 0) voltage and operational limits violations should not exist under normal and (n-1)-cases.
- Enough DERss must exist in the grid for the multiple use cases, in which enough set range for grid operation strategy is required.
- For the use case “State Estimation”, different penetration grades of measuring points should be defined to be compared between these scenarios.

3.1.4 Data analysis

A data analysis of real grid data will improve the chance of the proper selection and creation of grid data in Step 5 and make it possible to use the parameter choice as a starting point. With data analysis, it can be estimated whether the final benchmark dataset are realistic enough and fitting for the comparison of solutions and algorithms.

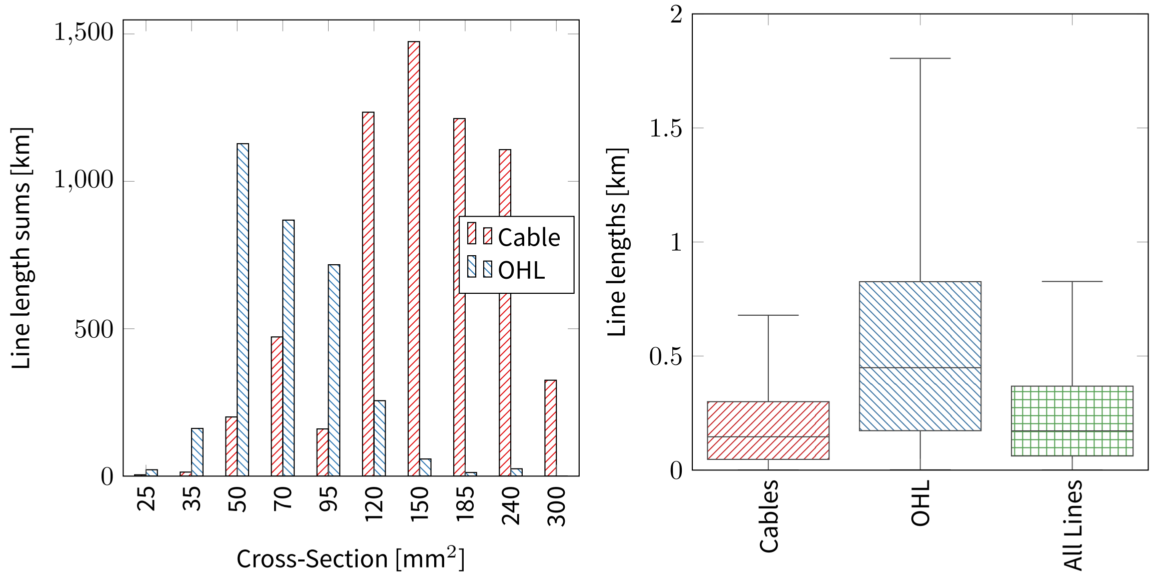


Figure 3.2: Example results of data analysis: cross-section distribution (left) and line length boxplots (right) by line type in real MV grids

In the publication [11], the methods of data analysis processes were introduced, such as analyses with expert questionnaires, statistical analysis of grid parameters, correlation analysis and complex analysis like cluster analysis, as well as their individual data requirements. Unlike EHV and HV, for MV the publicly available data from openstreetmap [33] or other sources are not sufficient for the analysis. While at LV level, grids may be deduced from pieces of information like population and building distribution and road maps, combined with assumptions on planning and operation principles, this is more difficult and uncertain for MV. As a result, we focused on analyzing parameter statistics of real grids and evaluating expert questionnaires for MV. Relevant information to create the benchmark grids are derived from power flow analysis and statistical parameter analysis of real grids. Distributions and correlations of grid parameters of 74 separately operated MV grids with a total line length of around 11 000 km from five distributed system operators (DSOs) were analyzed. Figure 3.2 exemplary illustrates the line cross-section distribution and total line lengths for cable and OHL. The deployed cable and OHL cross-sections correspond closely to their individual maximum line currents. The right diagram of the lengths boxplots gives an overview of MV line lengths and shows that OHL are frequently used for long distances. Since the lower OHL bars of the left diagram signify that the share of OHL is only 19.8 %, the boxplot of all lines is very similar to the boxplot of cables. Other parameters and correlations are analyzed similar to the results in Figure 3.2, e.g. DER position in feeder or MV/LV substations per HV/MV substation capacity ratio.

3.1.5 Grid generation by data selection

In this step, data selection and grid generation are described, given that all requirements have properly been considered in the previous steps. The final benchmark grid will be created in this step as long as to be qualified as satisfactory in Step 6. SimBench used the simple five-step process proposed in the publication [11].

The required number of the MV grids to be created in Step 3 is defined as four as frequently identified in literature in Step 2. The MV grids created in the first iteration are described with the parameter values in Table 3.4. The parameters in blue will be tuned noticeable in the validation step. The final grid parameters are summarized in Table 4.2.

3.1.6 Dataset evaluation

The grid dataset will be validated in this step to guarantee the the requested quality and functionality through visual inspection, power flow simulation, use cases execution and evaluation and also evaluation within the consortium as well as with the grid operators. Use cases to be executed for testing of MV are summarized in Table 3.5.

Repetitions of Step 5 and 6 are requested by the methodology and were also done in SimBench, from which the following exemplary improvements are suggested:

- In order to have a (n-1)-secure base grid, it is important to ensure that the grid topology is designed to ensure that the resupply feeder is properly dimensioned for the feeder to be connected and both parts of the opened ring to be connected at different MV busbar sections.
- DERs should be positioned at the beginning or end of a feeder to enable the study of the different influencing factors (relevant for use case VNB1-8)
- For the use cases VNB6-7, multiple DERs are connected to the same feeder, ideally with similar installed capacities.
- Inter voltage-level conjunction points and respective grid boundaries must be modeled properly in order to simulate the exchange of reactive power with HV grids (use case VNB1).

The final MV dataset will be introduced in Section 4.1.3.

Table 3.4: Overview of grid describing parameter of the MV grids created within the first iteration

Grid character	Rural	Semi-urban	Urban	Commercial
Topology	Open ring systems	Open ring system with triple-system	Open ring system with cross-links and base station, MV double busbar	Open ring systems with unsupplied remote station, MV single busbar with two vertical couplers
Rated Voltage [kV]	20 kV	20 kV	20 kV	20 kV
No. of nodes	106	121	180	104
HV/MV Transformer rated power	25 MVA	40 MVA	2x63 MVA	40MVA & 25 MVA
Sum of loads	20.7 MW	40.4 MW	120.6 MW	45.9 MW
Sum of DER	19.6 MW	17.4 MW	19.8 MW	12.5 MW
No. of feeders	8	9	14	9
Extreme feeder lengths	10-30 km	3.8-12.1 km	2.6-5.8 km	4.8-16 km
Medium feeder length	16.3 km	7.8 km	3.7 km	9 km
Extreme no. of supply points per feeder	5-26	6-22	9-20	3-21
Medium no. of supply points per feeder	13	13	12.5	11.1
Share of cables	40 %	70 %	100 %	73 %
DER types directly connected to MV	PV, Wind, Biogas	PV, Wind, Hydro	PV, Waste	Gas

Table 3.5: Overview of the executed evaluation of MV Grid

Study subjects	Associated use cases
Time series based grid utilization	VNB1-8
Voltage stability - Comparison of operation strategies	VNB1-4, VNB8, VNB11-12
Reactive power provision - Comparison of operation strategies	VNB1-4, VNB8, VNB11-12
Peak shaving - Comparison of operation strategies	VNB6-7, VNB11-12
Topology test (including (n-1)-check)	VNB9-10
State Estimation	VNB13

3.2 Methodology on extra high voltage level

This section is intriduced by a brief overview of the characteristics of the extra high voltage grid. The extra high voltage grid is used for electricity transport within Germany and is characterized by the increasing share of feed-in from DER by power flows in a north-southwest direction, which may lead to overloads. In addition to the electricity transport within Germany, increasing European electricity trade leads to transit flows, which can also lead to a higher utilisation.

Due to the differing supply tasks at transmission level, no typical grid structures can be derived. In addition, modeling of the extra high voltage level as an entire grid is state of the art. From the above points it can be deduced that it does not make sense to divide the extra high voltage grid into different network areas. Furthermore, the reproducibility of transit flows is of high relevance for the generation of a realistic grid model. For this reason, extra high voltage is not modeled as a part of the network, but the entire grid is modeled in this approach.

The approach for generating the grid model for the extra high voltage level is based on the use of the SciGrid dataset. Here, only the nodes and lines as well as the device characteristics of the dataset are transferred. This dataset is extended to suit the derived use cases by modeling transformers, a supply task (conventional power plants and regenerative energy generation as well as loads) and switchgear configurations. The result of this extension is a computable grid model on the EHV level as a basis for the simulation of grid planning and grid operation. The individual steps involved in generating the network model are described in detail below.

3.2.1 Topology

Basically, the SimBench project is motivated the same way as the SciGrid project: A publicly available dataset is to be generated for the execution of simulations. Initially, the publicly available data will be downloaded from OpenStreetMap for this purpose. The first filtering of the data takes place in order to prevent the download of a larger amount of data. The filtered data is stored in a database suitable for geoferenced data and abstracted to a coherent bus-branch model as shown

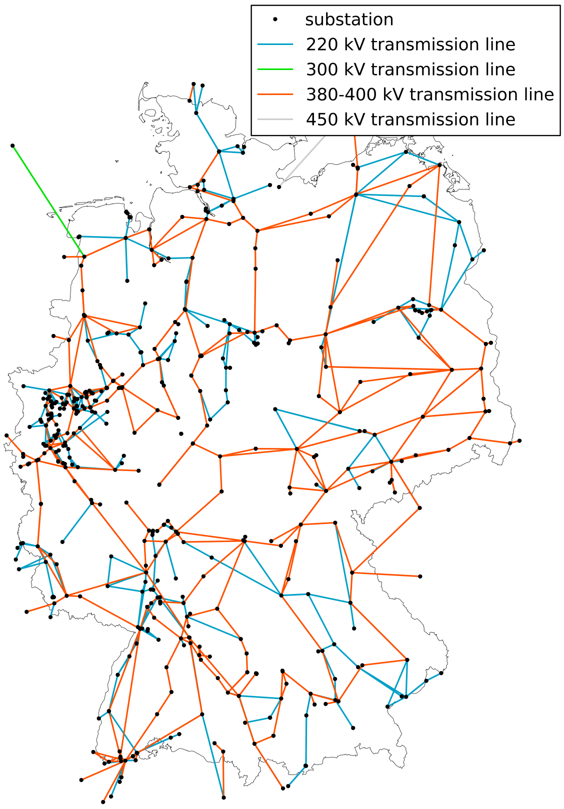


Figure 3.3: Grid model SciGrid

in Figure 3.3. The abstraction is based on the information available in the form of *nodes*, *ways* and *relations*. For a description of the detailed procedure refer to [34].

After generating the bus-branch model, the grid model is visualized (see Figure 3.3). The focus of SciGrid compared to SimBench is more on providing the source code for grid model generation. With SimBench, the focus is on providing a dataset that is as comprehensive as possible for simulating a large number of different use cases. For this reason, the dataset is extended to include the SimBench" use cases. The equipment parameters used in SimBench are shown in Table 3.6 for the cable types and in Table 3.7 for the selected transformer type. The equipment parameters of the transformers are based on the data of standard equipment. It should be noted that parallel circuits are modeled as line types with a higher maximum load.

Starting from the topological description of the EHV grid, the model is validated with available grid maps as given in [35] and [36].

Table 3.6: Equipment parameters of the EHV lines

id	r (Ω/km)	x (Ω/km)	b (μS/km)	iMax (A)
LineType_1	0.08	0.32	3.613	1300
LineType_2	0.025	0.25	4.304	2600
LineType_3	0.05	0.5	2.152	1300
LineType_4	0.033	0.333	3.228	1950
LineType_5	0.04	0.16	7.226	2600
LineType_6	0.1	1.0	1.076	650
LineType_7	0.16	0.64	1.806	650
LineType_8	0.053	0.213	5.419	1950
LineType_9	0.017	0.167	6.456	3900
LineType_10	0.013	0.125	8.608	5200
LineType_11	0.008	0.083	12.912	7800
LineType_12	0.006	0.063	17.216	10400

Table 3.7: Equipment parameters of EHV-transformers

id	sR	vmHV	vmLV	va0	vmImp	pCu	pFe	iNoLoad
Typ_x_380/220	600	380	220	0	18.5	1500	250	0.042

id	tapable	tapside	dVm	dVa	tapNeutr	tapMin	tapMax
Typ_x_380/220	1	HV	1	0	0	-16	16

3.2.2 Supply task

Next to the grid topology, the calculation of power flows requires the modeling of a realistic supply task as basis for the use cases. The supply task includes the respective infeed and load at the grid nodes and is described in detail below.

Infeed

The following steps are used to describe the the modeling of infeed

1. adjustment of the power plant list of the Federal Network Agency (BNetzA) for decommissioned power plants
2. selection of all power plants in grid connection levels from 110 kV
3. calculation of the area centres of the postcode areas from publicly available shape file with QGIS

Table 3.8: Assumed Merit Order List of Conventional Power Plants

Rank	Technology
1	Nuclear
2	Lignite
3	Coal
4	Gas
5	Waste
6	Oil

4. calculation of the smallest distances from postcode area centres to previously determined grid nodes

The BNetzA power plant list contains the individual generation units as well as the respective allocation to postcode areas. In addition to current generation units, this list also contains power plants that have already been decommissioned and must first be filtered out. In addition, only power plants with a minimum voltage level of 110 kV or higher are taken into account. For the postcode areas assigned to the individual power plants, the respective centre calculated using QGIS [37]. When allocating power plants at the EHV level, the use of Voronoi areas is not necessary for generating the "SimBench" dataset, since the power plants are allocated exclusively to a node and the procedure therefore leads to the same results as determining the smallest distance. By determining the smallest distance between the centers of postcode areas and the previously determined grid nodes, the generation units are assigned to the existing grid topology.

To model the market results of conventional power plants, the utilization of conventional power plants is determined on the basis of the infeed from renewable power plants and the loads. In a first step, the residual load is calculated based on the time series of the infeed from renewable energies and the loads.Since losses occur during grid operation depending on the line parameters, a certain factor must be applied to the load in order to avoid imbalances between the market and the grid. A load factor with a share of 2 % of the load per time step is assumed, so that the residual load must be increased by this value. For the use of conventional power plants to cover the residual load and the losses, a simplified heuristic is used under specification of a merit order list, as shown in Table 3.8.

For the determination of the power plant usage according to the merit order list, a share of 70 % of the maximum power is defined to achieve a homogeneous distribution. The maximum power is limited to 70 %, so that, for example, the provision of control power is modeled in a simplified way and the load is not only covered by a small number of power plants in maximum operation. The homogeneous distribution concerns on the one hand the geographical, on the other hand also a technology-specific distribution. The resulting power plant dispatch for an exemplary week is shown in Figure 3.4.

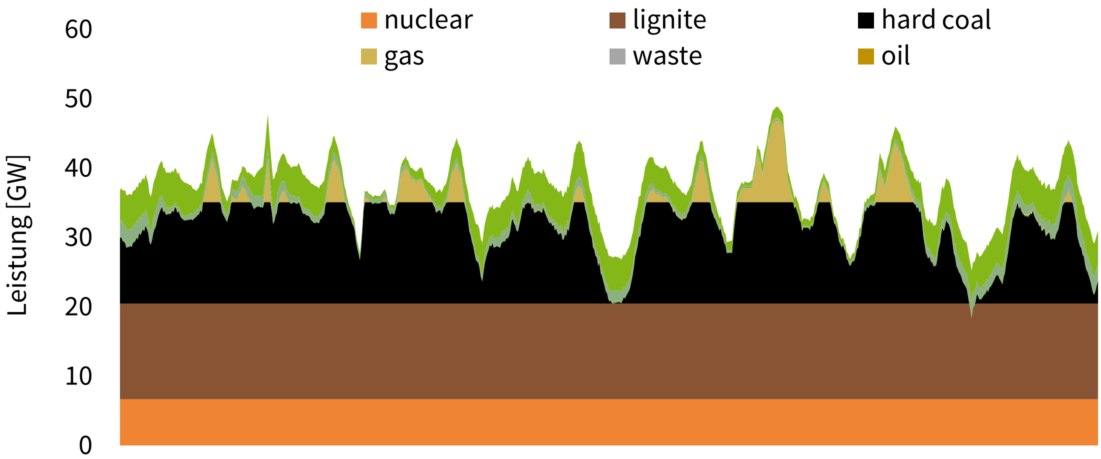


Figure 3.4: Power plant dispatch for an exemplary week

The neighboring countries are represented by boundary nodes with an export time series and a slack. By specifying a value for the slack from the boundary nodes, it is also possible to model transit flows.

Load

The distribution of the load is based on the total load according to the publication of ENTSO-E. This involves the aggregation of spatially highly resolved time series into extra-high voltage nodes using Voronoi regions. The assignment of the total load is made by the absolute peak values of the aggregated time series. A detailed description of the load allocation can be found in Section 3.5.3.

3.3 Methodical approach of the HV level

The generation of benchmark grids for the HV level is carried out in the same way as for the other voltage levels with the aim of a realistic representation of HV network structures as a benchmark for innovative solutions in the simulation of network planning and network operation. In the following, the characteristics of the HV network are described first.

The overall German HV grid is divided into several grid areas assigned to individual grid operators. These grid areas in turn are subdivided into individual groups, which are in some cases galvanically isolated. The HV grid has a high degree of intermeshing and an inhomogeneous grid structure. Both the network structure and the use of resources are regionally dependent and historically influenced. In urban grid areas, for example, there is a high share of cables and in rural

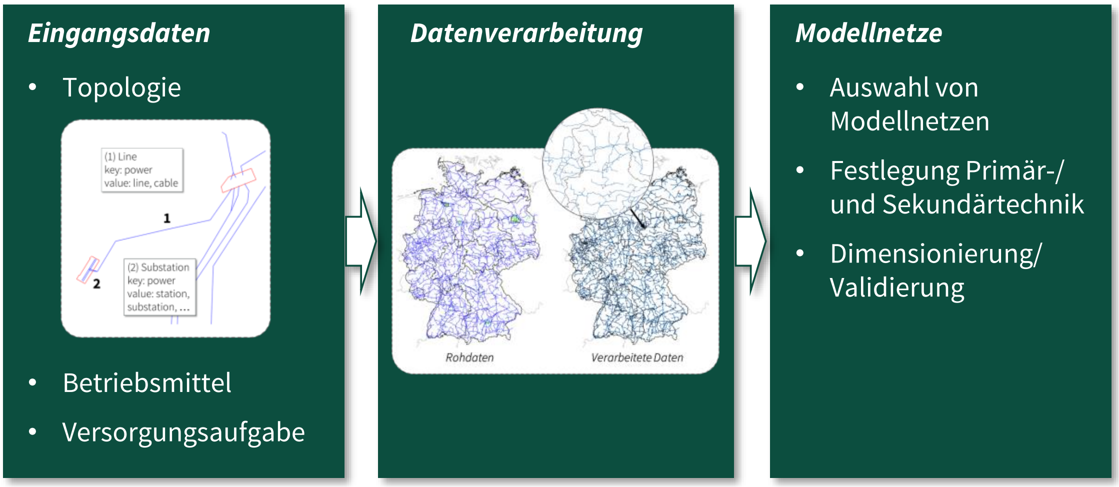


Figure 3.5: Overview of the procedure at HV level

grid areas there is a high share of overhead lines. The characteristics shown here suggest that the calculation of the overall HV level for many use cases results in a very high calculation effort. In addition, the calculation of the overall grid is not effective against the background of the galvanic isolation of grid areas. For this reason, the SimBench dataset in the HV level is limited to two representative networks. This decision was made consciously despite the knowledge that no representativeness for all HV networks can be guaranteed. Here it is again underlined, that the main focus of SimBench is to cover a variety of use cases in network planning and operation and no representation of the overall German HV grid is provided.

The general procedure for generating benchmark grids for the HV is shown in Figure 3.5 and is explained below. The input data for the generation contain the topology of the networks, the parameters of the equipment and the supply task. Based on this input data, data processing is performed with the aim of generating a coherent bus-branch model that fulfills the corresponding supply task. Finally, the selection of the benchmark grids, the determination of the primary and secondary techniques as well as the dimensioning and validation of the models are carried out using an (n-1)-failure calculation. The steps presented here in an overview are described in detail below.

3.3.1 Input data

The first step is a detailed description of the available data. Data sources are georeferenced data from the OpenStreetMap project, publications by HV network operators, e.g. the annual maximum load or the overhead line or cable length in their network areas, as well as the power plant register [38] published by the BNetzA.

OpenStreetMap

OpenStreetMap is a publicly accessible and expandable map for georeferenced data [39]. The raw data are either collected by volunteers or made available from other sources and drawn in afterwards with the help of an editor, so that it is possible to identify geographical routes. An essential advantage, besides the availability, is the so-called *Tagging*. *Tags* are included in the OpenStreetMaps data and contain information about certain properties of the data. With regard to the electricity supply system, for example, information on voltage levels or lines can be stored as a tag and later read out again. Due to the large amount of data in the HV level, the completeness of the elements of the electricity grid is not given. In particular, data such as the number of circuits, electrical parameters or cabling are subject to uncertainties. Here assumptions are made in the SimBench dataset, which are represented in Section 3.3.3. In contrast to the MV and LV levels, however, the database is sufficient for deriving the bus-branch model.

Network structure data of the network operators

Distribution system operators are obliged to publish their network structure data in the internet. According to § 17 StromNZV this includes the vertical load, the annual maximum load, the load curve and the sum of all infeeds per voltage level as well as the circuit lengths, the installed capacities of the transformer levels, the annual work taken from the previous year, the number of tapping points, the number of inhabitants, the area supplied and the geographical area according to § 27 Abs. 2 Nr. 1 to 7 StromNEV. These data are used to complete missing data from OpenStreetMap.

Power plant register

The power plant register provides a data base for renewable energy sources (RESs) in order to make the expansion transparent. Due to the protection of personal data, the BNetzA publishes the so-called power plant basic data, so that only the communal key, the town and the postcode are given for the locations of small power plants. By using the information on the postcode areas of the respective installation, a geographical distribution of these can be carried out.

3.3.2 Data processing

Based on the described data the generation of the benchmark grids is explained. First, the overall German HV grid model is generated. From this, network sections are generated as benchmark grids depending on the supply task and the topology. In this section the procedure and the algorithms are described in more detail.

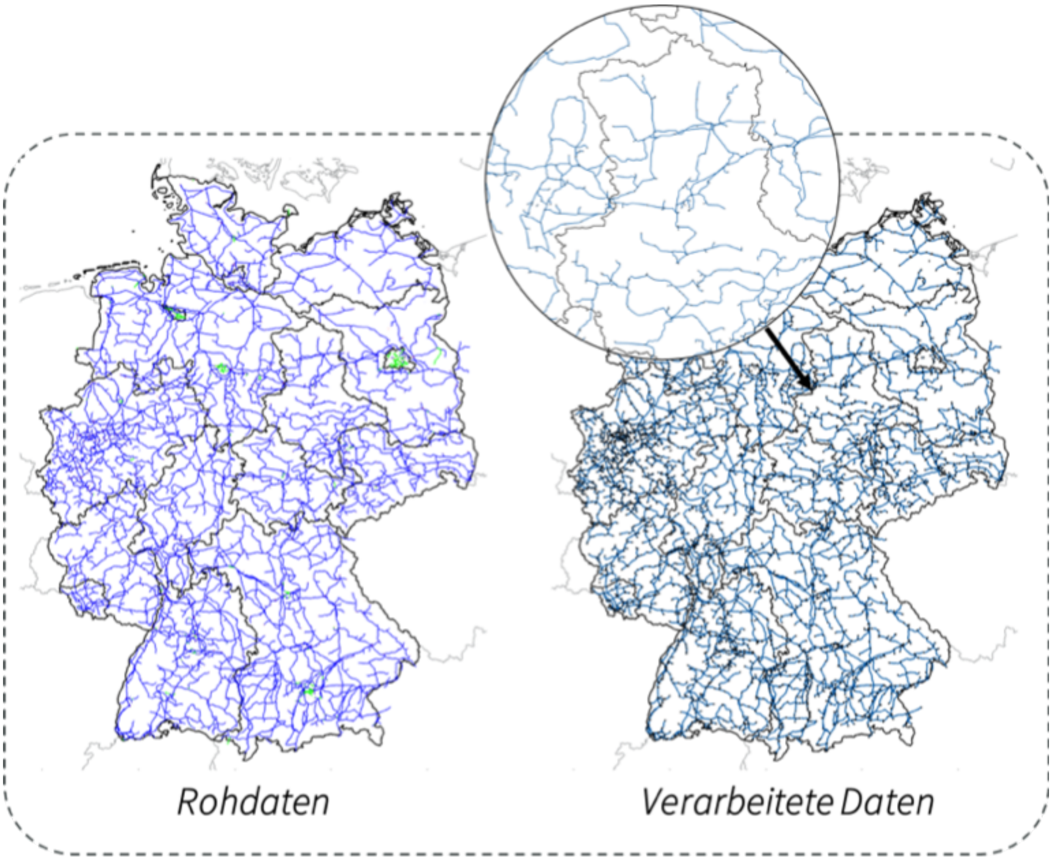


Figure 3.6: Georeferenced data for the HV grid

Bus-branch model

The raw data for the grid can be downloaded from the server provided by OpenStreetMap and filtered a priori to reduce memory requirements. This data is stored in a postgreSQL database [40], which is publicly available and especially suitable for storing georeferenced data. With the help of the QGIS application it is possible to visualize these georeferenced data represented in Figure 3.6 for the HV level in Germany.

Since the raw data are data that do not claim to be complete or correct, an extensive processing is necessary. Therefore, the aim is to generate a complete, coherent bus-branch model for Germany. SimBench uses an optimistic approach for filtering the data. This means that even stations without information about the voltage level are initially included in the dataset. If no intersection with the HV level is identified, these stations are sorted out again. The processing of the data from OpenStreetMap to generate the bus-branch model is shown in Figure 3.7 as an example for a station.

The left part of the Figure 3.7 shows a station that is not assigned to a voltage level in the raw data. In a first step, all stations without assignment to a voltage level are evaluated to determine

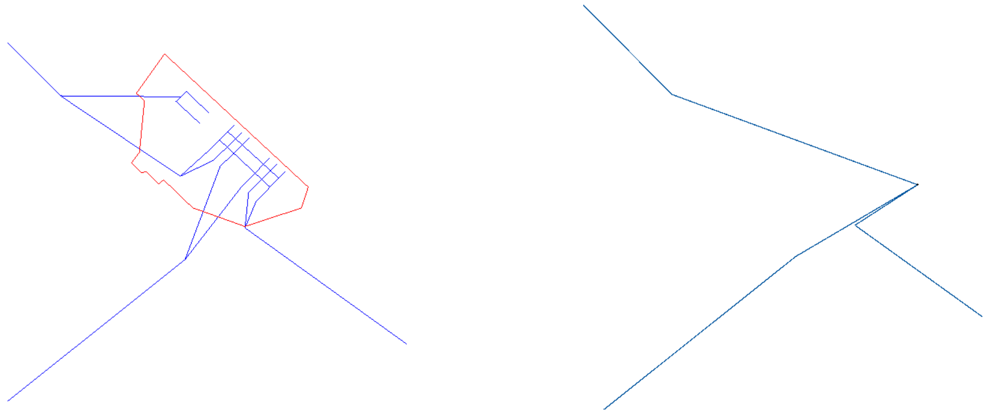


Figure 3.7: Proceed of the assignment of the supply task using Voronoi areas

whether they have at least one intersection with an element of the HV level. This is possible because for each station there is a polygon shown in Figure 3.7. In a second step, all lines ending inside the polygon of a station are merged to a node for this station, thus no open line ends exist at the stations anymore and a coherent network is created.

Additionally, neighbouring stations with a short distance are combined to one station and thus to one node. Finally, open line ends are connected to the nearest stations.

Supply task

In order to obtain a computable network, the supply task must be defined after generating the bus-branch model. The installed capacities of the renewable power plants are assigned to the respective nodes using the data from the power plant register in order to comply with the requirements of the bus-specific representation of the generators. However, it should be noted that only the postcode area is specified in the power plant register to ensure data protection. The allocation is made on the basis of so-called Voronoi areas, thus each HV node is covered by one of these areas and has the smallest distance to the centre compared to the centers of other areas. Figure 3.8 shows the Voronoi regions for the HV nodes of the previously described bus-branch model.

The exact procedure of the procedure will not be discussed further here, hence a reference is made to [41].
Using this method, intersections between the Voronoi areas of each HV node and the postcode areas can be determined, resulting in a percentage allocation of installed services from a postcode area to the nodes. In addition to the allocation of the infeed from renewable power plants, the supply task also includes the load and the distribution of this load to the individual network nodes. The maximum annual load of 83.7 GW from the year 2015 is assumed [42] and distributed to the nodes of the HV level. For this purpose the assumption is made that the number of inhabitants is

Figure 3.8: Voronoi areas of HV nodes

sufficient for an estimation of the load distribution. The number of inhabitants for each postcode area is published by the Federal Statistical Office [43], thus a distribution of the load on the HV network nodes is possible by assigning the postcode areas to the HV network nodes.

3.3.3 Grid generation

The generation of the HV grids includes the selection of regions and their grids, the determination of the primary and secondary technology as well as the dimensioning and validation of the generated networks.

Selection of regions and their grids

A predominantly urban and a predominantly rural network area are selected to generate the SimBench HV grids. The selection of the predominantly urban network model focuses on a region for where publicly available cable data is available. Due to the use of publicly available data and the routing of cables in the ground, the data are incomplete or partly non-existent for most regions. The predominantly rural grid comprises one mesh and longer feeders. Moreover, there are also several network coupling points to the EHV level. This allows, for example, the investigation of different levels of detail in the representation of the EHV level for calculations in HV networks as shown in [44].

Determination of primary and secondary technology

Based on the determination of the topology and the supply task, the equipment parameters must be determined for the calculation of power flows. For this purpose standard equipment is used

Table 3.9: Characteristics of HV overhead lines and cables

id	r (Ω/km)	x (Ω/km)	b (μS/km)	iMax (A)	type
Al/St_265/35	0.1095	0.296	2.827	680	ohl
1x630_RM/50	0.122	0.123	58.748	652	cable

Table 3.10: Characteristics of EHV/HV transformers

id	sR	vmHV	vmLV	va0	vmImp	pCu	pFe	iNoLoad
350MVA_380/110	350	380	110	0	22	900	120	0.06
300MVA_220/110	300	220	110	0	12	385	70	0.04

id	tapable	tapside	dVm	dVa	tapNeutr	tapMin	tapMax
350MVA_380/110	1	HV	1	0	0	-16	16
300MVA_220/110	1	HV	1	0	0	-16	16

for overhead lines, cables (Table 3.9) and transformers (Table 3.10).

In addition to the definition of the network equipment, a realistic representation of the station concepts is of importance. Various concepts are possible with regard to busbar configuration and coupling. Figure 3.9 shows the different station concepts.

The concepts differ in terms of the number of possible connections, operational flexibility and total costs. Analyses of real HV grids, in particular for the coupling to the MV level, have shown that both double busbars with high flexibility and single busbars or H-circuits are used due to lower costs. In most cases a high number of connections leads to the use of double busbars. As a result, concepts with double busbars as well as concepts with single busbars are used in both SimBench HV grids. The realistic representation is particularly important if topology switching measures are to be represented, for example for the use case of topology optimization.

Dimensioning

The dimensioning of the HV grids is based on a (n-1)-failure simulation, since this corresponds to the state of the art in real grids. The power flows for the failure of each branch of a grid are calculated. From the respective determined power flows, the highest value of the load represents the most critical failure. Based on this (n-1)-failure simulation, an (n-1)-load is calculated for each network resource. If a resource has a higher load as the maximum load, a parallel extension is performed and the (n-1)-failure simulation is repeated. This procedure is repeated until there are no more overloads in (n-1)-situations.

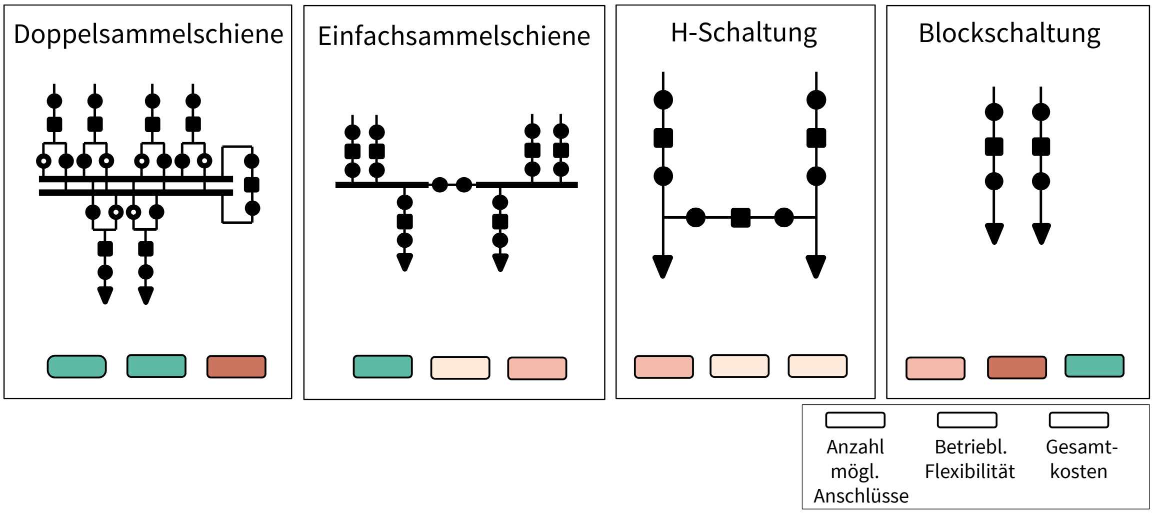


Figure 3.9: Station concepts in the HV level

3.4 Methodology on low voltage level

The LV network in Germany is used for the distribution of electrical energy to the end consumer, whereby the largest proportion of end consumers is also directly connected to the LV network. Accordingly, there are many regional distribution network operators that operate LV networks. This leads to the fact that at this voltage level the network structures as well as the use of operating resources are regionally different, have grown historically and are dependent on the respective planning and operating principles of the distribution network operator. LV networks are often constructed as radial topologies and have a lower degree of meshing compared to the higher voltage levels.

The goal for the LV level in the SimBench dataset is therefore to describe a large number of LV networks with a manageable number of network models. In Germany there are about 500 000 LV networks, but public information regarding the topology of real LV networks is hardly available. This is also the case, for example, in OpenStreetMap, because in contrast to the overhead lines of the EHV and HV levels, the lines of the LV level generally run underground as cables. Accordingly, it is not comprehensible to outsiders where lines are laid, so this cannot be included in OpenStreetMap. In order to nevertheless identify relevant common properties of LV networks and to derive representative network models from them, a methodology has been developed which is described in the following. It is to be understood as a sub-methodology to Section 3.1 and follows on from step 4) Data analysis (Section 3.1.4) (see Figure 3.1).

The methodology for generating the LV network models can be divided into two main sub-areas, the description of the supply task and the LV network model generation. Figure 3.10 shows the sequence of the methodology. The basic idea was based on classifying network models and se-

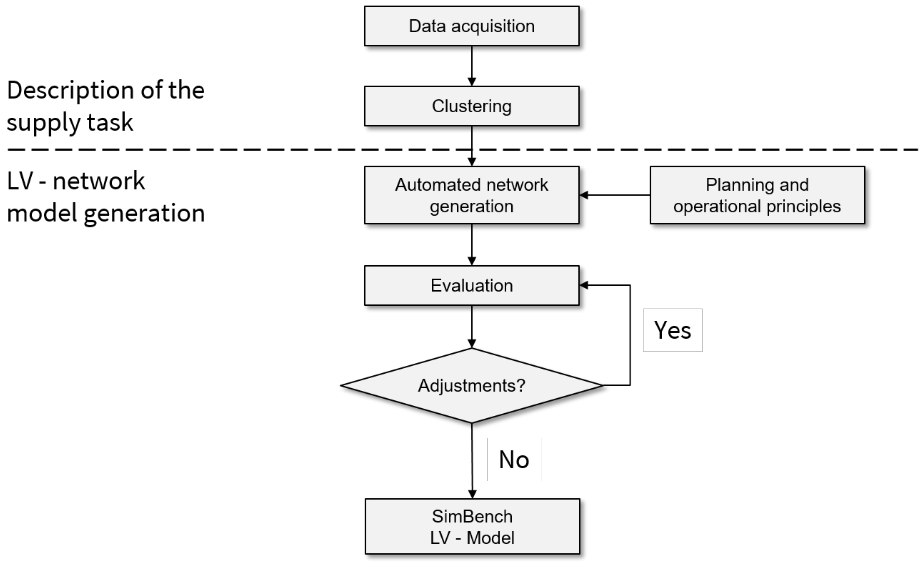


Figure 3.10: Methodology for LV network model generation

lecting networks from the resulting classes that are representative of the individual classes. Due to the fact that real, publicly accessible network topology data on the LV level are not or hardly available, their classification is also not possible. Therefore, the focus of the methodology lies on the description of the supply task and its classification. Here the central assumption is that the supply task is closely linked with the network topology, i.e. with the solution of this task. However, the concept of the supply task is not clearly defined, e.g. within the framework of a standard or comparable documents, so that a definition of the term has been made first. According to [45] the following is taken as a basis for the supply task:

"*A low-voltage supply task consists of geographically inhomogeneously distributed requirements on the electrical power supply, which are served by means of a common coupling point in this voltage level, which is collected by the collective of end customers with their individual properties.*"

In the following, the classification of the supply task is first described and then the procedure for the actual LV network generation is explained.

3.4.1 Classification of the supply task

Before a classification can be carried out, data must first be acquired in order to describe the supply task at the municipal level. The data used in SimBench to describe the supply task are essentially land use data that can be obtained from the Federal Statistical Office. There are various areas that can be included as parameters in the classification. The underlying parameters for the classification are:

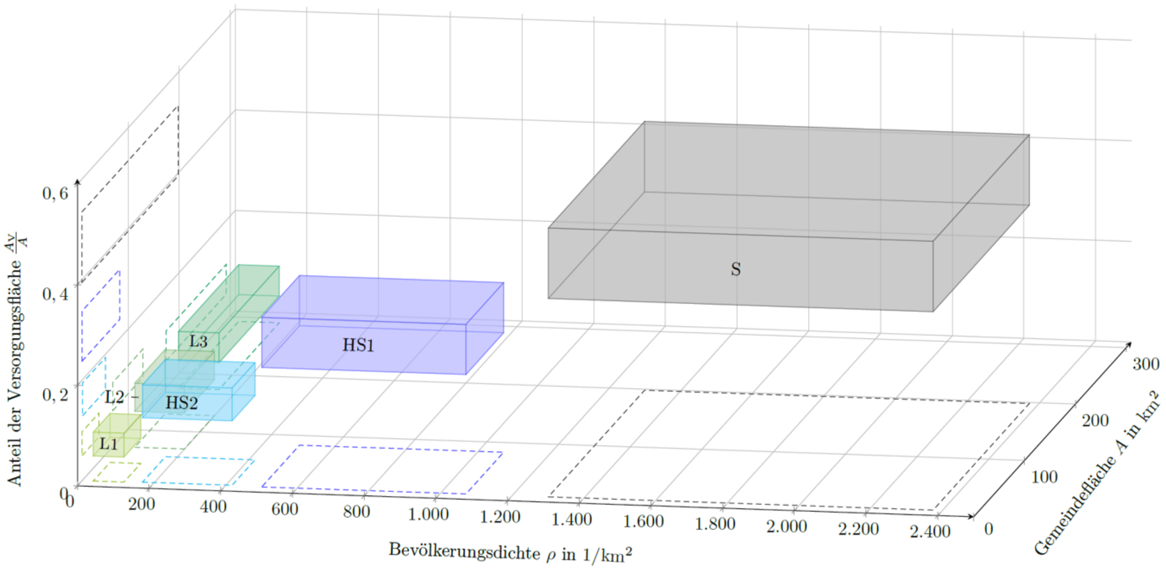


Figure 3.11: Classification result of the LV supply tasks

- population density ρ (in $1/km^2$)
- community area A (in km^2)
- share of the supply area in the total area A_V/A

The supply area includes buildings and open spaces as well as traffic areas. These areas are regarded as particularly relevant with regard to electrical networks, which is why the supply area is included as a parameter in the classification.

After the data acquisition, the data were classified using the k-means method, so that as a result of the first part of the methodology, a description of the supply task for different classes is available.

The results of the classification are shown in Figure 3.11. There are six classes, which are subdivided into three "rural" (L1-L3), two "semi-urban" (HS1 and HS2) and one "urban" (S). Approximately 8000 municipalities have been assigned to these classes. A more detailed description of the classification carried out and the results is published in [45] and should therefore not be described here.

3.4.2 Low voltage network model generation

Based on the classification of the supply tasks, the next step is the actual modeling of the LV network models. For each of the six classes, the municipality closest to the centre of the class and thus most representative of this class is selected. Network models have been planned or generated for these six selected communities based on the greenfield approach. A tool developed at the Institute for Energy Systems, Energy Efficiency and Energy Economics (ie^3) of the TU Dortmund was used, which automatically generates LV grids using OpenStreetMap map data. Among other things, a consumption estimation and a cluster analysis for the assignment of consumers to transformers are carried out. According to the graph theory, a bus-branch model is built, which represents the network. The underlying formal description of this algorithm is described in [46]. The tool is parameterized with real planning and operating principles as well as with standard resources. These principles are also described in [47]. After the generation of the network, i.e. the creation of the bus-branch model, this model has been used and further processed for SimBench. In an iterative process, the dataset was adapted to the needs of the research project and, for example, subsequently DERs were added.

3.5 Approach for compiling the time profiles

In addition to the network data and scenarios, realistic time series for one entire year are an essential aspect for a comprehensive benchmark dataset, especially in terms of future research questions. As part of the SimBench project, the focus is therefore set on generating representative load, feed-in and storage time series that adequately represent consumers, producers and prosumers in Germany.

The default for the annual time series used in SimBench is a realistic time series over time with random variations, which at the same time should be typical for the usual consumers, producers and prosumers present in the grid.

In the following, the methodology for generating the time series of consumers, producers and prosumers are explained. In addition to accumulated consumers such as households, commercial enterprises, etc., individual consumers such as HPs and electric vehicles (EVs) are also included. The producers considered here are DERs, i.e. renewable producers, including wind power, photovoltaics (PV) and biomass (BM) plants as well as hydroelectric power stations. As representative for the prosumers solely battery storages are included.

3.5.1 Accumulated consumers

The following relevant accumulated consumers are identified: Households, commercial enterprises, agricultural holdings and industry.

A dataset of anonymised recorded power measurement recorded power measurements (RPM) profiles is used for commercial enterprises and agricultural load profiles. The measured data are from 2016 and are available with a resolution of 15 minutes. Due to the anonymisation, the data can neither be explicitly associated to a consumer type nor to a voltage level. However, the goal is to find profiles, which are a good correspondence to the standard load profiles standard load profile (SLP) over time.

To do so, following procedure is followed: An average weekly time series with a resolution of 15 minutes for each measurement is created. This is done by averaging each individual weekday over time over an entire year. Seasonal differences are hereby not considered. Each value of an averaged weekly time series is normalized to the weeks mean value and compared to the corresponding time series of the classified SLPs B0, G0-G6, H0 and L0-L2. The normalized cumulative sum of the euclidean distance (load and time) between each point of the load profile and the nearest point of the SLP and vice versa serves as the distance measure.

The time series for each SLP category are chosen as follows:

- shortest Euklidean distances to the respective SLP category
- no shorter Euklidean distances between to another SLP category
- no data inconsistencies in form of missing or duplicated measured values

Due to similarities among the profiles, a time series can have a similarly low distance to multiple profiles. In this case, the assignment is made in a way, that each category is sufficiently represented.

To additionally enable a classification of the consumers regarding size and variance, the mean value, power factor (($\cos(\varphi)$)) and standard deviation each load profile are calculated as well.

Time series of unusual file sizes (>1000 kB kB or <828 kB) are suspected to be false measurements and excluded from the analysis. These make up about 10 % percent of the total dataset. The remaining data contain 2539 time series. Most of these time series describe relatively small consumers with an average consumption under 5 kWh ever 15 minutes. 622 of the time series (25.5 %) are consumers with a consumption of 2.85 kWh, which adds up to a yearly consumption of 100 000 kWh. This resembles the limit where a RPM measurement is obligatory.

Some time series contain extremely high reactive power values, which are probably incorrect readings or measurement errors. Thus, time series with unusually low power factors ($\cos(\varphi)$ < 0.8), that make up about 14 % of the data, are discarded.

A different consumer distribution within different voltage levels is plausible, but as mentioned above the considered data contain no information regarding the voltage level. For a rough classification the time series are therefore divided by average consumption; consumptions of 0-4 kWh,

Table 3.11: New registrations of EVs from 2013 to 2018 in Germany [49]

Brand	Renault	Smart	Kia	Tesla	BMW	VW e-Golf	Nissan	VW e-up!	Mercedes	Hyundai
Share	19 %	14 %	13 %	12 %	11 %	10 %	8 %	7 %	3 %	2 %

10-20 kWh and >SI100kWh are chosen as plausible demand clusters for customers connected to the LV, MV and HV level.

Household consumers are represented by a dataset that was published by the HTW Berlin. This dates from 2010. As in the publication, in the following the data will be referred to as IZES dataset. The IZES dataset is processed so that it also has a resolution of 15 minutes. In an initial evaluation, the time series of the IZES dataset seem very similar to each other but show strong short-term fluctuations. To avoid smoothing out the data, instead of averaging the values, each 15th measured value is used.

The same methodology, as used for the grid operator data, is applied on the IZES dataset. However, the purpose of the methodology is not to categorise the time series (since the category is already known) but rather on the one hand to filter for the series which are closest to the H0 profile, and on the other hand to verify if H0 profiles adequately represent real household measurements [48].

3.5.2 Individual consumers

The following types of individual consumers are included in the SimBench dataset: EVs and HPs. The modeling procedure of the time series are described in the following.

Approach regarding electric vehicles

In order to model EV time series a buttom-up approach is used. Technical data, charging profiles and user behavior have been identified as the relevant variables. How these are mapped is explained in the following.

Technical data

In order to model the technical data of the EVs properly, currently registered EV types are used as reference. Sales numbers from 2013 to 2018, which are distributed according to Table 3.11, serve as reference.

The average consumption as well as the typical battery sizes result from the information above and are derived as follows: The average consumption with 15 kWh/100 km of currently registered

Table 3.12: Assumed battery sizes and thier associated market share [49, 50]

Battery size	20 kWh	30 kWh	40 kWh	75 kWh	90 kWh	100 kWh
Share	60 %	25 %	3 %	4 %	4 %	4 %

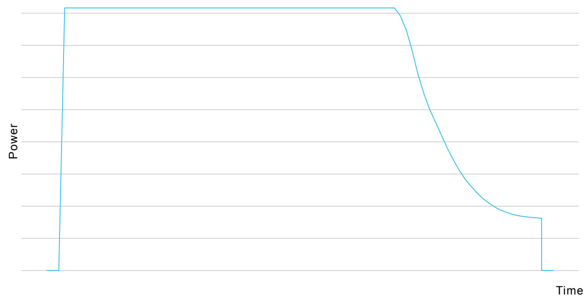


Figure 3.12: Schematic charging profile of an EV

EVs amount to 75 %. The rest consume approximately 25 kWh/100 km [50]. Table 3.12 shows the distribution of the currently used battery sizes.

In the bottom-up approach brand/model, consumption and battery size are randomly selected for each simulated time series depending on the distributions listed above. These remain constant for each time series.

Even though this seems to be a good first approach, these assumptions still need to be further verified in the future. It is expected, that the data basis with regard to the technical data will change considerably, especially due to the enormous dynamic within the mobility sector. This needs to be considered in future studies.

Charging profiles

Another important aspect to consider is the charging behavior of an EV at the charging station. The typical charging behavior of a battery can be illustrated by a charging profile setting power demand and time in context. The charging profile of an EV mainly depends on the battery management system. These systems differ from manufacturer to manufacturer, but they all show certain similarities. Figure 3.12 displays a schematic representation of a common and widely spread charging profile.

Batteries are usually charged with a constant maximum power value at the beginning. As soon as the battery is almost completely charged, the power is continuously reduced. The exact power reduction depends on the battery type. As soon as the battery is completely charged, the power drops to 0 W.

Table 3.13: Weighting of the charging profiles according to the market shares [49]

Model	i3	I-MiEV	KANGOO	fortwo	Stromos	e-Golf	e-up!	Vito	Zoe	Ampera
Share	0,145	0,035	0,035	0,175	0,035	0,135	0,105	0,065	0,225	0,035

The considered charging profiles were recorded in a measurement campain by Fraunhofer IEE. The following EVs were measured: BMW i3, Mitsubishi I-MiEV, Renault KANGOO, Smart fortwo, Stromos, VW e-Golf, VW e-up!, Mercedes Vito E-Cell, Renault Zoe and Opel Ampera.

These in turn do not belong to the most frequently bought EVs and vice versa. To comply with this, in a first step the charging profiles are weighted according to the overlaps between the two data sets. In a second step, the unrepresented portion is evenly distributed among the given measurements, resulting in die distribution shown in Table 3.13. Depending on this weighting, one charging profile is randomly selected for each simulated time series.

User behavior

The last relevant variable to be modeled is the user behavior. The recorded data from the study “Mobilität in Deutschland” is used for this purpose. Based on this data, the following probability distributions will are derived:

- number of routes and possible charging operations per day
- arrival time,
- route purpose,
- average speed as well as
- distance of each ride

Figure 3.13 shows an exemplary probability distribution for the arrival time. Apparently, the participants in the survey arrive at work mostly early in the morning and partly in the afternoon on weekdays. In comparison to this they arrive at home mainly in the evening, which is clearly to be recognised by a peak at 18:00 hrs. Also here, a small midday peak at noon can be seen, i.e. that part of the respondents come home at midday.

In addition to the distributions that result directly from the study “Mobilität in Deutschland”, a further assumption regarding the charging behavior of the users is made: The charging probability is at 80 %, if the parking period exceeds three hours, while it is reduced to 20 % for parking periods shorter than that.

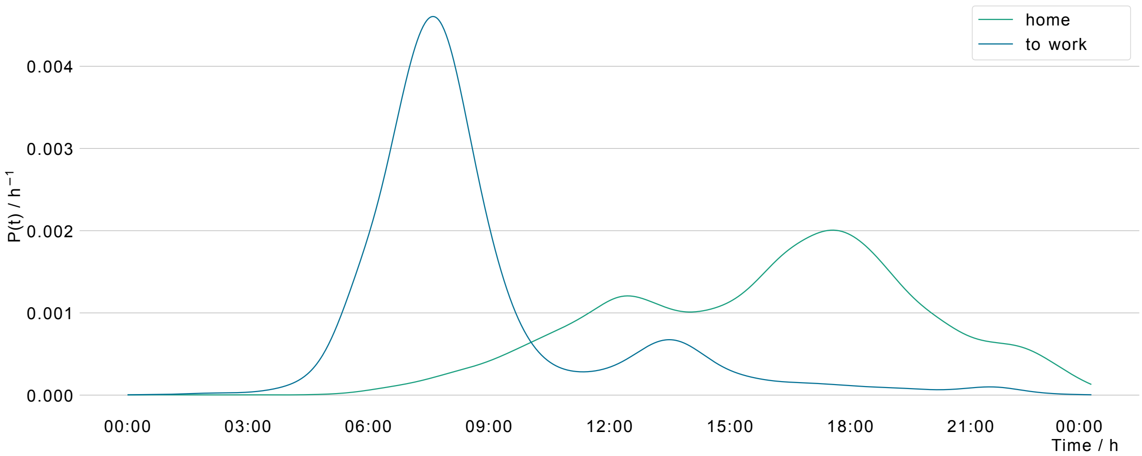


Figure 3.13: Probability distribution of the arrival times at home and at work on weekdays

Table 3.14: Number of time series used in SimBench LV grids with regard to the type of location [49]

Charging station power value	Home charging station	Workplace charging station
3.7 kW	3x	2x
11.0 kW	2x	2x
22.0 kW	1x	1x
50.0 kW	0x	1x

Each distribution now is used to derive realistic and proper weighted values for the parameters mentioned above in order to eventually model a representative time series.

Combining the different parameters

The actual challenge is now, to bring the above variables adequately together. Starting from a user the EV model, the corresponding battery size and charging profile as well as the average consumption are randomly chosen.

In a next step, the charging station is selected, for which a time series shall be provided. This is required as the charging behavior shall be derived from the grids point of view and not from the driver's point of view. In SimBench only two different kinds of charging stations are considered: stations at home and stations at the workplace. This does not mean, that no other charging stations are approached, but these are not examined in the context of SimBench. The power consumption of the individual charging stations is determined beforehand. Table 3.14 shows the charging power values of the different time series.

For all undefined charging station being approached, the charging power value is chosen randomly. These values can vary, except in case of the home charging station.

In the following step, it is to determined, how many rides are undertaken per day. The corresponding arrival times, route purposes, distances and speeds are assigned to each ride. In case two rides overlap, new dices are thrown. If individual rides still overlap after 20 dice rolls, these are filtered out.

Subsequently it is determined if the car is charged after each ride. Irrespective of the charging probability, if the state-of-charge (SOC) is below 20 $\%$, the car is always charged. All rides are consequently filtered out, if it would result in a SOC below 0 $\%$ after the trip.

This approach is repeated for each day of the period under investigation. In the case of SimBench, the period under consideration is the entire year 2016. The initial SOC is chosen randomly, but has to lie within the limits of 50 $\%$ and 100 $\%$. Since there is no information on reactive power given, a fixed lagging power factor of $\cos(\varphi) = 0.93$ is assumed.

Approach regarding heat pumps

Load profiles of a HP are purely controller-based. The relevant variables are the heat energy required in the household, the technical restrictions, heat sources and operation modes. The modeling is explained in the following.

Heat demand

The heat energy consumption occurring in a typical household results from the domestic hot water and the space heating demand. In SimBench these are simulated for the regions around Hannover and Lübeck. These regions were selected, since they were derived from the results on the HV level. The time series for a single family house with three persons is shown in Figure 3.14.

The heat demand shown here have been modeled to match the time stamp of 2016. However, weather data from 2011 were used to correlate with the results of the feed-in time series.

Technical restrictions

The restrictions considered relevant are blocked periods, storage design and used heating devices. These will be discussed in more detail below.

- Blocked periods

  For all HP profiles lockout periods are assumed during which a shutdown is forced. These periods are daily from 07:45 to 09:30 hrs., from 11:30 to 12:30 hrs. and from 16:45 to 19:00 hrs. These assumptions are based on the reference [51].

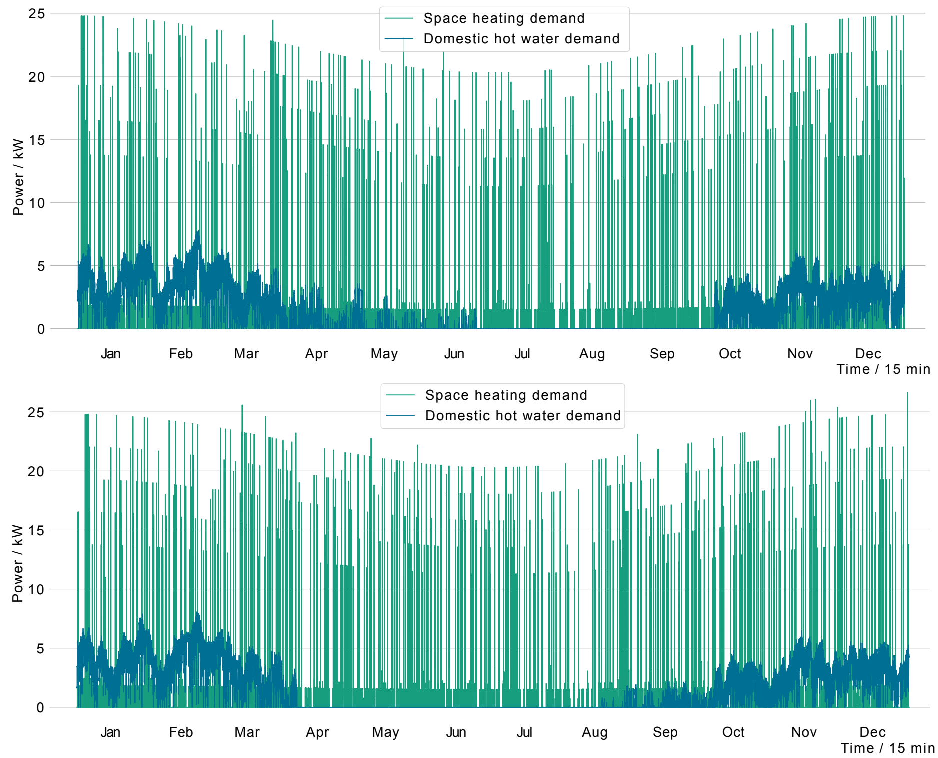


Figure 3.14: Representation of the heat demand in a three-person single family house in Hannover (top) and Lübeck (bottom) in 2016

- Storage design

  The modeling always assumes that there are a domestic hot water as well as an independent space heating storage tank. For both storage tanks the initial SOC is always assumed to be 100 %. Furthermore, it is supposed that no losses occur during the charging and discharging processes. A charging process starts as soon as at least one SOC of a storage falls below 50 %, and ends when a SOC of 100 % is reached. The lower limit was set in a way so that in most cases the heat demand could be met.

- Heater

  In addition to the HP, it is assumed that a heater is installed able to cover peak loads. Both, the size of the storage tanks as well as the nominal power value of the heater depend in particular on the operation mode and the heat source. They are explained in the following.

Air heat pump

In case of an air-HP, the ambient air serves as heat source. Thus, the outside temperature is decisive for the efficiency of the HP and therefore is the the crucial factor for the operation mode and the associated design of the heaters and the storage tanks. SimBench distinguishes the following operation modes and provides the corresponding profiles:

- Parallel operation

  In case of a parallel operation mode, at a certain temperature the HP and the heater operate simultaneously and support each other. In SimBench this temperature is set to −2 °C. The capacity of the domestic hot water storage is 8.722 kWh for Hanover as well as for Lübeck, since in both cases a three-person household is assumed. The space heating storage has a capacity of 13.736 kWh for Hanover and 12.781 kWh for Lübeck. The nominal power value is set to 4.91 kW/4.49 kW in case of the HP and 1.63 kW/2.75 kW in case of the heater for Hannover and Lübeck, respectively.

- Alternative operation

  In case of an alternative operation, the HP is turned off at a certain temperature and the heater covers then the complete heating demand. Again a temperature of −2 °C is assumed. The nominal power value of the HPs as well as the size of the storage tanks remain the same, while the power of the heater increases significantly. It is set to 10.28 kW for Hannover and 10.68 kW for Lübeck, respectively.

- Semi-parallel operation

  In case of a semi-parallel operation, there is a temperature range in which both HP and heater operate simultaneously and support each other. This range is limited downwards by a temperature at which the HP is completely switched off, i.e. the heater is switched on from a temperature below −2 °C and the HP is shut down as soon as the temperature drops below −5 °C. Thus, the power value of the HP and heater as well as the capacities of the storage tanks remain the same as in case of the alternative operation mode.

Soil-heat pump

Unlike an air-HP, a soil-HP does not use the air as heat source, but the soil instead. In case of SimBench the HP is designed as probe HP. Since the temperature below ground can be assumed to be constant, the above operation modes are less meaningful. Therefore, in case of the SimBench dataset only the parallel operation mode is considered, whereby the heater supports the HP in case of an increased heat demand caused by lower outside temperatures. Due to a constant soil temperature, that is estimated at 7 °C in SimBench, the space heating storage tank can be designed smaller compared to the realisations using an air-HP. So the sizes are set to 11.934 kWh for Hannover and 11.130 kWh for Lübeck. The HPs have a nominal power value of 4.131 kW for Hannover and 3.79 kW for Lübeck and the heater is set to 0.5 kW in both cases. The small dimension of the supporting heater can be justified by the fact that the HP has significantly smaller efficiency losses due to a constant soil temperature. As in case of the air-HP, the heater is switched on at -2 °C [52].

Control of the heating system consisting of heater and heat pump

It is assumed, that the heat demand is always covered by the storagem tanks. As soon as the SOC drops below 50 %, the heating devices are switched on according to their operation mode. This does not apply, if the charging process falls within the blocking period. Heating load demands, that can not be covered by the heating and storage system, are not served. In principle, domestic hot water demand is prioritised over space heating, i.e. the domestic hot water demand has to be completely covered before the coverage of the space heating demand is provided. Storage tanks are always fully charged when required, i.e. if the SOC drops below 50 %, the storage gets refilled back all the way to 100 %. The efficiency factor of the heater is set to 1.0. The efficiency factor of the HP results from the temperature of the heat source and is calculated with the following formula:

$$COP_{HP} = COP_{Carnot} \cdot \eta_{HP} = \frac{(273{,}15 + T_{source})}{(T_{flow} - T_{source})} \cdot 0.36 \tag{3.1}$$

with the variables:

COP_{HP}	power factor of the HP
COP_{Carnot}	power factor of the Carnot process
η_{HP}	efficiency of the HP
T_{source}	source temperature / K
T_{flow}	flow temperature / K

The flow temperature is set to 55 °C. Since there are no reactive power values here either, a constant lagging power factor of $\cos(\varphi)$ = 0.93 is assumed.

3.5.3 Aggregated load time series

Aggregated load time series are relevant for all grid levels above the LV level. While they are generated by a bottom-up procedure for the lower grid levels (MV and HV), they are derived at the EHV nodes via a top-down procedure. In the following, the basic approach is briefly explained:

Bottom-up method: aggregated load time series in the MV and HV level

Basically, the aggregated load time series are the summed load time series of the downstream grid levels. That means, that a simulation for one entire year is carried out for all grid levels and the results at the slack nodes as transition to the next grid level are recorded and documented. This time series serves as input to the next higher grid level.

Top-Down method: aggregated load time series in the EHV level

Since the EHV level represents entire Germany, while the downstream grids are only modeled for specific regions in Germany, adequate load time series for the remaining nodes are required. For this reason, as mentioned above in the description of the EHV level, a method is applied that is able to map the loads independently from the downstream grid levels. This method allows a depiction of the loads per consumer group. As starting point a load profile resembling the total power demand of Germany is used which is provided by the European network of transmission system operators for electricity (ENTSO-E) [53]. Based on the data released on the web pages of the federal states' offices, the specific net power demand for each sector and state can be determined. By this the annual net power consumption for the sectors industry, transport, households, commerce, services and trade as well as agriculture can be retrieved federal state sharply. To eventually get a municipality-specific representation for the individual sectors following method is followed:

Households
In case of households, a municipality-wide distribution of the total energy demand is based on the number of inhabitants per community. In combination with the H0 profile, a load time series for the households per community is obtained.

Agriculture
For the agriculture sector, it is assumed that the amount of energy is equal to 2 % of the net power demand. Based on the cultivated agricultural area in combination with the L0 profile, it is possible to obtain a load time series for agricultural holdings per municipality.

Commerce, services and trade
Commerce, services and trade is only published in sum with the agricultural sector. To determine the energy demand for commerce, services and trade the total energy demand of the agricultural sector must be subtracted from the total energy consumption. Based on the number of employees and the commercial area used plus the G0 profile a load time series for commerce, services and trade per municipality can be created.

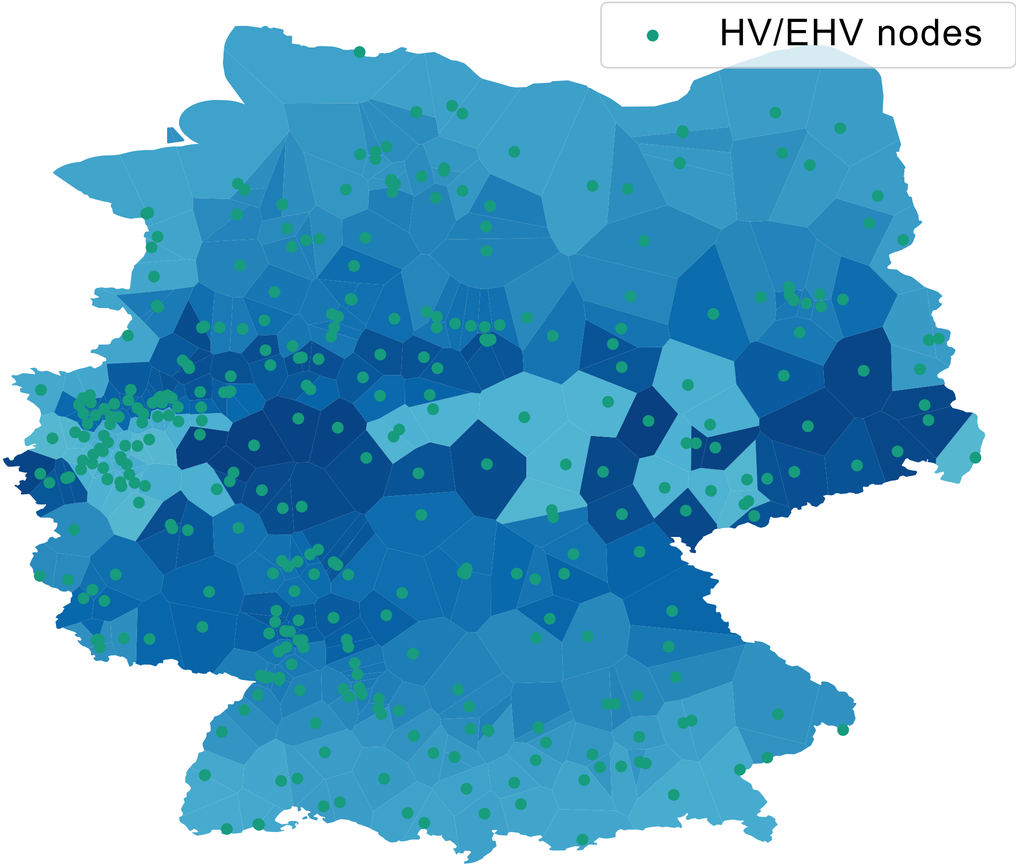


Figure 3.15: Voronoi polygons and the corresponding HV/EHV nodes

Industry and transport

To get a representative profile for the industry and transport sector in a first step the total energy demand of households, agricultural businesses, commerce, services and trade is subtracted from the ENTSO-E profile. Based on the length of the electric public transport network and the industrial area a load time series profile per municipality for industry and transport can be determined.

To determine the loads per node, in a first step a Voronoi analysis is carried out. The centres of the Voronoi polygon form the Voronoi centroids, as displayed in Figure 3.15. They correspond to the EHV/HV nodes. Each load falling in a single polygon is assigned to the corresponding EHV/HV node. This method is applied to loads localized within Germany.

A simplified method is applied to loads localized outside of Germany. Previously determined energy demand allocated to Germany's neighboring countries are evenly distributed among the nodes of the respective countries.

Instead of providing a load time series for each node, a representative load time series is deter-

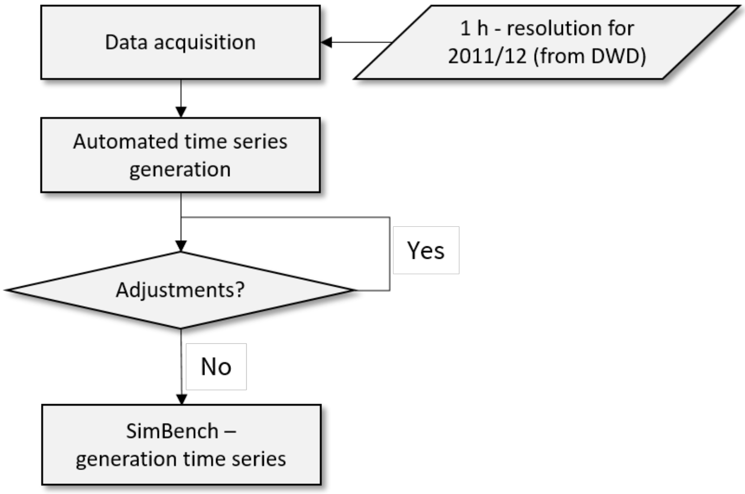


Figure 3.16: Generation Methodology of the Generation Time Series

mined using a k-means algorithm. Since the focus of this study is set on active power, a constant lagging $\cos(\varphi)$ of 0.93 is assumed.

3.5.4 Feed-in time series

For the generation of DER time series for wind, PV and BM, *SIMONA*, an agent-based simulation tool developed at ie³ for optimised and time series-based grid expansion planning, was used. Operational degrees of freedom, interdependencies and innovative network resources are taken into account. With *SIMONA*, detailed and realistic time series can be generated. Further information on this simulation tool can be found in [54, 55, 56, 57]. Furthermore, [58] provides a comparison between real measurement data and feed-in time series generated with *SIMONA*.

The basic methodology for generating feed-in time series is shown in Figure 3.16. First the required data are acquired, these are weather data for Germany from the German meteorological service (DWD) for the years 2011 and 2012. These weather data serve as input parameters for the plant models contained in *SIMONA*.

The generation plants are geographically distributed in order to take into account the locally varying weather conditions and thus generate different time series. The geographical location of the plants is strongly oriented to the location of the HV networks. This ensures, for example, that for real wind farms connected to the HV networks, realistic time series with real weather data are also available. The geographical locations for wind and PV are generally limited to the regions:

- North Sea and Baltic Sea (1 location each)
- North Sea coast, Baltic Sea coast and East Germany (1 location each)

- Hannover (3 locations)
- Lübeck (3 locations)

In addition to these locations, which are selected on the basis of the location of the HV networks and are located in northern Germany, there are further time series for wind and PV for the other cardinal points, as these are required for the EHV model.

In addition to the time series generated with *SIMONA*, three time series for hydropower plants are provided in the "SimBench" dataset. These time series correspond to real, anonymised data from the year 2017, which have been provided for SimBench.

After time series generation, manual adjustments to the data are still necessary, as these are for 2011, 2012 and 2017, but are needed for 2016. For all time series, both load and feed-in time series, to be used together, they must have the same time stamp. For this purpose, the time stamp has been adapted to the year 2016 and the respective time change has been taken into account. In addition, 2016 was a leap year. Therefore, additional values have been generated for the leap day, based on an averaging of previous and subsequent values of the corresponding weekday.

3.5.5 Storage time series

The approach of the storage time series focuses on the most relevant storage types that are used in Germany. A distinction is made between:

- storage devices used to maximise self-consumption of generated PV energy
- grid beneficial storages

It is important, that the usage of storage devices guarantees that they are not operated based on a grid beneficial, non-transparent control. If that would be the case, research questions regarding grid beneficial storage operations could not be examined with the SimBench dataset.

How these restrictions are fulfilled is explained in the following:

Storage devices used to maximise self-consumption of generated PV energy

Time series of storage devices used to maximise the self-consumption of generated PV energy are generated by coupling individual PV time series to the load time series. The dimensioning of the PV system and thus the scaling of the PV time series is determined by multiplying the energy of a household time series with a factor of 0.00071/h. This factor was set in a way, that the results of the nominal PV power values correspond approximately to the systems already installed in the LV grids.

The control algorithm works as follows: If the PV feed-in exceeds the load demand, the excessive energy is fed into the storage. Reversely, the storage is discharged, if the load exceeds the PV feed-in, provided that the storage is not empty.

The storage devices are dimensioned to be able to store any excess energy. Charging and discharging are impinged with an efficiency factor of 0.95. Furthermore, a self-discharge of 4 $\%$ per month is assumed [59]. The power factor is based on the PV time series and thus set to $\cos(\varphi)$ = 1.0.

Grid beneficial storage devices

For the approach of modeling grid beneficial storage devices the individual wind and PV time series are taken and a curtailment factor of 3$\%$ of the generated energy is assumed. This is realised by following a simple algorithm: A fixed maximum power limit is determined in such a way that the accumulated feed-in above this maximum power limit would make up exactly 3$\%$ of the total feed-in provided. A corresponding optimal dimensioning of the storage is assumed. The technical data comply with those mentioned above.

3.6 Approach to generate future scenarios

The aim of this chapter is to provide a basic understanding of the method to create the future scenarios. For this purpose, an overview of the applied overall method is given in the following subsection. The individual steps are then discussed in detail in the subsequent subsections.

3.6.1 Methodology overview

The unique feature of SimBench is not to provide networks, scenarios and time series that map reality but to ensure that the relevant use cases derived from network analysis, planning and operation are covered. The approach for creating the future scenarios is therefore as follows: Instead of generating networks that are representative for entire Germany or which are real but irrelevant from the network analysis, planning and operation point of view, the developed method ensures to create scenarios with relevant challenges faced by the network analysis, planning and operation in near future. The flowchart displayed in Figure 3.17 describes the exact procedure.

In a first step, the termination criteria, that the scenario grid needs to fulfil, are defined. This describes the first step in determining the scenario networks and is shown schematically in Figure 3.18. The procedure for determining the termination criteria is described in Section 3.6.2 in more detail.

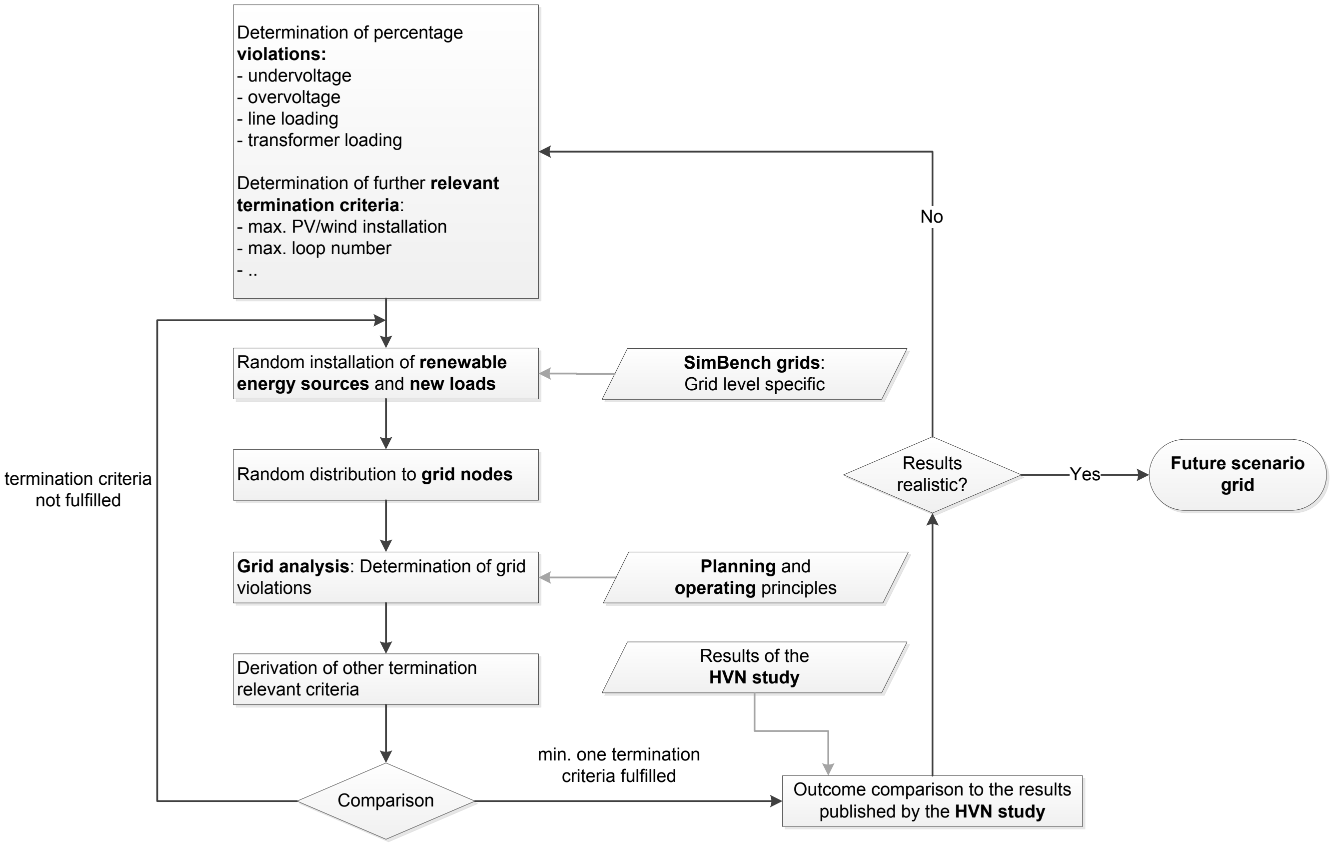


Figure 3.17: Flowchart showing the generation of the future scenarios

In a next step these termination criteria are embedded in the scenario realisation of the concrete grids. The section of the general overview, highlighted in Figure 3.19, describes the necessary procedure. This is explained in more detail in Section 3.6.3.

To validate that the generated networks fall within a realistic future scenario scope the integration study for the German state of Hesse (HVN) [60] study is used. A description of this is given in Section 3.6.4. In the flowchart this step is described by Figure 3.20.

This method is used for the LV, MV and HV grid levels. Since the EHV level does not only depict a small part of Germany but the entire country, and therefore being very close to reality, the model is rather oriented to the power system development plan (NEP). It should be noted that on the EHV level due to the great effort involved and the associated uncertainties, specific scenarios are deliberately omitted. Only the part that is directly connected to the SimBench grids is adjusted accordingly. The exact procedure is described in Section 3.6.5

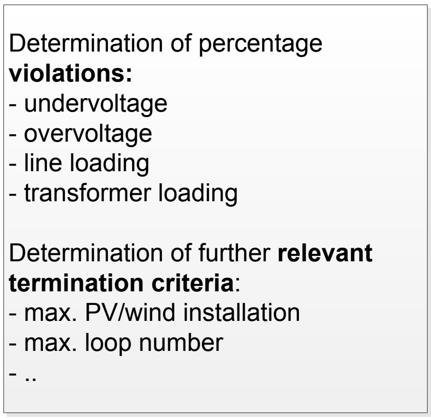


Figure 3.18: Overview of the considered limit violation values and further termination criteria for the generation of the future scenarios

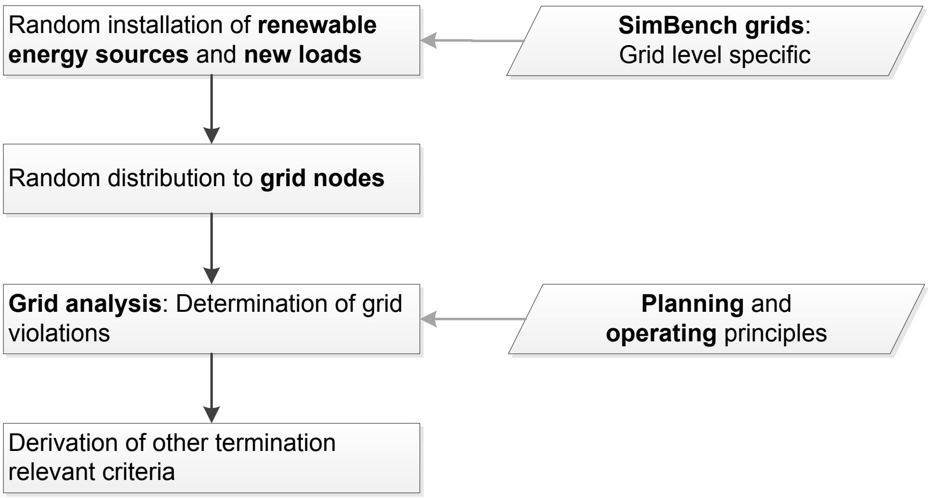


Figure 3.19: Linking the termination criteria with the SimBench grid

3.6.2 Determination of the termination criteria

The scenarios and therefore also the termination criteria are defined for two years in future: on the one hand for the year 2024, and on the other hand for the year 2034. Hereby, it is strongly oriented to the HVN study and the NEP. In case of the HVN study the focus was set on these two years as well, while in case of NEP the focus was rather set on the years 2025 and 2035.
To determine the grid scenarios, different termination criteria categories with different prioritisation are used.

The highest priority is given to the share of the overloaded lines and transformers as well as the nodes with voltage violations. Only by this the individual grids can fulfil all the previously defined requirements. The share of overloaded lines and the nodes with voltage violations is set to 15 % for all grids levels in the year 2024. Overloaded transformers are only considered on EHV level,

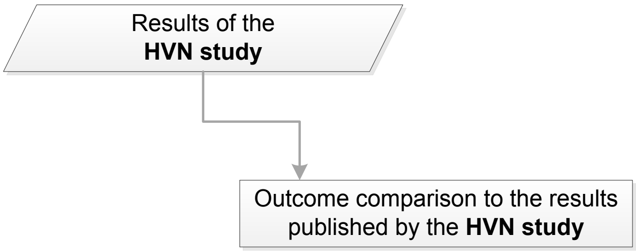


Figure 3.20: Validation process by involving the HVN

other than that they are ignored. For the year 2034 the value for the share of nodes with voltage violations as well as the overloaded lines is set to 30%. All the overloaded transformers on each grid level are not considered in the year 2034.

Since in the SimBench dataset individual grids with fewer problems or no problems at all should also occur, further termination criteria are defined. For that, information coming from the HVN is primarily used. According to this study, the addition of PV systems in 2024 should be approximately 100 % of the already installed stock. This is used as another termination criterion for the LV grids. For 2034, in turn, a share of the EV load in the total load is set as the termination criteria for 2034. These termination criteria are relevant for the SimBench grids LV 04 to LV 06 for the year 2024 and for the SimBench grids LV 04 and LV 06 for the year 2034.
Since the third MV grid is a grid in a city and the construction of wind turbines is therefore rather unrealistic, the installation of new PV systems also serves as a final criterion for the year 2024. The situation is different in case of the 4th MV grid. Instead of the value of new installed PV systems, the installation value of new wind turbines is used as termination criterion for the year 2024. Same as in case of the PV systems the value is set to 50 %. For the other grids these termination criteria are irrelevant. In case of the year 2034, The values for the termination criteria are increased to 66 %, which can also be deduced from the HVN study. However, for the year 2034 this is only relevant for the third MV grid.
In terms of the HV grids, no termination criteria of this kind are specified.

As a last criterion, if the others don't take any effect, maximum algorithm repetitions are defined. Here, the number of repetitions is set to 20, which is only relevant in case of MV and HV grids.

3.6.3 Integration of the termination criteria in the implementation of the future scenarios

Depending on the respective grid level, a random installaion of DERs, prosumers and new consumers is undertaken. PV plants and PV storage plants are added as producer and HP and EV as consumers on LV level. On MV level, additionally BM, wind power plants and wind power storage plants are considered. On HV level, only wind power plants and wind power storage plants play a

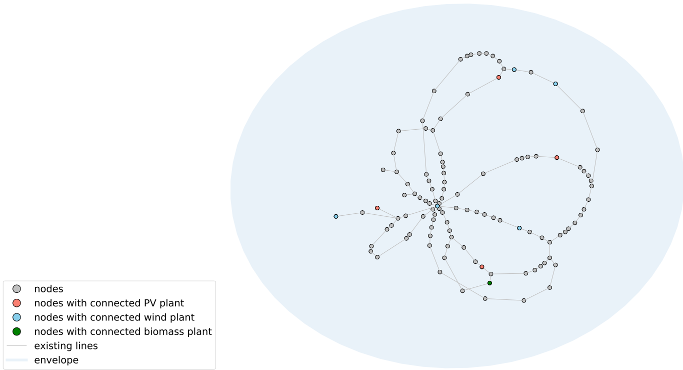


Figure 3.21: Determination of the net enveloping area

role. In the 4th MV grid, a wind turbine is being dismantled, while on the MV and the HV level due to a "repowering" process an increase of wind power is detected. The wind power on the MV level increases by 15 % or 30 % and on the HV level by 10 % or 30 % for the years 2024 and 2034, respectively. The load demand are generally reduced to 99.6 % of their original value for the year 2024 and 98.5 % of their original value for the year 2034. These values are derived from the HVN study. Although the load demand according to HVN will increase overall due to new consumers, the efficiency of each individual consumer in turn increases, which is why a corresponding reduction of the originally installed load is assumed.

On the LV level, the allocation of the producers, prosumers and consumers to the grid nodes is random. It is taken into account that no more than one PV system, one PV storage system or one HP is installed per node. It is important that the size of the PV system, PV storage system and the households stay in a fixed ratio to each other to reduce the number of possible combinations and thus time series. In case of EVs a maximum of two charging station for electric cars at residential buildings (HLS) per household connection can be installed, while in case of commercial loads several charging station for electric cars at the worksite (APLS) are also possible. Other types of charging stations are not considered in SimBench.

Unlike for the LV level generic priority areas are defined for the MV and HV levels. For this purpose, however, georeferenced data are required. They are generated generically for the individual nodes and lines based on the line lengths. The priority areas are determined for both PV and wind power plants. Here, the wind power plants priority areas are defined such that their summed areas corresponds to approximately 2 % of a net enveloping area (see example in Figure 3.21). Additionally, it is taken into account that a minimum distance of about one kilometre to the nodes is respected.

The 2 % corresponds to one of the key energy policy goals of the State of Hesse [61]. In case of PV the priority areas are many times smaller. The sizes used for the individual priority areas result from the priority areas already approved for the MV level. They can be found under [62]. They are scaled according to the size of the grids in the HV level.

For each priority area, new connections points are realised to which each new installed plant can be connected. In case of the MV level one and in the case of HV level three connection points are made. A connection is realised directly to the transformer station (TS) if the power is above 8 MW on MV level or higher than 40 MW on HV level. In addition to these priority areas, on the MV level, PV systems or PV storage systems can also be directly installed on households. Besides, wind power and PV plants an installation of a new BM can be realised on the MV level. They can only be built directly next to agricultural holdings. Also in this case, a direct connection to the TS is made if the power exceeds 8 MW. The size of each plant is derived from the list of existing plants [38]. In addition to producers and prosumers, new consumers are also possible on the MV level, but larger in size than the consumers on the LV level. So, EVs and HPs can also be installed on commercial or agricultural holdings on the MV level.

In order to integrate the termination criteria of the first priority category in particular, previously defined planning and operating principles are required. On the one hand, they describe the relevant load cases in the grids and on the other hand the permissible power limits of the transformers and the lines as well as the voltage limits of the lines. The required limits and load cases can be found in Section 5.1. Given the load cases, for each calculation and analysis step the ratio of the grid violations under consideration of the grid violation limits are determined. In addition to the grid violations, the other indices relevant for termination are derived.

Finally, the determined characteristic values are compared with the specified termination criteria. If none of the termination criteria is met, the entire process is repeated once more. As soon as at least one termination criteria is fulfilled, the repetition process is interrupted.

3.6.4 Validation of the development scenarios results

In a final step, the results are checked for plausibility. For this purpose, the results from the HVN study are used. For example, the HVN states that it can be assumed a total installed capacity of 3.15 GW for wind energy in Hesse in 2024, and that this value will even increase to 5.35 GW in the medium energy scenario in 2034. In comparison, the value was 1.18 GW in 2014. In case of PV, an increase of 3.0 GW till 2024 and 4.65 GW till 2034 is expected. The installed capacity was 1.77 GW in 2014. For reasons of simplicity, uniform limit values for wind energy and PV plants are derived from these values. This means that the wind energy and PV total installed capacity summed up to 2.95 GW in 2014 and that it will rise up to 6.15 GW till 2024, what is more than double of the already installed capacity. In 2034, the value is expected to increase further to 10.0 GW, which is slightly more than three times the already installed capacity. An estimation of the increase of new consumers is a lot more difficult. The procedure is as follows: In the HVN study in case of EVs, a total share of 2 % in 2024 and 20 % in 2034 is assumed. For this purpose as comparison value, the number of charging stations is set in relation to the total number of connected households. The assumption behind this is that there are currently about 45 million cars and about 41 million households in 2017 [63, 64]. This means that on average every household has a car. In turn, this means that by 2024 2 % of all households have an EV and thus a charging station, while by 2034 already 20 % of all households have an EV and as assumption a charging station.

3.6.5 Generation of the scenario grids on the EHV level

Unlike in the downstream grid levels, the EHV scenarios are only changed in such a way that the changed new situation of producers, prosumers and consumers of the individual grid levels are correctly mapped at each node at which a SimBench grid is connected to. Everything else is retained since a comprehensive mapping of the NEP scenarios for 2024 and 2034 would have exceeded the goals of SimBench. Furthermore, due to their relevance, the HVDC lines and the future installed offshore wind parks are connected to the respective future grid connection points. Here, however, only the topological positioning plays a role. A concrete installation and integration is omitted in the SimBench project.

4 Overview of the SimBench dataset

The SimBench dataset contains various benchmark networks from low to high voltage. There are three different variants per network model, one base case and two evolution scenarios (future scenarios). In addition, time series are provided for generators, consumers and storages. The individual network models are presented in detail in Chapter 4.1 and the time series are explained in Chapter 4.1.5. Chapter 4.2 then describes the interconnection of networks across all voltage levels. The "SimBench code" introduced there clearly defines which network combination is considered in which variant. Chapter 4.3 describes the accessibility of SimBench network data and the data format. This is a CSV format specifically defined for SimBench. Chapter 4.3 also points out that SimBench networks are also available in data formats from several common power flow calculation programs.

4.1 Description of the SimBench benchmark network models

Table 4.1 shows an overview of the SimBench network models in their initial state, i.e. scenario 0. These network models are described in detail below for each individual voltage level. In addition to the various topologies, important key figures are also mentioned.

4.1.1 Extra high voltage

As described in Section 3.2, the extra high voltage grid corresponds to a grid model derived from the SciGrid project. The grid model was validated and extended by the corresponding supply task as well as the primary and secondary technology.

This results in a grid model with a line length of 32 425 km, 464 sites, 530 stations and 209 transformers. The topology of the network is shown in Figure 4.1. A comparison with the network data from the VDE/FNN fault statistics, which have a line length of 34 579 km and 466 stations, shows that with the transmission network of the SimBench dataset a dataset is available which has a similar problem size to the real transmission network.

In addition to the topology of the transmission network, the dataset also contains the corresponding supply task. The procedure described in Section 3.2 using the power plant list of the BNetzA

Table 4.1: Overview of SimBench grids of scenario 0

Acronym	SimBench code	Urbanization characteristic	Rated voltage [kV]	No. of supply points	Transformer types	Generation unit types	Geo references with relation to reality
EHV1	1-EHV-mixed–0-sw	mixed	380, 220	390	209x600MVA	Nuclear, Coal, Gas	yes
HV1	1-HV-mixed–0-sw	mixed	110	58	2x300MVA, 4x350MVA	Wind	yes
HV2	1-HV-urban–0-sw	urban	110	79	3x300MVA	Wind	yes
MV1	1-MV-rural–0-sw	rural	20	92	2x25MVA	Wind, PV, BM, Hydro	no
MV2	1-MV-semiurb–0-sw	semi-urban	20	112	2x40MVA	Wind, PV, BM, Hydro	no
MV3	1-MV-urban–0-sw	urban	10	134	2x63MVA	Wind, PV, Hydro	no
MV4	1-MV-comm–0-sw	commercial	20	98	2x40MVA	Wind, PV, BM, Hydro	no
LV1	1-LV-rural1–0-sw	rural	0.4	13	1x160kVA	PV	no
LV2	1-LV-rural2–0-sw	rural	0.4	93	1x250kVA	PV	no
LV3	1-LV-rural3–0-sw	rural	0.4	118	1x400kVA	PV	no
LV4	1-LV-semiurb4–0-sw	semi-urban	0.4	39	1x400kVA	PV	no
LV5	1-LV-semiurb5–0-sw	semi-urban	0.4	104	1x630kVA	PV	no
LV6	1-LV-urban6–0-sw	urban	0.4	53	1x630kVA	PV	no

leads to an installed capacity per technology according to Figure 4.2. The geographical distribution of the power plant park is also described in Section 3.2 and is based on the postal code area of the respective power plant. This distribution is shown in Figure 4.3. The distribution reflects the geographical distribution of power plant technologies in Germany. For example, there are large lignite-fired power plants in Eastern and Western part of Germany and large gas-fired power plants in Western and Southern parts. In addition to the characteristic distribution of onshore wind energy and PV plants, the offshore wind farms are also shown by their respective grid connection points on land. The resulting power plant dispatch has already been described in Section 3.2, thus it will not be discussed here.

In order to validate both the topology and in particular the supply task of the dataset, the power flow results of the "SimBench" dataset for the transmission system are compared with historical line loadings from the monitoring report of the BNetzA for the year 2017 [42]. Figure 4.4 shows the power flow result of the transmission grid for an exemplary hour with a high line loading. The presentation of this power flow result reflects characteristic congestions in the north-south and north-west direction of Germany, thus, for example, use cases such as the determination of redispatch and curtailment measures can be calculated.

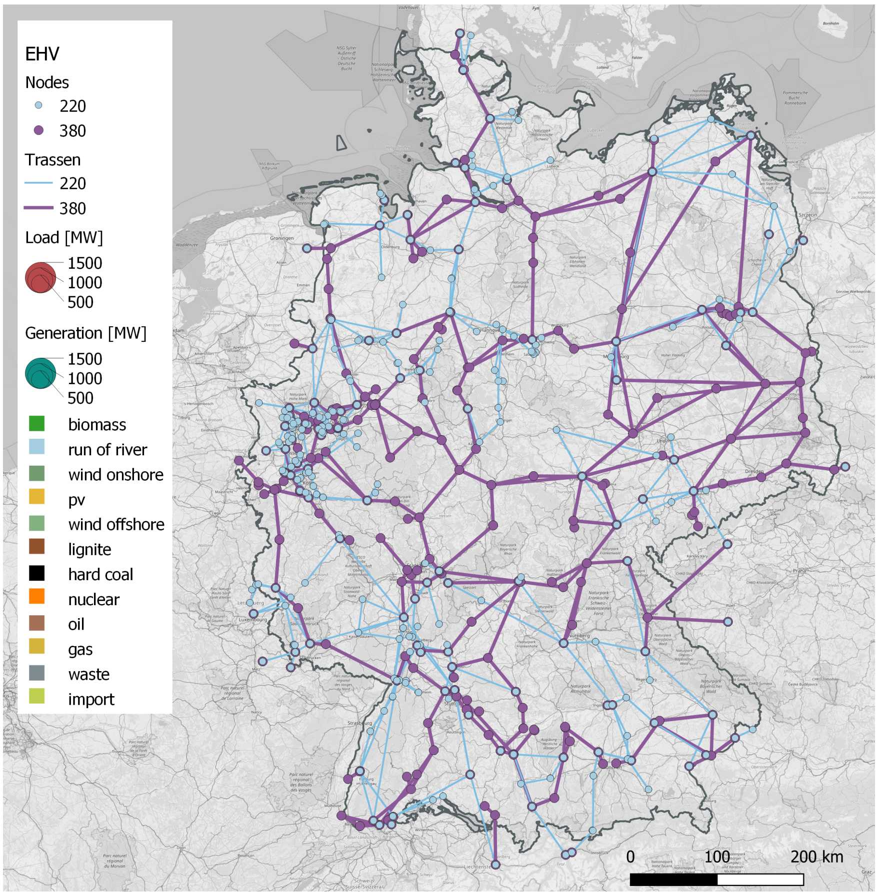


Figure 4.1: Topology of the EHV network

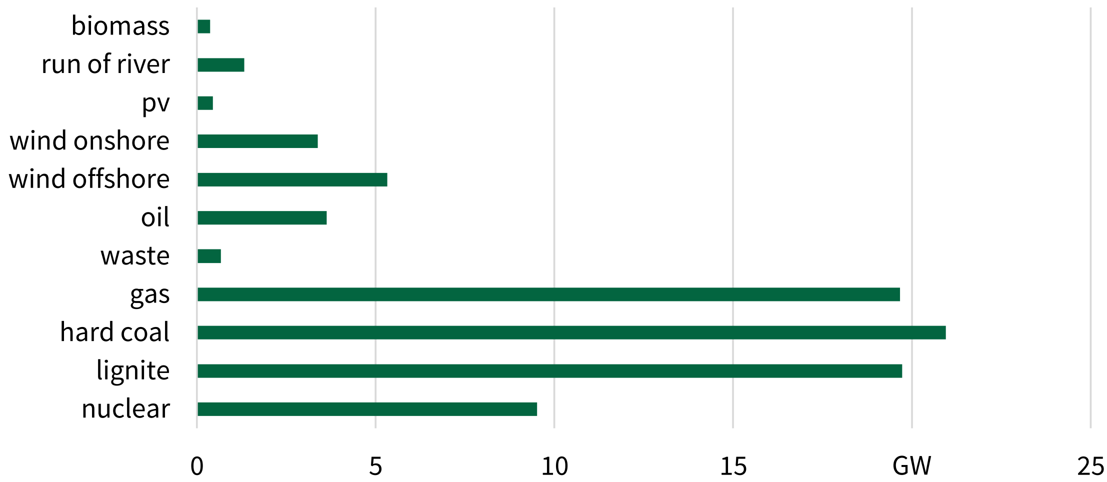


Figure 4.2: Installed power plant capacity in the EHV grid per technology

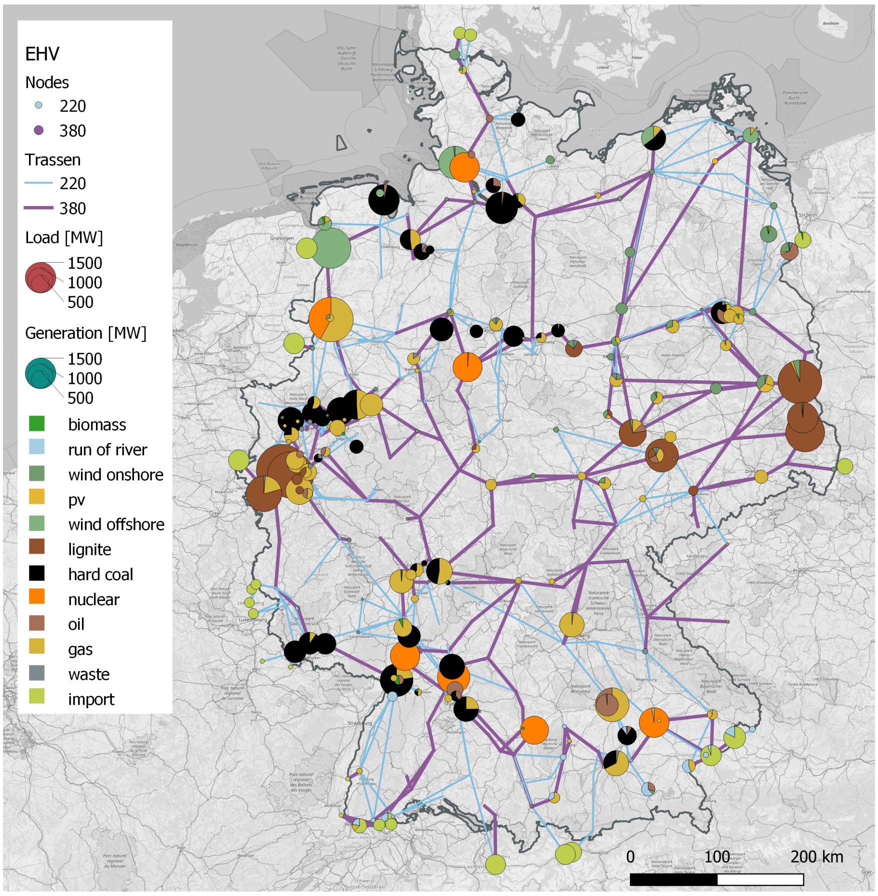


Figure 4.3: Geographical Distribution of Renewable Energy Power Plants and Conventional Power Plants

4.1.2 High voltage

Two networks result from the methodology described in Section 3.3 for generating the HV networks. For these networks, the resulting topology and the supply task are discussed first. Finally, the result of the dimensioning of the resulting networks is presented.

Topology

One network represents a predominantly rural network model with a high share of overhead lines, the other a predominantly urban network model with a higher share of cabling. The predominantly rural network model is marked as “HV1” in the "SimBench" dataset and shown in Figure 4.5. The network includes 64 locations with 64 stations. These stations are connected with 95 lines and represent a total circuit length of 1084 km. In this figure, stations and lines of the HV level are shown in orange.

In the network HV1 there are three network connection points to the EHV network. The transitions

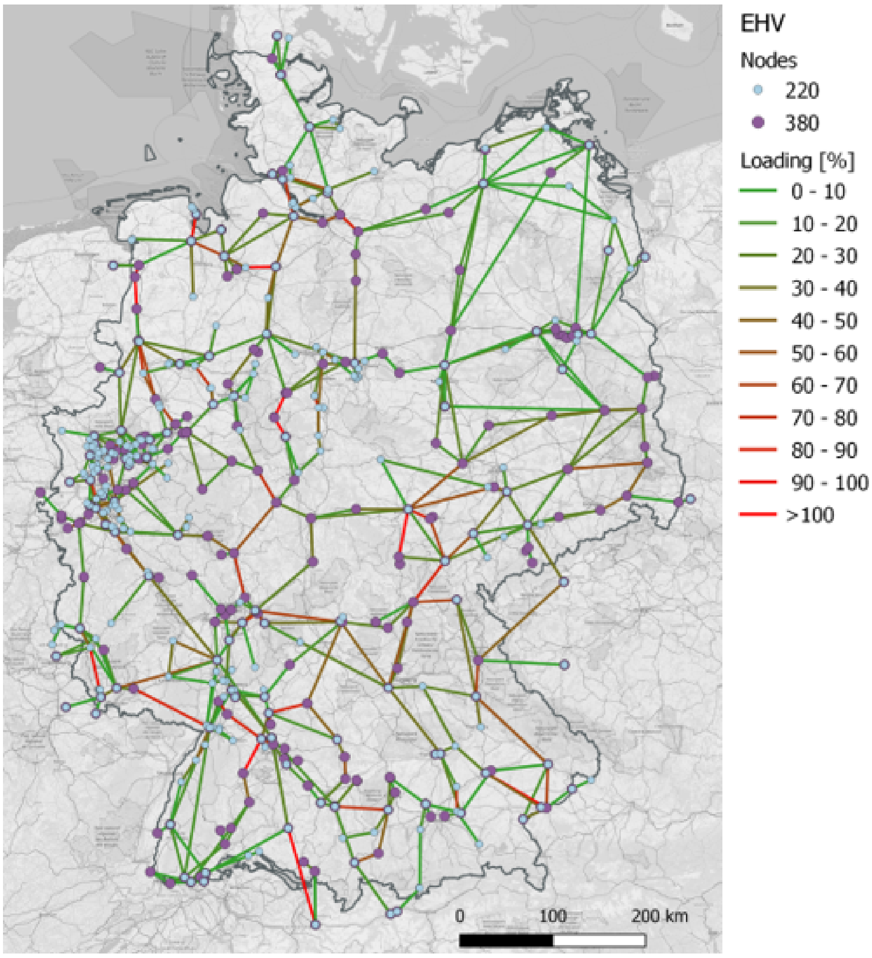


Figure 4.4: Exemplary power flow result for one hour

to the 220 kV network are shown in light blue and the transitions to the 380 kV network in purple. These stations are central stations. The topology of the grid has a mesh as well as a longer feeder in southern orientation. The lines between the central stations as well as the coupling transformers are redundant.

The predominantly urban HV grid is marked as “HV2” in the SimBench dataset and consists of 82 locations and 82 stations. These stations are connected by 113 lines with a total circuit length of 752 km. The network is shown in Figure 4.6. In comparison to the HV1 network it becomes clear that there is a higher level of intermeshing. A higher level of intermeshing is typical for predominantly urban networks, as there is a high population density. In addition, despite the higher number of lines, the overall circuit length is smaller compared to the predominantly rural network. This is due to an average short line length in the predominantly urban network model. In addition to the higher share of cabling mentioned before, another difference is that there is only one grid coupling point to the EHV network.

Figure 4.5: Representation of the predominantly rural HV network

The connection to the overlaid EHV level, both on the EHV level and on the HV level in the case of a cross-voltage level consideration, is realized using double busbars and thus offers high topological flexibility. The connection to the underlying MV level for a cross-voltage consideration shows differences in topological flexibility in reality, which means allowing different switchgear configurations to be used as described in Section 3.3. However, this will not be discussed in detail here and it should be referred to [47].

Supply task

In addition to the topology described, a corresponding supply task for the generated HV networks results according to the method presented. The supply task is shown in Figure 4.7 for both networks. For the purpose of transparency, one figure each is given for the generation and the load.

The dimensioning of the networks described in the methodology is carried out by conducting a failure simulation calculation using the generated time series of the load and generation. Exemplary power flow results are shown in Figure **??** at a high wind, low load situation.

An examination of the HV1 grid shows that a high infeed from wind turbines in this situation leads to high load factors at the feeders, as there is a low load density. However, due to the weak load in this situation, a high utilization of the upper part of the mesh can also be seen. In the HV2 network, it can be seen that a significantly higher load density in the centre of the network results in a lower load on the lines due to a higher load density closer to generation. The feeder in the north of the

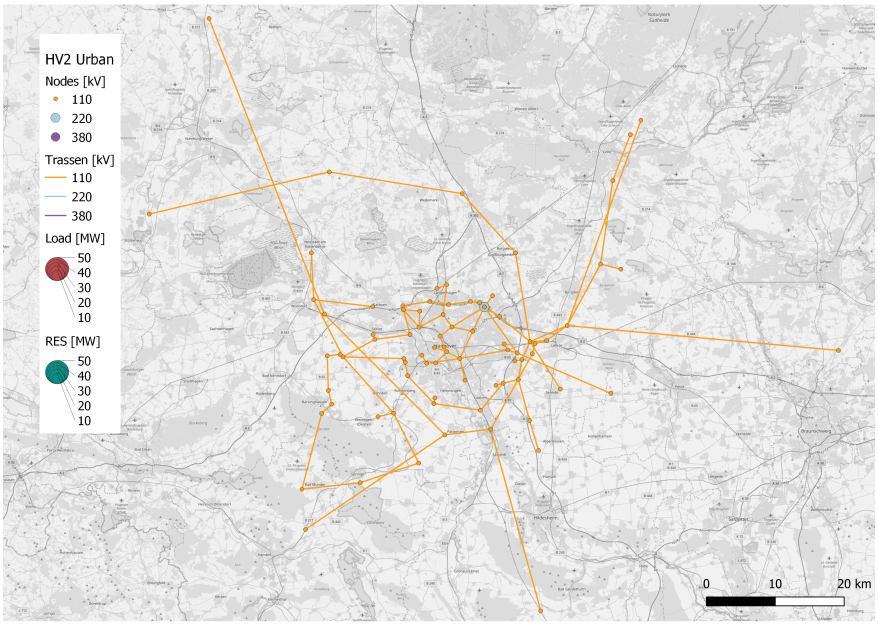
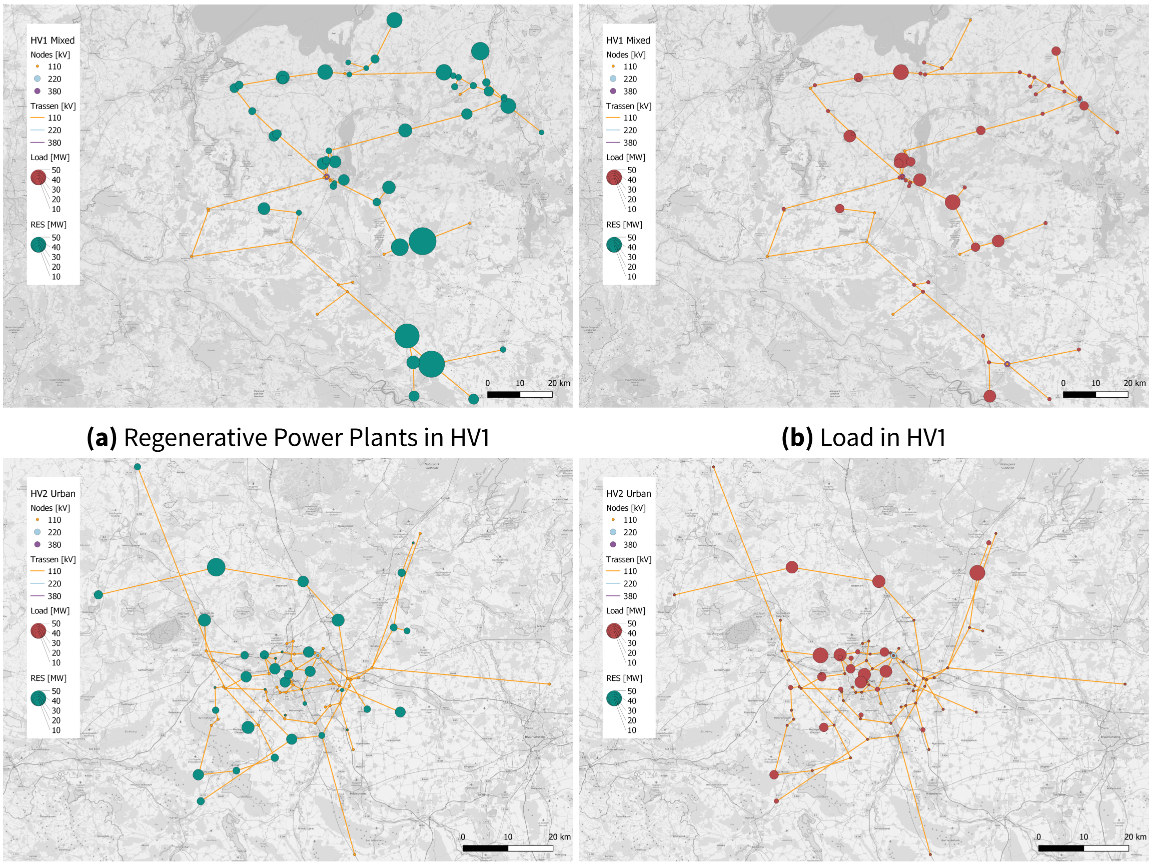


Figure 4.6: Representation of the predominantly urban HV network

grid is highly utilised, since in the high wind situation the infeed, which also includes the infeed of PV systems, is higher than the load.

In conclusion, it can be said that the different topologies and supply tasks of the two HV grids enable relevant use cases to be investigated. These are, for example, the voltage stability at long feeders such as in the HV1 network.



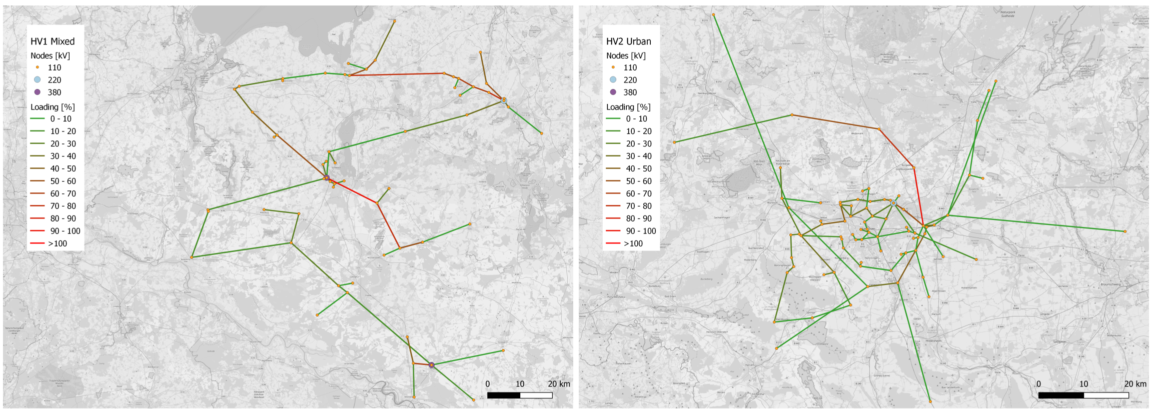
(a) Regenerative Power Plants in HV1

(b) Load in HV1

(c) Regenerative Power Plants in HV2

(d) Load in HV2

Figure 4.7: Supply mission of the HV grids



(a) HV1 grid

(b) HV2 grid

4.1.3 Medium voltage

The four SimBench MV grids are not created automatically, but according to the methodology described in Section 3.1. The grid generation is based on information about the nature of MV grids from literature reviews, on real data of Germany grids and on considering use case requirements. The grid data are therefore synthetical and do not represent any real supply area. The synthetic location data (geo data) of the MV grids nevertheless enable a fast visualization of the grids, see Figure 4.9. The geo data of the MV grids are placed with respect to the geo data of the HV nodes, to which the MV grids are connected. The graphical representation of lines within each grid correspond to the real line lengths. However, the different grids are not represented on the same scale. As the grid parameters which are summarized in Table 4.2 show, the line length of rural MV grids are approximately 23.3 km versus 4.7 km in urban MV grids. Therefore, the MV lines are significantly longer than Figure 4.9 would suggest. The topologies described in Table 4.2 should be recognizable. The rural grid mainly has a simple, open ring topology, while multiple closed rings are possible in the semi-urban grid. The urban grid has the same topology with an additional base station. This is visible to the left of the HV node in the figure. The base station is connected to four new open rings. The commercial grid include both, a radial feeder, that can be found on the bottom rigth of the HV node, as well as open rings with multiple closing options, located in the left and bottom left of the HV node. In addition, four feeders are connected at the remote station in the top right area of the HV node. Consequently, as described in Section 3.1.2, the four MV grids meet the topological requirements of Section 3.1.3 while considering the most common MV grid topologies. As a result, different solutions and algorithms can be tested under multiple variations and requests. For example, from the rural grid to the suburban grid and to the urban grid, different complex procedures to check N-1 contingency may find different numbers of resupplyable plural (primaries). This is because for the rural MV grids with open-ring topology, the algorithm only has to change one switch position after the fault clearance, while in triple system, two outgoing branches exist, of which the algorithm must find which one to be resupplied fully or partially. In the end, it is possible to obtain a state of complete resupply of the MV grids in scenario 0 without limit violations according to Section 5.1, regardless which elements failed.

The grid parameters described in Table 4.2 were chosen as shown in Section 3.1, so that the requirements of the use cases are satisfied, and the grids are close to reality, e.g. the length of outgoing branches is similar as in reality. The supply points are all grid nodes on which the energy consumers of the MV and LV level are connected. The interconnection point of the outgoing branches with opened switch was chosen in the way that might be challenging but still solvable for the resupply algorithm. Therefore, the switch positions are not optimized. This was implemented on purpose for the users, depending on the definition of optimality, who intend to optimize the switch position.

If a consumer is indirectly connected to the MV grid in a commercial area, this will be handled the

Table 4.2: Overview of grid describing parameter of the MV grids

Grid character	Rural	Semi-urban	Urban	Commercial
Topology	Open ring systems	Open ring system with triple-system	Open ring system with cross-links and base station, MV double busbar	Open ring systems with unsupplied remote station, MV single busbar with two vertical couplers
Rated Voltage [kV]	20 kV	20 kV	10 kV	20 kV
No. of nodes	97	117	144	107
HV/MV Transformer rated power	2x25 MVA	2x40 MVA	2x63 MVA	2x40 MVA
Sum of loads	17.3 MW	31.6 MW	49.7 MW	34.5 MW
Sum of DER	25.6 MW	23.8 MW	13.6 MW	16.6 MW
No. of feeders	8	9	14	9
Extreme feeder lengths	7.3-22.3 km	3.4-11.9 km	0.7-4.7 km	2.6-11.1 km
Medium feeder length	12.4 km	6.4 km	2.2 km	5.8 km
Extreme no. of supply points per feeder	5-22	6-22	4-18	3-20
Medium no. of supply points per feeder	11.4	12.3	9.5	10.8
Share of cables	60 %	70 %	100 %	70 %
DER types directly connected to MV	PV, Wind, Hydro, BM	PV, Wind, Hydro, BM	Hydro	PV, Wind, Hydro, BM

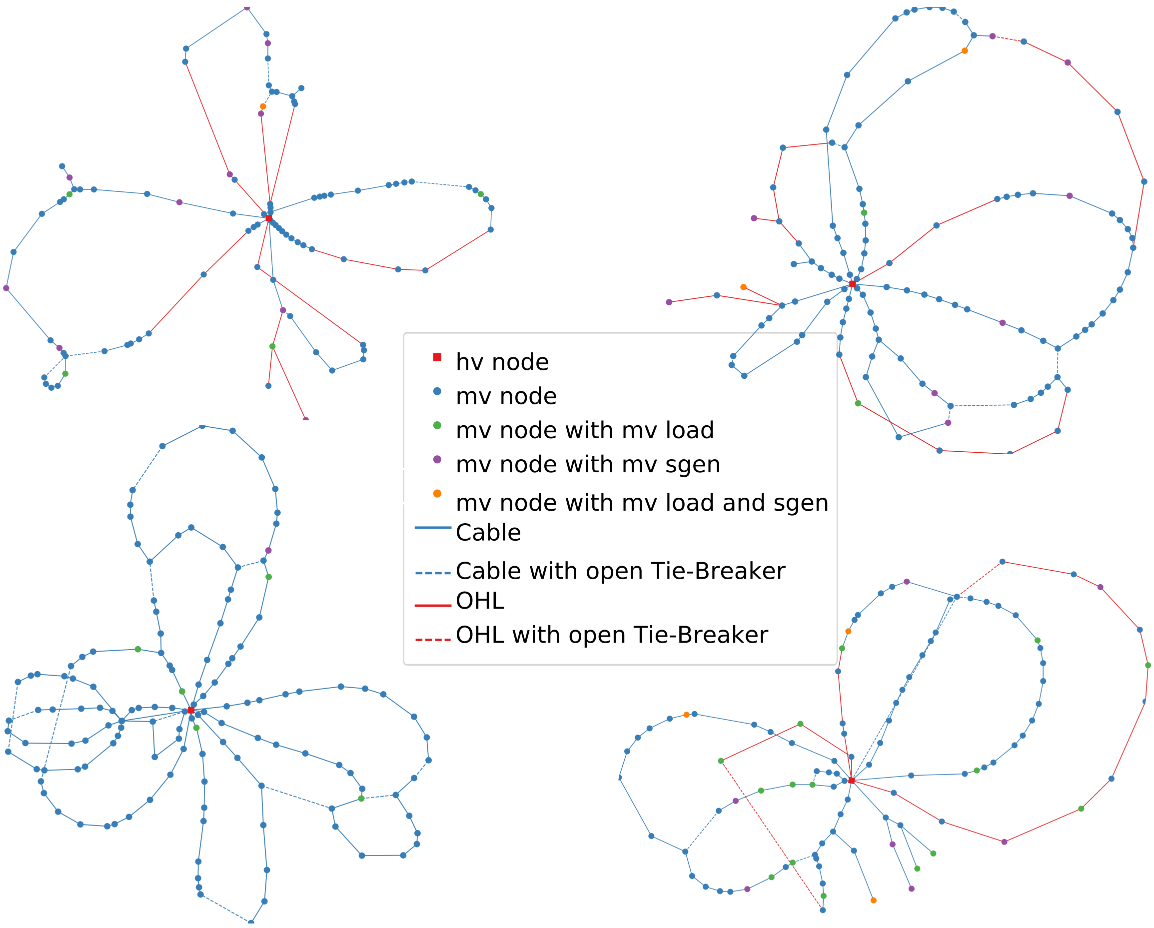


Figure 4.9: Plot of MV grids: rural (top left), semi-urban (top right), urban (bottom left) and commercial (bottom right)

same as a LV grid. Since it is a synthetic MV grid, the distribution of the types of the connected LV grids cannot be directly referred to a real grid area. However, it was ensured that the realistic assumptions are still valid. This means, for example, a faraway located local grid station will not be characterized as type “lv_urban6”, which represents a very urban LV grid. Also, the time series of rural areas will not be assigned to the consumers near an urban LV grid station. The same pattern can be applied to the LV grid types connected to the same MV grids, that on a rural MV grids all LV grids will be characterized as rural grids. Table 4.3 offers a full overview of the distribution of the LV grid types of the MV grids listed in the first row. This showed that in these rural MV grids, $36 + 37 + 7 = 80$ rural LV grids and 10 suburban LV grids are connected.

The relationship between the grid parameters share of cable, line type, cross-section area and length were already introduced in Section 3.1.4 and shown in Figure 3.2. The line parameters are mainly selected from published information from the German DSOs and in article [46]. The OHL in the real MV grids as well as in SimBench MV grids tends to be longer than the cable, which is

Table 4.3: Overview of SimBench LV grid types connected to MV grids

Acronym	Urbanization character	Rural	Semi-urban	Urban	Commercial
LV1	rural	36	6		1
LV2	rural	37	25		9
LV3	rural	7	18	9	6
LV4	semi-urban	10	36	42	23
LV5	semi-urban		23	50	22
LV6	urban		2	32	18

Table 4.4: Sum of line lengths [km] of different line types with MV grids

Line type	Cross-section [mm^2]	Rural	Semi-urban	Urban	Commercial
OHL	34	35.4			
	48		20.6		19.3
	70	11.4			1.2
Cable	70	37.2	40.8		
	95		3.2		9.8
	120	32.0	2.7		21.1
	150			2.2	16.8
	185			4.5	0.4
	240			14.9	
	300			8.6	
	400			7.6	

shown in grid topology figure colored in red (Figure 4.9). The sum of the line length of different line types and cross-section areas are summarized in Table 4.4. It should be mentioned that, for the same rating transmission power, larger cross-section area is required for the lines with the lower nominal voltage. In urban LV grids, which have a nominal voltage of 10 kV and more consumer loads, larger cross section is required compared to grids in the rural area with a nominal voltage of 20 kV.

The realism of SimBench MV grids can be estimated using Figure 4.10. It shows the distribution of network parameters of real grids using boxplot diagrams. The parameters of the SimBench MV grids are marked with four differently colored stars. The x-axes of the graphics are only included to provide a suitable and easily recognizable representation, as otherwise the star-shaped markings would overlap. Some grid parameters, like the sum of the loads and generators, are already introduced in Table 4.2 and are visualized here again with the real grid data. Other graphs represent relevant and chained parameters like the HV/MV transformer rating of each MV grid supply points, or further quantities like the average relative distance of the DER to the grid station. The distance can be ranged from 0 (DERs is directly connected to the grid station) and 1 (DERs are connected at the last nodes of the outgoing branch). For the comparison of the SimBench grids against the real grids, all the real grids assigned to exactly one grid station, although some outgoing branches can

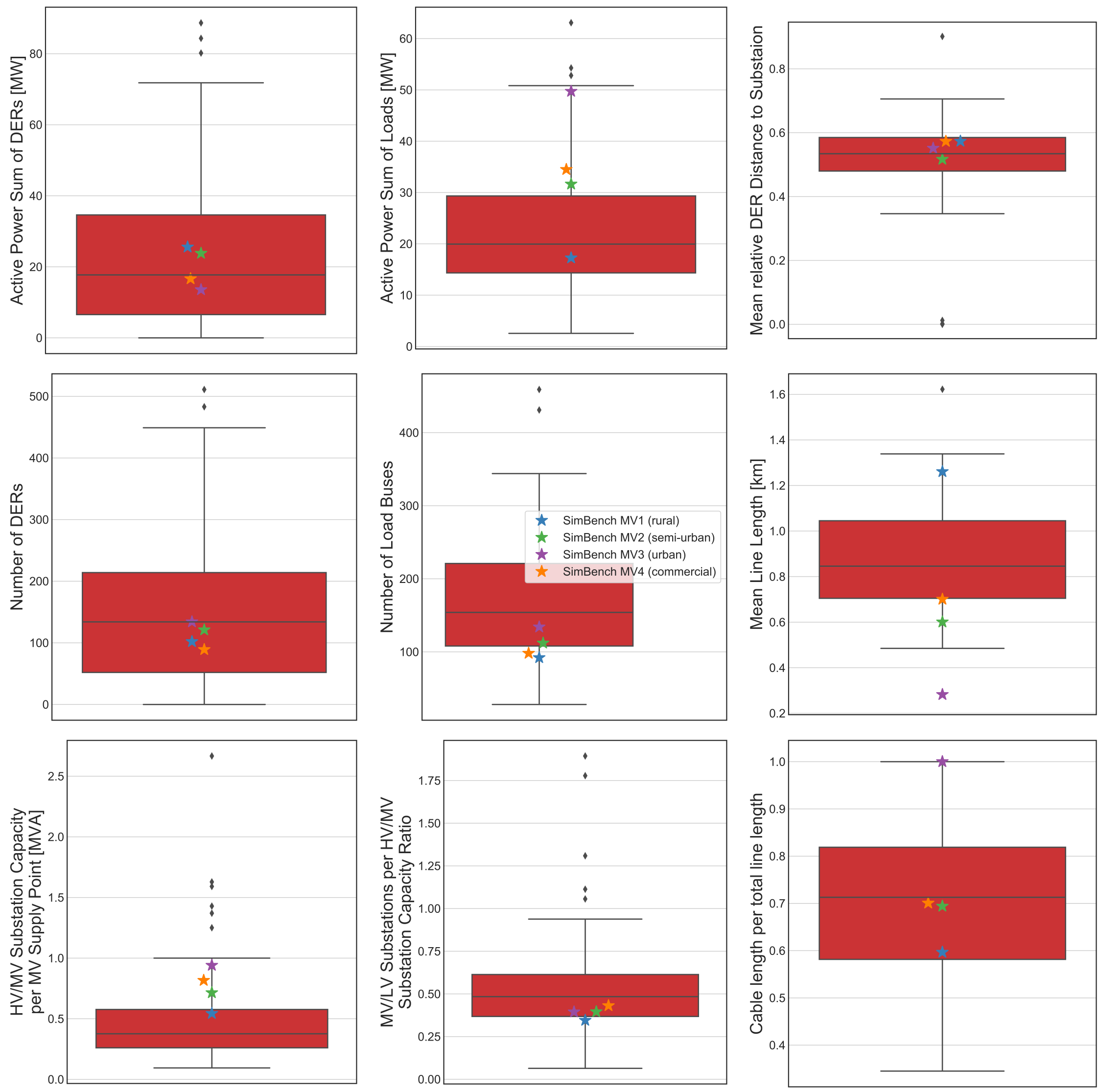
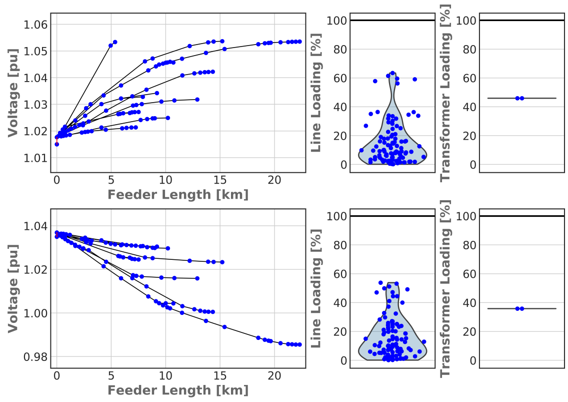
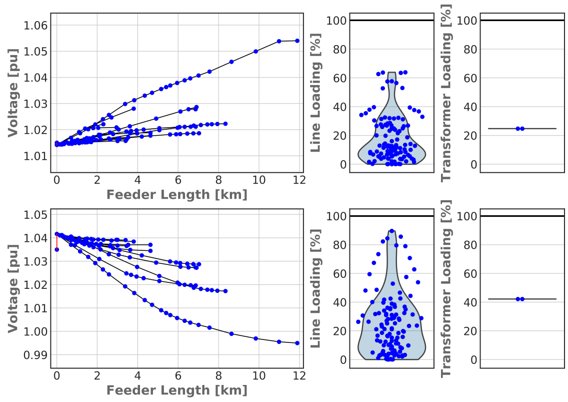


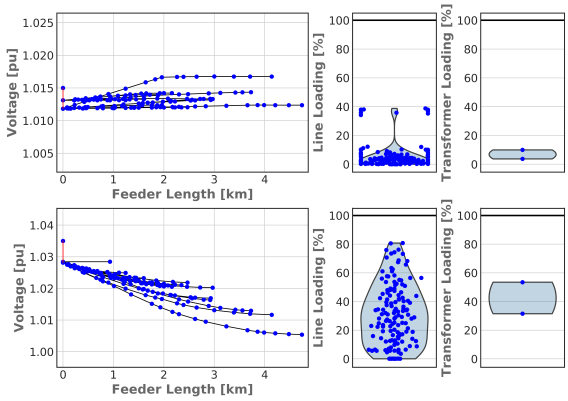
Figure 4.10: Comparison of grid parameters of SimBench MV grids and real grids



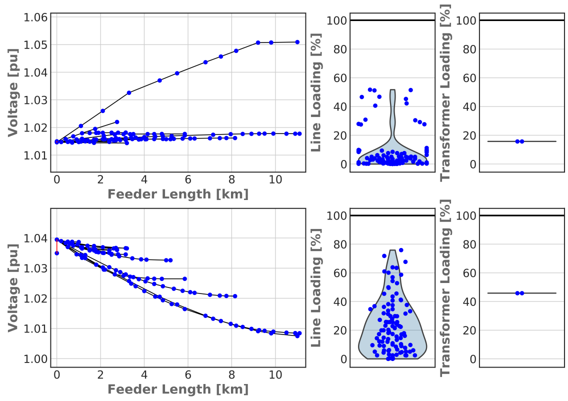
(a) Rural MV grid



(b) Semi-urban MV grid



(c) Urban MV grid



(d) Commercial MV grid

Figure 4.11: Voltage values in dependancy on the distance to the HV/MV transformer station as well as line and transformer loadings for the study cases lW (top) and hL (bottom)

be supplied by multiple grid stations according to the switch positions. It can be assumed that the switch position of the available real grid data do not exactly match reality. These switch positions are adapted by the system operator only when grid configuration changes. Due to the extensive data base with 74 MV grids from five different DSOs and a total line length of more than 11.000 km, the SimBench grids can be classified as meaningful.

Because benchmark grids are provided in SimBench grids, the LV grids are not weakly loaded and relatively challenging. Due to the application of the bottom-up approach for the loads, the SimBench MV networks are also relatively heavily loaded. This can be seen in Figure 4.10 with the classification of the sum of all load active power (top, middle) as well as the HV/MV Transformer rating, which must be reserved in each local grid station (down, left). The distribution of the SimBench grid data (bottom, middle) results directly from the in standard equipment used in SimBench LV grids (power transformer rating) and the distribution of the LV grid types given in Table 4.3.

The grid utilization of the four SimBench MV grids of scenario 0 is shown in Figure 4.11 for every two calculation cases. All six calculation cases defined in SimBench are presented in detail in Section 5.1 and their use in conjunction with the SimBench data is discussed. The two calculation cases used here are "Heavy loaded, less infeed (HL)" and "Low load, very high wind generation (lW)". The figures show the voltage curve alongside the distance to the grid station and the line and transformer utilization. The blue points each represent a grid node, a line or a transformer in the grid. Grey lines connect the node voltage points, where a real line in the grid exists. The vertical red lines represent the connection between HV nodes and MV busbars with transformers. With the from calculation case specific slack voltage set point on the HV node and the discrete transformer tap control of the voltage of the MV busbar, the voltage difference of the two sides of the transformer is minimized. The violin plot is used here, in which the envelope contains the information about the frequency of occurrence. The points around the y-axis are placed in this way for a better recognizability with minimal overlap. The voltage curve shows that the lower voltage limit of 0.965 pu. was never reached in normal operation. The upper voltage limit of 1.055 pu. was violated in the rural grid and the both terminals from the suburban and commercial grids, to which the wind turbines are connected. The maximum allowed line utilization under normal operation depends heavily on the existing resupply possibilities. Branches, which is required to resupply another branch under similar condition, is only allowed to be loaded up to 50 %. The same should be applied to the transformer, since in the SimBench MV grid transformers are rated with redundancy. Through the already discussed various resupply possibilities with triple system, remote station or base station, the suburban, urban and commercial area grids lines can be heavily loaded, without losing the capability of resupplying the local grid station. The comparison of the grid utilization of the both calculation cases of the urban grids show very different characteristics as the rural grid, since the connected load are much higher than the generations.

4.1.4 Low voltage

According to the methodology in Section 3.4, six LV network models are generated automatically, i.e. one LV model is available for each of the classes described in Section 3.4. The assignment of the network models to the classes from Section 3.4 is as follows:

- LV rural 1: class "rural 3"
- LV rural 2: class "rural 2"
- LV rural 3: class "rural 1"
- LV semiurb 4: class "semi-urban 2"
- LV semiurb 5: class "semi-urban 1"
- LV urban 6: class "urban"

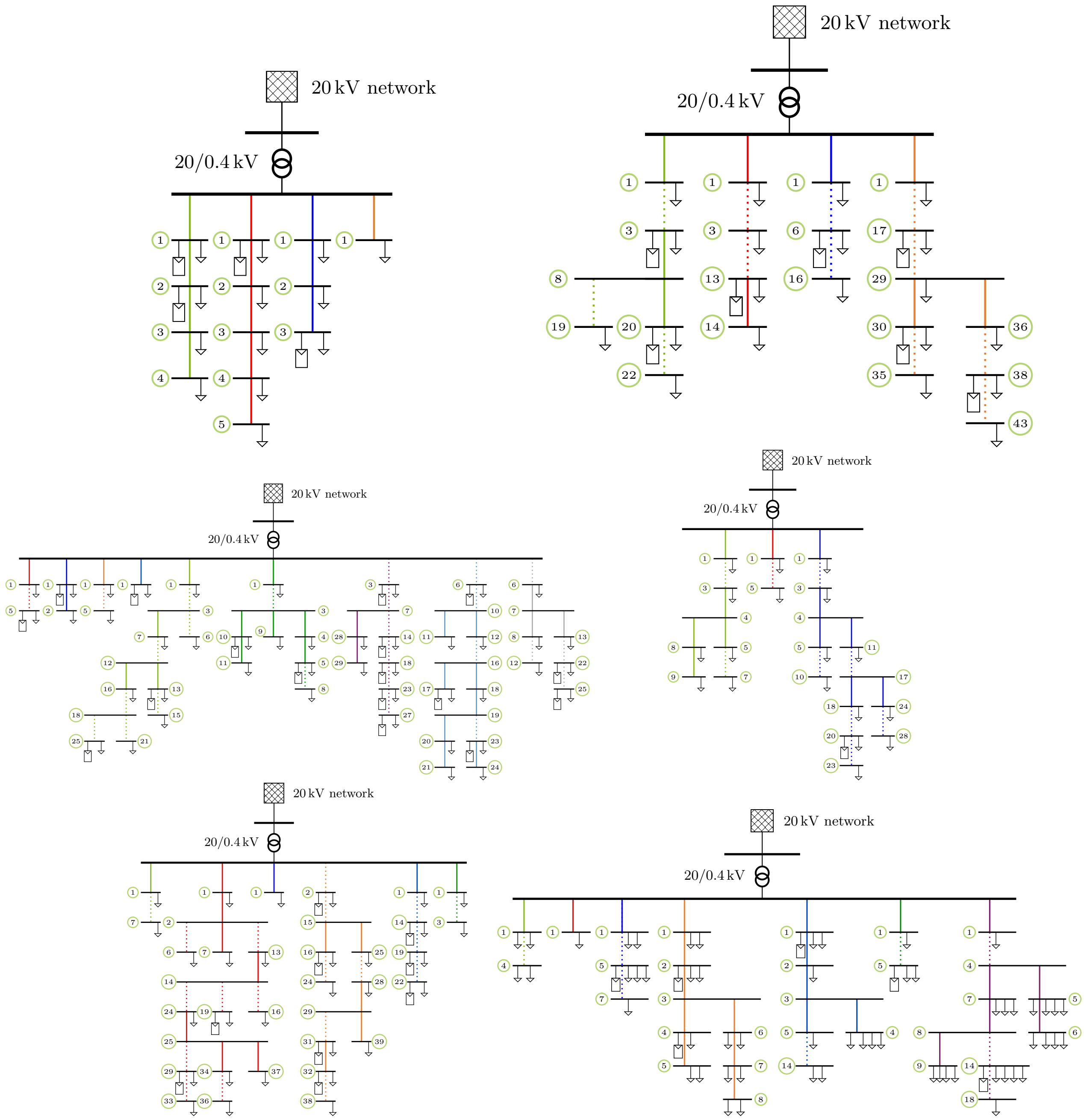


Figure 4.12: Schematic representation of the LV networks (from top left to bottom right): three rural networks, two suburban networks and one urban network.

A schematic representation of the individual LV network models can be found in Figure 4.12. It can be seen that the models have a radial topology, but they differ in the number of feeders and nodes as well as the types of equipment. The LV networks are always connected to the superimposed MV network via a transformer in a local network station.

Since the network models are generated with the algorithm described in Section 3.4, which uses

OpenStreetMap data, real georeferenced data can in principle be specified. Since the use cases from Table 3.1, Table 3.2 and Table 3.3 do not require these, the real georeferenced data are no longer used. In addition, the aim is to generate representative and realistic LV network models, which can generally and geographically unspecifically represent average network structures in Germany and not a locally specific LV network model for a defined municipality, so that the real georeferenced data do not offer any particular benefit in this context. The real georeferenced data thus only serve to generate the network models for the corresponding municipality from the different classes. In order to enable a visualization of the networks as in the MV level, synthetic georeferenced data are generated for the LV networks. Their main purpose is to map the relative positions to the MV nodes and thus simplify processing in the network calculation tools used.

Table 4.5 summarizes the main network parameters of the LV level. It can be seen that more consumers can be found in more densely populated supply areas, which is why, for example, larger transformers are used. Furthermore, the line lengths of the individual network models also vary because the consumers have different distances to each other, which tend to be shorter in more densely populated areas than in rural areas. The line types used correspond to the types used by distribution system operators for new lines (see [47]). The electrical parameters of the line types used are shown in Table 4.6. Here, r describes the ohmic resistance covering, x the reactance covering, b the susceptance covering and i_{max} the nominal current.

The consumers are dimensioned using the algorithm from Section 3.4. The consumer performance is estimated on the basis of the building floor area stored in OpenStreetMap. The number of floors cannot be taken into account because this information is often not stored in OpenStreetMap. For the calculation, an average power of $P_{L,average} = 2kW$ is determined and calculated according to

$$P_{L,V} = P_{L,average} * \frac{A_G}{A_D} \tag{4.1}$$

the power of a building is determined. A_G describes the building floor area and A_D an assumed average living area. More details on the performance estimation can be found in [46]. The value $P_{L,average} = 2kW$ is also used as the base value for the SimBench models. In order to obtain a variation between the different LV models, this value is additionally changed. For example, it is chosen larger for more densely populated municipalities in order to the greater power consumption of an apartment building compared to a single-family house. Without this variation, a single-family house and a multi-family house would receive the same power value if the building floor areas were identical. This provides for more realistic initial values for the consumer power in the network models. Within the framework of the iterative adjustments during the evaluation (see 3.4), some consumer power values have been changed manually. For example, power levels have been increased in order to achieve a higher network utilisation in one model. The load types are assigned manually and randomly. The load types are important for the assignment of time series.

At the LV level, the DERs are limited to PV systems, since generally no wind turbines are connected at this voltage level. The DERs have been added subsequently, i.e. after the automated generation of the LV grid models. Real grid data have been evaluated and the number of DERs per LV grid model has been selected based on this data. The dimensioning of the individual plants is carried out randomly with performance values taken from the real dataset.

To classify and validate the synthetically generated LV network models, an evaluation of real network models was carried out. For the evaluation, topological parameters between the real dataset and the SimBench models are compared. From the overall data of the real network models, a subdataset is filtered for each of the six SimBench models. This subdataset enables a comparison between real and synthetic network models based, among other things, on the transformer size. Thus, a comparison dataset is available for each LV SimBench model. In total, data from 180 real networks are evaluated. From these 180 network models, subsets with approx. 20 models per SimBench model are formed. For example, 22 real network models are used for comparison with model LV 01 (corresponds to class "rural 3").

Figure 4.13 (left) shows the comparison of the number of consumers. On the one hand, the number of consumers of the respective SimBench LV models can be seen; on the other hand, the range of real data is listed. The range is the range of the real available network data. Thus, the lower end of a bar represents the minimum. In this case, the minimum means that a real network model is available in the comparative dataset with this small total number of consumers. Analogously, the upper end of a bar represents another real network model, which has the most consumers within the comparison dataset. It can be seen that the SimBench LV models are very close to the mean value of the real network models and thus represent good "average" real networks. This can also be seen when comparing the effective power of the loads (further graphs in Figure 4.13).

The result of the comparison of consumer active power can be seen in Figure 4.13 (centre). The range of the SimBench network models shown here shows the range of the individual loads, i.e. the maximum of a SimBench range corresponds to a load in the model with this active power value. In contrast, the ranges of the real network models have been calculated. Since in this case not one real network is considered but several, mean values are shown here. This means that the maximum range of a real network category corresponds to the mean value of the maximum outgoing loads of the individual real networks. With the exception of the "rural 3" class, the mean values between real data and SimBench data are also close together here. The difference in class "rural 3" results from the fact that the SimBench model contains many agricultural farms, which leads to higher power consumption. The comparative dataset includes smaller consumers, which

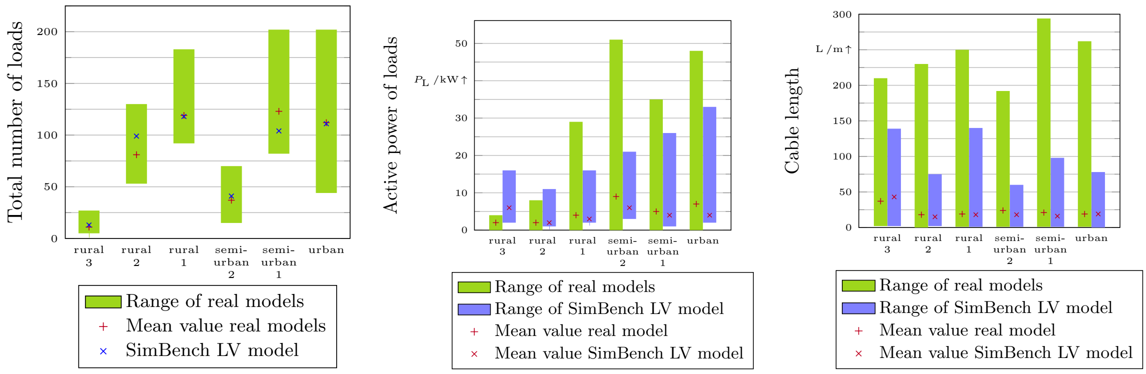


Figure 4.13: Comparison of real network data with SimBench LV networks with regard to number of loads (left), active load power (center) and cable lengths (right)

is more indicative of household loads. Since the classes “rural 2” and “rural 1” already predominantly contain household loads, the network model for class “rural 3” has been retained as a supplement to the two rural models.

Figure 4.13 (right) shows a comparison of the cable lengths, again showing that the average cable lengths of the SimBench LV models are close to the real data. The average of the maximum line lengths of the real data is higher than that of the SimBench models. Since the comparative dataset per SimBench network model is relatively small with approx. 20 real models, it serves more as an orientation and less as a reference that represents the average of all LV networks in Germany. In addition, it can be seen that the maximum line lengths in the SimBench models clearly exceed the average line length, so that the line lengths can be left as they are and a need to increase them even further does not appear necessary.

Table 4.5: Overview of network describing parameters of the LV networks

	LV rural 1 (rural 3)	LV rural 2 (rural 2)	LV rural 3 (rural 1)	LV semiurb 4 (semi-urban 2)	LV semiurb 5 (semi-urban 1)	LV urban 6 (urban)
Topology	Radial network	Radial network	Radial network	Radial network	Radial network	Radial network
nominal voltage	0.4 kV	0.4 kV	0.4 kV	0.4 kV	0.4 kV	0.4 kV
MV/LV-Transformer-rating	160 kVA	250 kVA	400 kVA	400 kVA	630 kVA	630 kVA
Number of feeders	4	4	9	3	6	7
Number of nodes	13	96	128	43	110	58
Line type	NAYY 4x150SE 0.6/1kV	NAYY 4x150SE 0.6/1kV	NAYY 4x150SE 0.6/1kV	NAYY 4x150SE 0.6/1kV	NAYY 4x240SE 0.6/1kV	NAYY 4x240SE 0.6/1kV
Line length (total)	0.56 km	1.47 km	2.35 km	0.746 km	1.79 km	1.078 km
Line length (mean)	43.05 m	15.44 m	18.52 m	17.76 m	16.42 m	18.90 m
Line length (minimum)	2.15 m	1.52 m	1.19 m	0.69 m	1.08 m	0.19 m
Line length (maximum)	137.22 m	75.00 m	139.52 m	60.00 m	98.00 m	77.75 m
Number of consumers	13	99	118	41	104	111
Consumer power (total)	80 kW	202 kW	331 kW	243 kW	409 kW	441 kW
DER number	4	8	17	1	9	5
DER power (total)	160.4 kW	145 kW	190 kW	6.5 kW	137 kW	57 kW

Table 4.6: Overview of the electrical parameters of the cable types in the LV networks

Parameter	r (Ω/km)	x (Ω/km)	b (μS/km)	iMax (A)
NAYY 4x150SE 0.6/1kV	0.2067	0.0804	260.752	270
NAYY 4x240SE 0.6/1kV	0.1267	0.0798	273.319	357

4.1.5 Times series

In the following, the results of the time series generation are discussed. The arrangement of the subsections are the same as in Section 3.5.

Accumulated consumers

The result of the assignment using the methodology described in Section 3.5 is as follows:

As expected, most of the RPM profiles of the collected data most likely correspond to commercial and agricultural profiles. Household and B0 (band load) profiles are rarely found. The average distance from the associated profile is in general slightly higher than in the IZES dataset, presumably because there is a wider distribution of different kinds of profiles given.

Although the IZES profiles are household data sets, they are unexpectedly mainly assigned to the agricultural SLP classes L0-L2 and to the commercial profile G6. The commercial profiles G0-G5 do not appear. An assignment to the category B0 is only rarely made and at a very high distance, which suggests that more atypical or very random profiles fall into this category.

Both results can be seen in figure 4.14 as bar chart.

On the one hand, it can be seen here the proportion of assigned profiles to the individual SLP categories (left y-axis) and the average distance of the measured data to the SLP categories (right y-axis). The distance values are only used for relative comparison and have no other physical meaning. The bars represent the dataset percentage distribution amongst the different SLP categories. For example, more than 20 % of the RPM dataset are G1 profiles, while in case of the IZES dataset most profiles are assigned to L1. A check, whether this is an error in the actual method, can be excluded. The assignment to the L-profiles is due to the fact that they consistently have a similar load demand, regardless of the day of the week. In addition they show high peaks in the morning and the evening. A comparison with the IZES measurement data can confirm such behavior within the measurement data. Also the assignment to G6 does not seem to be an error. G6 profiles show a high weekend consumption. The respective assigned household profiles also show a markedly high demand at weekends, which in turn is not depicted in the H0 profile as these do not show such a strong increase at weekends. In case of industrial profiles and agricultural load time series, the distance measure indicates that in case of G3, G4 and L2 profiles, the profiles best match the SLP. In case of household profiles in turn, the distance measure indicates that the best equivalences, and thus the lowest distances are found for the categories H0, L0 and L2. The individual selected time series are described in more detail below.

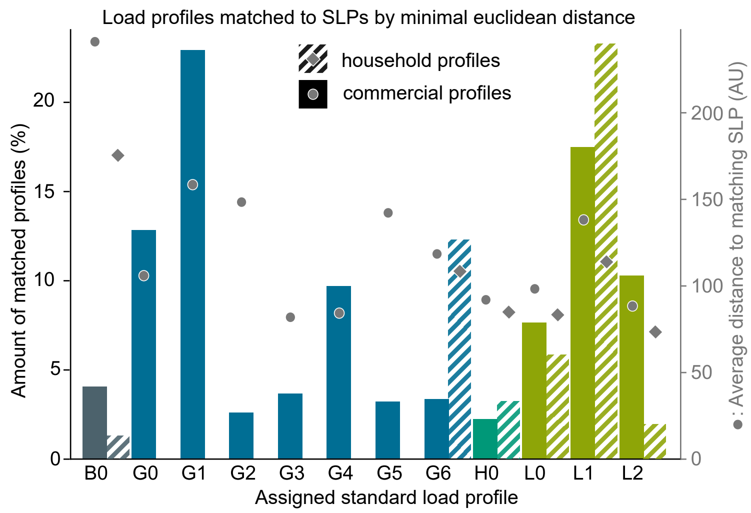


Figure 4.14: Distribution of assigned profiles and average distance of the measurements to the individual SLP classes

Household time series

The selected household profiles and their comparison to the assigned SLPs are shown in Figure 4.15. The three profiles that correspond the most to the H0 profile are displayed here. Here a good agreement between the average measurement profiles and the SLP can be seen.

However, as described above, an all-encompassing, representative picture of all households is important. At the same time a wide range of consumer profiles are useful. For this reason, two additional profiles are selected which have a high correspondence to the L1 and G6 profile.

Commercial time series

The procedure for the commercial time series is the same as for the household time series. Therefore, only the differences of the profile selection shall be pointed out.

Since the G0 profile is a profile aggregated from other G-profiles, a mixture of several profiles makes actually more sense than the direct assignment of a time series. However, due to the additional effort instead of trying to model a G0 profile, a time series out of the dataset is nevertheless selected. This ensures that a G0 profile is available in case a consumer in a grid is assigned to a G0 profile. The selected profile has a slightly higher base load than the SLP but otherwise matches the load profile well.

The result is shown in Figure 4.16.

The profile shows a good agreement with the SLP on weekdays. Even the typical behaviour on weekends can be properly depicted by the measurement. A decrease in consumption on Saturdays and an only base load determined behaviour on Sundays reflects the G0 profile very well.

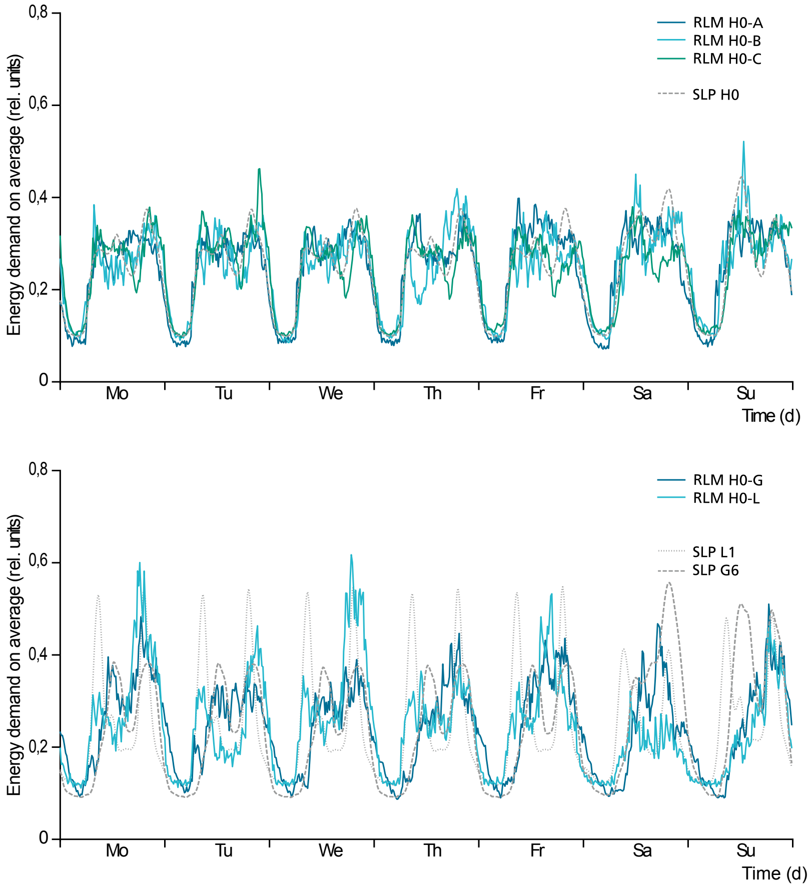


Figure 4.15: Comparison of the selected, normalised, average weekday household profiles and their assigned SLPs

Agricultural time series

The load profiles for the agricultural companies do not show any particular methodological characteristics. Therefore they are not considered additionally. However, if the reader is interested in how they look alike, all profiles can be easily generated using the SimBench dataset.

Commercial time series for the MV/LV level and the industry

Three profiles with a higher average demand (10-20 kWh per 15 min) are selected for consumers on the MV level. Profiles with such a size make up only a relatively small part of the dataset (318 profiles, 12.5%). Profiles with high average consumption (>100 kWh / 15 min) are selected to map consumers at the HV level. These are rarely found in the dataset (17 profiles, 0.7 %). The distribution to the SLP categories differ greatly from those with lower average consumption, as shown in Figure 4.17.

Significantly more frequent in case of the MV time series G3, G4, L0 and L2 can be found. In case

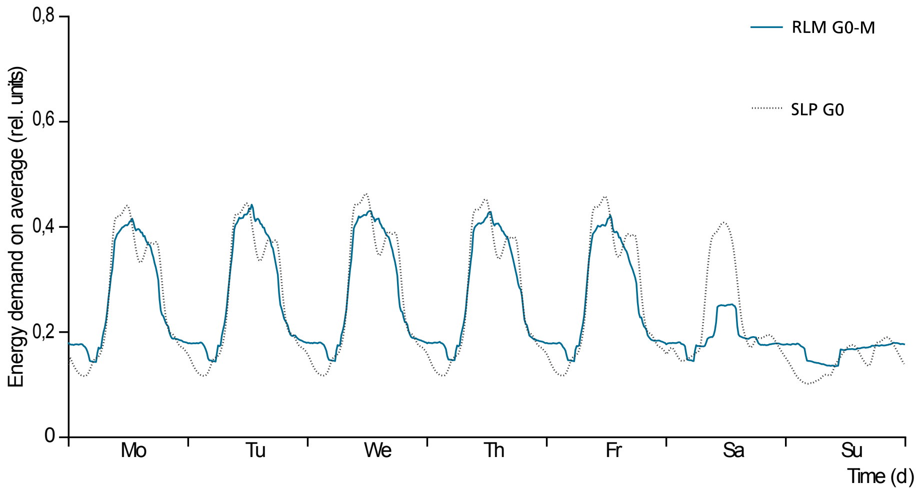


Figure 4.16: Comparison of the average commercial profile to the SLP

of the HV time series in turn, the categories B0, G2, G3, H0 and L2 are mostly found, while G0, G5, G6, L0 and L1 are completely missing.

For the MV level in the categories G0, G3 and G4, there are many profiles with good correspondence and significantly higher distance to other SLPs. Thus one profile per category can be easily selected. Again, a G0 profile is included, although such a profile cannot exist in reality. However, as this is often used by network operators for reasons of simplicity to be representative for all commercial enterprises, a G0 profile is also included on the MV level. Commercial profiles for other categories are omitted. In order to provide a profile for agricultural companies, an L2 profile is also provided.

The situation is somewhat different on the HV level. Due to the good agreement a profile from the category G3 and G4 is selected here as well. Surprisingly, there is also a good correspondence to the H0 profile given. This, however, can be attributed to the fact that the assigned profile has a high base load and a uniform power increase on all weekdays. Since this can correspond to the typical behaviour of a large industrial company that strives to keep its base load high while keeping power peaks low throughout the week, a profile similar to the H0 profile is also included. Two other profiles, assigned to categories B0 and L2, are considered on the HV level in the SimBench dataset as well. On closer examination we find that both of these profiles are bandload-like, as shown in figure 4.18.

Since these two do actually not fit into any of the given categories (due to the relatively constant power demand of B0 and L2 it is nevertheless assigned to these categories), it is decided to include them, but to assign them to a separate category “Other”.

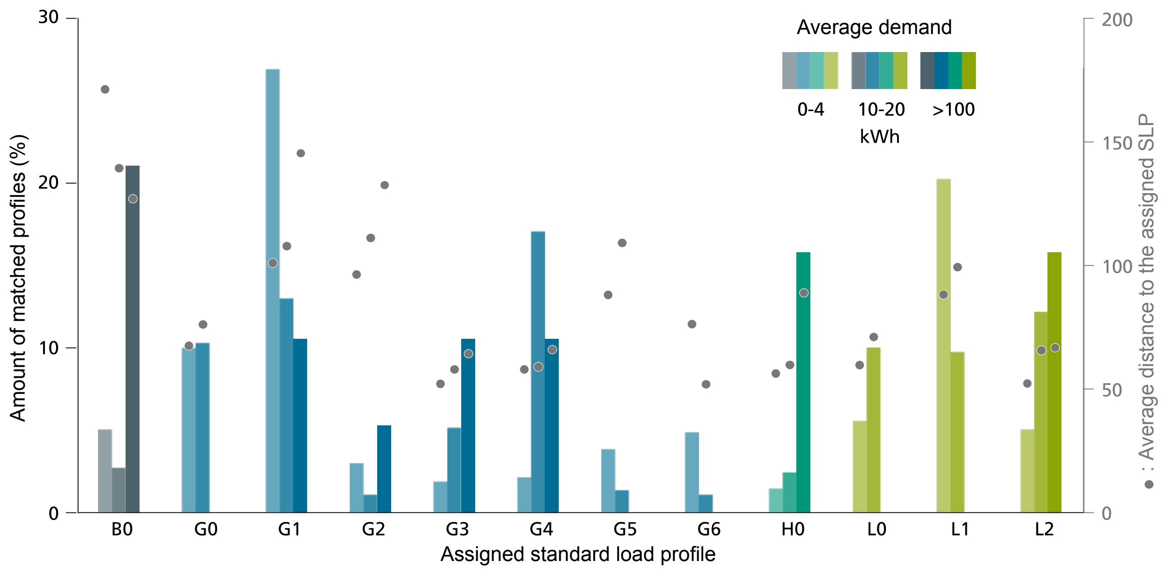


Figure 4.17: Distribution of assigned profiles and mean distance of the measurements to the individual SLP classes, subdivided according to mean consumption

General overview of all profiles

An overview of all given accumulated profiles and their assignment to the respective SLP can be found in figure 4.19. For each of these profiles, both an active power and a reactive power profile are provided.

Individual consumers

In this subsection we will discuss all time series which are made available for individual consumers. First the EV- and then the HP results will be described.

Extra high voltage

In case of EV, six time series each are provided for household charging stations and workplace charging stations. In case of household charging stations, three times a 3.7 kW, twice a 11 kW and once a 22 kW charging station is provided. In case of the workplace charging stations, charging stations at workplace are provided twice with 3.7 kW, twice with 11 kW, once with 22 kW and once with 50 kW. These time series are generated for the LV level and normalised to a maximum of one. On the MV level, all workplace charging station time series are summed up. This aggregated time series, in turn, is not normalised to one, because then a simultaneity of 1.0 would be assumed, i.e. that all charging stations are turned on at the same time. Here the nominal power is 101.4 kW. This time series is multiplied by five to get a time series for EV for large companies. The nominal

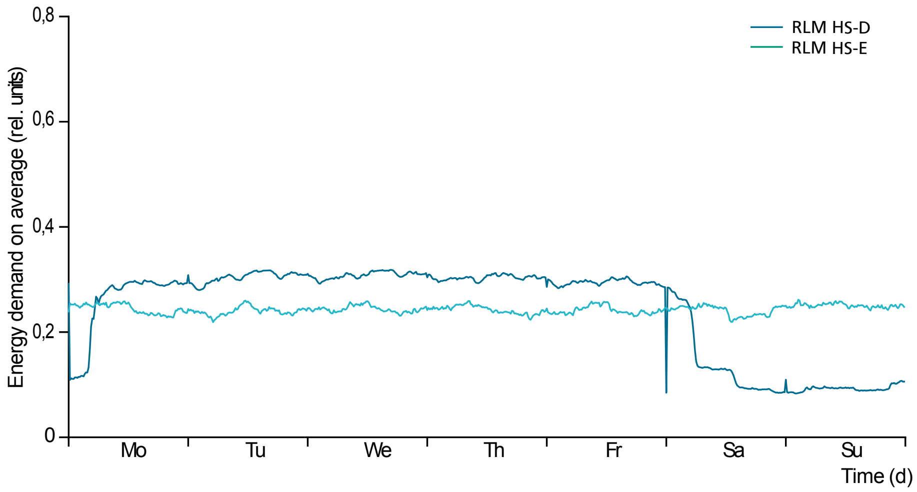


Figure 4.18: Exceptional bandload-like consumption pattern of a commercial time series in the SimBench dataset

power is set to a value of 507 kW. Each time series is given as active and reactive power time series.

Heat pump

For the HP time series, four time series are provided for each city (Hannover and Lübeck). One parallel, alternative and semi-parallel operated HP per city where air serves as heat source. Additionally, one parallel operated soil-HP. Also in these cases, the value is normalised to one and both active and reactive power time series are provided. The sizes of the HP vary between 2 kW and 30 kW, whereby larger ones are mainly installed on MV level, smaller ones mostly on LV level.

Aggregated load time series

As in case of individual consumers, the time series provided here will be briefly discussed. First of all, the aggregated load time series of the MV and HV level generated by a bottom-up approach are depicted. Afterwards, the aggregated load time series of the EHV level generated by a top-down approach are introduced.

Aggregated load time series in the MV and HV level

A time series is provided for each grid of the MV and HV level. These are explicitly assigned to the nodes of the upstream grid levels by their designation. Same as in the terms of the other profiles, the profiles are normalised to one. The result of the time series simulation of each grid is both an active and a reactive power time series.

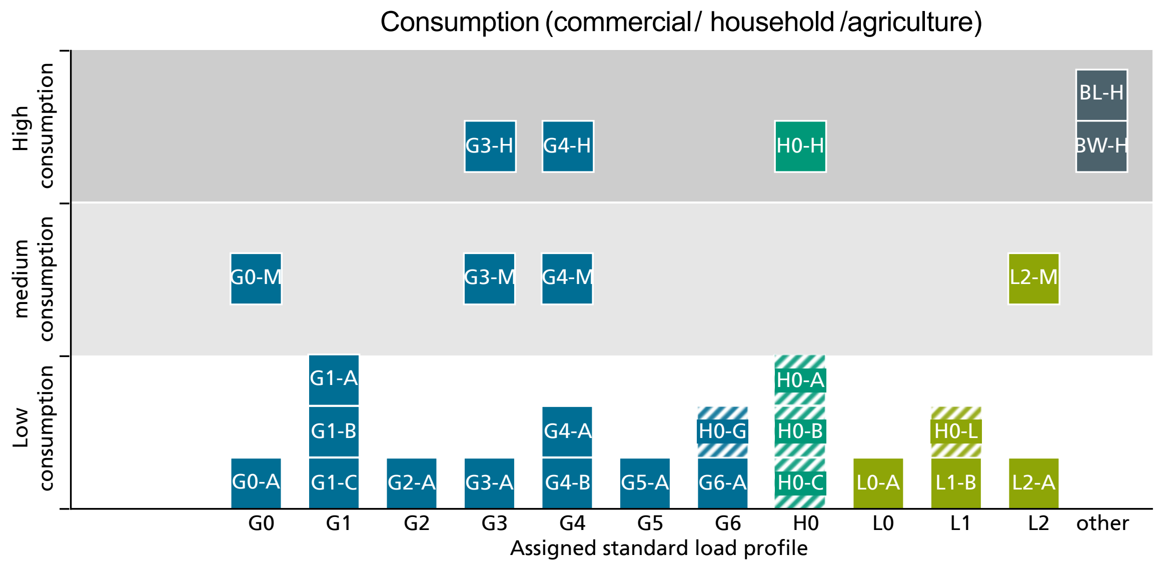


Figure 4.19: General overview of all provided profiles for accumulated consumers

Aggregated load time series in the EHV level
On the EHV level, 28 load time series within Germany and two time series representing the neighbouring countries are determined using the k-Means algorithm. A distinction between the time series located inside and outside of Germany are made by the addition of "exp". All time series are normalised to one. Both active and reactive power time series are available.

Feed-in time series

A total of 28 feed-in time series for wind, PV, BM and hydropower are made available in the SimBench dataset. There are 8 for PV, 12 for wind, 5 for BM and 3 for hydropower, all normalised to one. Only active power profiles are provided. The reactive power profiles depend on the control method and are therefore left to the user of the SimBench dataset. In the defined basic use cases, which are presented in Section 5.1, a $\cos(\varphi)$ of 1 is assumed. As described in Section 3.5.4, the time series are geographically located differently. The geographical assignment of the time series for PV and wind can be found in table 4.7.

Aggregated feed-in time series

In addition to the time series of distributed energy resources, there are also aggregated grid time series. These represent the entire feed-in within a grid model, i.e. the power sum that is fed into the upstream voltage level. These aggregated time series are available from the LV to the HV level, so that there are 14 aggregated feed-in time series in total.

Table 4.7: Geographical assignment of the time series for PV and wind

profile	location	orientation
WP1	Baltic Sea	
WP2	North Sea	
WP3	Baltic Coast	
WP4	East of HV1	
WP5	East of HV2	
WP6	East Germany	
WP7	North of HV1	
WP8	North of HV2	
WP9	North Sea Coast	
WP10	South of HV1	
WP11	South of HV2	
PV1	Hannover (location 3)	East
PV2	Lübeck (location 1)	East
PV3	Hannover (location 1)	South
PV4	Hannover (location 2)	South
PV5	Lübeck (location 2)	South
PV6	Lübeck (location 3)	South
PV7	Hannover (location 2)	West
PV8	Hannover (location 2)	West

Storage time series

In the first part, the storage devices used to increase the self-consumption of generated PV energy will be discussed, in the second part the storage devices running grid beneficially are considered.

Storage devices used to maximise self-consumption of generated PV energy
For each storage device installed in a grid and the corresponding combination of load and feed-in time series a time series is provided. No further time series, i.e. other combinations of load and feed-in time series, are provided, as this would have increased the size of the dataset many times over. As in case of the other time series, the profiles are normalised to one and an active and a reactive power time series is provided. Moreover, it is also important to know, that the given profile at the grid node corresponds to that as if only a PV system and a storage device are connected. The household, however, is not included. The is based on the reason that each storage device if installed is always connected to the grid in combination with a PV system. At the same time, however, the loads are already present. An additional consideration would therefore lead to an overestimation of the load.

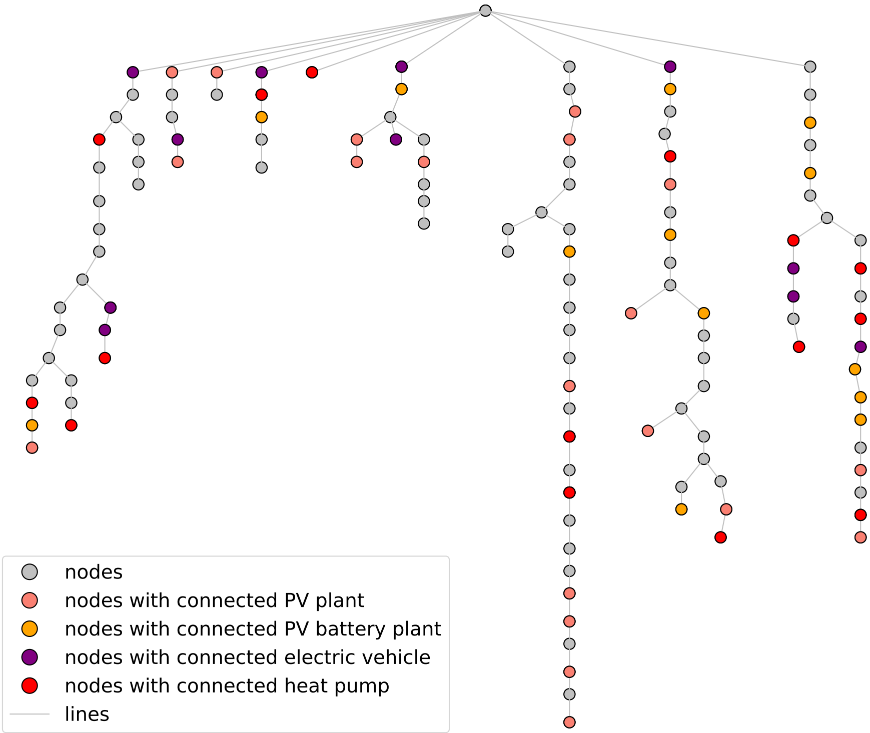


Figure 4.20: Picture of the LV grid LV3 in scenario 1 for the year 2024

Grid beneficial storage devices
Same as in terms of storage devices run to maximise self-consumption only the time series of the storage devices that are actually installed in the grid are made available. All other time series are omitted. The maximum value of each profile is again set to one and each storage time series consists of both active and reactive power profiles.

4.1.6 Future scenarios

In this section, an insight into the generated future scenarios will be given. Using the example of one grid per grid level and scenario, the respective distribution of the new producers and consumers and thus the changes in the grid will be highlighted. In addition, the consequences caused by these changes in the grid are shown.

Low voltage

The third LV grid can be seen in figure 4.20 for scenario 1. This grid shows that both the number of renewable energy producers and new consumers are increasing massively. Thus, the share of new PV plants corresponds to approx. 40 % of all PV plants. Accordingly, the share of PV plants

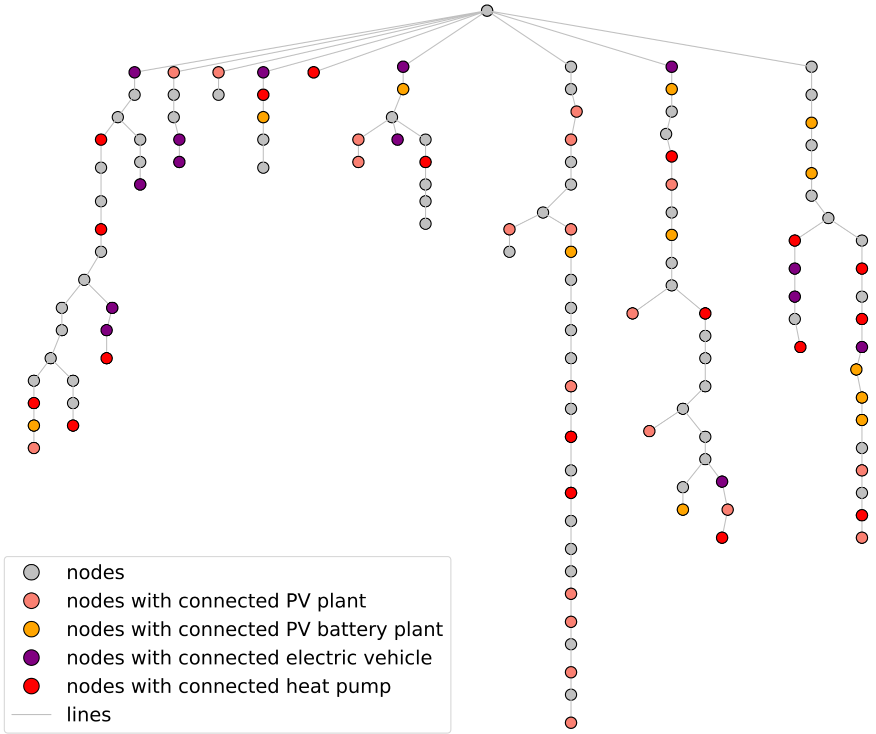


Figure 4.21: Picture of the LV grid LV3 in scenario 2 for the year 2034

has not doubled as described above, however, is only slightly lower. In comparison, the average of all LV networks is 55 %, has therefore more than doubled, which again corresponds roughly to what the HVN predicts.

The share of EV is at about 10 % and that of HP at 13 % in case of the third LV grid. This is far above the values of 2 % and 6 %. But again, this is compensated by the results of the other grids. Thus, the share of EV and HP of all LV grids is 4.5 % and 6 %, which is roughly what HVN predicts for the year 2024.

The third LV grid in scenario 2 is shown in figure 4.21. In case of this grid, the figure shows that the number of added RESs and new consumers in 2034 compared to 2024 is much smaller than in scenario 1 compared to the base scenario. The percentage share of new PV installations also shows that the share of 40 % has only increased to 45 %. Compared to the HVN study, this value is far below the prediction. However, taken the average value of all grids, a value of 70 % is reached, which corresponds to about a tripling of the original stock. The share of EVs is now at 14 % and that of HPs at 15 %. The proportion of EVs is slightly below the value of the prediction in the HVN study and that of HPs is slightly above. On average over all LV grids, the value of the EV is 19 %, which corresponds exactly to what the HVN predicts. In case of the HPs, the value of 23 % is even higher than that of the example grid described above, which is far above the value of the HVN

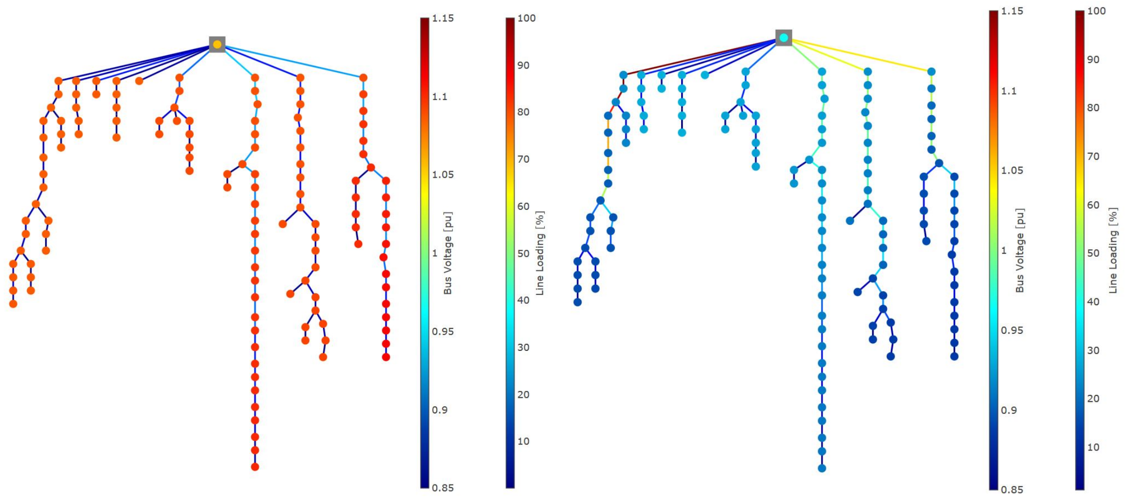


Figure 4.22: Picture of the LV grid LV3 with calculated bus voltages and line loadings displayed as heat map for scenario 1 (see left) und 2 (see right)

study. However, the value of the HVN study refers to the total energy share, whereas in case of the SimBench grids, the share of houses with a HP is as reference used. Since the energy demand in houses with a HP is usually much lower, the calculated value in the SimBench grids generally leads to an overestimation, which is why this deviation is considered acceptable.

To emphasise the relevance of the SimBench grids for grid planning, operation and analysis, figure 4.22 shows a heat map for the LV grid for the years 2024 and 2034. The exciting thing about the two future grids is that in case of the 2024 grid, primarily the overvoltages (orange, red) cause problems. This shows that mainly along feeder one and three (from right to left) voltage problems can be detected. Figure 4.23 also shows the voltage distribution over the feeder length. In addition, the transformer and line load are shown. Here it can be seen that the lines and transformers tend to cause fewer problems, while the voltage limits are clearly exceeded at numerous nodes.

In 2034 in turn, mainly the undervoltages (light blue, blue) in particular cause problems in the first two feeders and in the last feeder (from right to left). Moreover, in figure 4.24 (year 2034) it is also apparent that other problems arise in 2034 compared to 2024. Transformers and some lines, for example, also show massive capacity problems.

This shows that both other feeders, equipment and other load cases are relevant in both scenarios and could therefore lead to different decisions in grid planning, operation and analysis if both scenarios are considered in combination.

The defined share of violations according to the previously defined termination criteria show the first three grids of the year 2024 (15 % of all lines or nodes are overloaded or show voltage violations). The fifth grid also depicts violations, but the percentage of all violations is below the

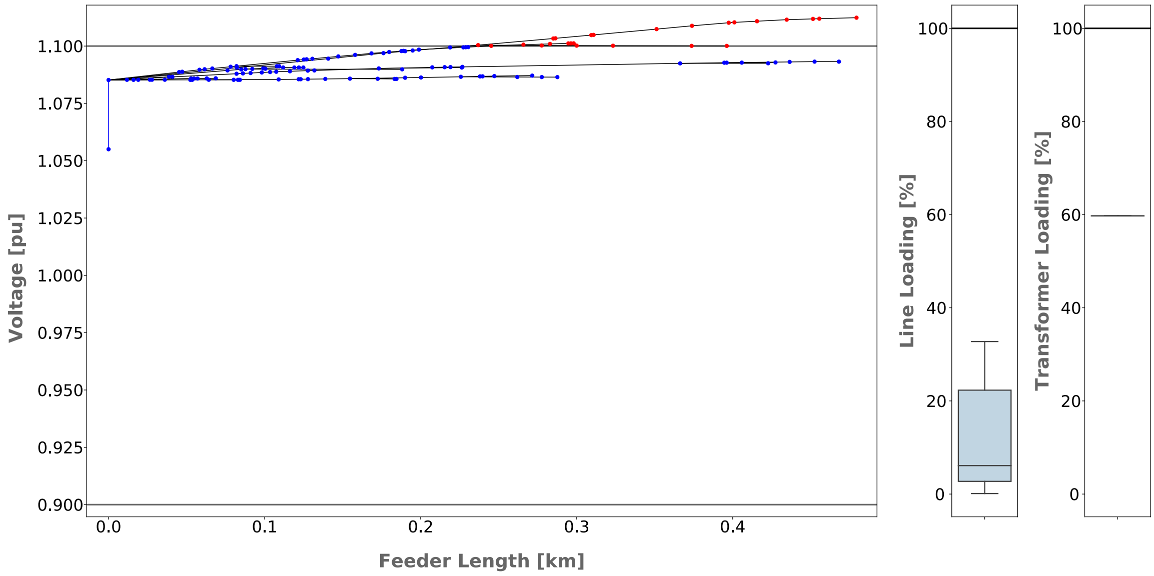


Figure 4.23: Violations detected in LV grid LV3 in scenario 1

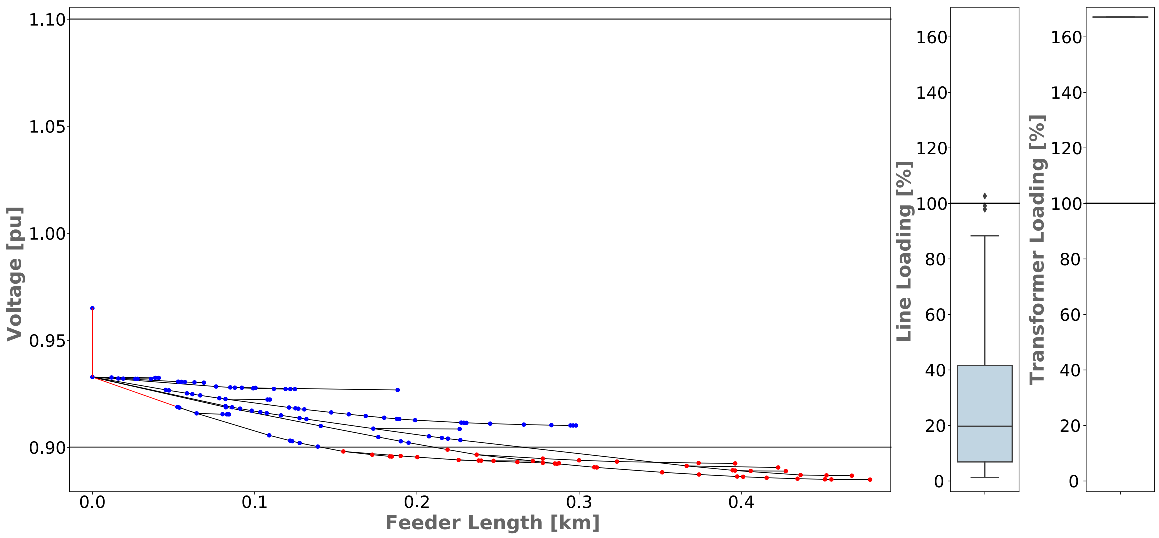


Figure 4.24: Violations detected in LV grid LV3 in scenario 2

previously defined termination criteria. In the fourth and sixth grid there are no violations at all. For the year 2034, violations are detectable in all grids, but only in the first three grids as well as the fifth grid the termination criteria are reached.

Medium voltage

The grid that is to be considered in more detail on the MV level is the fourth (commercial) MV grid. In the base scenario, the grid looks like the one shown in figure 4.25. In comparison, figure 4.26

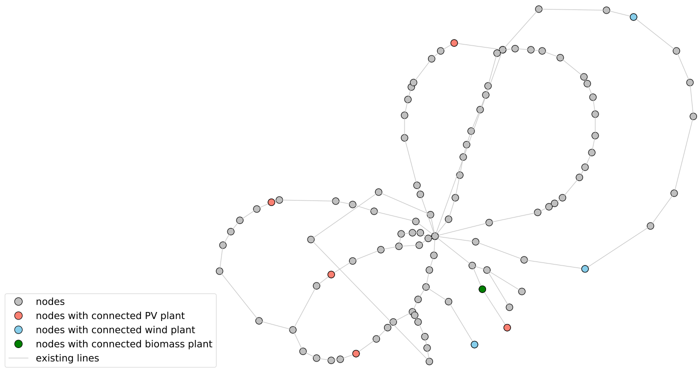


Figure 4.25: Picture of the commercial MV grid in scenario 0

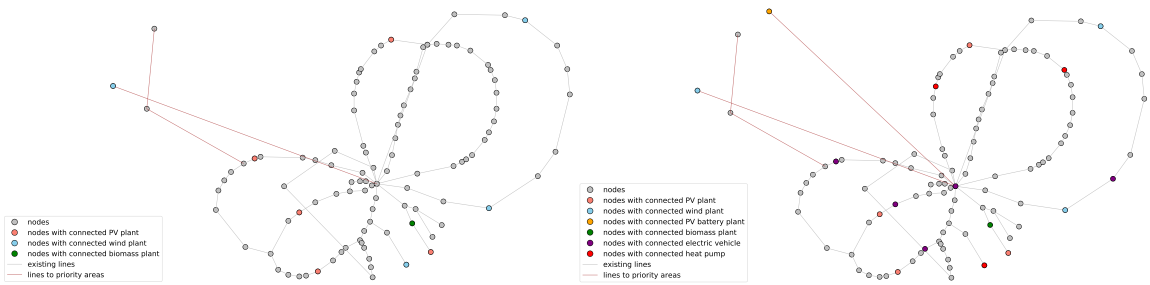


Figure 4.26: Picture of the MV grid for the scenarios 1 (seen left) and 2 (seen right)

shows the changes realised in the scenarios 1 and 2 for the years 2024 and 2034. First of all, it can be seen that new nodes and lines are being installed in the individual scenarios. As described above, these are priority areas for wind and PV that will be newly tendered in the future. If the nominal capacities of the respective new plants do not exceed previously defined capacities, they are connected to the grid via the newly installed lines and nodes. If this is not the case, which clearly happened in the scenario grids, a direct connection to TS is made. These fictitious newly tendered priority areas can also be found in the first and second grids, but not in the third. This is due to the fact that the third grid is an urban grid in which it can be assumed that no new priority areas will be added in the future.

What is exciting about the example grid selected here is that from 2024 to 2034 massive numbers of new consumers are added.

The share of PV in the year 2024 is about 56 %, i.e. it more than doubles. In 2034 the share even rises further being 76 % on average, i.e. it more than triples. Thus the results are close to those of the HVN study. The proportion of new wind turbines in 2024 is only 38 % and thus far below the predictions of the HVN study. However, this is also due to the fact that no wind power plants are installed in the urban MV grid and thus the result is strongly distorted downwards. In case of scenario 2034, the share of wind power plants does not exceed 43 % on average.

The share of consumers is not examined further here, as it is primarily influenced by the LV level,

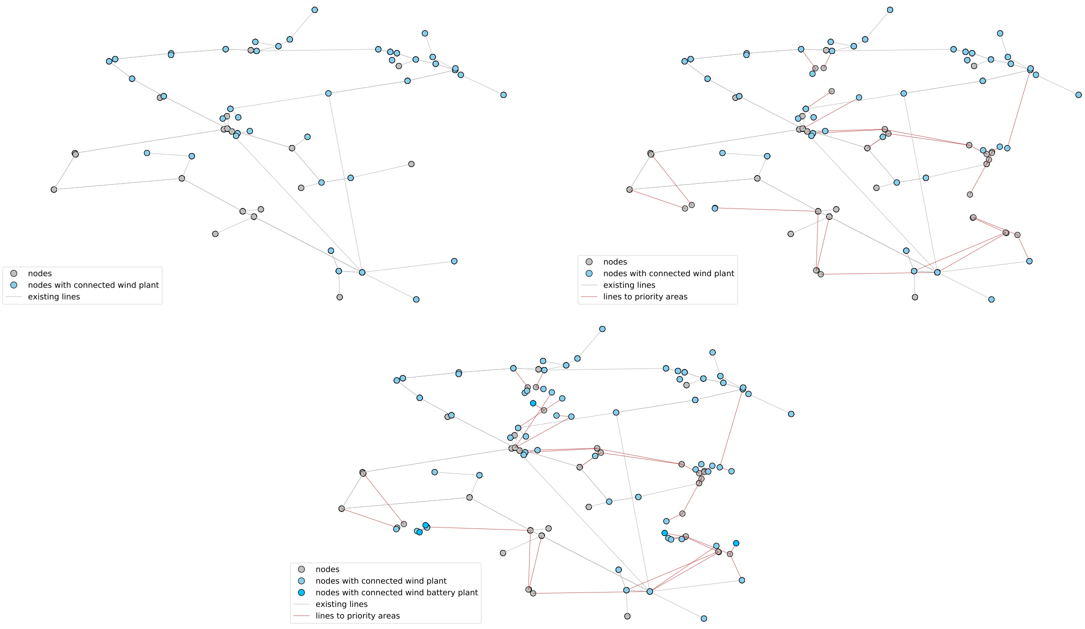


Figure 4.27: Picture of the mixedHV grid for the different scenarios (0: top left, 1: top right, 2: bottom)

which is why we do not take a closer look at it here.

In scenario 1, only the first and second grid show problems. In scenario 2, problems also occur in the fourth grid. The third network does not show problems at any time.

4.1.7 High voltage

In HV the mixed grid is to be considered more closely. Figure 4.27 displays the individual scenarios in direct comparison.

In the figures, similar to the MV level, one can see the capacity expansion on previously defined priority areas. In case of the HV grid, however, there are only priority areas for wind turbines. Another special feature is the installation of wind battery plants in 2034. The installation of wind power plants between the scenarios increases successively. A similar result is observed in the urban HV grid.

Overall, the average increase of wind power plants in the first scenario is 33 % and in the second scenario 61 %. While the results in scenario 2 are very close to those of the HVN study, they are much lower in the first scenario. Nevertheless, no further adjustment is made here, since both grids are already overloaded in scenario 1 and, due to the appropriate choice in the other grid levels, the termination criteria are retained for simplification reasons on the HV level.

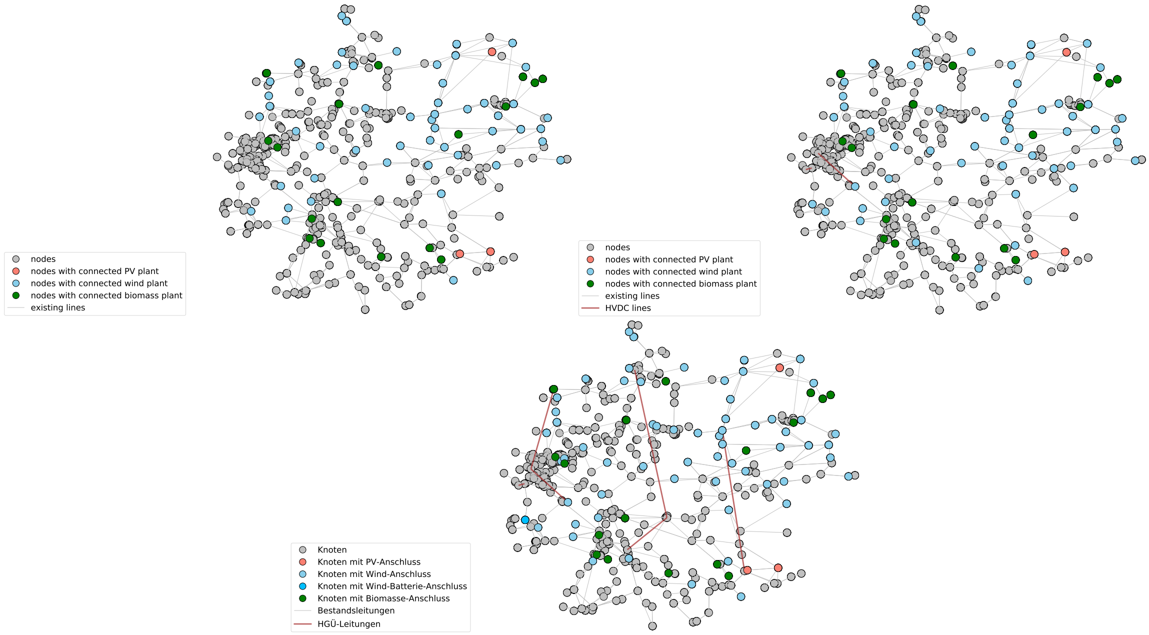


Figure 4.28: Picture of EHV grid for the two scenarios (0: top left, 1: top right, 2: bottom)

Extra high voltage

The EHV grid already contains connections to PV, wind and BM plants in its basic scenario. Figure 4.28 shows the grid in the basic scenario and the two future scenarios. In particular, the installation of the HVDC lines is clearly visible. As already mentioned in Section 4.1.1, however, no energy transport is considered at this time. Only the topology, the time of installation and thus the connection point of the HVDCs are included in the scenarios in order to make investigations in this field comparable.

Further wind parks are being installed in northern Germany. In addition, a wind park with a battery installation is also realised in scenario 2, whereby here the NEP is not taken as basis. Instead it is considered in the grid as an assumption. Currently, the expected apparent power for the individual wind parks given in the NEP are stored within the grids. A value of zero is assumed for active and reactive power. Since the active and reactive power values are used in the grid calculation tools and the apparent power is usually only included for completeness, the installed wind parks are currently not taken into account. However, they can be switched on if required by converting the apparent power into active and reactive power values.

All other scenario predictions given in the NEP are not represented in the SimBench grid and are therefore ignored.

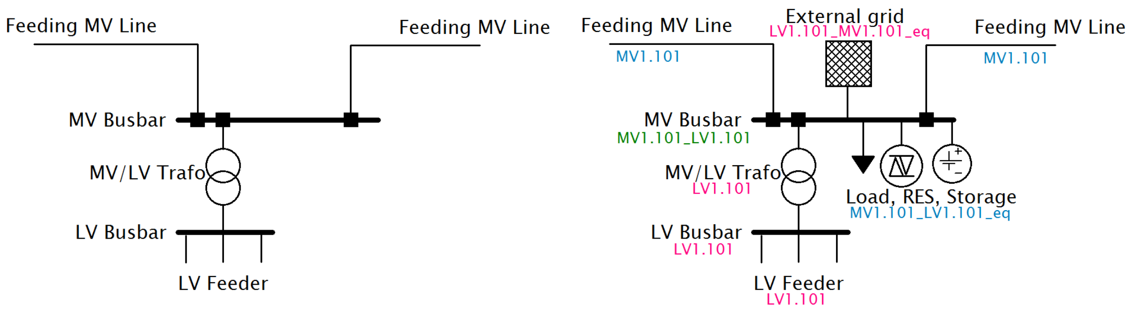


Figure 4.29: Principle of a MV/LV connection (left) including all equivalent elements and "subnet" parameters (right)

4.2 Encoding of Grid and Grid Combination with the SimBench Code

Since the SimBench grids are created in a way that each grid level is compatible with the connected other voltage levels, detailed simulations across voltage levels are possible. However, similar to the implementation of development scenarios, this leads to an increased amount of grid data within the SimBench dataset. In order to obtain an overview of the dataset, the SimBench code is introduced. This describes clearly and transparently, which SimBench grid or SimBench grid combination in which variation is currently used. In order to explain the SimBench code in Section 4.2.3 in more detail, we will start with explanations of the modeling across voltage levels (Section 4.2.1) and then the "subnet" parameter will be introduced in Section 4.2.2.

4.2.1 Modeling principles between voltage levels

To explain the interconnection of two voltage levels, Figure 4.29 (left) shows the principle of the combination of MV-LV grids. The state-of-the-art grid modeling and simulating with the focus of only one of both voltage levels does not model the other voltage levels in detail but only as equivalent elements. For the lower voltage grid, in this case the LV grid, such grid equivalents are typically contain only constant P, Q load or infeed. Thus, instead of the connected transformer supplying LV grid, an aggregated load is directly connected to the MV busbar.
In SimBench, the grid equivalent is modeled in more detail by individual load, generation and storage. This allows a better active power scaling by study cases and time series.
The equivalent of a high voltage grid, here the MV grid, is normally a slack element instead of all the connected feed-in lines. By defining a voltage setpoint, the slack equalizes the power flow of the grid. The SimBench dataset contains the grid data of all the connected voltage levels and the equivalent elements, which are required when the detailed grid modeling is not requested.
Figure 4.29 (right) shows all required elements of an MV-LV grid station.

4.2.2 Subnet parameter

Each element in the SimBench dataset contains information about the "subnet" parameter. The subnet parameter indicates the grid to which the element belongs. In this way, the subnet parameter increases the clarity of the datasets. For example, if the grid with subnet name "MV1.101" is selected, all the elements starting with the subnet "MV1.101" are considered. In the case of nodes, also such with "MV1.101" after the separator "_" must also be considered. This is due to border nodes do not belong only to MV1.101 but also another grid. As a result, all all elements, whose subnets are printed in blue and green in Figure 4.29 (right), must be considered for the "MV1.101" grid. If only the "LV1.101" grid is required, the elements, whose subnets are printed in pink and green, are relevant. If both voltage levels are required, then all the elements should be included, whose subnets begin with one of both grid names. However, equivalent elements, which contains both sub grid parameters and ends with "_eq" must be excluded from the selection.

The subsequent indentation explains the construction of subnet values of a single grid elements. HV and EHV subnets consist of two parts, LV and MV subnets consist of three parts.

subnet (in general): $sn_1 sn_2.sn_3$
subnet (Example 1): HV2
subnet (Example 2): MV3.201

The three individual parts sn_1, sn_2 and sn_3 are explained in Table 4.8. The SimBench EHV grid and two HV grids appear only once in the datasets, so that real German georeferenced data can be used. The SimBench MV and LV grids are connected to the higher voltage level grids multiple times. In order to identify these MV and LV grids, the subnet is numbered consecutively. They start with 1 plus the number of the higher voltage level grid type multiplied by 100. This means that the MV grids connected to the first HV grid, ends with 101, 102, ... MV grids connected to the second HV grid are numbered with 201, 202, ... Thus, the type of a SimBench grid can be read by the subnet (sn_1) and, in case of MV and LV, the grid type of the connected higher voltage level grid, too (first digit in sn_3). Table 4.1 provides the information on the order, the grid types are numbered, and on how the digits in sn_2 and sn_3 correspond to the abbreviations.

4.2.3 SimBench Code

For the unique labelling of the selection of the grid or grid combination from the entire SimBench datasets, the usage of the so-called SimBench code can make it entirely transparent which dataset

Table 4.8: Description of the parts of the parameter "subnet"

Part of subnet	Description	Possible contents	Example 1	Example 2
sn_1	Voltage level	{ EHV, HV, MV, LV }	HV	MV
sn_2	Number of grid types	$\mathbb{N}_{\leq x} \vert x = \begin{cases} 1, & sn_1 = \text{EHV} \\ 2, & sn_1 = \text{HV} \\ 4, & sn_1 = \text{MV} \\ 6, & sn_1 = \text{LV} \end{cases}$	2	3
sn_3	Serial numbering of MV and LV grids	The numbering starts with $1 + 100 \cdot sn_{2,higher\ voltage\ grid}$		201

is used. The SimBench code consists of six parts, which are separated with "-". The following shows an exemplary code and its components, which are explained in detail in Table 4.9.

SimBench code (in general): $code_1 - code_2 - code_3 - code_4 - code_5 - code_6$

SimBench code (example): 1 − MVLV −rural − 2.107 − 0 − sw

The combination of grids with different voltage levels results in a large number of possible combinations. Since all grids have three development scenarios and two types of switch position representations, the total number is increased by a factor of $3 \cdot 2 = 6$. With a large number of available grids, there is a risk of encountering difficulties in the comparison and evaluation of simulation results. The grid combinations, which are considered most relevant, are provided within the SimBench codes. These include the grid combinations with up to two voltage levels modeled in detail. Furthermore, only two types of the detailed modeled downstream grids are designed: Either only *one* of them or *all* of them are modeled in detail. In addition, for the first case, in which only one of the downstream grid is modeled in detail, three grids of different types, which are connected to different positions of the upstream grid, have been preselected for the SimBench codes. This will briefly be explained according to the above-mentioned example of the rural MV grids of the above code "1-MVLV-rural-2.107-0-sw".

90 LV grids are connected to this MV grid, so that the possibility of selection of the 90 different LV grids for detailed modeling exists. Though the potential selection of the LV grids to be modeled in detail, more than $2^{90} - 1 \approx 1.24 \cdot 10^{27}$ different combinations exist. In order to limit the number of potential combinations, only the detailed modeling of one of the three LV grids 1.108, 2.107 and 4.101 and all the LV grids has been considered to be relevant. With this limitation, the possible number of combinations of the SimBench codes is reduced to 246. The full list is available in appendix A. For the use cases, in which the limitation is too restrictive, e.g. when more than two voltage levels are required with detailed model, SimBench codes that contain the

Table 4.9: Description of the parts of the parameter “subnet”

Part of code	Description	Possible contents		Example
$code_1$	SimBench version	1		1
$code_2$	Selected voltage levels	{ EHV, HV, MV, LV, EHVHV, HVMV, MVLV }		MVLV
$code_3$	Urbanization character of the higher voltage level	{mixed}	$code_2 \in$ {EHV, EHVHV}	rural
		{mixed, urban}	$code_2 \in$ {HV, HVMV}	
		{rural, semiurb, urban, comm}	$code_2 \in$ {MV, MVLV}	
		{rural1, rural2, rural3, semiurb4, semiurb5, urban6}	$code_2 \in$ {LV}	
$code_4$	number of the subnetof the lower voltage level grid		$code_2 \in$ {EHV, HV, MV, LV}	2.107
		sn_2	$code_2 \in$ {EHVHV}	
		$sn_2.sn_3$	$code_2 \in$ {HVMV, MVLV}	
$code_5$	Selected scenario	{ 0, 1, 2 } $\hat{=}$ { “heute”, “morgen”, “übermorgen” }		0
$code_6$	Switch consideration level	{ sw, no_sw } $\hat{=}$ { complete, only open line and transformer switches }		sw

complete data ($code_2$ = complete_data) or all the voltage levels without equivalent elements ($code_2$ = EHVHVMVLV) have been included in the list.

Providing the SimBench datasets with two variations of the switch position representations is an additional contribution to the user-friendliness. In the SimBench data in CSV-format, all the switches are modeled as node-node switches. This leads to that the situation that, between bus bar and branches elements, like lines or transformers, the switches are connected to nodes, which are inserted extra as type “auxiliary”. The branch elements are connected to the auxiliary nodes and then connected to the bus bar with the switch. This has the advantage of supporting the grid calculation software, which have no support to the modeling switch on the branch elements. However, the insertion of auxiliary busses reduces the clarity of the dataset. In some use cases, when the switch configurations are not required, the variant “no_sw” can be selected, in which all buses connected by closed switches are rigidly connected and the reduce the number of auxiliary nodes and may result in an acceleration of the simulation, depending on the grid calculation software.

4.3 Data format and accessibility

The SimBench dataset is available and can be downloaded from the SimBench homepage (www.simbench.net). Not only the individual network models of the respective voltage levels are available there, but also defined combinations, i.e. cross-voltage level network models. A data format based on CSV tables is used to ensure that the SimBench data is comprehensible, clear and independent of specific software tools. The CSV format was chosen because it is a relatively simple and open data format and can be processed and used in various software tools. In the following, the data format developed for SimBench is presented and then it is described how the dataset can be obtained. A GUI integrated into the website, which is also described here, helps to select the network model.

4.3.1 Data format

The complete SimBench dataset, i.e. individual network models of the various voltage levels and their defined combinations as well as time series and data of equipment types, is provided in the form of CSV files. In addition, the individual network models are also available for direct download for the software tools PowerFactory [1], Integral [2] and `pandapower` [3]. The combinations of the individual network models can be imported into Integral or PowerFactory via converters, which are also provided. For `pandapower` the complete dataset, i.e. also the network model combinations, is already available through the Python package "simbench" (via GitHub or PyPI). How to use the converters for Integral and PowerFactory and how to open and use the network models in `pandapower` is described in appendix C.

The individual CSV tables of the SimBench format are described in detail below. The data structure follows an object-oriented approach. Thus, the components of the dataset are regarded as individual objects with attributes, i.e. all elements of an electrical network are described in a table. The data is stored in a line-oriented, relational database format, i.e. each row corresponds to an object and each column contains an attribute of this object. There are also type and profile tables. The type tables describe detailed parameters of a group of systems, e.g. cable types, while the profile tables contain time-dependent scaling factors. The following conventions and assumptions also apply:

- voltages are assumed as three-phase and symmetrical
- currents are assumed as line currents
- power values are three-phase specified
- the network frequency is 50 Hz

Table 4.10: Overview of the SimBench data format tables

Element Class	Counting Arrow System	Element	Type	Time Profile	More
Knoten		Node			
Cross branches	Producers	ExternalNet			
		Powerplant		PowerPlant-Profile	
		RES		RESProfile	
	Consumer	Load		LoadProfile	
		Storage		StorageProfile	
		Shunt			
Edges		Line	LineType		
			DCLineType		
		Transformer	Transformer-Type		
		Trans-former3W	Trans-former3WType		
		Switch			
Other					Measurement
					Substation
					Coordinates

An overview of the SimBench data format tables is shown in Table 4.10. The external relationships of the nodes and buss elements are shown in Figure 4.30. The ones show that the buss elements can only be connected to one node. Furthermore, transverse elements, e.g. loads, can have a time dependency in the form of a time series. Coordinates and substations are also assigned to the nodes. Coordinates and substations serve the user for a simplified overview and organization of the data. In various software tools, such as PowerFactory, these assignments can also mean improved organization.

The external connections of the branch elements to the nodes are similar to those of the buss elements, except that branch elements have two connections to nodes. Some branch elements have types assigned to them. In addition to nodes, transformers and switches can also be assigned to a substation. Measuring instruments can be positioned at nodes as well as lines or transformers and are therefore related to these elements.

Nodes

The structure of the "Node" model class is shown in Table 4.11. Meaning in here:

- vmSetp: voltage magnitude setpoint (nominal value)

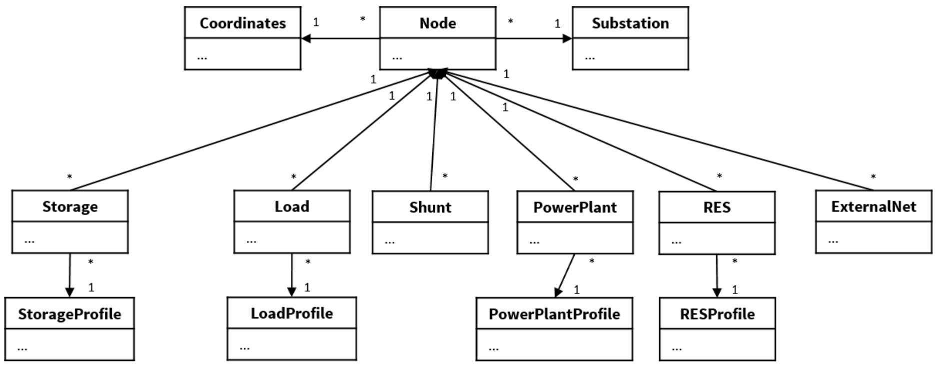


Figure 4.30: External relationships of the nodes and buss elements of the SimBench CSV format

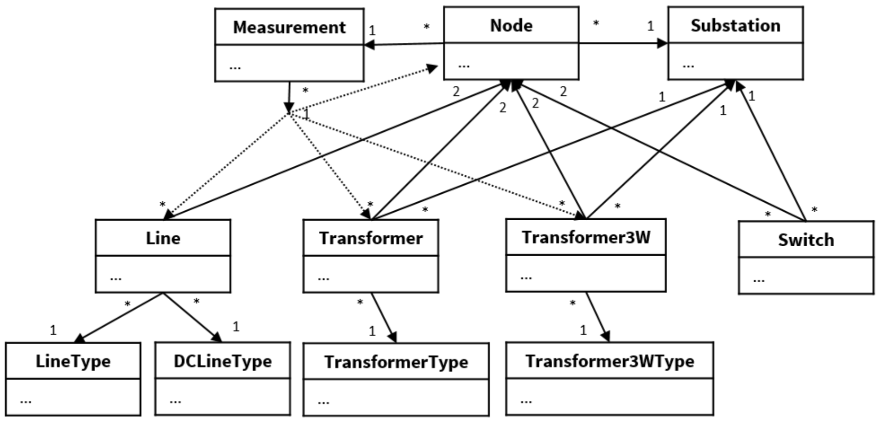


Figure 4.31: External relations of the branch elements of the SimBench CSV format

- vaSetp: voltage angle setpoint
- vmR: voltage magnitude rated (nominal voltage)

Tables 4.12 and 4.13 show the structure of the classes “Substation” and “Coordinates”. The class “Substation” serves more as organization class, which can be helpful for the overview in software tools. In PowerFactory, for example, nodes can be filtered using the “Substation”. The World Geodetic System 1984 (WGS 84) is used as coordinate system, so that real georeferenced coordinates are stored for the HV and EHV network models. Since the network models of the MV and LV level are synthetic and independent of a geographical location, synthetic coordinates are used which are oriented to the nodes of the superimposed HV plane.

Table 4.11: Collection and description of the parameters of the model class "Node"

Node	Example	Unit
id:Varchar	EHV_Bus_850	-
type: Varchar	double busbar	-
vmSetp: Float	1.0	p.u.
vaSetp: Float	0.0	°
vmR: Float	220	kV
vmMin: Float	0.9	p.u.
vmMax: Float	1.1	p.u.
substation: Varchar	EHV_HV_substation_4	-
coordID: Varchar	coord_4559	-
subnet: Varchar	EHV1_HV2	-
voltLvl: Int	1	-

Table 4.12: Collection and description of the parameters of the model class "Substation"

Substation	Example	Unit
id:Varchar	EHV_HV_substation_4	-
subnet: Varchar	EHV1_HV2	-
voltLvl: Int	1	-

Table 4.13: Collection and description of the parameters of the model class "Coordinates"

Coordinates	Example	Unit
id:Varchar	Coord_1	-
x: Float	9.75309	-
y: Float	52.399	-
subnet: Varchar	HV2_MV1.201	-
voltLvl: Int	3	-

Bus elements

Table 4.14 shows the structure of "ExternalNet" classes. In this case:

- calc_type: Type of calculation in a power flow calculation
- dspf: "distributed slack participation factor"
- pExtNet, qExtNet, pWardShunt, qWardShunt, rxWard, xXWard, vmXWard: Parameters for (Extended) Ward Equivalents

The possibilities for the parameter "calc_type" are:

- vavm: Slack node (voltage magnitude and voltage angle are given)
- pvm: PV node
- pq: PQ node
- Ward: Ward equivalent
- xWard: Extended Ward equivalent

The parameters "pExtNet" and "qExtNet" are only set for the calculation types pvm, pq, Ward and xWard. Furthermore, the parameters "pWardShunt" and "qWardShunt" are only taken into account for Ward and xWard and "rxWard", "xXWard" and "vmXWard" are only taken into account for xWard.

For "PowerPlants" (see Table 4.15), "type" describes the power plant type, e.g. coal, and "profile" describes the associated time series. "calc_type" again describes the type of calculation in a power flow calculation. For "calc_type" with "PowerPlants" the first three possibilities of "ExternalNet" exist. The parameter "sR" generally describes the nominal apparent power of power plants, distributed energy resources (Table 4.17) and loads (Table 4.18). While the parameters "pRES" and "qRES", which are named slightly differently depending on the element, indicate the maximum power values and are relevant for the power flow calculation and the determination of the p and q values of a time series, "sR" serves only as an orientation value and can be used for control strategies or scenario extension if necessary.

Table 4.16 shows the structure of the time series. The model classes "RESProfile", "LoadProfile" and "StorageProfile" have the same structure as "PowerPlantProfile".

The term "RES" (Table 4.17) refers to distributed energy resources (RES = "Renewable Energy Source"). The attribute "type" determines the type of plant, e.g. wind or PV.

The meaning of the storage parameters from Table 4.19 is:

Table 4.14: Collection and description of the parameters of the model class “ExternalNet”

ExternalNet	Example	Unit
id: Varchar	EHV Ext_grid 5	-
node: Varchar	EHV Bus 849	-
calc_type: Varchar	vavm	-
dspf: Float	1.0	p.u.
pExtNet: Float	NULL	MW
qExtNet: Float	NULL	MVAr
pWardShunt: Float	NULL	MW
qWardShunt: Float	NULL	MVAr
rxWard: Float	NULL	Ω
xXWard: Float	NULL	Ω
vmXWard: Float	NULL	p.u.
subnet: Varchar	HV2_EHV1_eq	-
voltLvl: Int	1	-

- eStore: Maximum charging capacity in MWh
- etaStore: Efficiency
- sdStore: Self-discharge in % per day

The parameters “p0” and “q0” of compensation systems from Table 4.20 describe the active and reactive power at nominal voltage.

Table 4.15: Collection and description of the parameters of the model class “PowerPlant”

PowerPlant	Example	Unit
id: Varchar	PP_5	-
node: Varchar	Expl_12_1	-
type: Varchar	hard coal	-
profile: Varchar	coal profile 1	-
calc_type: Varchar	pvm	-
dspf: Float	0.3	-
pPP: Float	100	MW
qPP: Float	30	MVAr
sR: Float	500	MVA
pMin: Float	25	MW
pMax: Float	500	MW
qMin: Float	-100	MVAr
qMax: Float	100	MVAr
subnet: Varchar	HV2	-
voltLvl: Int	1	-

Table 4.16: Collection and description of the parameters of the model class “PowerPlantProfile”

PowerPlantProfile	Example	Unit
time: Varchar/date	01.01.2016 00:00:00	-
ID1: Varchar/Float	0.15	p.u.
ID2: Varchar/Float	0.2	p.u.

Table 4.17: Collection and description of the parameters of the model class “RES”

RES	Example	Unit
id: Varchar	MV2 Sgen 1	-
node: Varchar	MV2 Bus 1	-
type: Varchar	PV	-
profile: Varchar	PV3	-
calc_type: Varchar	pq	-
pRES: Float	1.25	MW
qRES: Float	0.61	MVAr
sR: Float	1.7	MVA
subnet: Varchar	MV2	-
voltLvl: Int	5	-

Table 4.18: Collection and description of the parameters of the model class “Load”

Load	Example	Unit
id: Varchar	HV2 Load 1	-
node: Varcha	HV2 Bus 2	-
profile: Varchar	mv_suburb	-
pLoad: Float	32.75	MW
qLoad: Float	12.94	MVAr
sR: Float	35.22	MVA
subnet: Varchar	HV2_MV2.201_eq	-
voltLvl: Int	3	-

Table 4.19: Collection and description of the parameters of the model class “Storage”

Storage	Example	Unit
id: Varchar	Stor_1	-
node: Varchar	Expl_1	-
type: Varchar	Type1	-
profile: Varchar	Profile 1	-
pStor: Float	0.005	MW
qStor: Float	-0.00045	MVAr
chargeLevel: Float	85.2	%
sR: Float	0.02	MVA
eStore: Float	4.1	MWh
etaStore: Float	0.95	-
sdStore: Float	0.02	% pro Tag
pMin: Float	-0.02	MW
pMax: Float	0.02	MW
qMin: Float	-0.02	MVar
qMax: Float	0.02	MVar
subnet: Varchar	LV3	-
voltLvl: Int	7	-

Table 4.20: Collection and description of the parameters of the model class “Shunt”

Shunt	Example	Unit
id: Varchar	Shunt1	-
node: Varchar	Expl_11	-
p0: Float	-1.5	MW
q0: Float	15	MVAr
vmR: Float	20	kV
Step: Int	1	-
subnet: Varchar	MV1	-
voltLvl: Int	5	-

Branch elements

The tables of all branch elements are listed below. The data format for cables is described in Table 4.21, cable types in Table 4.22.

Table 4.23 describes the structure of DC cable types. In this table, "relPLosses" stands for the power flow dependent active power losses and "fixPLosses" for the constant active power losses.

Table 4.24 shows the structure of the transformer data. "HV" indicates the high voltage node and "LV" the low voltage node.

The structure of the transformer types is shown in Table 4.25. In addition, three-winding transformers have also been taken into account (see Table 4.26 and 4.27), even if they are not used in the SimBench dataset. This did not appear to be necessary for generating the benchmark dataset. Finally, Table 4.28 and Table 4.29 summarize the structure of the data format for switches and measuring instruments.

Table 4.21: Collection and description of the parameters of the model class "Line"

Line	Example	Unit
id: Varchar	HV2 Line 1	-
nodeA: Varchar	HV2 Bus 164	-
nodeB: Varchar	HV2 Bus 165	-
type: Varchar	Al/St_265/35	-
length: Float	4.68	km
loadingMax: Float	100	%
subnet: Varchar	HV2	-
voltLvl: Int	3	-

Table 4.22: Collection and description of the parameters of the model class "LineType"

LineType	Example	Unit
id: Varchar	NAYY 4x150SE 0.6/1kV	-
r: Float	0.21	Ω/km
x: Float	0.08	Ω/km
b: Float	260.75	μS/km
iMax: Float	270	A

Table 4.23: Collection and description of the parameters of the model class "DCLineType"

DCLineType	Example	Unit
id: Varchar	Typ_DC1	-
pDCLine: Float	0.7	MW
relPLosses: Float	1.2	%
fixPLosses: Float	0.025	MW
pMax: Float	1.2	MW
qMinA: Float	0	MVAr
qMinB: Float	0.5	MVAr
qMaxA: Float	0	MVAr
qMaxB: Float	0.5	MVAr

Table 4.24: Collection and description of the parameters of the model class "Transformer"

Transformer	Example	Unit
id: Varchar	HV2 Trafo 1	-
nodeHV: Varchar	EHV Bus 2992	-
nodeLV: Varchar	HV2 Bus 163	-
type: Varchar	200MVA_220/110	-
tappos: Int	0	-
autoTap: Int	1	-
autoTapSide:Varchar	LV	-
loadingMax: Float	50	%
substation: Varchar	EHV_HV_substation_4	-
subnet: Varchar	HV2	-
voltLvl: Int	2	-

Table 4.25: Collection and description of the parameters of the model class “TransformerType”

TransformerType	Example	Unit
id: Varchar	63 MVA 110/10 kV YNd5	-
sR: Float	63	MVA
vmHV: Float	110	kV
vmLV: Float	10	kV
va0: Float	150	°
vmImp: Float	18	%
pCu: Float	201.6	kW
pFe: Float	22	kW
iNoLoad: Float	0.04	%
tapable: Int	1	-
tapside: Varchar	hv	-
dVm: Float	1.5	p.u./Stufe
dVa: Float	0	°/Stufe
tapNeutr: Int	0	-
tapMin: Int	-9	-
tapMax: Int	9	-

Table 4.26: Collection and description of the parameters of the model class “Transformer3W”

Transformer3W	Example	Unit
id: Varchar	Trafo1	-
nodeHV: Varchar	Expl_11	-
nodeMV: Varchar	Expl_12	-
nodeLV: Varchar	Expl_13	-
type: Varchar	Tr3WType_1	-
tapposHV: Int	5	-
tapposMV: Int	NULL	-
tapposLV: Int	NULL	-
autoTap: Int	1	-
autoTapSide: Int	LV	-
loadingMax: Float	100	%
substation: Varchar	HV2_MV3_Substation	-
subnet: Varchar	MV3	-
voltLvl: Int	3	-

Table 4.27: Collection and description of the parameters of the model class “Transformer3WType”

Transformer3WType	Example	Unit
id: Varchar	Tr3WType_1	-
sRHV: Float	63	MVA
sRMV: Float	40	MVA
sRLV: Float	31.5	MVA
vmHV: Float	110	kV
vmMV: Float	20	kV
vmLV: Float	10	kV
vaHVMV: Float	30	°
vaHVLV: Float	60	°
vmImpHVMV: Float	12	%
vmImpHVLV: Float	10	%
vmImpMVLV: Float	10	%
pCuHV: Float	15	kW
pCuMV: Float	15	kW
pCuLV: Float	15	kW
pFe: Float	0	kW
iNoLoad: Float	3	%
tapable: Int	1	-
tapside: Varchar	“HV”	-
dVmHV: Float	1	p.u./Stufe
dVmMV: Float	1.5	p.u./Stufe
dVmLV: Float	2.5	p.u./Stufe
dVaHV: Float	0	°/Stufe
dVaMV: Float	0	°/Stufe
dVaLV: Float	0	°/Stufe
tapNeutrHV: Int	0	-
tapNeutrMV: Int	0	-
tapNeutrLV: Int	0	-
tapMinHV: Int	-10	-
tapMinMV: Int	-5	-
tapMinLV: Int	-3	-
tapMaxHV: Int	12	-
tapMaxMV: Int	5	-
tapMaxLV: Int	10	-

Table 4.28: Collection and description of the parameters of the model class “Switch”

Switch	Example	Unit
id: Varchar	Sw_1	-
nodeA: Varchar	SampleNode1	-
nodeB: Varchar	SampleNode2	-
type: Varchar	CB	-
cond: Int	1	-
substation: Varchar	HV2_MV3_Substation	-
subnet: Varchar	MV3	-
voltLvl: Int	3	-

Table 4.29: Collection and description of the parameters of the model class “Measurement”

Measurement	Example	Unit
id: Varchar	Meas_1	-
element1: Varchar	HV2 Bus 6	-
element2: Varchar	NULL	-
variable: Varchar	p	p, q, i oder (o.) v
value: Float	3.5	MW, MVAr, A o. p.u.
stdDev: Float	0.01	%
Subnet: Varchar	HV2	-
voltLvl: Float	3	-

4.3.2 Accessibility by means of website and GUI

To learn more about the project or to download the dataset, you can find all important information on https://simbench.de/en.

Due to the allocation of numerous grids in the different voltage levels, several future scenarios and interconnections of grids across different voltage levels, as described in Section 4.2, a multitude of grid combinations are possible. To assist the user in selecting and downloading a suitable grid dataset, a SimBench GUI is integrated on the homepage. Figure 4.32 shows the appearance

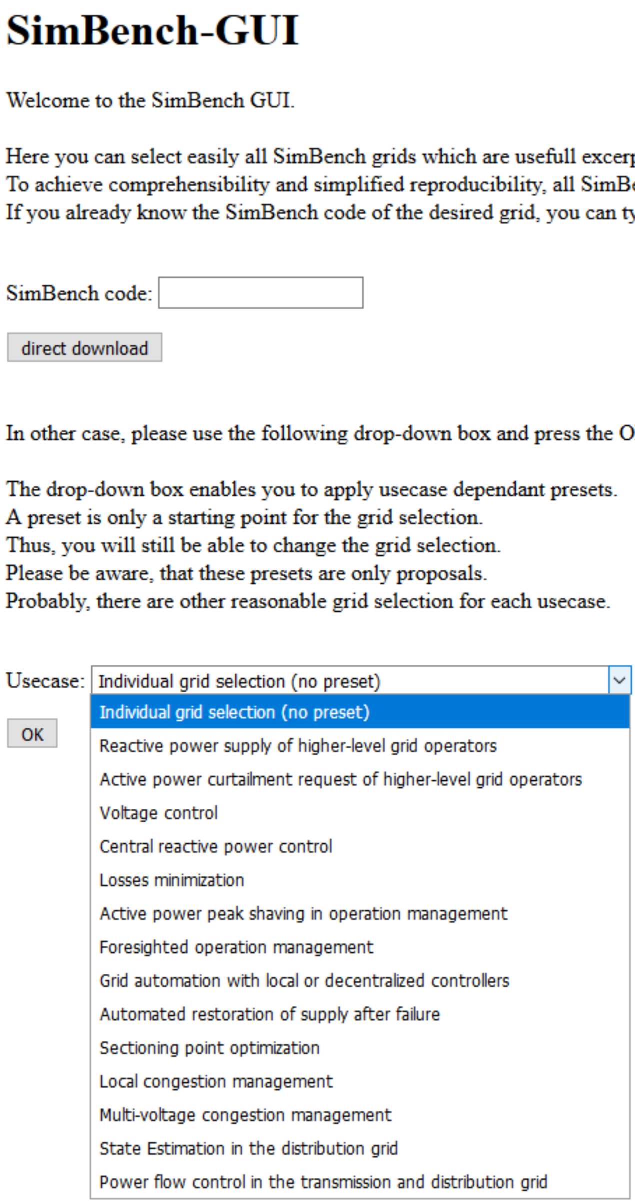


Figure 4.32: Selection of a suitable SimBench grid combination using the SimBench GUI

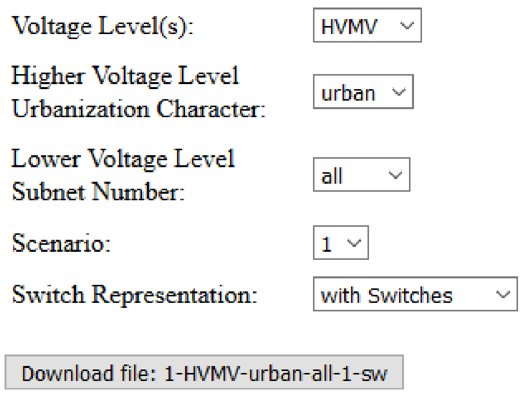


Figure 4.33: Parameter overview for unique identification of a SimBench grid

of the GUI homepage. In the upper area you can download a dataset by entering a SimBench code and clicking the “direct download” button. The SimBench code, introduced in Section 4.2.3, can be e.g. specified directly in a publication one wants to compare his own method with. The downloadable dataset contains several CSV files, which are described in Section 4.3.1.

As an alternative to the direct download, a predefined dataset suitable for the respective use case can be selected using the drop-down menu below. Confirming by pressing the “Ok” button when selecting a use case will take you to another page with a pre-selection of the individual "SimBench code components". Figure 4.33 shows this second page of the GUI.

In the displayed example, the parameters for a SimBench grid combination suiting the use case “Multi-Voltage congestion management” are selected. Without adaptation by confirming the “Download file: …” button the download of the corresponding grid dataset will directly start. Alternatively, these parameters can be checked again and adapted according to the user’s needs.

If no preselection should be made, there is also the possibility via “Individual grid selection (no preset)” that the second page opens without a preset SimBench code. Individual parameters can now be selected from a drop-down menu. Since, as explained in Section 4.2.3, not all grid combinations make sense because individual parameters depend on each other, not every parameter selection is possible. For example, the parameter “High Voltage Level Urbanization Character” depends on “Voltage Level(s)” and “Lower Voltage Level Subnet Number” depends on both parameters mentioned above. Therefore, in order to avoid invalid selections, when changing the “Higher Voltage Level Urbanization Character” parameter the selection of the “Lower Voltage Level Subnet Number” parameter is reset. If you proceed from top to bottom, all dependencies are considered in the correct order and no parameter selection is reset. The download is started by clicking the button “Download file: …”. The button shows the currently selected SimBench code.

If an error window appears after confirming the download request, not all necessary parameters have been selected. Please note that only the parameter “Lower Voltage Level Urbanization Character" may remain empty and this only in cases where a single voltage level (EHV, HV, MV or LV) is selected.

In case of working with a power system analysis tools like `pandapower` [3], PowerFactory [1] or Integral [2], either

1. the CSV files can be downloaded and then converted or
2. the files can be directly downloaded in the corresponding format.

For case 1 please refer to the appendix C. For `pandapower` the Python package "simbench" on GitHub is recommended. Models of the other two power system tools can be found in the list on Homepage. This list also includes the complete data sets with all four voltage levels, which are not selectable via the GUI.

5 Collection of various, basic use cases

In this chapter exemplary simulation results are presented using the SimBench dataset. On the one hand, this should enable a better understanding of the dataset and, on the other hand, serves to validate the dataset. For this purpose, Section 5.1 first shows the necessity of defining study cases relevant for planning and their application. In Section 5.2 the power flow results of the different calculation tools PowerFactory [1], Integral [2] and `pandapower` [3] are presented for an exemplary selected grid and study case. This allows to harmonize basic assumptions when using the tools and represents the basis for all use cases based on power flow calculations. [3] for an exemplary selected grid and a calculation case. This makes it possible to harmonize basic assumptions when using the tools and represents the basis for all application cases based on power flow calculations. Section 5.3 compares grid planning on the basis of defined study cases and on the basis of annual simulations. Finally, in Section 5.4 a comparison of applied algorithms is presented using the example of the state estimation use case.

5.1 Defined SimBench study cases

In order to improve comparability and transparency of results, SimBench defined uniform study cases for distribution networks [47]. Study cases are mainly used in network planning. In particular, two operating cases are considered: the heavy load case with low generation and the low load case with high generation by decentralized plants. Based on these frequently used operating conditions, SimBench has defined its own planning relevant grid study cases, in which a distinction is made between wind and PV generation. This is because it is assumed that wind and PV do not always have the maximum peak at the same time [65]. These study cases are described by the scaling factors of the load and generation capacities of Table 5.1 and the corresponding nominal voltage values of the slack and the transformers as well as the power factor of the loads of Table 5.2. Since different simultaneities are to be assumed for the LV and MV than for the HV, the scaling factors are chosen differently. No study cases have been defined for the EHV, since most calculations are already based on time series in practice.

For reasons of simplicity, no load-dependent voltage setpoints for the automatic step position have been specified for the HV. For MV and LV, it is assumed that these are connected by means of classic local grid stations, i.e. without a controlled primary transformer, and that the voltage

Table 5.1: Scaling factors of the defined study cases

Acronym	Description of the study case	Load	Generation		
			Wind	PV	Others
		p	p	p	p
hL	high load, low DER generation	1.00	0	0	0
n1	high load, low DER generation & contingency case	1.00	0	0	0
hW	high load, very high wind, high PV, high other DER generation	1.00	1.00	0.80	1.00
hPV	high load, high wind, very high PV, high other DER generation	1.00	0.85	0.95	1.00
lW	low load, very high wind, high PV, high other DER generation	0.25 (HV), 0.10 (MV/LV)	1.00	0.80	1.00
lPV	low load, high wind, very high PV, high other DER generation	0.25 (HV), 0.10 (MV/LV)	0.85	0.95	1.00

Table 5.2: Voltage values for different voltage levels and power factors of the loads of the study cases

Study cases	Voltage setpoints for the slack and transformers			Load
	HV	MV	LV	$\cos(\varphi)$
hL, n1, hW, hPV	1.025 pu	1.035 pu	0.965 pu	0.93 underexcited
lW, lPV		1.015 pu	1.055 pu	0.9 underexcited

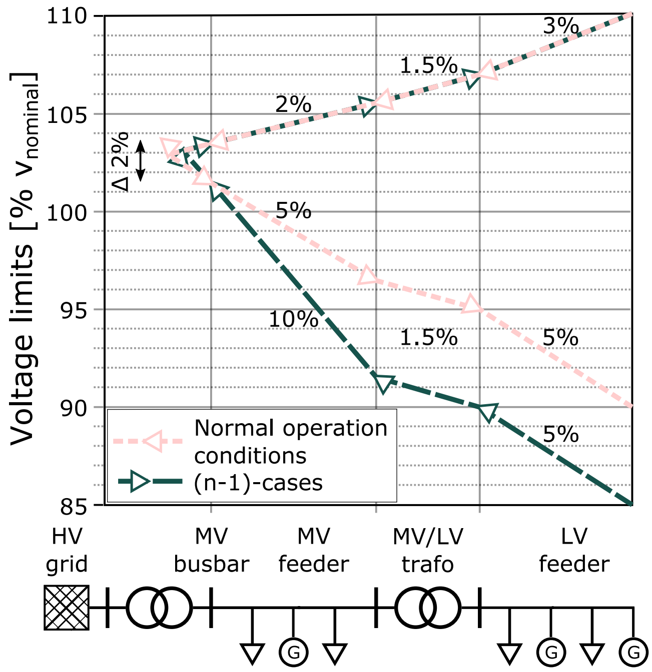


Figure 5.1: Voltage limits of MV and LV level depending on the study case

limits of normal operation are clearly separated from each other for good comparability between the two voltage levels. This means for the LV that it must be assumed that the voltage limits of the upstream MV system are fully exploited and for the MV that each connected LV system in turn fully exploits the permitted voltage range. The specified voltage limits are shown in Figure 5.1. It also takes into account the voltage rise and drop ranges of the transformers. The dead band of the tap changer of the HV/MV transformer is 2 % of the nominal voltage of the MV. Since in reality there are no rigid, fixed voltage limits at local grid stations and no small scaling factors are defined in Table 5.1, an HV/MV step control is assumed for the MS, which varies the voltage setpoint on the MV level between 1.015 pu and 1.035 pu depending on the load case. Otherwise, stricter requirements than usual and necessary would have been imposed on the network planning of MV networks. Such a voltage setpoint control can be done, for example, using the simple characteristic curve in Figure 5.2. In reality, the variables of the transformer step control are selected grid-specifically. There are therefore no standard values. In addition, controls for operation management are not part of the basic SimBench dataset, but fall within the user area. Therefore, no active power values are given. The voltage setpoints of the voltage levels from HV to LV as well as assumptions for the reactive load are given in Table 5.2.

The dataset contains data of the defined study cases in the file "StudyCases.csv". Further information on the defined study cases can be found in the publication [47]. This publication also contains general information on the planning and operating principles used to create the SimBench dataset and compiled in consultation with the advisory board consisting of six distribution

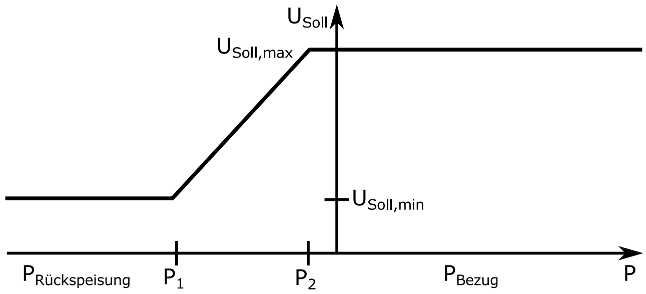


Figure 5.2: Characteristic curve for a simple, exemplary voltage setpoint control of HV/MV transformer tapchangers as a function of the load case

system operators.

5.2 Power flow analysis with different calculation tools

The use case of the power flow calculation with different software tools (see Sim2 in Table 3.3) is used in this section to document exemplary power flow results and to record assumptions when using different tools. Users of the SimBench dataset can use these results as a reference for their own calculations with the dataset and users of the three calculation tools PowerFactory [1], Integral [2] and `pandapower` [3]. [3] get information about how these results were achieved.

power flow calculations are the basis for almost all further use cases. Power flows over the branches are determined on the basis of the complex node voltages, the active and reactive power injections as well as the tap positions of the transformers [66]. The results presented are based on the predominantly urban network model with the SimBench code “1-HV-urban--0-sw” and the study case high wind, low load “lW”. Figure 5.3 shows an overview of the distribution of the line loading and the voltages at the nodes. The complete node and branch results can be found in the appendix B. The figure shows that the voltages have a high level, but no limits are exceeded. In terms of line utilization, the level is rather low. This is to be justified with the dimensioning of the gridaccording to the (n-1)-criterion.

For a better traceability of the results, the dialog box for setting the control parameters of Integral is given in Figure 5.4. These settings can be used in other calculation tools as well to obtain comparable results.

The maximum absolute deviations of the two network calculation programs PowerFactory and `pandapower` compared to Integral are given in Table 5.3. They show that the power flow results between the network calculation programs agree with a high accuracy.

In addition to the power flow result comparison presented in this section, the result tables with the file names “NodePFResult.csv” contained in the "SimBench" dataset also offer the possibility

Table 5.3: Maximum absolute deviations of further network calculation programs in comparison to the presented power flow results determinedby INTEGRAL

	vm [p.u.]	va [°]	Leitungsauslastung [%]	Transformatorauslastung [%]
PowerFactory	2.77 E-04	2.77 E-04	2.73 E-02	1.62 E-04
pandapower	2.9 E-06	3.0 E-05	4.6 E-04	6.9 E-05

of detecting deviations of a basic power flow. The power flow results contained in the dataset do not refer to a defined planning relevant study case, but to the unscaled original state of the network data without any voltage control.

5.3 Comparison between conventional and time series based grid planning

5.3.1 Conventional grid planning based on defined study cases

In conventional grid planning, load cases are usually defined in order to dimension electrical grids using their corresponding load flow simulations results. The load cases relevant for planning are cases that rarely occur in reality, possibly with an additional safety margin. In reality, high and low load cases are often used [67].

A big advantage of the conventional approach is its simplicity as well as the short simulation time, because only a small number of static load cases have to be calculated. Especially if failure simu-

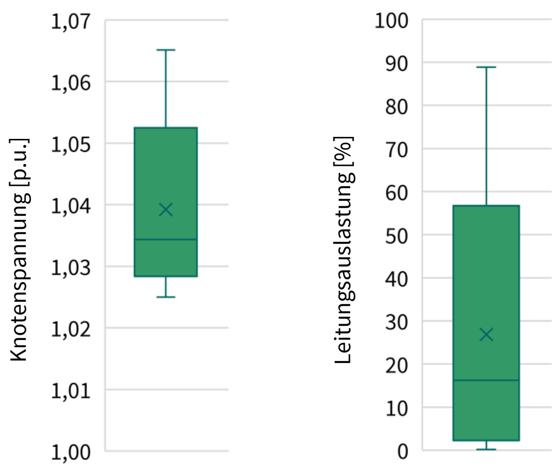


Figure 5.3: Results of the basic power flow calculation for the grid “1-HV-urban--0-sw” in case of load “lW” depicted by boxplots

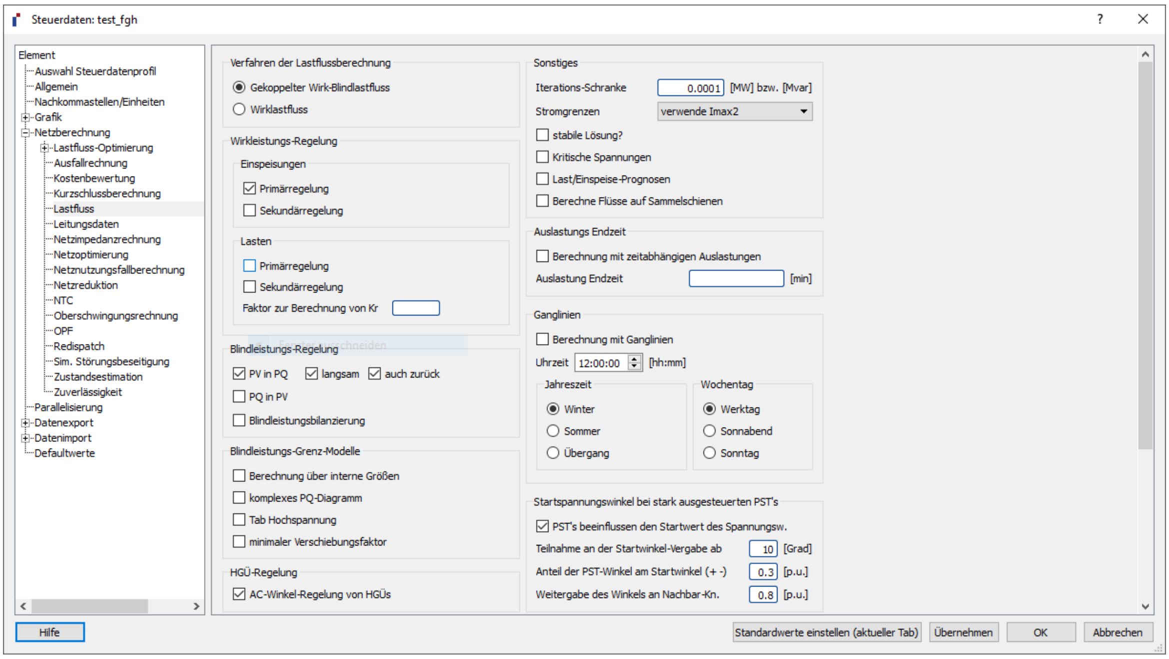


Figure 5.4: Control data in INTEGRAL

lations, i.e. (n-1)-cases, are to be considered, the occurring loadings and the corresponding violations can be determined quickly and easily.

Disadvantages of this approach, however, are that neither the frequency nor the duration of an overload can be determined. As a result, it is not possible to include grid operation strategies in grid planning investigations and to evaluate them in terms of costs based on the estimated frequency of their use [67]. The influence of intelligent operation management strategies and loads as well as storage technologies on occurring grid violations cannot be examined sufficiently precisely with the conventional approach [68]. In addition, conventional grid expansion is mainly based on measures of line expansion or line reinforcement as well as the construction and expansion of substations and transformers. However, there are limits to these measures in many respects, for example due to legal requirements and conditions, the social acceptance of grid expansion measures or the high investment costs [69].

5.3.2 Time series-based grid planning

In contrast to conventional grid planning, in case of time sereis-based grid planning representative annual time series are usually taken for all consumers, producers and prosumers, and grid planning costs are estimated on this base. In this way, the grid situation is determined for realistic grid situations instead of just for individual fictitious extreme load cases. This approach offers the following advantages compared to the conventional approach [68]: An estimation can be made

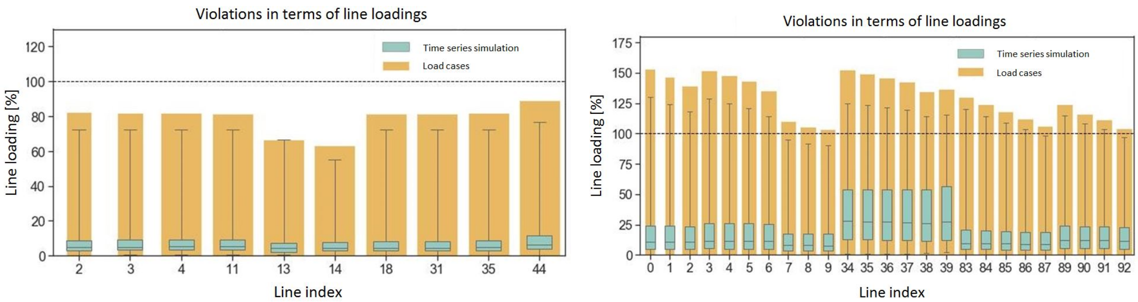


Figure 5.5: Comparison of the maximum line loadings based on all defined calculation cases (except n-1) and the annual time series simulations exemplary for the urban LV grid (seen left) and suburban MV grid (seen right) in case of scenario 1

about the frequency and duration of overloads of grid elements such as lines and transformers as well as undesirable grid conditions such as overvoltages and undervoltages. It is therefore possible to weigh whether a technically tolerable grid load is accepted in order to avoid expensive grid expansion measures. Furthermore, the time series-based approach can also be used to test and simulate innovative operation management strategies, for example the use of intelligent loads and storage technologies as well as the useful and grid benefical integration of EVs and HPs into the grid, since these heavily depend on time [67]. This makes it possible to design the grid planning process efficiently and future-oriented [70].

While for conventional grid planning the definition of load cases is the major challenge, in terms of time series-based grid planning the determination of relevant and representative time series can be considered most challenging. This is even more difficult in the LV and MV levels, in contrast to the HV and EHV levels, as real measurement data is often not available. If, in addition, failure simulations have to be taken into account, a relevant increase in the computing effort must be expected.
The challenge of time-series based network simulation is therefore characterized by the long computing time on the one hand and the large amount of data on the other hand.

5.3.3 Exemplary simulation with SimBench

The data sets provided by the SimBench project enable the user to calculate both the conventional approach using the defined load cases and the time series-based approach using the given annual time series with a resolution of 15 minutes.

Both approaches are simulated and compared exemplarily regarding the equipment loading and the resulting grid expansion measures. Figure 5.5 shows an exemplary result of the urban LV grid for scenario 1 on the left and the suburban MV grid of scenario 1 on the right. Both figures show a comparison between the calculations of the extreme load cases and the annual time series.

For this purpose, the loadings and their distributions are displayed as percentages for individual lines. In figure 5.5 (seen left), the permissible line loadings are neither exceeded in terms of the conventional nor the time series-based approach. However, it can be seen that the conventional approach tends to lead to higher maximum line loadings than the time series-based approach. In figure 5.5 (seen right), the lines with the indices 7, 8, 9, 87 and 92 would have to be replaced in terms of the conventional approach due to the caused violations, but not in case of the time series-based approach. Accordingly, the costs of grid expansion using the time series-based approach would be lower here.

5.4 State Estimation

The SimBench dataset also contains information about type, placement of measurements in the power grids. In general terms, the density of measurements rises with the rated voltage and the scenario number, which corresponds to scenarios further in the future. For example, the EHV Grid (or similar) will be completely monitored and the LV Grid will be placed with no measurements under scenario 0, while in scenario 1 and 2 a small number of measurements will be placed.

On the MV level, which is currently not sufficiently monitored by measurements (represented in scenario 0), the installation of measurements could be beneficial, because by knowing the actual minimum and maximum voltages, the line loading and ideally all power flow results enable a grid optimization with active and dynamic control.

In many grid control centers, the state estimation according to Schweppe et al. [71] are implemented. With this method, the grid state is estimated using a large number of real time measurements, which is common in EHV and HV grid, where enough measurements are placed. For MV grids, similar measurement placement would cause very high investment. Therefore, in the past few years, researchers proposed various methods, with which even with a low number of measurements the estimation of characteristics of grid state is possible. For example, it would be good enough to find out any voltage violations or line loading violations.

By providing measuring point information, SimBench can serve as a data basis for developments and comparisons of new, improved grid monitoring procedures. In the following, this is done by comparing two exemplary procedures. The first method, which is considered as "state of the art" or "benchmark" here, is the extension of the mentioned state estimation in EHV and HV to a method for the generation of pseudo measurements. With these pseudo measurements, the required, redundant number of measurements can be made. As a second method, a new method of grid monitoring based on artificial neural networks and appropriate neural network training is used, with no limitation on a minimum number of measurements [72]. For both methods, the

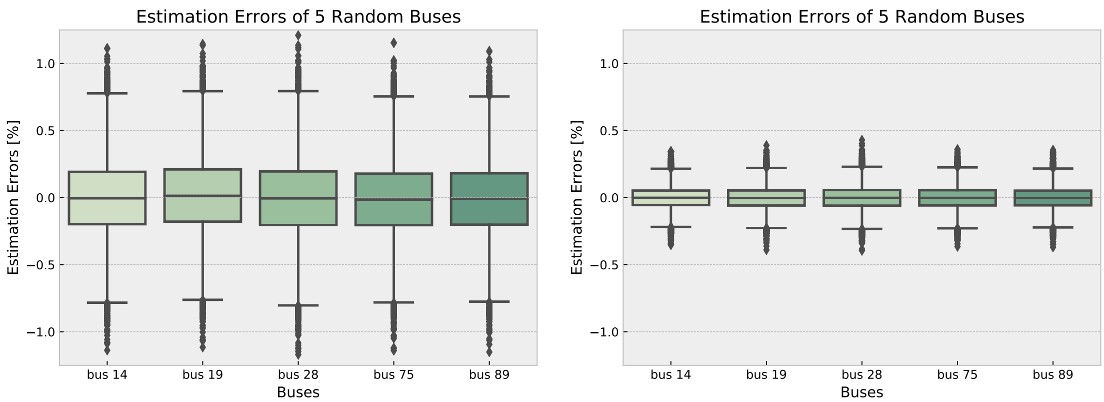


Figure 5.6: Comparison of estimation errors for the commercial MV network at five randomly selected nodes for the established state estimation (left) and the new method (right)

estimation errors are to be determined and compared based on the given measuring point distribution of the SimBench MV grids.

In all four MV grids, the measurements have been placed sparsely in scenario 0 in order to represent the real situation in many current distribution grids. The measurements are mainly located in the HV to MV substations, occasionally also at local grid stations. In scenario 1 and 2, the measurements 0 will be extended to further grid stations on the basis on scenario 0. In the commercial area grid, the measurements are scenario-related placed at 13 grid stations. In the other three MV grids, around four grid stations are scenario-related placed by measurements. The measurements at a grid station include voltage magnitude measurements and active, reactive power measurements of all connected loads, generators and lines. The measurement redundancy is defined as measurements per 2n-1 grid node. In the commercial area grid under scenario 0, it has a redundancy of 35 % and the other grids only around 15 %. In scenario 1 and 2, the measurement density increases by a few percent, which are comparable to the trends in real MV grids nowadays.

The commercial area grid and suburban area grids in scenario 0 are selected for the methods benchmark. For the training of the new method, the first nine months of the time series data are used and the rest three months of data are used for test. For both methods, the estimation error of relevant grid state parameters will be calculated, which are normally the voltage magnitude and line loading. If needed in some cases, the determination of power flows is also possible through the calculation of voltage angles.

The result of the commercial area grid is shown in Figure 5.6. The figure shows the error between the estimated voltage magnitude and exact voltage magnitude of five randomly chosen grid nodes. Each bar shows the distribution of the errors of all time steps within the three months for test purpose. The left plot shows the results of the standard state estimation method and the right presents the results of the new method. Similarly, as the result of suburban area grids shown

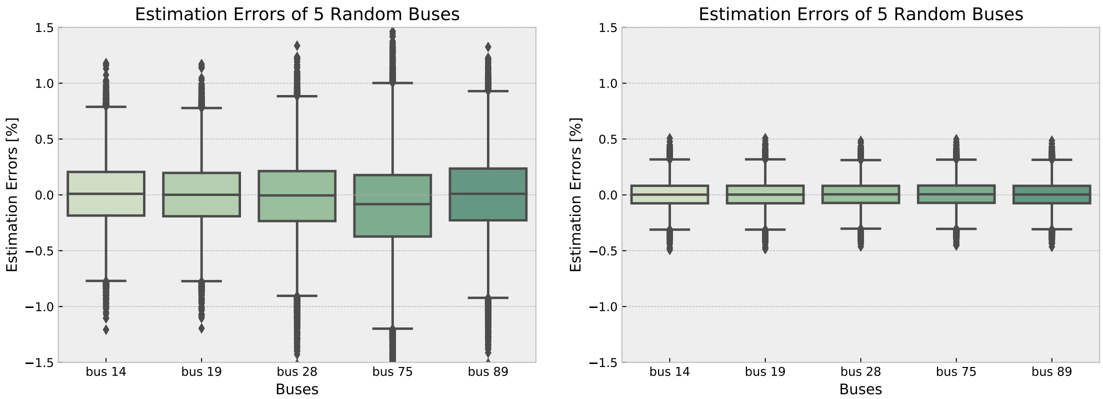


Figure 5.7: Comparison of estimation errors for the semi-urban MV network at five randomly selected nodes for the established state estimation (left) and the new method (right)

in Figure 5.7, the difference of estimation error is clear. With the standard state estimation method, the estimation errors are clearly higher than with the new method. Similar to the comparison made here, based on the same grid, time series data and placement of measurements, further methods can be tested and compared to each other with the reality close SimBench grids.

6 Conclusion and Outlook

SimBench provides a benchmark dataset that is suitable to be used as a data base for comparing different methods and algorithms. Researchers and developers can use this thoroughly generated grid data to test their methods and publish simulation results in a comprehensible manner. This saves time and effort for developing, adapting and improving the dataset and thus supports scientific progress.

The following are some key points worth to be highlighted to describe SimBench's contributions:

- up-to-date benchmark dataset for Germany (and comparable regions in the world, e.g. Europe)
  - consideration of new technologies (EV, HVDC, HP, storage technologies)
  - consideration of the increase of RESs
  - consideration of current planning and operating principles [47]
- effort has been invested to make SimBench easy to use
  - development of the SimBench GUI
  - converters provide datasets in different formats which are suitable for different power system analysis tools
  - the dataset is provided online under the ODbL license conditions (see Chapter 1)
- extensive dataset including combinable voltage levels and time series
  - time series from real measurements (no SLPs)
  - reactive power time series provided for loads
- both, grids that comply with the limits of electrical operation (scenario 0) and grids with challenging future scenarios (scenarios 1, 2)
- extensively tested to include appropriate grid states for grid simulations and fair comparisons
- effort was invested to enable reproducibility and comparability

- SimBench codes enable clear naming and referencing of datasets
- line and transformer types as well as all time series are assigned unambiguously in the grid
- complete definition of the voltage setpoints as well as load and generation power values within defined and relevant study cases

By using the SimBench dataset, a high degree of transparency, comparability and reproducibility is achieved. In addition, future work on generating benchmark datasets can build on SimBench approaches and procedures.

Due to the objective of generating a benchmark dataset, the objectives of most previous grid modelling approaches compared to the SimBench approach differ. The SimBench grids are not developed primarily to represent German or existing grids. Since both frequently occurring challenges in grid operation management and grid planning as well as future-oriented, relevant requirements are integrated into the SimBench dataset, the SimBench grids can neither be described as purely average nor extreme grids. The scale, i.e. number of buses, of SimBench grids (LV, MV) and grid groups (HV) is occuring frequently in reality.

Despite addressing a large number of use cases, there are still outstanding matters within SimBench. These are listed here. Future benchmark projects can, for example

- include dynamic grid parameters,
- take into account grid parameters for unsymmetrical power flow calculations, especially on LV level, or
- consider other sectors, such as heat or gas grids, and thus substantially advance studies on sector coupling.

Appendix

A SimBench Codes

Tabelle A.1 lists all SimBench codes with complete switch representation “sw”. The codes are divided horizontally and vertically into three sections. In a row, the same grid is listed with different scenarios. Codes with only one voltage level, with two voltage levels and with all four voltage levels are divided by horizontal lines. All codes with one or two voltage levels also occur in the variant with incomplete switch representation “no_sw”. Thus, the complete list includes $120 \cdot 2 + 6 = 246$ SimBench codes.

Table A.1: List of all SimBench codes with complete switch representation “sw”

Scenario 0	Scenario 1	Scenario 2
1-EHV-mixed–0-sw	1-EHV-mixed–1-sw	1-EHV-mixed–2-sw
1-HV-mixed–0-sw	1-HV-mixed–1-sw	1-HV-mixed–2-sw
1-HV-urban–0-sw	1-HV-urban–1-sw	1-HV-urban–2-sw
1-MV-rural–0-sw	1-MV-rural–1-sw	1-MV-rural–2-sw
1-MV-semiurb–0-sw	1-MV-semiurb–1-sw	1-MV-semiurb–2-sw
1-MV-urban–0-sw	1-MV-urban–1-sw	1-MV-urban–2-sw
1-MV-comm–0-sw	1-MV-comm–1-sw	1-MV-comm–2-sw
1-LV-rural1–0-sw	1-LV-rural1–1-sw	1-LV-rural1–2-sw
1-LV-rural2–0-sw	1-LV-rural2–1-sw	1-LV-rural2–2-sw
1-LV-rural3–0-sw	1-LV-rural3–1-sw	1-LV-rural3–2-sw
1-LV-semiurb4–0-sw	1-LV-semiurb4–1-sw	1-LV-semiurb4–2-sw
1-LV-semiurb5–0-sw	1-LV-semiurb5–1-sw	1-LV-semiurb5–2-sw
1-LV-urban6–0-sw	1-LV-urban6–1-sw	1-LV-urban6–2-sw
1-EHVHV-mixed-all-0-sw	1-EHVHV-mixed-all-1-sw	1-EHVHV-mixed-all-2-sw
1-EHVHV-mixed-1-0-sw	1-EHVHV-mixed-1-1-sw	1-EHVHV-mixed-1-2-sw
1-EHVHV-mixed-2-0-sw	1-EHVHV-mixed-2-1-sw	1-EHVHV-mixed-2-2-sw
1-HVMV-mixed-all-0-sw	1-HVMV-mixed-all-1-sw	1-HVMV-mixed-all-2-sw
1-HVMV-mixed-1.105-0-sw	1-HVMV-mixed-1.105-1-sw	1-HVMV-mixed-1.105-2-sw
1-HVMV-mixed-2.102-0-sw	1-HVMV-mixed-2.102-1-sw	1-HVMV-mixed-2.102-2-sw
1-HVMV-mixed-4.101-0-sw	1-HVMV-mixed-4.101-1-sw	1-HVMV-mixed-4.101-2-sw
1-HVMV-urban-all-0-sw	1-HVMV-urban-all-1-sw	1-HVMV-urban-all-2-sw
1-HVMV-urban-2.203-0-sw	1-HVMV-urban-2.203-1-sw	1-HVMV-urban-2.203-2-sw
1-HVMV-urban-3.201-0-sw	1-HVMV-urban-3.201-1-sw	1-HVMV-urban-3.201-2-sw
1-HVMV-urban-4.201-0-sw	1-HVMV-urban-4.201-1-sw	1-HVMV-urban-4.201-2-sw
1-MVLV-rural-all-0-sw	1-MVLV-rural-all-1-sw	1-MVLV-rural-all-2-sw
1-MVLV-rural-1.108-0-sw	1-MVLV-rural-1.108-1-sw	1-MVLV-rural-1.108-2-sw
1-MVLV-rural-2.107-0-sw	1-MVLV-rural-2.107-1-sw	1-MVLV-rural-2.107-2-sw
1-MVLV-rural-4.101-0-sw	1-MVLV-rural-4.101-1-sw	1-MVLV-rural-4.101-2-sw
1-MVLV-semiurb-all-0-sw	1-MVLV-semiurb-all-1-sw	1-MVLV-semiurb-all-2-sw
1-MVLV-semiurb-3.202-0-sw	1-MVLV-semiurb-3.202-1-sw	1-MVLV-semiurb-3.202-2-sw
1-MVLV-semiurb-4.201-0-sw	1-MVLV-semiurb-4.201-1-sw	1-MVLV-semiurb-4.201-2-sw
1-MVLV-semiurb-5.220-0-sw	1-MVLV-semiurb-5.220-1-sw	1-MVLV-semiurb-5.220-2-sw
1-MVLV-urban-all-0-sw	1-MVLV-urban-all-1-sw	1-MVLV-urban-all-2-sw
1-MVLV-urban-5.303-0-sw	1-MVLV-urban-5.303-1-sw	1-MVLV-urban-5.303-2-sw
1-MVLV-urban-6.305-0-sw	1-MVLV-urban-6.305-1-sw	1-MVLV-urban-6.305-2-sw
1-MVLV-urban-6.309-0-sw	1-MVLV-urban-6.309-1-sw	1-MVLV-urban-6.309-2-sw
1-MVLV-comm-all-0-sw	1-MVLV-comm-all-1-sw	1-MVLV-comm-all-2-sw
1-MVLV-comm-3.403-0-sw	1-MVLV-comm-3.403-1-sw	1-MVLV-comm-3.403-2-sw
1-MVLV-comm-4.416-0-sw	1-MVLV-comm-4.416-1-sw	1-MVLV-comm-4.416-2-sw
1-MVLV-comm-5.401-0-sw	1-MVLV-comm-5.401-1-sw	1-MVLV-comm-5.401-2-sw
1-complete_data-mixed-all-0-sw	1-complete_data-mixed-all-1-sw	1-complete_data-mixed-all-2-sw
1-EHVHVMVLV-mixed-all-0-sw	1-EHVHVMVLV-mixed-all-1-sw	1-EHVHVMVLV-mixed-all-2-sw

B Power flow results

Table B.1: 1-HV-urban--0-sw-lW: power flow results nodes

node	vm [p.u.]	va [°]	P[MW]	Q[MVar]
EHV Bus 1865	1.0250	0.0000	-398.8084	-15.4685
EHV Bus 1866	1.0250	0.0000	0.0000	0.0000
HV2 Bus 1	1.0314	2.9713	-0.2500	-0.1212
HV2 Bus 2	1.0314	2.9713	0.0000	0.0000
HV2 Bus 7	1.0289	2.8895	-0.2500	-0.1212
HV2 Bus 8	1.0289	2.8895	0.0000	0.0000
HV2 Bus 23	1.0339	3.7375	-0.4500	-0.6055
HV2 Bus 24	1.0339	3.7375	0.0000	0.0000
HV2 Bus 27	1.0348	3.7929	-0.2500	-0.1212
HV2 Bus 28	1.0348	3.7929	0.0000	0.0000
HV2 Bus 33	1.0439	5.0302	9.1300	-0.1212
HV2 Bus 34	1.0439	5.0302	0.0000	0.0000
HV2 Bus 38	1.0345	3.8595	-0.2500	-0.1212
HV2 Bus 39	1.0345	3.8595	0.0000	0.0000
HV2 Bus 43	1.0342	3.8212	10.5400	-0.1212
HV2 Bus 44	1.0342	3.8212	0.0000	0.0000
HV2 Bus 46	1.0289	2.8890	-0.2500	-0.1212
HV2 Bus 47	1.0289	2.8890	0.0000	0.0000
HV2 Bus 49	1.0436	5.9117	33.2300	-0.1212
HV2 Bus 50	1.0436	5.9117	0.0000	0.0000
HV2 Bus 53	1.0294	2.9343	-0.2500	-0.1212
HV2 Bus 54	1.0294	2.9343	0.0000	0.0000
HV2 Bus 59	1.0299	2.9546	16.1410	-2.0896
HV2 Bus 60	1.0299	2.9546	0.0000	0.0000
HV2 Bus 61	1.0447	4.9673	12.8200	-0.1212
HV2 Bus 62	1.0447	4.9673	0.0000	0.0000
HV2 Bus 65	1.0313	3.0570	-0.2500	-0.1212
HV2 Bus 66	1.0313	3.0570	0.0000	0.0000
HV2 Bus 71	1.0505	5.7211	-0.2500	-0.1212
HV2 Bus 72	1.0505	5.7211	0.0000	0.0000
HV2 Bus 75	1.0347	4.1707	8.4700	-0.1212
HV2 Bus 76	1.0347	4.1707	0.0000	0.0000
HV2 Bus 78	1.0407	4.5640	-0.2500	-0.1212
HV2 Bus 79	1.0407	4.5640	0.0000	0.0000
HV2 Bus 83	1.0393	4.5708	-1.5795	-6.0187
HV2 Bus 84	1.0393	4.5708	0.0000	0.0000

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Table B.1 Continued from previous page

node	vm [p.u.]	va [°]	P[MW]	Q[MVar]
HV2 Bus 86	1.0609	9.2146	57.3500	-3.8309
HV2 Bus 87	1.0609	9.2146	0.0000	0.0000
HV2 Bus 90	1.0322	4.1359	-0.4500	-0.6055
HV2 Bus 91	1.0322	4.1359	0.0000	0.0000
HV2 Bus 93	1.0441	5.0139	-0.2500	-0.1212
HV2 Bus 94	1.0441	5.0139	0.0000	0.0000
HV2 Bus 96	1.0433	4.8039	24.4210	-2.0896
HV2 Bus 97	1.0433	4.8039	0.0000	0.0000
HV2 Bus 98	1.0414	4.4296	9.8200	-0.1212
HV2 Bus 99	1.0414	4.4296	0.0000	0.0000
HV2 Bus 102	1.0347	3.5082	23.3000	-0.1212
HV2 Bus 103	1.0347	3.5082	0.0000	0.0000
HV2 Bus 105	1.0378	3.7568	-0.2500	-0.1212
HV2 Bus 106	1.0378	3.7568	0.0000	0.0000
HV2 Bus 108	1.0334	3.6990	-0.2500	-0.1212
HV2 Bus 109	1.0334	3.6990	0.0000	0.0000
HV2 Bus 119	1.0354	3.8359	-0.4500	-0.6055
HV2 Bus 120	1.0354	3.8359	0.0000	0.0000
HV2 Bus 122	1.0319	3.0117	-0.2500	-0.1212
HV2 Bus 123	1.0319	3.0117	0.0000	0.0000
HV2 Bus 125	1.0314	2.9600	-0.2500	-0.1212
HV2 Bus 126	1.0314	2.9600	0.0000	0.0000
HV2 Bus 130	1.0317	3.0096	-0.2500	-0.1212
HV2 Bus 131	1.0317	3.0096	0.0000	0.0000
HV2 Bus 133	1.0366	3.9155	-0.2500	-0.1212
HV2 Bus 134	1.0366	3.9155	0.0000	0.0000
HV2 Bus 137	1.0336	3.1863	-0.4500	-0.6055
HV2 Bus 138	1.0336	3.1863	0.0000	0.0000
HV2 Bus 141	1.0340	3.2341	-0.4500	-0.6055
HV2 Bus 142	1.0340	3.2341	0.0000	0.0000
HV2 Bus 149	1.0314	2.9595	-0.2500	-0.1212
HV2 Bus 150	1.0314	2.9595	0.0000	0.0000
HV2 Bus 152	1.0337	3.7235	-0.2500	-0.1212
HV2 Bus 153	1.0337	3.7235	0.0000	0.0000
HV2 Bus 155	1.0322	3.0885	-0.4500	-0.6055
HV2 Bus 156	1.0322	3.0885	0.0000	0.0000
HV2 Bus 161	1.0337	3.2270	4.6840	-4.1751
HV2 Bus 162	1.0337	3.2270	0.0000	0.0000
HV2 Bus 163	1.0311	2.9769	4.6840	-4.1751
HV2 Bus 164	1.0311	2.9769	0.0000	0.0000
HV2 Bus 165	1.0315	2.9652	4.0000	0.0000
HV2 Bus 166	1.0315	2.9652	0.0000	0.0000
HV2 Bus 168	1.0314	2.9630	-0.2500	-0.1212
HV2 Bus 169	1.0314	2.9630	0.0000	0.0000
HV2 Bus 172	1.0339	3.7360	-0.2500	-0.1212

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Table B.1 Continued from previous page

node	vm [p.u.]	va [°]	P[MW]	Q[MVar]
HV2 Bus 173	1.0339	3.7360	0.0000	0.0000
HV2 Bus 175	1.0340	3.7424	-0.2500	-0.1212
HV2 Bus 176	1.0340	3.7424	0.0000	0.0000
HV2 Bus 182	1.0344	4.1344	11.4900	-0.1212
HV2 Bus 183	1.0344	4.1344	0.0000	0.0000
HV2 Bus 187	1.0355	3.9912	-0.2500	-0.1212
HV2 Bus 188	1.0355	3.9912	0.0000	0.0000
HV2 Bus 192	1.0496	5.8076	11.1200	-0.6055
HV2 Bus 193	1.0496	5.8076	0.0000	0.0000
HV2 Bus 195	1.0323	4.1385	-1.5795	-6.0187
HV2 Bus 196	1.0323	4.1385	0.0000	0.0000
HV2 Bus 199	1.0429	4.7284	-0.2500	-0.1212
HV2 Bus 200	1.0429	4.7284	0.0000	0.0000
HV2 Bus 204	1.0378	3.7570	16.1410	-2.0896
HV2 Bus 205	1.0378	3.7570	0.0000	0.0000
HV2 Bus 206	1.0355	3.8362	-0.2500	-0.1212
HV2 Bus 207	1.0355	3.8362	0.0000	0.0000
HV2 Bus 212	1.0450	5.0054	10.6000	-0.1212
HV2 Bus 213	1.0450	5.0054	0.0000	0.0000
HV2 Bus 216	1.0317	3.0099	-0.2500	-0.1212
HV2 Bus 217	1.0317	3.0099	0.0000	0.0000
HV2 Bus 221	1.0471	5.4336	24.8200	-0.1212
HV2 Bus 222	1.0471	5.4336	0.0000	0.0000
HV2 Bus 226	1.0348	3.8290	-0.2500	-0.1212
HV2 Bus 227	1.0348	3.8290	0.0000	0.0000
HV2 Bus 229	1.0343	3.7555	-0.2500	-0.1212
HV2 Bus 230	1.0343	3.7555	0.0000	0.0000
HV2 Bus 236	1.0337	3.7239	3.5000	0.0000
HV2 Bus 237	1.0337	3.7239	0.0000	0.0000
HV2 Bus 243	1.0557	6.3241	9.5600	-0.1212
HV2 Bus 244	1.0557	6.3241	0.0000	0.0000
HV2 Bus 246	1.0309	2.9732	-0.2500	-0.1212
HV2 Bus 247	1.0309	2.9732	0.0000	0.0000
HV2 Bus 254	1.0428	4.8787	33.2300	-0.1212
HV2 Bus 255	1.0428	4.8787	0.0000	0.0000
HV2 Bus 257	1.0346	3.8372	-0.2500	-0.1212
HV2 Bus 258	1.0346	3.8372	0.0000	0.0000
HV2 Bus 260	1.0370	3.9430	-0.2500	-0.1212
HV2 Bus 261	1.0370	3.9430	0.0000	0.0000
HV2 Bus 265	1.0360	4.0446	-0.2500	-0.1212
HV2 Bus 266	1.0360	4.0446	0.0000	0.0000
HV2 Bus 270	1.0399	4.2102	-0.4500	-0.6055
HV2 Bus 271	1.0399	4.2102	0.0000	0.0000
HV2 Bus 274	1.0418	4.4909	-0.2500	-0.1212
HV2 Bus 275	1.0418	4.4909	0.0000	0.0000

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Table B.1 Continued from previous page

node	vm [p.u.]	va [°]	P[MW]	Q[MVar]
HV2 Bus 278	1.0500	7.3277	14.2340	-4.1751
HV2 Bus 279	1.0500	7.3277	0.0000	0.0000
HV2 Bus 280	1.0362	3.3876	-0.2500	-0.1212
HV2 Bus 281	1.0362	3.3876	0.0000	0.0000
HV2 Bus 286	1.0318	3.0126	-0.2500	-0.1212
HV2 Bus 287	1.0318	3.0126	0.0000	0.0000
HV2 Bus 290	1.0301	2.9316	11.1300	-3.8309
HV2 Bus 291	1.0301	2.9316	0.0000	0.0000
HV2 Bus 296	1.0392	4.1093	-0.2500	-0.1212
HV2 Bus 297	1.0392	4.1093	0.0000	0.0000
HV2 Bus 304	1.0332	3.1445	16.1410	-2.0896
HV2 Bus 305	1.0332	3.1445	0.0000	0.0000
HV2 Bus 306	1.0313	2.9729	-0.2500	-0.1212
HV2 Bus 307	1.0313	2.9729	0.0000	0.0000
HV2 Bus 310	1.0315	2.9897	11.1300	-3.8309
HV2 Bus 311	1.0315	2.9897	0.0000	0.0000
HV2 Bus 313	1.0371	3.9444	-0.4500	-0.6055
HV2 Bus 314	1.0371	3.9444	0.0000	0.0000
HV2 Bus 318	1.0394	4.1324	-0.2500	-0.1212
HV2 Bus 319	1.0394	4.1324	0.0000	0.0000
HV2 Bus 322	1.0343	3.8556	-0.2500	-0.1212
HV2 Bus 323	1.0343	3.8556	0.0000	0.0000
HV2 Bus 329	1.0317	3.0222	-0.2500	-0.1212
HV2 Bus 330	1.0317	3.0222	0.0000	0.0000
HV2 Bus 336	1.0651	9.7946	16.5600	-0.1212
HV2 Bus 337	1.0651	9.7946	0.0000	0.0000
HV2 Bus 339	1.0303	3.1494	-0.2500	-0.1212
HV2 Bus 340	1.0303	3.1494	0.0000	0.0000
HV2 Bus 347	1.0443	4.9073	16.1410	-2.0896
HV2 Bus 348	1.0443	4.9073	0.0000	0.0000
HV2 Bus 349	1.0316	3.0379	-0.2500	-0.1212
HV2 Bus 350	1.0316	3.0379	0.0000	0.0000
HV2 Bus 354	1.0343	3.7552	-0.2500	-0.1212
HV2 Bus 355	1.0343	3.7552	0.0000	0.0000
HV2 Bus 357	1.0423	4.5216	-0.2500	-0.1212
HV2 Bus 358	1.0423	4.5216	0.0000	0.0000
HV2 Bus 361	1.0312	2.9595	-0.4500	-0.6055
HV2 Bus 362	1.0312	2.9595	0.0000	0.0000

Table B.2: 1-HV-urban--0-sw-lW: power flow results of lines

line	bus_start	bus_end	P_start [MW]	P_end [MW]	Q_start [MVar]	Q_end [MVar]	P_losses [MW]	Q_losses [MW]	loading [%]
HV2 Line 1	HV2 Bus 23	HV2 Bus 172	0.2500	-0.2500	-0.0500	-0.1212	0.0000	-0.1712	0.2074
HV2 Line 2	HV2 Bus 108	HV2 Bus 339	70.2222	-69.9776	-3.5294	3.9779	0.2446	0.4485	52.5167
HV2 Line 3	HV2 Bus 108	HV2 Bus 339	70.2222	-69.9776	-3.5294	3.9779	0.2446	0.4485	52.5167
HV2 Line 4	HV2 Bus 8	HV2 Bus 290	-25.5157	25.5408	-7.0765	4.1930	0.0251	-2.8835	20.7170
HV2 Line 5	HV2 Bus 65	HV2 Bus 155	-27.2189	27.2395	-7.5044	5.4265	0.0206	-2.0779	22.0398
HV2 Line 6	HV2 Bus 246	HV2 Bus 8	27.5118	-27.4638	1.6723	-6.5574	0.0481	-4.8851	22.0916
HV2 Line 7	HV2 Bus 60	HV2 Bus 65	-27.0725	27.0939	-7.5018	7.4438	0.0215	-0.0580	21.0531
HV2 Line 8	HV2 Bus 155	HV2 Bus 161	-27.4645	27.4923	-5.7292	5.6525	0.0278	-0.0767	20.9798
HV2 Line 9	HV2 Bus 109	HV2 Bus 236	-6.2750	6.2763	-2.0784	1.9567	0.0013	-0.1217	4.9373
HV2 Line 10	HV2 Bus 176	HV2 Bus 237	4.6520	-4.6513	1.8652	-1.9947	0.0008	-0.1295	3.7788
HV2 Line 11	HV2 Bus 175	HV2 Bus 229	-5.1270	5.1276	-2.0753	1.9937	0.0006	-0.0816	4.1287
HV2 Line 12	HV2 Bus 141	HV2 Bus 162	25.1551	-25.1503	7.1838	-7.7400	0.0048	-0.5563	20.4917
HV2 Line 13	HV2 Bus 7	HV2 Bus 53	-34.9905	35.0019	-7.3790	7.3720	0.0115	-0.0070	26.8266
HV2 Line 14	HV2 Bus 28	HV2 Bus 230	5.3793	-5.3776	1.8741	-2.0951	0.0017	-0.2210	4.3071
HV2 Line 15	HV2 Bus 297	HV2 Bus 205	45.1540	-45.0544	-5.7036	5.7609	0.0996	0.0574	33.8028
HV2 Line 16	HV2 Bus 27	HV2 Bus 206	-5.5043	5.5063	-1.9347	1.6892	0.0019	-0.2455	4.3518
HV2 Line 17	HV2 Bus 260	HV2 Bus 313	-6.1115	6.1117	-2.0256	1.5827	0.0002	-0.4429	4.9979
HV2 Line 18	HV2 Bus 75	HV2 Bus 182	8.4700	-8.4680	-0.1212	0.0072	0.0020	-0.1140	6.3192
HV2 Line 19	HV2 Bus 175	HV2 Bus 229	-5.1270	5.1276	-2.0753	1.9937	0.0006	-0.0816	4.1287
HV2 Line 20	HV2 Bus 27	HV2 Bus 206	-5.5043	5.5063	-1.9347	1.6892	0.0019	-0.2455	4.3518
HV2 Line 21	HV2 Bus 212	HV2 Bus 347	7.3484	-7.3437	-0.1610	-0.2151	0.0047	-0.3761	5.4301
HV2 Line 22	HV2 Bus 62	HV2 Bus 212	-3.2508	3.2516	-0.3864	0.0398	0.0008	-0.3467	2.4187
HV2 Line 23	HV2 Bus 8	HV2 Bus 340	-69.7792	69.8943	4.2295	-4.0183	0.1151	0.2112	52.4476
HV2 Line 24	HV2 Bus 349	HV2 Bus 216	8.4903	-8.4884	-6.4217	6.3554	0.0019	-0.0663	7.9652
HV2 Line 25	HV2 Bus 96	HV2 Bus 199	24.4210	-24.4094	-2.0896	2.0344	0.0116	-0.0552	18.1331
HV2 Line 26	HV2 Bus 182	HV2 Bus 322	17.9239	-17.8921	-6.0338	5.7321	0.0318	-0.3018	14.1116
HV2 Line 27	HV2 Bus 39	HV2 Bus 323	1.5853	-1.5851	2.0949	-2.2332	0.0002	-0.1383	2.0438
HV2 Line 28	HV2 Bus 38	HV2 Bus 108	51.1724	-51.1191	0.7231	-0.6670	0.0533	0.0561	38.1852
HV2 Line 29	HV2 Bus 7	HV2 Bus 46	0.2500	-0.2500	0.0496	-0.1212	0.0000	-0.0717	0.2084
HV2 Line 30	HV2 Bus 204	HV2 Bus 280	52.9999	-52.8774	-6.8524	6.9956	0.1225	0.1432	39.7479
HV2 Line 31	HV2 Bus 60	HV2 Bus 65	-27.0725	27.0939	-7.5018	7.4438	0.0215	-0.0580	21.0531
HV2 Line 32	HV2 Bus 152	HV2 Bus 236	-0.2500	0.2500	-0.1212	0.0761	0.0000	-0.0451	0.2075
HV2 Line 33	HV2 Bus 71	HV2 Bus 243	-9.5214	9.5600	-1.7337	-0.1212	0.0386	-1.8549	7.1106
HV2 Line 34	HV2 Bus 270	HV2 Bus 318	32.2302	-32.2141	-0.5799	0.5550	0.0161	-0.0249	23.9269
HV2 Line 35	HV2 Bus 192	HV2 Bus 221	11.1200	-11.0933	-0.6055	-0.3103	0.0267	-0.9158	8.1899
HV2 Line 36	HV2 Bus 229	HV2 Bus 354	0.2500	-0.2500	0.0816	-0.1212	0.0000	-0.0396	0.2074
HV2 Line 37	HV2 Bus 38	HV2 Bus 187	-53.0077	53.0539	-2.9392	2.9931	0.0462	0.0538	39.6106
HV2 Line 38	HV2 Bus 72	HV2 Bus 222	9.2714	-9.2517	1.6124	-2.5593	0.0197	-0.9469	7.0757
HV2 Line 39	HV2 Bus 133	HV2 Bus 260	-11.9702	11.9729	-3.9966	3.9299	0.0027	-0.0667	9.3966
HV2 Line 40	HV2 Bus 187	HV2 Bus 265	-25.5900	25.5991	-1.4975	1.4621	0.0090	-0.0354	19.1067
HV2 Line 41	HV2 Bus 188	HV2 Bus 266	-27.7139	27.7237	-1.6168	1.5880	0.0098	-0.0288	20.6922
HV2 Line 42	HV2 Bus 33	HV2 Bus 265	53.9243	-53.5727	3.5858	-3.1713	0.3516	0.4145	39.9851
HV2 Line 43	HV2 Bus 98	HV2 Bus 270	32.7265	-32.6802	-0.0412	-0.0256	0.0463	-0.0668	24.2571

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Table B.2 Continued from previous page

line	bus_start	bus_end	P_start [MW]	P_end [MW]	Q_start [MVar]	Q_end [MVar]	P_losses [MW]	Q_losses [MW]	loading [%]
HV2 Line 44	HV2 Bus 195	HV2 Bus 183	-2.0295	2.0341	-6.3646	5.9054	0.0046	-0.4592	4.9948
HV2 Line 45	HV2 Bus 105	HV2 Bus 205	-0.2500	0.2500	-0.1212	0.0934	0.0000	-0.0279	0.2067
HV2 Line 46	HV2 Bus 176	HV2 Bus 237	4.6520	-4.6513	1.8652	-1.9947	0.0008	-0.1295	3.7788
HV2 Line 47	HV2 Bus 350	HV2 Bus 7	14.4890	-14.4687	6.5508	-6.8359	0.0203	-0.2850	12.0046
HV2 Line 48	HV2 Bus 257	HV2 Bus 323	-0.2500	0.2501	-0.1212	-1.0817	0.0001	-1.2029	0.8286
HV2 Line 49	HV2 Bus 119	HV2 Bus 207	-0.4500	0.4500	-0.6055	0.5726	0.0000	-0.0329	0.5624
HV2 Line 50	HV2 Bus 155	HV2 Bus 161	-27.4645	27.4923	-5.7292	5.6525	0.0278	-0.0767	20.9798
HV2 Line 51	HV2 Bus 102	HV2 Bus 349	23.3000	-23.2293	-0.1212	-0.2504	0.0707	-0.3716	17.3820
HV2 Line 52	HV2 Bus 347	HV2 Bus 357	23.4847	-23.4276	-1.8745	1.5660	0.0572	-0.3084	17.4128
HV2 Line 53	HV2 Bus 109	HV2 Bus 236	-6.2750	6.2763	-2.0784	1.9567	0.0013	-0.1217	4.9373
HV2 Line 54	HV2 Bus 49	HV2 Bus 109	119.6599	-118.0076	-10.5571	14.5150	1.6523	3.9578	88.8463
HV2 Line 55	HV2 Bus 50	HV2 Bus 279	-86.4299	87.2018	10.4359	-8.8086	0.7719	1.6273	64.4267
HV2 Line 56	HV2 Bus 86	HV2 Bus 278	73.8476	-72.9678	-3.0189	4.6335	0.8798	1.6147	53.7744
HV2 Line 57	HV2 Bus 141	HV2 Bus 281	-52.6666	52.7958	3.4651	-7.0591	0.1292	-3.5941	41.3796
HV2 Line 58	HV2 Bus 142	HV2 Bus 280	-52.5800	52.7090	3.4530	-7.0534	0.1290	-3.6004	41.3121
HV2 Line 59	HV2 Bus 226	HV2 Bus 322	-0.2500	0.2502	-0.1212	-1.4042	0.0002	-1.5254	1.0644
HV2 Line 60	HV2 Bus 260	HV2 Bus 313	-6.1115	6.1117	-2.0256	1.5827	0.0002	-0.4429	4.9979
HV2 Line 61	HV2 Bus 53	HV2 Bus 59	-35.1269	35.1430	-7.4326	6.4570	0.0161	-0.9756	28.0779
HV2 Line 62	HV2 Bus 361	HV2 Bus 125	-1.5156	1.5158	-3.1896	-0.5060	0.0002	-3.6955	2.7566
HV2 Line 63	HV2 Bus 130	HV2 Bus 217	-0.2500	0.2500	-0.1212	-0.7084	0.0000	-0.8297	0.5862
HV2 Line 64	HV2 Bus 125	HV2 Bus 149	0.2500	-0.2500	-0.9084	-0.1212	0.0000	-1.0296	0.7353
HV2 Line 65	HV2 Bus 137	HV2 Bus 141	-25.6502	25.6680	8.4305	-10.3268	0.0177	-1.8963	21.5405
HV2 Line 66	HV2 Bus 65	HV2 Bus 155	-27.2189	27.2395	-7.5044	5.4265	0.0206	-2.0779	22.0398
HV2 Line 67	HV2 Bus 141	HV2 Bus 162	25.1551	-25.1503	7.1838	-7.7400	0.0048	-0.5563	20.4917
HV2 Line 68	HV2 Bus 246	HV2 Bus 8	27.5118	-27.4638	1.6723	-6.5574	0.0481	-4.8851	22.0916
HV2 Line 69	HV2 Bus 247	HV2 Bus 290	20.5579	-20.5420	-0.1767	-2.7937	0.0159	-2.9704	16.2014
HV2 Line 70	HV2 Bus 78	HV2 Bus 83	1.5823	-1.5795	5.6954	-6.0187	0.0028	-0.3233	4.6212
HV2 Line 71	HV2 Bus 246	HV2 Bus 329	-34.5854	34.6136	0.6062	-2.4562	0.0283	-1.8500	27.0753
HV2 Line 72	HV2 Bus 247	HV2 Bus 163	-6.6608	6.6620	-4.5016	2.8185	0.0012	-1.6830	6.2776
HV2 Line 73	HV2 Bus 362	HV2 Bus 291	19.4278	-19.4097	6.1400	-9.4232	0.0182	-3.2833	16.8619
HV2 Line 74	HV2 Bus 138	HV2 Bus 304	25.2002	-25.1849	-9.0360	7.2990	0.0153	-1.7370	20.8509
HV2 Line 75	HV2 Bus 142	HV2 Bus 305	28.8185	-28.7811	-11.5643	8.3637	0.0374	-3.2006	24.1757
HV2 Line 76	HV2 Bus 305	HV2 Bus 330	35.0535	-34.9889	-8.8762	4.8738	0.0647	-4.0024	28.1736
HV2 Line 77	HV2 Bus 1	HV2 Bus 361	6.3817	-6.3806	-2.9817	1.0213	0.0011	-1.9603	5.4980
HV2 Line 78	HV2 Bus 2	HV2 Bus 306	2.2290	-2.2287	5.1818	-5.8521	0.0003	-0.6703	4.8882
HV2 Line 79	HV2 Bus 163	HV2 Bus 307	-1.9780	1.9787	-6.9936	5.7309	0.0007	-1.2627	5.6740
HV2 Line 80	HV2 Bus 1	HV2 Bus 310	-11.1270	11.1300	2.0237	-3.8309	0.0030	-1.8073	9.1859
HV2 Line 81	HV2 Bus 296	HV2 Bus 199	-40.0467	40.2051	1.5145	-1.5226	0.1584	-0.0081	29.7766
HV2 Line 82	HV2 Bus 126	HV2 Bus 168	-2.0158	2.0159	1.2931	-2.3920	0.0001	-1.0990	2.4416
HV2 Line 83	HV2 Bus 2	HV2 Bus 169	2.2663	-2.2659	-4.3450	2.2708	0.0004	-2.0742	3.8251
HV2 Line 84	HV2 Bus 286	HV2 Bus 329	-0.5000	0.5005	1.2743	-4.9563	0.0005	-3.6820	3.8869
HV2 Line 85	HV2 Bus 361	HV2 Bus 165	-3.9991	4.0000	-3.6158	0.0000	0.0009	-3.6158	4.2086
HV2 Line 86	HV2 Bus 362	HV2 Bus 216	-7.9825	7.9884	-0.9614	-5.7682	0.0059	-6.7296	7.6880
HV2 Line 87	HV2 Bus 274	HV2 Bus 358	-23.1656	23.1776	-0.1489	-1.6873	0.0120	-1.8361	17.9484

Continued on next page

Table B.2 Continued from previous page

line	bus_start	bus_end	P_start [MW]	P_end [MW]	Q_start [MVar]	Q_end [MVar]	P_losses [MW]	Q_losses [MW]	loading [%]
HV2 Line 88	HV2 Bus 8	HV2 Bus 290	-25.5157	25.5408	-7.0765	4.1930	0.0251	-2.8835	20.7170
HV2 Line 89	HV2 Bus 108	HV2 Bus 322	-18.7083	18.7269	0.9559	-1.1342	0.0186	-0.1783	14.0014
HV2 Line 90	HV2 Bus 24	HV2 Bus 175	-0.7000	0.7000	-0.5555	0.2989	0.0000	-0.2566	0.6671
HV2 Line 91	HV2 Bus 34	HV2 Bus 93	0.2501	-0.2500	-1.0180	-0.1212	0.0001	-1.1392	0.7751
HV2 Line 92	HV2 Bus 61	HV2 Bus 200	16.0708	-16.0457	0.2652	-0.6330	0.0251	-0.3678	11.8845
HV2 Line 93	HV2 Bus 87	HV2 Bus 336	-16.4976	16.5600	-0.8121	-0.1212	0.0624	-0.9333	12.0177
HV2 Line 94	HV2 Bus 296	HV2 Bus 78	-31.2415	31.3304	5.6997	-5.8478	0.0889	-0.1481	23.6387
HV2 Line 95	HV2 Bus 297	HV2 Bus 319	-31.9594	31.9641	0.6686	-0.6762	0.0047	-0.0077	23.7421
HV2 Line 96	HV2 Bus 296	HV2 Bus 314	12.6896	-12.6733	3.4032	-3.7709	0.0163	-0.3677	9.8411
HV2 Line 97	HV2 Bus 196	HV2 Bus 90	0.4500	-0.4500	0.3459	-0.6055	0.0000	-0.2596	0.5641
HV2 Line 98	HV2 Bus 122	HV2 Bus 286	-0.2500	0.2500	-0.1212	-1.3956	0.0000	-1.5168	1.1061
HV2 Line 99	HV2 Bus 79	HV2 Bus 254	-33.1626	33.2300	0.0312	-0.1212	0.0674	-0.0901	24.5968
HV2 Line 100	HV2 Bus 33	HV2 Bus 221	-45.0444	45.1650	-2.6891	2.7483	0.1206	0.0592	33.3655
HV2 Line 101	HV2 Bus 134	HV2 Bus 206	11.7202	-11.7126	3.8754	-4.0722	0.0076	-0.1969	9.2435
HV2 Line 102	HV2 Bus 43	HV2 Bus 108	10.5400	-10.5317	-0.1212	-0.1800	0.0083	-0.3013	7.8675
HV2 Line 103	HV2 Bus 297	HV2 Bus 205	45.1540	-45.0544	-5.7036	5.7609	0.0996	0.0574	33.8028
HV2 Line 104	HV2 Bus 99	HV2 Bus 274	-22.9065	22.9156	-0.0800	0.0276	0.0091	-0.0524	16.9785
HV2 Line 105	HV2 Bus 28	HV2 Bus 230	5.3793	-5.3776	1.8741	-2.0951	0.0017	-0.2210	4.3071
HV2 Line 106	HV2 Bus 108	HV2 Bus 339	70.2222	-69.9776	-3.5294	3.9779	0.2446	0.4485	52.5167
HV2 Line 107	HV2 Bus 8	HV2 Bus 340	-69.7792	69.8943	4.2295	-4.0183	0.1151	0.2112	52.4476
HV2 Line 108	HV2 Bus 204	HV2 Bus 280	52.9999	-52.8774	-6.8524	6.9956	0.1225	0.1432	39.7479
HV2 Line 109	HV2 Bus 246	HV2 Bus 329	-34.5854	34.6136	0.6062	-2.4562	0.0283	-1.8500	27.0753
HV2 Line 110	HV2 Bus 305	HV2 Bus 330	35.0535	-34.9889	-8.8762	4.8738	0.0647	-4.0024	28.1736
HV2 Line 111	HV2 Bus 53	HV2 Bus 59	-35.1269	35.1430	-7.4326	6.4570	0.0161	-0.9756	28.0779
HV2 Line 112	HV2 Bus 8	HV2 Bus 340	-69.7792	69.8943	4.2295	-4.0183	0.1151	0.2112	52.4476
HV2 Line 113	HV2 Bus 7	HV2 Bus 53	-34.9905	35.0019	-7.3790	7.3720	0.0115	-0.0070	26.8266

Table B.3: 1-HV-urban--0-sw-lW: power flow results transformer

trafo	bus_hv	bus_lv	P_hv [MW]	P_lv [MW]	Q_hv [MVar]	Q_lv [MVar]	P_losses [MW]	Q_losses [MW]	loading [%]
HV2 Trafo 1	EHV Bus 1865	HV2 Bus 7	-132.9361	133.0821	-5.1562	12.0008	0.1459	6.8446	43.2898
HV2 Trafo 2	EHV Bus 1866	HV2 Bus 7	-132.9361	133.0821	-5.1562	12.0008	0.1459	6.8446	43.2898
HV2 Trafo 3	EHV Bus 1866	HV2 Bus 7	-132.9361	133.0821	-5.1562	12.0008	0.1459	6.8446	43.2898

C Description of converters and how to apply SimBench in calculation tools

The SimBench dataset is prepared in the form of CSV files, which are simple, open, readable and can be processed by many software tools. The grid elements and their parameters are described in Section 4.3.1. To increase the user-friendliness of SimBench dataset, we developed converter for the power system calculation and optimization software like PowerFactory [1], integral [2] and `pandapower` [3]. These are described in this chapter.

C.1 PowerFactory

C.1.1 Python installation

To use the SimBench converter in PowerFactory, Python must be installed. Python 3.5 and PowerFactory 2017 have been used to create the SimBench converter. It is therefore recommended to also use Python 3.5 (or higher). Python can be downloaded from the website www.python.org under "Downloads" in different versions for different operating systems. Once Python is installed, the converter requires the installation of additional packages/libraries. These are:

- sys
- os
- csv

For example, missing packages can be installed using the package manager "pip", which is installed by default when Python is installed. The command line for installing a package with the name "project name" via pip (under Windows) is:

```
pip install "project name"
```

After Python 3.5 and the required packages are installed, the SimBench converter can be used. More information on setting up Python can be found in the PowerFactory manual (for PowerFactory 2017) in Section "21.2.1 Installation of a Python Interpreter".

C.1.2 Application of the converter in PowerFactory

To use the SimBench converter in PowerFactory, a Python command object (ComPython) must first be created in a PowerFactory project. This Python command object creates a link between PowerFactory and a python script file. How to build and use the Python command object is described in detail in the PowerFactory manual under Section “21.2.3 The Python Command (ComPython)”. In the following, the integration of the converter in PowerFactory is briefly described.

In a new project, a new Python command object must first be created under “Library” → “Scripts”. In the command object, a name can be assigned to the command object under “Name” in the “Basic Options”. Furthermore, it is important to specify the path where the CSV files of the SimBench dataset are located under “Input parameters”. An example can be seen in Figure C.1. It is important to select “string” as type and “folder” as name, the value to be specified here is the file path. In this example a folder “LV-Model” is selected as file path as subfolder of “SimBench” on the drive “D:”.

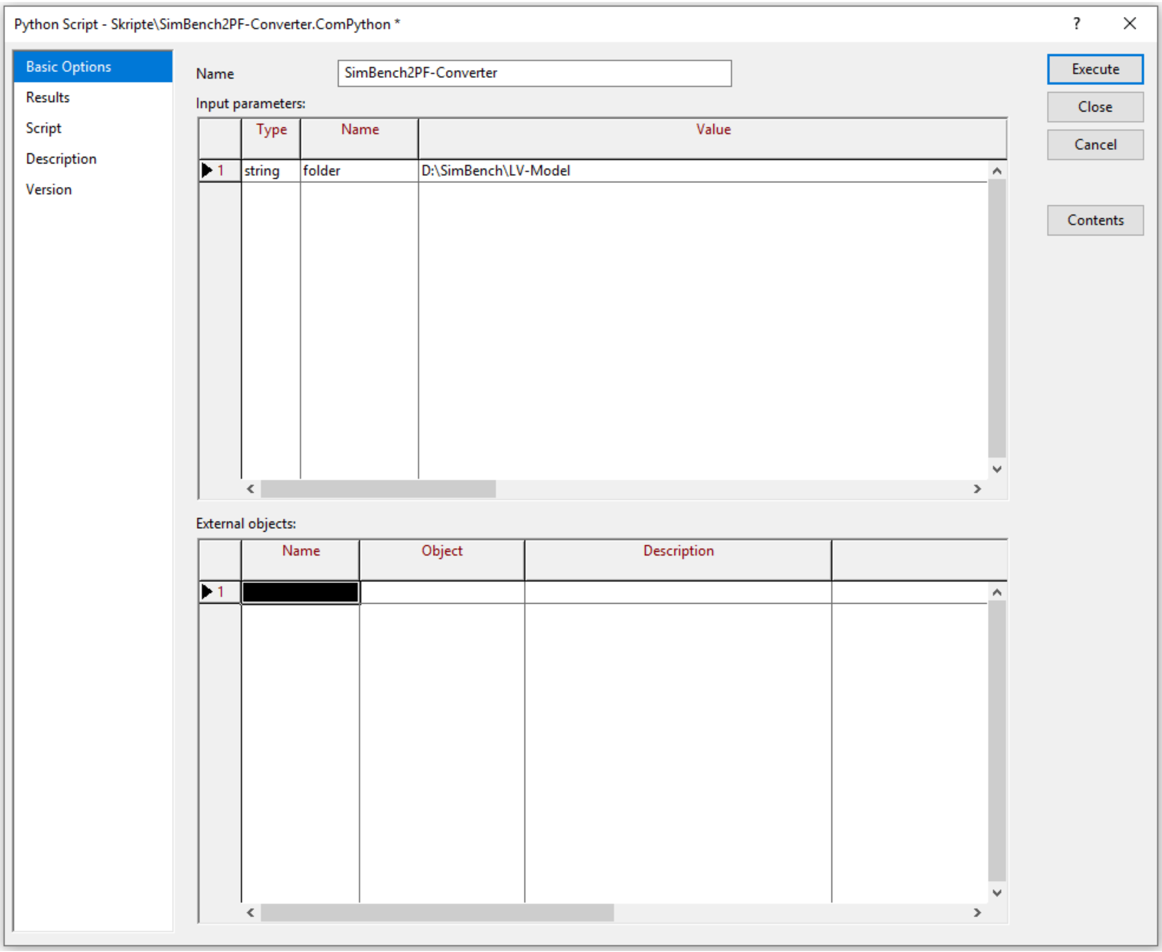

Figure C.1: Structure of the Python Command Object in PowerFactory

Next, enter the path of the SimBench converter file. This is done in the command object under the tab “Script”. There the Python converter file can be searched for and selected under “Script file”. Thus the “SimBench2PowerFactory_Converter.py” is to be selected there.

The command object is then prepared for importing a SimBench model. With a click on “Execute” the converter is started and imports the network topology from the file path stored under “Input parameters”.

C.2 Pandapower

In order to use SimBench grids with pandapower, installing the python package “SimBench” is recommended . It is available at GitHub and PyPI. The installation is similar to pandapower and is described in the documentation of the package. To obtain the desired SimBench grid data, the function get_simbench_net(simbench_code) should be called. The SimBench code must be passed as input to this function. A minimal example of the code looks like this:

```
import simbench
simbench_code = "1-complete_data-mixed-all-0-sw"
net = simbench.get_simbench_net(simbench_code)}
```

In the python package SimBench, the csv files of the complete datasets of SimBench are the starting points to provide grid data. The complete datasets include all grids, time series of all voltage levels and all the grid equivalents. For scenario 0, the code is “1-complete_data-mixed-all-0-sw”. The function get_simbench_net() calls the subfunction get_extracted_csv_data(), which extracts the rural MV grid according to the subgrid parameters (see Section 4.2.2). The grid data is then converted to the pandapower format using the converter function csv_data2pp(). The converter function is programmed in a generic way, so that it can also handle other grids of the SimBench CSV format. Another helpful feature is the pp2csv_data() function. With this function it is possible to convert pandapower grids into the CSV format of SimBench. Hints and code examples are available in the python package SimBench as jupyter notebooks.

C.3 Integral

Within the scope of the project a conversion of the SimBench data format into an INTEGRAL-compliant data format was also implemented. INTEGRAL is a commercial network planning software for applications in network planning and operation. The software is provided by FGH GmbH. Further information and contact details can be found in [2]. The aim of this section is to describe the use of SimBench networks in INTEGRAL. Instructions for INTEGRAL in general are not given here. Please refer to the INTEGRAL help or the support.

For the relevant use cases described in Subsection 4.2.3 the SimBench datasets are available in xml format. The load cases or time series of the corresponding datasets are available separately in csv format, since they cannot be integrated into the xml format. In the following, instructions for calculating the datasets based on Figure C.2 are given.

The grids in xml format are dragged into the box with the number 1 via *Drag and Drop*. After the successful import of the grid, a schematic representation of the grid can be generated under the “Projects” tab in the same box. This is possible because all grids contain georeferenced data. The georeferenced data are partly synthetically generated and serve only for visualization. For a calculation of different load/infeed situations the import of the grid usage cases in csv format is necessary. However, it is only possible to

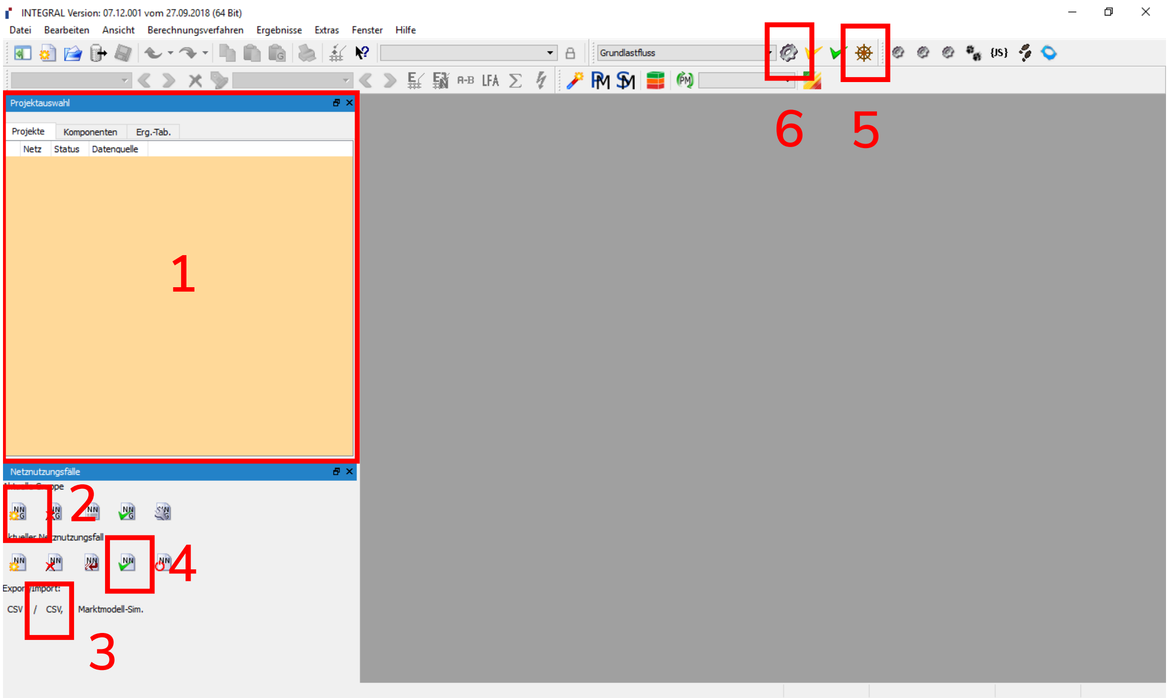

Figure C.2: INTEGRAL User Interface

import grid usage cases if the imported grid is stored in a project database. This is possible via "File/Save to project database" or the keyboard shortcut "Ctrl+Shift+S". After saving the project with the imported grid in the project database, a usecase group (according to number 2) has to be created. After saving the project again, the grid use cases (number 3) can be imported. The grid use cases are selected by number 4. For the selected calculation method, for example the calculation of the base power flow, various settings related to the use case can be specified under number 5. These are, for example, iteration limits for the power flow or maximum line loadings. The selected calculation method is now carried out using number 6.

Nomenclature

Definitions

boxplot	A boxplot diagram figures a distribution of numeric data. The area between the upper and lower quantil of the distribution is colored. Therein the median is marked by a horizontal line. In this documentation the “whiskers” reach to the last occuring value, which distance to the neighboring quantil does not exceed the distance of the quantil to the median by a factor of 1.5. Outlying values are marked by diamonds.
feeder	Supplying outgoing connection of an overhead line or cable from a substation
primary	Substation including busbars, outgoing feeders and transformers with connection to the MV and LV level
tie-line	Line with sectionalizing point in open loop operation
violin plot	A violin plot depicts a distribution of numeric data. It uses an enveloping contour to graphically depict the density of the distribution. In the violin plots used here, individual values are marked by points. They are spread over the y-axis for a clear visualization.

Abbreviations

APLS	charging station for electric cars at the worksite (in German: Arbeisplatzladestationen)
BDEW	German association of energy and water industries (in German: Bundesverband der Energie- und Wasserwirtschaft)
BM	biomass
BNetzA	Federal Network Agency (in German: Bundesnetzagentur)
DER	distributed energy resource
DSO	distributed system operator
DSO2	2nd use case for distribution system operation
DWD	German meteorological service (in German: Deutscher Wetterdienst)
EHV	extra high voltage

ENTSO-E	European network of transmission system operators for electricity
EV	electric vehicle
HLS	charging station for electric cars at residential buildings (in German: Heimladestationen)
HP	heat pump
HV	high voltage
HVDC	high-voltage direct current
HVN	integration study for the German state of Hesse (in German: Hessenverteilnetzstudie)
ICT	information and communication technology
LV	low voltage
MV	medium voltage
NEP	power system development plan (in German: Netzentwicklungsplan)
OHL	overhead line
RES	renewable energy source
RPM	recorded power measurements
Plan3	3^{rd} use case for grid planning
PV	photovoltaics
Sim4	4^{th} use case for grid simulation
SLP	standard load profile
SOC	state-of-charge
TS	transformer station
TSO	transmission system operation
TSO1	1^{st} use case for transmission system operation

List of Figures

List of Tables

Acknowledgement

This work was supported by the German Federal Ministry for Economic Affairs and Energy and the Projektträger Jülich GmbH (PTJ) within the framework of the project SimBench (FKZ: 0325917A). The authors are solely responsible for the content of this publication.

Federal Ministry for Economic Affairs and Energy

SimBench

Furthermore, the authors would like to thank the participating system operators for their active participation, helpful feedback and comments as well as the provision of network data. They were:

Prof. Matthias Hable, DREWAG NETZ GmbH

Marvin Reiting, Energie Netz Mitte GmbH

Dr. Jörg Dickert, ENSO NETZ GmbH

Franziska Fischer, Netze BW GmbH

Guntram Naurath, Syna GmbH

Daniel Telöken, Westnetz GmbH

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