The eGo grid model: An open-source and open-data based synthetic medium-voltage grid model for distribution power supply systems

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Abstract. The increasing integration of renewable energy into the electricity supply system creates new challenges for distribution grids. The planning and operation of distribution systems requires appropriate grid models that consider the heterogeneity of existing grids.

In this paper, we describe a novel method to generate synthetic medium-voltage (MV) grids, which we applied in our DIstribution Network GeneratOr (DINGO). DINGO is open-source software and uses freely available data.

Medium-voltage grid topologies are synthesized based on location and electricity demand in defined demand areas. For this purpose, we use GIS data containing demand areas with high-resolution spatial data on physical properties, land use, energy, and demography. The grid topology is treated as a capacitated vehicle routing problem (CVRP) combined with a local search metaheuristics. We also consider the current planning principles for MV distribution networks, paying special attention to line congestion and voltage limit violations. In the modelling process, we included power flow calculations for validation.

The resulting grid model datasets contain 3608 synthetic MV grids in high resolution, covering all of Germany and taking local characteristics into account. We compared the modelled networks with real network data. In terms of number of transformers and total cable length, we conclude that the method presented in this paper generates realistic grids that could be used to implement a cost-optimised electrical energy system.

1. Introduction
The transition of the energy system in Germany from fossil fuels to renewable energy sources (RES) (the Energiewende) brings new challenges to grid operation and extension planning. These include new demands on grid topology, vast grid expansion needs, and reverse power flows in distribution grids (DGs) due to distributed generation in low and medium-voltage grids. The first point is addressed by the Netzentwicklungsplan (NEP), a public participatory process to identify the expansion needs of the transmission grid [1]. However, the NEP has shortcomings. Specifically these are considering the DG extension planning while determining transmission grid extension needs and a severe incorporation of batteries as one flexibility option. Separated grid extension planning of the transmission and distribution grid level [2, 3] may overestimate overall grid extension needs in terms of capacity and costs. The research project open_eGo [4] tackles this problem by interlinking grid extension planning and operation of transmission and
distribution systems. Our objective is to unveil untapped cost reduction potential of combined planning across the transmission and distribution grid levels. To accomplish this, our method considers the requirements of the transmission system in planning distribution grids. The work described in this paper is complemented by other work of Müller et al. on the eGo transmission grid model [5].

Our research requires access to grid topology data and assets such as transformers. Whereas grid data at the transmission level are available through Open Street Map (OSM) [6], publicly accessible data of DGs are missing. Generally, distribution system operators (DSOs) do not publish infrastructure data. This hinders research on grid integration of RES. How might this problem be addressed? The Conseil International des Grands Réseaux Électriques (CIGRE) provides sample medium-voltage (MV) grid data having typical characteristics of MV grids in Europe [7]. Operators do publish some structural characteristics of grids in order to comply with German legislation [8, 9]. One study analyzing DGs used real grid data provided by operators to partners in a specific project [2]. To obtain a variety of distinct MV and low-voltage (LV) grid data, Monte-Carlo variations of structural characteristics have been used [3]. Rui et al. created synthetic MV test grids on the basis of two-dimensional combinations of load density [10]. Some define reference grids which approximate a specific set of real-world grids [11].

So far, however, there are no freely available tools or methods for modelling the full variety of DGs found in Germany while taking into account local characteristics such as loads and generators. We wanted to develop a set of methods that generate a representative dataset of DGs in Germany using open data. The methods we developed produce synthetic MV grids for Germany. We use high-resolution spatial data of load and generation in order to approximate the grid topology. The approximation of MV grid topology is achieved using a routing technique [12, 13]. The methods, model parameters, and assumptions used in this work were developed in close collaboration with grid planning experts from the German DSO LVN. Our paper focuses on modelling MV grid topology; the construction of LV grids will be treated in a future publication. Low-voltage grids are represented by aggregated load and generation at MV-LV substations. The implementation uses open data and is released under an open-source licence.

2. Fundamental data basis

Our objective is to synthesize status quo MV grid topologies. For this reason, we use an approach to reflect their historic development. Historically, DGs were created with the goal to distribute power from large central power plants to customers. Thus, the peak load was the crucial design parameter [14]. However, as capacity of RES increases, the focus on peak demand for DG planning will become less important [15]. In order to reflect grid topology that was originally built decades ago, we focus on peak demand as the main parameter. The impact of RES generation units on grids will be subsequently considered.

To synthesize a MV grid topology based on the peak load, a high-resolution spatial representation of the electricity demand is required. This is provided by Hülk et al. [16] and is available on the OpenEnergy Platform (OEP) [17], which was developed within the open_eGo research project. The data model of Hülk et al. (see Fig. 1) includes, among other data, the so-called medium-voltage grid districts (MVGDs) which are supply areas of MV grids named MVGDs. These typically contain multiple load areas (LAs), which are defined as geographic clusters where electricity is consumed. Sector-specific electricity demand are associated to these LAs. The LAs are identified by a GIS analysis of high-resolution spatial data which contain information about physical properties, land use, energy, and demography.

Within each LA, we define locations of MV-LV substations using an equidistant grid of points with an interval of 360 m. Each of these substations has a supply area called low-voltage grid district (LVGD). The LVGDs are defined by a Voronoi partition of a LA using the locations of the MV-LV substations. The result is a hierarchical representation of real supply structures.
Figure 2 perfectly visualizes this structure of a MVGD with its areas and substations.

Figure 1: Simplified scheme of voltage levels, substations, and areas. Figure adapted from [16].

Annual electricity consumption is assigned to LAs for the following sectors: residential, retail, industrial, and agricultural [5]. Using standard load profiles for Germany [18], we obtain the peak load for each of these areas. The standard load profiles are supplemented by a profile describing industrial electricity demand assuming discrete load levels (weekday 6am-10pm: 0.8, other 0.6). It is scaled by actual annual consumption.

Data on conventional and renewable generators are publicly available [19, 20]. We use preprocessed versions of these datasets from [21, 22]. Some of them contain implausible information on grid level, therefore generators are allocated to grid levels according to Table 1 [16]. A realistic DG model requires power plants with precise information about their voltage levels and geographic locations. Conventional power plants are provided with exact locations, whereas RES data have a low spatial accuracy. Due to privacy concerns, its spatial resolution is reduced by the original data provider. This leads to errors of up to several kilometres. In order to obtain realistic locations, we allocate RES capacity to certain areas. The targeted allocation areas are defined for each type and subtype of each technology as presented in Table 2. This is achieved by using different technology-specific distribution methods as described below.

Biomass and gas power plants are relocated to agricultural areas of MVGDs presuming a spatial proximity to the origin of their fuel. The same areas are used for roof-mounted solar plants of voltage levels 4 and 5. We assume these are usually located on farm buildings that typically provide suitable sites for medium-size solar plants, whereas ground-mounted solar generators are distributed in the MVGDs to random locations. The data contain wind energy converters (WECs) of voltage levels 4 and 5 [20]. Those of voltage level 4 are expected to be wind farms or clusters of single WECs. They are relocated to wind potential areas (WPAs) provided by [23]. WPAs are defined as sites that are not classified as unsuitable for use of WECs (i.e. settlement areas, national parks, and infrastructure) and that are sufficiently distant from existing EOL installations.
Table 1: Allocation of generators to voltage level according to their nominal capacity, sum of allocated capacity for Germany (adapted from [16]).

| Voltage level | Nominal capacity | Allocation target | Cumulative cap. (renewable) | Cumulative cap. (conv.) |
|---------------|-----------------|-------------------|-----------------------------|-------------------------|
| 4 (HV-MV)    | 4.5 - 17.5 MW   | Transition point  | 9.73 GW                     | 2.48 GW                 |
| 5 (MV)       | 0.3 - 4.5 MW    | MV grid           | 34.89 GW                    | 0.05 GW                 |
| 6 (MV-LV)    | 0.1 - 0.3 MW    | Distribution subst.| 5.18 GW                     | 0 GW                    |
| 7 (LV)       | ≤ 0.1 MW        | LV grid           | 21.33 GW                    | 0 GW                    |

from settlements in order to be compliant with distance limits. The reallocation takes place successively in descending order in terms of nominal capacity and size of the WPA. Voltage levels 5 and 6 are dominated by single scattered WECs which are distributed throughout the WPAs. To avoid local concentrations, WPAs are represented by a 500 x 500 m$^2$ grid of points that ensures a minimum distance of 500 m between two WECs, which is a common value for current WECs [24]. Hydroelectric and geothermal power plants retain their original location. Finally, solar and wind energy plants of voltage level 7 are assigned to LVGDs. These are assumed to be installed on roofs of buildings (solar plants) or nearby buildings (WEC). The distance between buildings varies considerably, several analyses show a typical range between 9 m and 102 m [25, 26, 27]. We assume an average distance of 50 m. Therefore, we derive potential locations by applying a 50 x 50 m grid of points on each LVGD.

The processed data form a high-resolution spatial model of load and generation in Germany which is used to determine distribution grids as described below.

3. Synthetic medium-voltage grids
The structure of synthetic MV grids resulting from the application of our method depends on the choice of input data and the assumptions, which we will review below.

3.1. Types of medium-voltage grid districts and load areas
For historical reasons and due to local conditions, MV grids have certain topologies. The load and the size of a supply area were crucial parameters of grid design [28]. Meshed grids are mainly used in urban areas with high load density, whereas radial and ring structures are typically used in regions of low load density. Since 84.3% of German MV grids have a ring topology [3], we assume this type of topology for all MV grids analysed in our paper. This topology consists of a main route and branching stubs and provides a reasonable trade-off between costs and reliability of supply [12].

First, we categorise MVGDs as urban or rural supply areas. Urban areas are usually equipped with underground cables at a voltage of 10 kV, whereas grids in rural areas mostly constitute of overhead lines at a rated voltage of 20 kV [28, 12]. We use the maximum distance from the HV-MV substation to the LAs’ centres and a value of 1 kV/km line length [28]. To distinguish between these two area types, we define a threshold of 15 km. Consequently, MVGDs with a maximum distance of \( \geq 15 \) km are treated as rural (20 kV), whereas MVGDs with \(< 15\) km are treated as urban areas (10 kV).

In accordance with these prerequisites, the LAs (introduced in Section 2) are categorised according to their peak load. We define three categories of LAs (see Figure 3):

1. Aggregated LAs represent regions with high cumulative peak load. Future grid problems
Table 2: Spatial distribution of generators according to type and sub-type [20] throughout distribution supply area.

| Voltage level | Generation type          | Generation subtype       | Allocation area                  | Cumulative cap. [MW] |
|---------------|--------------------------|--------------------------|----------------------------------|----------------------|
| 4 (HV-MV)     | biomass, gas             | all                      | agricultural area                 | 943                  |
|               | geothermal               | all                      | -                                 | 27                   |
|               | hydro                    | all                      | -                                 | 235                  |
|               | solar                    | roof-mounted             | agricultural area                 | 156                  |
|               | solar                    | ground-mounted, none     | randomly in MVGD                  | 3923                 |
|               | wind                     | all                      | WPA (wind farms)                  | 4451                 |
| 5 (MV)        | biomass, gas             | all                      | agricultural area                 | 4835                 |
|               | geothermal               | all                      | -                                 | 12                   |
|               | hydro                    | all                      | -                                 | 957                  |
|               | solar                    | roof-mounted             | agricultural area                 | 2785                 |
|               | solar                    | ground-mounted, none     | randomly in MVGD                  | 5893                 |
|               | wind                     | all                      | WPA                               | 20408                |
| 6 (MV-LV)     | biomass, gas             | all                      | agricultural area                 | 1029                 |
|               | hydro                    | all                      | -                                 | 162                  |
|               | solar                    | all                      | randomly in LVGDs                 | 3942                 |
|               | wind                     | all                      | WPA                               | 42                   |
| 7 (LV)        | biomass, gas             | all                      | agricultural area                 | 128                  |
|               | hydro                    | all                      | -                                 | 164                  |
|               | solar                    | all                      | randomly in LVGDs                 | 21011                |
|               | wind                     | all                      | randomly in LVGDs                 | 24                   |

involve line congestion and violation of the maximum permissible voltage band produced by generators. They will rarely occur in urban areas because these areas have fewer available RES sites and comparatively strong electrical grids to integrate them. Therefore, regions of high peak load are excluded from grid reinforcement measures and modelled using aggregated load and generation capacities. The threshold is defined by the current carrying capacity of the line used to connect Regular LAs. Aggregated LAs are directly connected to the MV bus bar of the HV-MV substation.

(2) Regular LAs are connected to MV rings and thus determine the rings’ topology. As the literature does not distinguish between LAs that are part of the main ring and those connected via stubs, we assume a minimum peak load of 100 kW for LAs being considered in the main route of a ring (this assumption is made based on personal communication with the grid planning department of a DSO [29]).

(3) Satellite LAs incorporate regions with low electricity peak demand (≤100 kVA) and lower requirements in terms of reliability of supply. These are connected to rings via branch lines. LAs with a peak load of less than 1 kVA are assumed to be the result of errors in data processing and therefore omitted.

3.2. Technical constraints and scenarios
When planning and operating DGs, DSOs have to comply with the legal framework: The system must meet minimum technical requirements. In Germany, MV grids must be able to withstand
the outage of any single component e.g. a cable or transformer ((n-1)-criterion). Redundancy is realised using switch disconnectors in MV-LV substations to isolate parts of the grid in case of a failure. HV-MV substations meet this requirement by using at least two parallel transformers. Common practice of DSOs is to evaluate two worst-case scenarios in order to test the stability of grids [30]: heavy load flow (annual peak load, min. generation) and reverse power flow (max. generation, min. load). The most important aspects of grid stability in this context are thermal ampacity of lines and transformers, and the tolerable voltage range. The (n-1)-criterion applies to loads only. Generators connected to the grid are not (n-1)-secure. To ensure (n-1)-secure supply, transformers and lines need to have reserve capacity. Therefore, different load factors for equipment are used in power flow analysis (see Table 3 [2]). The (n-1)-criterion does not apply to LV networks.

| Equipment               | Load factor (LF) heavy load flow | Load factor reverse power flow |
|-------------------------|----------------------------------|-------------------------------|
| HV-MV transformer       | max. 60 %                        | max. 100 %                    |
| MV cable                | max. 60 %                        | max. 100 %                    |
| MV-LV transformer       | max. 100 %                       | max. 100 %                    |
| LV cable/overhead line  | max. 100 %                       | max. 100 %                    |

To account for temporal variability of load and generation, typically the coincidence factor
is used. It reflects the coincidence of a group of loads and the availability of generation of a
group of generators [2]. As our method assumes the minimum generation/load with zero and
the maximum generation/load with 1, these factors have no effect and are neglected.

Furthermore, constraints on voltage stability apply. The EN 50160 standard defines the
acceptable voltage range that must be guaranteed for each customer connected to the grid [31].
Grid codes define rules for connection of RES in MV grids [18] and LV grids [32]. To account for
reactive power, we assume a power factor $\cos \varphi$ of 0.9 [12] for all loads and 1.0 for generators.

Our grids are equipped with standard cable types, overhead lines, and transformers according
to [33, 28, 12] (see Table A1 in the Appendix). MV-LV substations are equipped with ideal
transformers neglecting losses.

### 3.3. Grid topology

As mentioned above, an open ring structure of the MV grids was chosen as the base topology.
The LAs from Section 3.1 are supplied by an indefinite number of rings, which are fed by a
single HV-MV substation. The identification of MV rings is based on a method from operations
research – the capacitated vehicle routing problem (CVRP) [34]. In the CVRP, customers are
supplied by vehicles with limited capacity that start their route from a central depot. In an
electrical grid, the HV-MV substation serves as depot while customers are represented by the
centers of load areas. The center of an LA is calculated as the centroid or as a point on the
surface if the centroid is located outside of the area. The objective is to minimise the cumulative
route length. In our case, material and installation of lines are the main cost factors [35].
This is based on fundamental work by Tao [12] who applied CVRP to grid planning. There is a variety
of approaches to solve CVRPs including exact, heuristic, and metaheuristic techniques [36].
We employ a two-stage metaheuristics. The initial route construction is done using the parallel
savings heuristic of Clarke and Wright [37]. It is subsequently improved by a local search using
graph operators as described in Section 3.3.2. Figure 4 presents steps of MV grid generation
at a glance. The improved topology of the MV grid’s main route is followed by extending the
topology with additional dispersed LAs and generators. In the last two steps the resulting grid
model is tested for grid stability and reinforced if required.

![Figure 4: Steps of MV grid generation.](image)

In reality, routes of underground cables and overhead lines follow geographical characteristics
such as transport infrastructure [38]. Since the approach does not involve these constraints, the
estimated route lengths tend to be underestimated. To account for differences in route length,
a detour factor is used. Typically this value ranges from 1.1 to 1.5 [12]. We assume a detour
factor of 1.3.

#### 3.3.1. Identification of base topology

The main route of a MV grid is identified by formulating a CVRP while considering technical
constraints (cf. Section 3.2). In order to find the initial solution of the CVRP the maximum
rated apparent power $S_{\text{line, max, th}}$ of lines and cables in each MVD must be defined. This
depends primarily on the cumulative peak load $S_{MVD, max}$ of all regular LAs (cf. Section 3.1).
Therefore, we assume the typical number of outgoing lines/half-rings \( n_{\text{lines}} = 8 \) for each MVGD [3]. The line type is selected such that

\[
S_{\text{line,max,th}} \geq \frac{S_{\text{MVGD,max}} \cdot LF}{n_{\text{lines}}}
\]

(1)

with \( LF \) referring to the load factor in the heavy load flow case. In doing so, we suppose an equally distributed load for each of the half-rings as reflected by Equation (1). As line and cable equipment has discrete rated power \( S_{\text{line,max,th}} \), we always choose the type of the next larger value (see Table A1 in the Appendix). This identified line type is used as a default for all lines in the particular MVGD. The HV-MV substation is equipped with two transformers each having a nominal apparent power greater than \( S_{\text{MVGD,max}} \cdot LF \) (as small as possible). Their operating voltage at the MV bus bar is set to nominal voltage.

Figure 5: Example for savings heuristic: (a) initial solution, (b,c) iterations, (d) savings solution. Figure adapted from [12].

Using these technical guidelines, the savings heuristic can be applied to CVRP. The grid structure obtained employing this method is described by a graph structure. Lines are represented by edges, while loads and generators are nodes in the graph. In the initial solution, each load area is located on a separate route which consists of two edges, see the example in Figure 5 (a). The next step searches for possible savings by combining two routes with one-way distances i.e. \( d_{0,i} \) and \( d_{j,0} \). Equation (2) shows the saving \( s_{i,j} \) for one step ((b) of Figure 5).

\[
s_{i,j} = (2 \cdot d_{0,i} + 2 \cdot d_{j,0}) - (d_{0,i} + d_{i,j} + d_{j,0})
\]

\[= d_{0,i} + d_{0,j} - d_{i,j}\]

(2)

The savings are calculated for all combinations of two routes and subsequently sorted in descending order by the amount of savings. These savings are successively applied (b,c) until there are no further improvements left (d).

The feasibility of a move is determined by restrictions on current carrying capacity and voltage stability. They are continuously verified in each iteration (cf. Section 3.2). Therefore, we use two modes of operation (normal and faulty) and adjust thresholds of tolerable current and voltage:

1. Under normal operating conditions, MV rings are operated as isolated half-rings [28]. These are usually split by a switch disconnector at the location creating minimal power flows in closed conditions [38]. Subsequently, current carrying capacity and voltage stability are checked for each of the two half-rings as depicted in Figure 6 (a). A maximum line loading of 60% [2] and a maximum voltage drop of 5% [15] from the secondary side of the HV-MV substation to the primary side of the MV-LV substations are accepted.
In case of a failure, the faulty segment is isolated by switch disconnectors, while the remaining part of the ring is fed by one side (b). In the worst case, the faulty segment is the closest to the substation. For this purpose, we allow a maximum line loading of 100% of its current rating [2] and a tolerable voltage drop of 10% [39].

Figure 6: Modes of operation: (a) normal, (b) failure in one half-ring. (For visualisation purposes, the switch disconnector is located on line).

Due to the high number of route alterations and computational cost of power flow calculations, simplified methods for detecting line congestion and voltage violations are required. Current rating violations can be detected with small computational effort using the cumulative peak load of a ring. The total voltage drop $\Delta U$, however, needs to be calculated for every node considering active and reactive power. In terms of the longitudinal voltage, this can be done by using Equation (3) assuming the transverse voltage drop to be negligible [18, 40].

$$\Delta U = \sum_{i=1}^{n} \Delta U_i = \sum_{i=1}^{n} \frac{(R_k \cdot P_i + X_k \cdot Q_i)}{U_N},$$

(3)

$R_k$ being the total resistance and $X_k$ being the total reactance of lines from node $i = \{1, ..., n\}$ to the MV-LV substation. $U_N$ equals the nominal voltage of the grid.

Moreover, we use additional criteria to decide on the feasibility of a move:

- The maximum number of substations per ring is 20 [28].
- The maximum length of a full ring is 60 km [38].

Following this method, computable and technically stable MV rings are generated. However, the savings heuristic produces solutions which are not necessarily optimal [34].

3.3.2. Improvement of initial topology

The identified grid topology is iteratively improved by exploring neighbouring solutions using a local search heuristic. We apply so-called graph operators to reduce the cumulative length of all rings in a MVGD. These include intra-route and inter-route techniques [41]. Intra-route operators apply modifications on a single route whereas inter-route operators involve segments of two routes.

The Or-Opt operator (intra-route) relocates all possible chains of three to one consecutive nodes within a route as illustrated in Figure 7 (a). It starts with three nodes followed by chains
with two nodes and finally relocates single nodes. The relocate operator (inter-route) moves a single node from one route to another (b). The exchange heuristic swaps two nodes of different routes (c). The three methods are applied consecutively in the order as mentioned. During execution of every method, the best of all possible moves is performed starting over again until there are no feasible improvements. The acceptance criterion given by the technical constraints (cf. Section 3.2) is tested for every operation on the graph.

The modifications can reduce the cumulative ring length in a MVGD. The potential for reduction by graph operators depends heavily on the quality of the initial savings solution [36]. It may happen that initial solutions are very close to a (local) optimum which cannot be improved by graph operators.

3.3.3. Extending the base topology
The initial MV grid topology omits connection of satellite LAs, generation units, and MV-LV substations in the LAs. These are connected to the grid after identification of the MV grid main route. Therefore, different grid connection principles are applied in a particular order:

1. Nodes close to an existing route of the grid (≤ 100 m) are included by modifying the route’s course slightly, making the node part of the route [29] (Figure 8 (1)). This applies not only to ring routes’ lines but also to branch lines.

2. Remaining nodes are connected to the grid at the closest possible connection point that is found using geographic information system (GIS) methods starting with a search radius of 2000 m (Figure 8 (2)). If no points are located inside this circular area, the radius is gradually expanded by 1000 m increments.

3. If the first two connection options fail due to technical constraints, nodes are connected directly to the main route via separate branch lines using the standard line type (cf. Section 3.3.1). See (Figure 8 (3)).

First, satellite LAs run through the grid connection procedure. Second, MV-LV substations are connected to the grid. Then, aggregated LAs that are not modelled in detail and therefore directly connected to the bus bar of the HV-MV substation follow, using the line type of largest capacity. Finally, generation units are connected to the grid via branch lines (Table 1).

Grid connection of satellite LAs is affected by technical boundary conditions, such as maximum length of and maximum cumulative peak load connected to a branch line. We define a maximum length of branch lines of 2 km [13]. Furthermore, the cumulative peak load of a branch line must not exceed 1 MVA. This is the maximum power of a typical emergency backup generator used by DSOs to supply branch lines in case of failure within the MV ring [29, 38]. In order to meet the latter condition, the cumulative peak load of satellite LAs must be considered. Therefore, we build groups of satellite LAs when connecting these to the grid. As
grid topology depends on the order of LAs connected to the grid, these are sorted alphabetically to retain a reproducible result. Load areas that cannot be connected to branch lines due to the 1 MVA constraint on cumulative peak load are connected individually to the main route of the MV grid.

Once LAs are connected to the centroid of the area, MV-LV substations inside the LAs are considered, as well as their surrounding supply areas (the LVGDs). The topology of MV grids is refined by connecting these MV-LV substations by the same method applied for connecting satellite LAs. In this step, technical constraints such as maximum length and maximum cumulative peak load connected by one branch line are omitted. In addition to the connection of MV-LV substations, overhead lines within LAs are replaced by underground cables. Therefore, we choose a cable type with at least the same current carrying capacity as the replaced overhead line.

As described in Section 3.3.1, a ring’s switch disconnector is located on the line where power flow is minimal in closed condition. Due to the extension of the grid, additional loads are connected to the rings. Therefore, the switch disconnectors are subsequently relocated to fulfill this requirement.

The grid connection of aggregated LAs takes place at the bus bar of HV-MV substations. These areas of large consumption and dense population are excluded from detailed analyses in the open eGo project, because their grids are assumed to be sufficiently equipped to carry the feed-in by RES. Such an aggregated LA is connected by the largest type of cable considered in our paper (see Table A1 in the Appendix).

The last step in extending the base topology is to connect generation units to the grid. These units are added similarly and in compliance with German grid connection codes [18] as described in Section 3.2. The method of grid connection as applied for connecting loads is adapted; technical constraints (maximum branch line length and maximum cumulative capacity) are not considered here.

The grid with extended topology results in a MV grid comprising a number of half-rings which have several branch lines that connect additional loads and generators.

3.4. Grid stability and reinforcement
The base topology of MV grids was tested for current and voltage limit violations (see Section 3.3.1). This does not include branch lines that were added afterwards in order to connect remaining LAs, MV-LV substations and generators. The extension of the base topology by these nodes may threaten grid stability. First, line congestion and overvoltages may exist.
in these branch lines as those are equipped with the MVGD’s standard cable/line type without verifying stable operation of the grid. Second, satellite LAs, MV-LV substations and generators add additional load and generation capacities to the grid. These lead to different power flows.

These potential grid stability problems must be identified. Line congestion arises when actual current exceeds rated current of a line/cable. Voltage violations occur when voltage at a node exceeds the tolerable voltage. In general, a DSO must guarantee a voltage range of ±10% compared to nominal voltage [31]. To allow for separate tests in MV and LV level, this range is usually split into two smaller ranges by DSOs. In MV grids, the connection of RES generators can be approved by ensuring a voltage deviation of at maximum ±2% relative to voltage levels without RES connected to the grid [18]. We use the open-source tool PyPSA [42] for power flow analysis to approve grid stability or identify stability problems.

These problems are subsequently eliminated by grid reinforcement to achieve a computable and stable grid model of the status quo. This can be achieved by using several different methods [30]. A hands-on approach that reflects state-of-the-art procedure of DSOs is described in the DENA Verteilnetzstudie [2, 43]. It includes straightforward measures of modifying grid topology and equipment type, both current and voltage-induced grid stability problems can be resolved. Nevertheless, this approach is neither applicable to ring grids with branch lines nor if multiple problems occur at once. Therefore, we use different strategies for grid extension inspired by existing approaches. Firstly, line congestion is resolved by installing a line/cable with appropriate current carrying capacity. Secondly, the resulting grid is tested again for remaining voltage limit violations. These are resolved by replacing affected line segments between the affected location and the HV-MV substation by equipment of the next larger current carrying capacity. Grid segments that are reinforced in case of a voltage violation are on the shortest route between that affected node and the HV-MV substation. If more than one node is affected, these routes are likely to share segments. These segments are reinforced only once. This procedure applies until all voltage limit violations are resolved.

4. Results & discussion
4.1. Grid topology example
In this work, we show that MV distribution grids can be constructed by applying heuristics to solve CVRPs. In this section, we apply all steps described in the previous section to a sample MVGD. We use a rural grid district with a cumulative peak load of 30.1 MVA and a mean load density of 0.16 MVA/km². The maximum distance from the HV-MV substation to the LAs’ centres is 19 km. Accordingly, it is equipped with 20 kV overhead lines (cf. Section 3.1).

Computing the solution of the savings heuristic in this rural grid district results in five rings with (1) and (4) having suboptimal routes with crossings (see Figure 9). In addition, there is one aggregated LA, which is connected to the HV-MV substation.

If we use the local search metaheuristics, the solution improves. It has fewer crossings and shorter routes (see Figure 10). The line crossings are removed by the Or-Opt intra-route operator. Due to these alterations, the switch disconnector in ring (1) is relocated to the position of minimal power flow in closed condition (cf. Section 3.3.1). In this example, the inter-route operators do not relocate or exchange nodes between rings.

This network is extended by satellite LAs, MV-LV substations and generators (see Figure 11). Using the connection principles of Section 3.3.3, the substations are connected forming an individual grid within each LA. The present MV generators of voltage level 5 (Table 1) are linked to the MV grid while generators of voltage levels 6 and 7 are aggregated inside LVGDs according to their particular locations.

To detect possible line congestion and violations of voltage band, the grid is validated using

1 Results were found using DINGO v0.1.2 [44]. Data is accessible via https://doi.org/10.5281/zenodo.795210
MV grid district (MVGD)
HV-MV substation (Transition point)
Satellite load area
Regular load area
Aggregated load area
LA centre
MV branch (line/cable)
Switch disconnector

Figure 9: MV rings produced by savings heuristic.

Figure 10: Improved MV rings using local search metaheuristics.

Figure 11: Extended topology with satellite load areas, MV-LV substations and generators.

power flow calculations for both the heavy load flow and the reverse power flow scenario. Figure
12 shows the results for reverse power flow. In this scenario, the max. cumulative generation is 2.62 MVA of voltage level 5 and 15.47 MVA of voltage levels 6 and 7 (demand are set to 0). The voltages induced by generators exceed the nominal voltage in rings (1) and (2) by up to 3.7 % and hence violate the tolerable voltage band of ±2 % (cf. Section 3.4). As expected, the overvoltage increases with distance to the HV-MV substation. In contrast, there is no line congestion.

![Node voltage and line load](image)

*Figure 12: Relative node voltage and line load of extended topology for reverse power flow (voltage at HV-MV substation is set to nominal voltage).*

After applying reinforcement measures to existing lines according to Section 3.4, all overvoltages were resolved. As depicted in Figure 13, the maximum overvoltage does not exceed 2 %.

What modifications were made during the reinforcement? The non-reinforced MV grid is equipped with two types of overhead lines and one type of underground cable (Figure 14), the latter being installed within LAs (cf. Section 3.3.3). Switch disconnectors are in an open state and consequently, each half-ring is connected separately to the HV-MV substation. Hence, replacement of line segments is done individually for each half-ring. There is no need for reinforcements in rings (3), (4) and (5) (Figure 15). However, rings (1) and (2) show substantial modifications. This corresponds to the significant violation of the voltage tolerance caused by additional RES. All critical nodes feed into two half-rings, which are therefore equipped with cables of 150 mm$^2$ (ring (1)) and 240 mm$^2$ (ring (2)). Finally, in some segments inside LAs, cables of 240 and 300 mm$^2$ are used to eliminate overvoltages. This can be traced back to the different types initially used in LAs as described before. Predictably, the line load was decreased due to the line extension.
Figure 13: Relative node voltage and line load of extended topology after reinforcement measures.

Figure 14: Relative node voltage and line types of extended topology.
4.2. Statistical evaluation of MV grids

In order to validate our method, we compared the data of the generated synthetic medium-voltage grids to real network data of Germany. Our data comprises 3608 MVGDs in total. We were unable to generate a grid topology for 239 districts (\(\approx 6.6\%\)) since half of them (119 in total) contain only one or several aggregated LAs which are directly connected to the HV-MV busbar. These grid districts are predominantly located in urban areas. The remaining 120 MVGDs fail for other reasons. The result of the comparison is shown in Table 4. In the following the presented parameters are discussed in detail.

Table 4: Comparison of modelled data (some values scaled up for 3,608 MVGDs) with real data (estimates according to [45]).

| Equipment                      | Model value \(m\) | Real value \(r\) | Deviation \(|(r - m)/r|\) |
|-------------------------------|-------------------|-----------------|-----------------|
| HV-MV transformers            | 8,276             | 7,500           | 10.3 \%         |
| MV-LV transformers            | 514,333           | 560,000         | 8.2 \%          |
| MV cables & overhead lines    | 495,499 km        | 507,000 km      | 2.3 \%          |

**HV-MV transformers**  Because HV-MV substations are usually equipped with at least two transformers to meet the (n-1)-criterion (cf. Section 3.2), our system has 7,728 HV-MV transformers for 3,369 MVGDs that are successfully treated by DINGO. In order to make this number comparable to the reference value of 7,500 found in the literature [45], we assume the same average number of transformers in substations for missing MVGDs. Thus, in total the number of HV-MV transformers for the 3,608 MVGDs adds up to 8,276.
The deviation of 10.3% can probably be attributed to several reasons. First, the number of HV-MV substations that was determined manually by Open Street Map users might be inaccurate. Second, the number of transformers included in a substation is calculated using peak demand and generation capacity of the MVGD. Overestimating these numbers directly affects the number of transformers.

**MV-LV transformers** Based on an equidistant grid of 360 x 360 m² describing the locations of MV-LV substations in LAs, we identified 514,333 MV-LV substations for Germany. We assume that this number also corresponds with the number of MV-LV transformers, since every substation is usually equipped with one MV-LV transformer. The number of identified transformers deviates from values found in the literature by about 8.2%.

The supply area of 360 x 360 m² for each substation is, of course, only an average estimation and is based on the experience of the distribution system operator LVN [29]. However, the mean distance between two substations in rural areas lies within the range of 500 and 2,000 metres and in urban areas between 100 and 400 metres [38]. Hence, the number of substations is overestimated in rural areas and underestimated in urban areas. It should be possible to achieve a more accurate estimation by differentiating between urban and rural areas when modelling the installation of MV-LV substations. Furthermore, we may underestimate the number of transformers by assuming that only one transformer is installed in each substation. Sometimes MV-LV substations are equipped with more than one transformer [46].

**MV cables and overhead lines** Only 464,180 (of in total 514,333) MV-LV substations are considered in the resulting grid topology. The remaining 50,153 MV-LV substations are located in aggregated load areas (that are of little interest for future studies), which are directly connected to the HV-MV substations by using a virtual substation in the centre of the load area (see Figure 9).

Accordingly, only 477,444 km of cables and overhead lines were laid in the model. This is significantly less than the reference value provided in Table 4. However, there are additional lines supplying the 50,153 substations in *aggregated* LAs which are not included in our model. Since each MV-LV substation supplies an area of 360 x 360 m², we assume a line length of 360 metres per substation. This results in a total line length of 495,499 km (≈ (50,153 · 0.36 km) + 477,444 km). This theoretical total line length exceeds values found in the literature by 2.3% (cf. Table 4).

### 4.3. Limitations

The method presented in this paper attempts to mimic characteristics of historic development of MV grids. It is designed to reflect local characteristics by using spatially highly disaggregated data. However, some local characteristics which have an impact on a grid’s topology are disregarded, such as natural boundaries (e.g. rivers, forests, etc.) as well as transport infrastructure. Furthermore, the large-scale spatial approach cannot consider particularities of solitary cases that often influence grid planning decisions.

The strategy of local search produces solutions based on sequential improvements which put restrictions on the solution space [36]. Applying the local search strategies in different orders may result in a different optimum. To address this, additional heuristics can be employed, such as large neighbourhood search and guided local search [12]. The first searches in a larger neighbourhood and is therefore less susceptible to be caught in a local optimum. Guided local search controls the local search algorithm using penalties in order to stimulate the local search to escape local optima.

While calculating the base topology of the MV grid, *regular* LAs define the main route of a ring. The exclusion of smaller loads does not consider if those agglomerate in a certain area.
However, current grid planning principles dictate that agglomerated loads forming a larger load might be treated as part of the main ring. This leads to a tendency for individually connected satellite LAs.

The topology of the grid and further characteristics are highly dependent on a set of assumptions. The most influential parameters are: the topology itself (we only account for ring grids), threshold peak load of a satellite LA, tolerable length and cumulative branch line peak load, and re-routing distance threshold (cf. Figure 8 (1)).

Another limitation of the identified MV grids is related to the quality of input data. The MVGDs that are used as a fundamental dataset to describe the area supplied by a MV grid are based on a combination of municipal boundaries and Voronoi partition and do not necessarily correspond to the actual shapes of supply areas. Furthermore, the geographical location of RES generators is inaccurate.

It should be noted that the grid topology is reproducible when the same input datasets are used. All methods that use random values are located in the data processing which precedes our tool.

Our method currently does not compute a representation of LV grids. Future publications will cover this topic in detail. Furthermore, sensitivity analyses on crucial parameters as mentioned above will be conducted.

4.4. Comparison with other approaches
The method presented in this paper produces a set of plausible MV grids in Germany. The most distinctive advantages of this dataset are the broad coverage and availability of data. The dataset covers almost all MVGDs in Germany and is publicly accessible through the OEP [17]. Furthermore, due to stringent open-source licensing, the research community can adapt and improve the method. The availability of grid data will allow third parties to evaluate results of studies that use these data. Compared to reference grid data [7, 11, 10], a large range of different grids can be created with the presented methods. Variations of grid topology and equipment properties introduced by Monte-Carlo variations [3] provide a larger variety of grid data. This allows for studies considering various scenarios in DGs returning results of increased robustness. Nevertheless, grid data obtainable from the approach presented in our paper go a step further by considering local characteristics of demand and supply for each grid.

5. Conclusions
To optimise the future electrical energy supply system while considering the interaction of all voltage levels, a holistic approach is required. However, an open dataset for performing this optimisation does not exist. Therefore, a core task of the research project open_eGo, funded by the German Federal Ministry for Economic Affairs and Energy, is to close this gap.

The aim of the approach presented in this paper is to model the German status quo distribution system as realistically as possible. While the electricity networks of the high and extra high voltage levels generally run above ground and therefore can be modelled very well in Open Street Map using aerial photographs, the modelling of the distribution grid is much more difficult. One reason for this is the fact that the network components at these voltage levels usually are not visible, since underground cables are used and the substations are often integrated into buildings. Furthermore, at these voltage levels a substantially greater number of network components is installed than at higher voltage levels. The challenge is to simplify the modelling of distribution networks, which we address by breaking the problem down, beginning with the medium-voltage networks. A further publication relating to the modelling of low-voltage networks is planned.

All medium-voltage grids are generated for given supply areas using local load and generation data [16]. To enhance our model (results / assumptions) we were able to work with a distribution
system operator from southern Germany and use their knowledge about planning principles.

The German electricity networks were designed in the post-war period to cover the energy demand of consumers. Since renewable energy plants have been installed starting in the 1990s, the requirements on the grids’ capacity have changed. To account for this development, we choose a two-step approach. Accordingly, in the first step of the modelling process the network topology is exclusively based on the load situation. To create the networks a CVRP is solved, which has a minimum circuit length as target function. In the second step, additional branches with loads as well as renewable energy power plants are connected to the electricity grids resulting from step one. In order to ensure that the generated networks are as realistic and as accurate as possible, typical parameters of medium-voltage components were used. In addition, the stability of these networks was ensured by the use of power flow calculations.

Using this method, the entire medium-voltage level in Germany was modelled. In total 3608 MV networks were created. In terms of the number of transformers and total cable length, the resulting networks show a deviation of <10% from real network data. It can be concluded that the method presented in this paper allows to create a cost-optimised electrical distribution system for Germany.

Appendix

Table A1: Types of cables and overhead lines considered. Lines and cables of a diameter greater than 300 mm$^2$ refer to parallel line/cable installation of smaller types.

| Type               | $U_n$ in kV | $I_{max,th}$ in A | $R$ in Ω/km | $L$ in mH/km | $C$ in μF/km |
|--------------------|-------------|-------------------|-------------|--------------|--------------|
| Cables             |             |                   |             |              |              |
| NA2XS2Y 3x1x185    | 10          | 357               | 0.164       | 0.38         | 0.41         |
| NA2XS2Y 3x1x240    | 10          | 417               | 0.125       | 0.36         | 0.47         |
| NA2XS2Y 3x1x300    | 10          | 466               | 0.1         | 0.35         | 0.495        |
| NA2XS2Y 3x1x400    | 10          | 535               | 0.078       | 0.34         | 0.57         |
| NA2XS2Y 3x1x500    | 10          | 609               | 0.061       | 0.32         | 0.63         |
| NA2XS2Y 3x1x150    | 20          | 319               | 0.206       | 0.4011       | 0.24         |
| NA2XS2Y 3x1x240    | 20          | 417               | 0.13        | 0.3597       | 0.304        |
| NA2XS(FL)2Y 3x1x300| 20          | 476               | 0.1         | 0.37         | 0.25         |
| NA2XS(FL)2Y 3x1x400| 20          | 525               | 0.078       | 0.36         | 0.27         |
| NA2XS(FL)2Y 3x1x500| 20          | 598               | 0.06        | 0.34         | 0.3          |
| Overhead lines     |             |                   |             |              |              |
| 48-AL1/8-ST1A      | 10          | 210               | 0.35        | 1.11         | 0.0104       |
| 94-AL1/15-ST1A     | 10          | 350               | 0.33        | 1.05         | 0.0112       |
| 122-AL1/20-ST1A    | 10          | 410               | 0.31        | 0.99         | 0.0115       |
| 48-AL1/8-ST1A      | 20          | 210               | 0.37        | 1.18         | 0.0098       |
| 94-AL1/15-ST1A     | 20          | 350               | 0.35        | 1.11         | 0.0104       |
| 122-AL1/20-ST1A    | 20          | 410               | 0.34        | 1.08         | 0.0106       |

Nomenclature

CIGRE  *Conseil International des Grands Réseaux Électriques*

CVRP  capacitated vehicle routing problem

DG  distribution grid
Table A2: Parameter assumptions applied

| Parameter                                           | Value | Unit  |
|-----------------------------------------------------|-------|-------|
| Max. branch line load                               | 1     | MVA   |
| Max. branch line length                             | 2,000 | m     |
| *Satellite* LA threshold                            | 100   | kW    |
| Main route modification threshold                   | 100   | m     |
| Grid connection search buffer                        | 2,000 | m     |
| Grid connection search buffer increment              | 1,000 | m     |
| 10 kV/20 kV load density threshold                  | 1     | MVA/km²|
| Branch detour factor                                | 1.3   |       |
| Max. count of half-rings                             | 20    |       |
| cos φ (loads)                                       | 0.9   |       |
| cos φ (generators)                                  | 1.0   |       |
| Nominal operational voltage at HV-MV substation     | 1.0   | p.u.  |
| Max. tolerable voltage deviation (heavy load flow case) | -5   | %     |
| Max. tolerable voltage deviation (heavy load flow case, failure) | -10  | %     |
| Max. tolerable voltage deviation (reverse power flow case) | +2   | %     |

**Abbreviations**

- **DS**: distribution substation
- **DSO**: distribution system operator
- **GIS**: geographic information system
- **HV**: high-voltage
- **LA**: load area
- **LF**: load factor
- **LV**: low-voltage
- **LVGD**: low-voltage grid district
- **LVN**: LEW Verteilnetz GmbH
- **MV**: medium-voltage
- **MVGD**: medium-voltage grid district
- **NEP**: Netzentwicklungsplan (Network Development Plan)
- **OEP**: OpenEnergy Platform
- **OSM**: Open Street Map
- **RES**: renewable energy sources
- **WEC**: wind energy converter
- **WPA**: wind potential area

**References**

[1] Rippel K M, Wiede T, Meincke M and König R 2017 Netzentwicklungsplan Strom 2030, Version 2017 – Erster Entwurf der Übertragungsnetzbetreiber Available online: [https://www.netzentwicklungsplan.de/de/netzentwicklungsplaene/netzentwicklungsplaene-2030](https://www.netzentwicklungsplan.de/de/netzentwicklungsplaene/netzentwicklungsplaene-2030)

[2] Agricola A C et al. 2012 Ausbau- und Innovationsbedarf der Stromverteilnetze in Deutschland bis 2030 (dena-Verteilnetzstudie): Endbericht Tech. rep. German Energy Agency (dena) Berlin available online: [https://shop.dena.de/fileadmin/denashop/media/Downloads_Dateien/esd/9100_dena-Verteilnetzstudie_Abschlussbericht.pdf](https://shop.dena.de/fileadmin/denashop/media/Downloads_Dateien/esd/9100_dena-Verteilnetzstudie_Abschlussbericht.pdf)
Büchner J, Katsfey J, Flörcken O and Moser A 2014 Moderne Verteilernetze für Deutschland (Verteileretzstudie) Tech. rep. E-Bridge, IAEW, OFFIS Available online: http://www.bmwi.de/Redaktion/DE/Publikationen/Studien/Verteileretzstudie.html

[4] IKS OvGU, Next Energy, RLI, ZNES 2015 Netzbebenen-übergreifendes Planungsinstrument - zur Bestimmung des optimalen Netz- und Speicherausbaus in Deutschland - integriert in einer OpenEnergy-Plattform Available online: https://openegoproject.wordpress.com

[5] Müller U P, Wienholt L, Kleinholds D, Cußmann I, Bunke W D, Pleßmann G and Wendiggesen J 2017 The eGo grid model: An open source approach towards a model of German high and extra-high voltage power grids SciGRID International Conference on Power Grid Modelling (submitted)

[6] Medjroubi W, Müller U P, Scharf M, Matke C and Kleinholds D 2017 Open data in grid modelling: New approaches towards transparent grid models Energy Reports 3 14–21 URL http://www.sciencedirect.com/science/article/pii/S2352484716300877

[7] Pilo F et al. 2014 Benchmark Systems for Network Integration of Renewable and Distributed Energy Resources (Conseil international des grands réseaux électriques. Comité d’études C6) ISBN 9782858732708

[8] Bundesministerium der Justiz und für Verbraucherschutz 2005 Verordnung über die Entgelte für den Zugang zu Elektrizitätversorgungsnetzen (Stromnetzentgeltverordnung – StromNEV) Available online: https://www.gesetze-im-internet.de/stromnetzentgeltverordnung/index.html

[9] Bundesministerium der Justiz und für Verbraucherschutz 2005 Verordnung über den Zugang zu Elektrizitätversorgungsnetzen (Stromnetzzugangsverordnung – StromNZV) Available online: https://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Sachgebiete/Energie/Unternehmen_Institutionen/Netzentgelte/Anreizregulierung/GA_AnalytischeKostenmodelle.pdf

[10] Rui H, Arnold M and Wellssow W II 2012 Synthetic Medium Voltage Grids for the Assessment of Smart Grid Techniques 2012 3rd IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe) (Berlin: IEEE) pp 1–8

[11] Schaller F, Karstädt F, Warweg O and Bretschneider P 2011 Modellierung realitätsnaher zukünftiger Referenznetze im Verteilnetzsektor zur Überprüfung der Elektroenergiequalität ETG-Fachbericht-Internationaler ETG-Kongress 2011 (VDE VERLAG GmbH)

[12] Tao X, Hausbruch H J and Maurer C 2006 Automatisierte Grundsystemplanung für Mittelspannungsnetze ET. Energiewirtschaftliche Tagesfragen 56 8–11

[13] Consentec GmbH 2006 Untersuchung der Voraussetzungen und möglicher Anwendung analytischer Kostenmodelle in der deutschen Energiewirtschaft Tech. rep. Consentec GmbH available online: https://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Sachgebiete/Energie/Unternehmen_Institutionen/Netzentgelte/Anreizregulierung/GA_AnalytischeKostenmodelle.pdf

[14] Strunz K et al. 2014 Planning and Optimization Methods for Active Distribution Systems (Conseil international des grands réseaux électriques. Comité d’études C6)

[15] Harnisch S, Steffens P, Thies H, Monscheidt J, Münch L, Böse C and Gensmijger B 2016 Planungs- und Betriebsgrundsätze für ländliche Verteilungsnetze - Leitfaden zur Ausrichtung der Netze auf ihre zukünftigen Anforderungen Tech. rep. Bergische Universität Wuppertal Available online: http://elpub.bib.uni-wuppertal.de/servlets/DerivateServlet/Derivate-5651/ea0216.pdf

[16] Hülk L, Wienholt L, Cußmann I, Müller U P, Matke C and Kötter E 2017 Allocation of annual electricity consumption and power generation capacities across multiple voltage levels in a high spatial resolution International Journal of Sustainable Energy Planning and Management (submitted)

[17] IKS OvGU, Next Energy, RLI, ZNES 2017 OpenEnergy Platform Available online: http://open-energy.de/ (launches in April 2017)

[18] Bundesverband der Energie- und Wasserwirtschaft eV (BDEW) 2008 Technische Richtlinie Erzeugungsanlagen am Mittelspannungsnetz - Richtlinie für Anschluss und Parallelbetrieb von Erzeugungsanlagen am Mittelspannungsnetz

[19] Bundesnetzagentur 2015 List of power plants Available online: http://www.bundesnetzagentur.de/cln_1911/DE/Sachgebiete/ElektrotaetigkeitGas/Unternehmen_Institutionen/Versorgungssicherheit/Erzeugungskapazitaet/Kraftwerksliste/kraftwerksliste-node.html

[20] Deutsche Gesellschaft für Sonnenenergie eV 2014 Die EEG-Anlagen der Region Bundesrepublik Deutschland (EnergyMap) Available online: http://www.energymap.info/energieregionen/DE/105.html

[21] Gerbaulet C and Kunz F 2016 Data provided by Open Power System Data - Data Package Conventional power plants, version 2016-10-27. Primary data from BNetzA Kraftwerksliste, Umweltbundesamt Datenbank Kraftwerke in Deutschland Available online: http://open-power-system-data.org/

[22] Bunke W D 2016 Data provided by Open Power System Data - Data Package Renewable power plants, early version 2016-02-10. Primary data from BNetzA, BNetzA PV, TransnetBW, TenneT, Amprion, 50Hz, Netztransparenz.de, Postleitzahlen Deutschland, Energinet.dk, Energiytreben, Geonames, French Ministry of the Environment, Energy and the Sea, OpenDataSoft, Urdag Regulacji Energetyki (URE) Available online: http://open-power-system-data.org/
[23] Degel M, Christ M, Becker L, Grünert J and Wingenbach C 2016 VerNetzen – Sozial-ökologische und technisch-ökonomische Modellierung von Entwicklungspfladen der Energiewende Tech. rep. Europa-Universität Flensburg Available online: http://www.uni-flensburg.de/fileadmin/content/abteilungen/industrial/dokumente/downloads/veroeffentlichungen/forschungsergebnisse/vernetzen-2016-endbericht-online.pdf

[24] Lütkehus I, Salecker H and Adlunger K 2013 Potenzial der Windenergie an Land Tech. rep. German Environment Agency (UBA) Available online https://www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/potenzial_der_windenergie.pdf

[25] Kerber G 2011 Aufnahmefähigkeit von Niederspannungsverteilnetzen für die Einspeisung aus Photovoltaikkleinanlagen Ph.D. thesis Technische Universität München

[26] Scheffler J 2002 Bestimmung der maximal zulässigen Netzschlussleistung photovoltaischer Energiewandlungsanlagen in Wohnsiedlungsgebieten Ph.D. thesis TU Chemnitz

[27] Mohrmann M, Reese C, Hofmann L and Schmiesing J 2012 Untersuchung von Niederspannungsverteilnetzen anhand von synthetischen Netzstrukturen VDE Kongress 2012 Smart Grid: Intelligente Energieversorgung der Zukunft (VDE)

[28] Heuck K, Dettmann K D and Schulz D 2010 Elektrische Energieversorgung 8th ed (Wiesbaden: Vieweg+Teubner)

[29] LEW Verteilnetz GmbH 2016 open_eGo workshop: Method and data basis for generation of medium- and low-voltage grids (private communication)

[30] Resch M, Bühler J, Klausen M and Sumper A 2017 Impact of Operation Strategies of Large Scale Battery Systems on Distribution Grid Planning in Germany Renewable and Sustainable Energy Reviews 74 1042–1063 URL http://www.sciencedirect.com/science/article/pii/S1364032117302976

[31] German Institute for Standardisation (DIN) 2011 Voltage characteristics of electricity supplied by public distribution networks; German version EN 50160:2010 + Cor.: 2010

[32] Verband der Elektrotechnik Elektronik Informationstechnik eV (VDE) 2011 VDE-AR-N 4105: Erzeugungsanlagen am Niederspannungsnetz – Technische Mindestanforderungen für Anschluss und Parallelbetrieb von Erzeugungsanlagen am Niederspannungsnetz

[33] Flodorf R and Hilgarth G 2005 Elektrische Energieverteilung 9th ed (Wiesbaden: Vieweg+Teubner)

[34] Wenger W 2010 Multikriterielle Tourenplanung Gabler Research : Produktion und Logistik (Gabler Verlag)

[35] Brässy O and Gendreau M 2005 Vehicle Routing Problem with Time Windows, Part I: Route Construction and Local Search Algorithms Transportation Science 39 104–118 URL http://dx.doi.org/10.1287/trsc.1030.0056

[36] Clarke G and Wright J W 1964 Scheduling of Vehicles from a Central Depot to a Number of Delivery Points Operations Research 12 568–581

[37] Forschungsgemeinschaft für Elektrische Anlagen und Stromwirtschaft e V 2008 Technischer Bericht 302: Ein Werkzeug zur Optimierung der Störungsbeseitigung für Planung und Betrieb von Mittelspannungsnetzen Tech. rep. Forschungsgemeinschaft für Elektrische Anlagen und Stromwirtschaft e. V.

[38] Booggaard C 2007 Dynamische Tourenplanung und -steuerung Ph.D. thesis Universität Passau

[39] Brown T, Horsch J and Schlachtberger D 2017 PyPSA: Python for Power System Analysis ArXiv e-prints (Preprint 1707.09913)

[40] Ackermann T, Untsch S, Koch M and Rothfuchs H 2014 Verteilnetzstudie Rheinland-Pfalz Tech. rep. energynautics GmbH, Öko-Institut e.V., Bird & Bird LLP

[41] Amme J and Pleßmann G 2017 Distribution network generator (dingo) URL https://doi.org/10.5281/zenodo.844045

[42] Brunekreeft G, Luhmann T, Menz T, Müller S and Neckagel P 2015 Regulatory Pathways For Smart Grid Development in China 1st ed (Springer Vieweg)

[43] Bühler J 2013 Instandhaltungs- und Erneuerungsoptimierung von städtischen Mittelspannungsnetzen Ph.D. thesis TU Darmstadt