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Validation of an open source high voltage grid model for AC load flow calculations in a delimited region

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Dorothee Peters[1] *, *Wilko Heitkoetter*[1], *Rasmus Völker*[1], *Axel Möller*[2], *Thorsten Gross*[2], *Benjamin Petters*[2], *Frank Schuldt*[1], *Karsten von Maydell*[1]

[1] *Energy Systems Technology, DLR Institute of Networked Energy Systems, Carl-von-Ossietzky Str. 15, 26129 Oldenburg, Germany*
[2] *Avacon Netz GmbH, Joachim-Campe-Str. 14, 38226 Salzgitter, Germany, E-mail: benjamin-georg.petters@avacon.de*
* *E-mail: dorothee.peters@dlr.de*

Abstract: Large shares of renewable energy production in the electricity grid make grid expansion and new technologies necessary. The unavailability of grid models to address upcoming research questions led to the development of open source grid models. Our work contributes to establish the open_eGo model for grid simulations by validating its assumptions and results for a rural region with high share of wind energy. In particular, assumptions on electrical parameters and the graph structure of the model are compared to the grid owner's model along with a validation of AC load flow results at the model boundaries. It was found that the graph structure deviates in the degree of nodes and connection characteristic. These deviations are less exterior nodes and a lower maximum degree of nodes as well as a higher number of parallel lines in the open_eGo model. The AC load flow results differ slightly in active power and significantly in reactive power, but are more reliable than an aggregation of loads and generation to the extra high voltage (EHV) nodes. Concluding, the open_eGo model has a limited usability for simulating, understanding and optimising DSO grid operation but can enhance EHV-only analysis in large area contexts.

1 Introduction

The integration of large shares of renewable energy production due to CO2 emission targets lead to more complex electricity grids and make grid expansion necessary. In Germany, the planning of new grid infrastructure is conducted by the four Transmission System Operators (TSOs) and approved by the Federal Network Agency for time horizons of 15-20 years. In and beyond these time frames, researchers have identified various questions concerning the grid infrastructure to be answered. These include the optimization of energy supply mix and network expansion as well as the utilization of storage and sector coupling technologies.

Research on these question requires grid models which are typically owned by TSOs and DSOs (Distribution System Operators) and are not available to researchers. Consequently, researchers have developed open source grid models derived from publicly available data to approximate the real power grid [1–5]. Another approach to make power grid models available to research are synthetic test cases e.g. [6, 7]. First, statistical parameters are derived from analysis of power grids in the USA. The algorithms creating the synthetic power grid cases are designed to match the statistical parameters which are also used as validation criteria. Both modeling approaches benefit from improved reproducibility and greater quality by the possibility of reuse compared to proprietary grid models [6, 8].

Available models partly include not only the extra high voltage layer (EHV) but also the high voltage layer (HV) in an integrated model. Modelling of the high voltage layer becomes increasingly important with higher shares of renewables which are mainly connected to lower grid levels than EHV [9, 10]. The high voltage grid allows transit power flows which relieve the EHV grid but are not contained in EHV-only models. The transit flows are calculated from the difference between EHV line loadings in two approaches, first by considering the HV grid and second by aggregating load and generation to the EHV nodes.

Although open source grid models are already used in various works [9–13], they are not yet trusted throughout the field because their assumptions and results are not validated exhaustively. Multiple authors only compare basic network characteristics and visual topology [1, 2, 10]. One publication uses AC load flow calculations and validates identified lines congestions against network reinforcement plans of the DSO [11].

In this perspective, our paper aims to validate the open source model open_eGo against the proprietary model of the DSO for the high voltage grid in a delimited region in north-west Germany. The open_eGo model aims to approximate the existent power grid. It is based on geographical information of electrical equipment available through open street map (OSM). The electrical characteristics are based on literature parameters rather than throughout assessment of the real power system (as done in [6]). In particular, basic and advanced network characteristics as well as the deployed electric parameters of both models are compared to check the OSM representation and assumptions of the open_eGo model. The compared variables are an available subset of the proposed variables by [7]. The validation process also uses system proportion variables on one hand and system topology on the other hand. Further, the deviations of AC load flow results between the open_eGo and DSO model are determined and compared to the results of an aggregation of loads and generation which is used in EHV-only models.

This paper contributes to the development of OSM based open source grid models by validation of the general assumptions of the open_eGo grid model. The results shall at best proof the usability of the open_eGo model for different purposes e.g. as integrated EHV-HV model or for simulation of grid operation on the HV level.

2 Methods and Data

The analysed grid model is part of the open_eGo project and henceforth denoted as open_eGo model. The project tries to develop an integrated grid planning tool to approximate the German EHV and

HV grid in an open source approach [14]. The assumptions and methods to create the grid model are extensively described in [1]. The grid model consists of geographical information on operational equipment such as lines, transformers and substations derived from OSM data. For electric parameters, generalised values per voltage level are assumed based on literature. Loads and generation time series were calculated for the reference year 2011 and were spatially allocated to the grid topology. There are three scenarios provided which are "status quo" which is the current state as of 2016, 'NEP 2035' which employs the scenario B1 of the German network development plan for 2035 and 'eGo100 %' which is a fully renewable electrical energy system.

As reference, the DSO provided a grid model of his high voltage grid. This model is used by the DSO for grid planning purposes. It contains electric parameters of HV buses and lines but no geographical information. Loads and generation units are included aggregated per technology comprising their power for a high wind infeed scenario. Reactive power is modelled by means of a fixed power factor of 0.975 for all generation units and reactive power infeed from MS cable networks.

Our validation approach comprises the comparison of network characteristics and load flow results. Hence, substation and line data of the open_eGo model for the status quo scenario in version 0.4.5 was used [15]. The grid information was filtered to the relevant region (see Figure 1) and converted to a PowerFactory model. The region was chosen because of the availability of grid and residual load data through the project enera which is placed in this region. Due to its coastal location and the high wind potential, the region has a high amount of installed renewable capacity, especially wind of approx. 1.7 GW and others of approx 0.3 GW (values for 2016). Most of the region is rural and the consumption is low, thus yearly total renewable generation was 235 % of the total consumption in 2015 [16]. The high voltage grid in the assessed region contains three

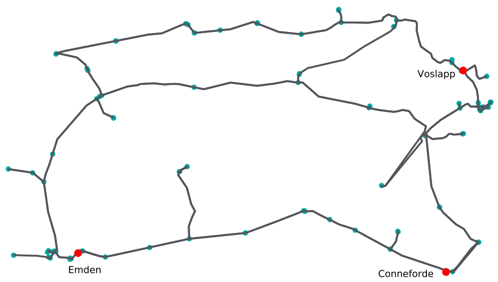


Fig. 1: open_eGo grid model of the assessed region with HV lines (grey), HV nodes (green), and connecting EHV nodes (red). The EHV nodes Emden and Voslapp are connected to Conneforde via 220 kV lines.

nodes to the extra high voltage grid which are located in Conneforde, Emden and Voslapp and named accordingly (see Figure 1). For simplification, only these nodes are considered as connection to the grid outside the region. Hence, no exterior connections on the HV level are considered. Emden and Voslapp are connected via 220 kV lines to Conneforde which is specified as slack bus. Transformer and line parameters of the EHV level were chosen identical in both models.

2.1 *Network characteristics*

Basic parameters of the open_eGo grid model filtered for the assessed region and the DSO model are listed in Table 1. The total length of lines is quite similar, however the open_eGo data includes a larger number of nodes, lines and cables. Further, it includes three offshore cables with a total length of 182 km. The offshore cables in the model region are connected to the EHV grid directly except for one which is connected to the HV grid. This cable is not represented explicitly in the DSO model as its reactive power is compensated by a coil. Hence, the offshore cables in the open_eGo model are neglected for the validation.

Table 1 Number of HV nodes and lines and length of lines of both models including parallel lines.

	Network element	DSO	open_eGo
Number	nodes	100	115
	total lines and cables	121	236
	lines	113	218
	cables	8	15
	offshore cables	0	3
Length in km	lines	634	682
	cables	36	44
	offshore cables	0	182

Additional to the basic characteristics, we compared the graph structure of the DSO model and the open_eGo grid model with the open source tool AutoGridComp [17, 18]. Applying the tool, distributions of two different network criteria [19] were calculated for the vertices v_i and the links l_{ij} of the grid models. In this context, vertices are the nodes of the grid models and links are unique connections between two nodes. Hence, two parallel lines will be interpreted as one link. The first criterion, the degree of a vertex v_i, is defined by the number of links l_{ij} that connect it to adjacent vertices $v_i \neq v_j$. The second criterion, the *betweenness centrality* of a link $l_{ij} = i, j$ is defined by

$$bc_{ij} = \sum_{v_s \neq v_i, v_j \neq v_t} \frac{\sigma_{st}(l)}{\sigma_{st}}. \tag{1}$$

Therein σ_{st} is the total number of *shortest paths* from vertex v_s to vertex v_t and $\sigma_{st}(l)$ is the subset of these shortest paths that passes the link l_{ij} [20, 21]. In order to better compare different networks, in this work we divide the betweenness centrality values by the total number of shortest paths in each network:

$$bc_{ij,normalised} = \frac{bc_{ij}}{n(n-1)/2}, \tag{2}$$

where n is defined as the overall number of vertices in each network. In the following, we only use the normalised betweenness centrality and refer to it simply as betweenness centrality.

2.2 *Electrical parameters*

Table 2 shows the primary line constants of the HV lines and cables used in both models. As the DSO model cannot be published, a range of occurring values is given. The open_eGo primary line constants lie mid-range of the DSO values for resistance (R'), inductance (L') and capacitance (C'). Conversely, the assumed cable values lie at the border of the DSO value range and therefore rather badly represent the existing cables. The nominal current (I_{nom}) which is assumed for cables is approx. twice as high as the maximum DSO value.

In the open_eGo dataset, transformers are characterised by their nominal apparent power and short circuit voltage. The capacity is inferred in such a way that no grid congestions can be expected in these elements. The capacity is calculated by the greatest sum of line capacities connected to one side (either low or high voltage side) of the transformer [22]. These transformer capacities are unrealistically high compared to literature values (e.g. [23]) and also the values obtained from the respective TSO for the enera region. The high apparent nominal power leads to lower reactance and impedance values. Provided that no real data is available, literature values instead of the inferred values should be used for transformer parameters. For the conducted simulations in PowerFactory, the transformers from HV to EHV were given the same parameters in both models (see Table 3).

Table 2 Comparison of HV primary line constants (R'), inductance (L') and capacitance (C') and nominal line current (I_{nom}) between open_eGo and DSO model for overhead lines (ol) and cables (c).

Model	Type	R' in Ω/km	L' in mH/km	C' in μF/km	I_{nom} in kA
open_eGo	ol	0.109	1.2	0.0095	1.364
DSO	ol	0.048-0.226	0.862-1.452	0.0079-0.014	0.30-1.52
open_eGo	c	0.0177	0.3	0.25	1.470
DSO	c	0.029-0.119	0.196-0.956	0.14-0.29	0.36-0.76

Table 3 Transformer parameters used: short circuit voltage (V_{sc}), copper losses (P_{Cu}), no load current (I_0) and resistive iron losses P_{Fe}).

Voltage levels in kV	V_{sc} in %	P_{Cu} in kW	I_0 in %	P_{Fe} in kW
110 - 220	15	250	0.12	90
110 - 380	15	755	0.12	144

Table 4 Summary of data sources used and modifications made to the network models.

	open_ego	DSO model
Network topology (Table 1)	Public data [12] (Except offshore cables)	Proprietary data
HV-Line parameters (Table 2)	Public data [12]	Proprietary data
HV-EHV Transformer rating	Modified by author based on [23]	Proprietary data
	common to both models	
HV-EHV Transformer parameters (Table 3)	Modified by author based on [23]	
Transmission lines (slack definition)	Public data [12], parameters [1]	
Allocation of load and generation buses	Added by author based on substation naming	
Load and generation capacities, time series	Proprietary data	

2.3 Adjustments for AC load flow calculations

AC load flow models require more input data than DC or single node models especially for reactive power and voltage behaviour [2]. The relevant parameters for the reactive behaviour of lines and transformers are already specified in the open_eGo model. Further, adjustments for voltage control had to be made to the open_eGo model. As both open_eGo and DSO model are simulated as balanced AC load flow, identical automatic tap changers at the EHV-HV transformers with a set point of 1.015 p.u. were introduced to harmonize the reactive power results.

Load and generation are kept similar in both models to enable comparison of differences in network characteristics. Instead of the synthetic residual time series of the open_eGo data set, measured residual time series of the year 2016 (01.01.2016 - 19.12.2016) in 15 minute resolution are used for active and reactive power. Additionally, constant loads of 115 MW, representing industrial loads, are added to cover the whole range from generation surplus to load surplus. However, identification of grid connection points of loads and generation in the open_eGo model encountered difficulties. OSM contains only few substation names which not necessarily correspond to the DSO's naming conventions. For 12 of 68 time series no corresponding node was found, therefore they were connected to geographically nearby nodes resulting in 36 nodes with load or generation time series.

2.4 Summary of data sources and modifications

Table 4 summarizes the data sources used and modification made by the author to the models. For the validation of the open ego model, the respective DSO model was chosen as reference.

3 Results

We present a comparison of the network characteristics in Section 3.1 and provide local topology examples to explain the observed differences in Section 3.2. Further, the deviations of active and reactive power from AC load flow results of the open_eGo model are described in Section 3.3. Additionally, in Section 3.4, results of model variations and the aggregation approach are given.

3.1 Network characteristic results

The results for the used network criteria are summarised in Table 5, showing the maximum and average values, as well as in Figure 2, showing the distributions of degree, normalised betweenness centrality of links and line lengths. The maximum degree value in the open_eGo model is 4, while in the DSO model there are also vertices having degree values of 5, 6 and 8. This also results in a 7% lower average degree value in the open_eGo model than in the DSO model. Furthermore, in the DSO model there are more vertices having a degree of 1 while in the open_eGo model there are more vertices having a degree of 2. As shown in Figure 2b, the median line length (orange line) is 4.5 km in the DSO model, whereas it amounts to 0.77 km in the open_ego model. These difference can be explained by the modelling of substations, as well as the connection of wind farms to the grid, as described in Section 3.2.

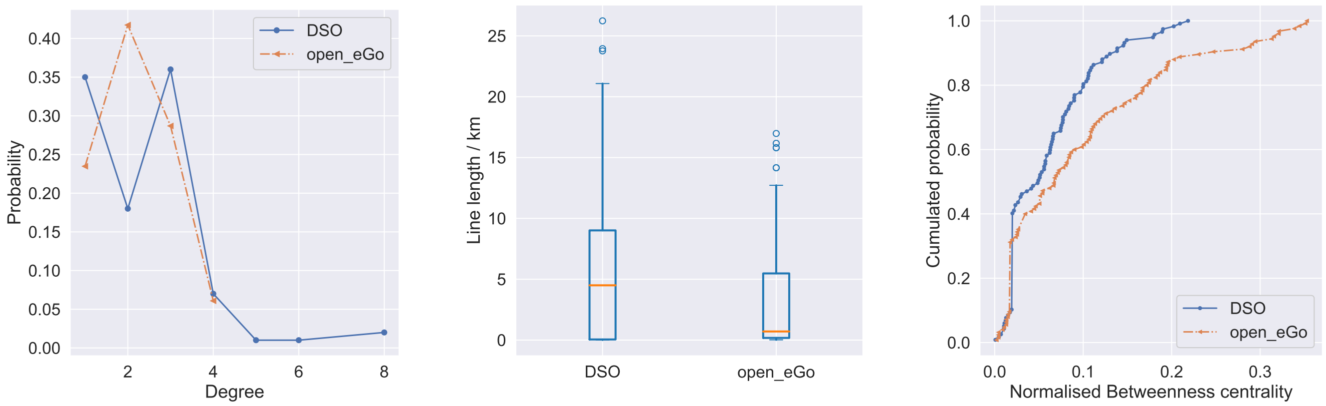
Table 5 Comparison of network criteria of both models excluding parallel links.

	DSO model	open_eGo
number of vertices	100	115
number of links	117	125
average link length in km	5.53	3.41
average degree	2.34	2.17
maximum degree	8	4
average betweenness centrality value for links	0.0609	0.0977
maximum betweenness centrality value for links	0.218	0.353

The average betweenness centrality value in the open_eGo grid model is 60% higher than in the DSO model and the maximum betweenness centrality is 62% higher. In Figure 2c a jump in the cumulative betweenness centrality distribution can be observed at $bc \approx 0.02$ for the DSO model and 0.0174 for the open_eGo model. All exterior links connecting vertices with degree 1 have such a betweenness centrality value because all shortest paths pass the exterior link that connect the exterior vertex with all other vertices in the grid [17]. The share of links having such a betweenness centrality value is higher in the DSO model, as it contains more exterior links, as described in the following section.

3.2 Local topology examples

The analysis of network criteria reveals differences in degree, line lengths and betweenness centrality between both models. For the explanation of these differences, two topology examples are given. The comparison of local topology is based on substation names. The substation name set of open ego was matched to the name set of the DSO. The first example in Figures 3a and 3b shows an exemplary substation (i) with a high degree value and the surrounding grid topology in the DSO and open_eGo model respectively. In the DSO model the node (i) has a degree value of 8 as parallel links are only counted once. Among other connections, the node (i) is directly connected to the nodes (ii), (iii) and (iv). Conversely, in the open_eGo model there is one node lying in between. The observed interjacent nodes lie in close proximity to node (i) and splits up lines



(a) (b) (c)

Fig. 2: **(a)** Degree. **(b)** Distribution of line lengths (Boxplot: orange line depicts median). **(c)** Normalised betweenness centrality of links.

into multiple shorter parts. This explains the lower line lengths and higher number of lines in the open_eGo model. Further, the prevalence of parallel links connecting two nodes reduces the degree in the open_eGo model.

The reason for more exterior nodes in the DSO model is shown in the second topology example in Figures 3c and 3d. In the DSO model, two three phase systems are operated separately between node i and iii. One system is connecting the load and generation node iv, while the other system connects the wind farm node ii. The wind farm is only connected by a single link, because the contingency criterium does not apply, making node ii an exterior node. The junction of node ii to the system is represented by a node without load or generation. Conversely, in the open_eGo model, the node ii and its junction node are connected by two parallel links (1ab, 3ab). In comparison to the separate systems in the DSO model, the parallel lines have more balanced loadings. Therefore, less overloads occur in the open_eGo model making their correct detection hardly possible.

3.3 AC load flow results

In this section, we compare the load flow results of the open_eGo and the DSO model. Therefore, we consider active power (P), reactive power (Q) and voltage (U) at the EHV nodes in Emden (EMDB), Voslapp (VOSL) and Conneforde (CONN), as depicted in Figure 1. The deviations of active and reactive power are analysed by using the mean biased error (MBE) binned over the range of total active power in Figure 4. For weighting of the binned error, the number of samples per active power bin is given in Figure 5a. As passive sign convention is used, negative active power denotes a surplus of generation while positive active power denotes a surplus of load within the region. The mean voltage values of both models are displayed in Figure 5b.

The total active power depicted in Figure 4a of the open_eGo model fits the DSO model well with a maximum deviation of -20 MW while the region has a large surplus of generation. While active power fits well in Emden, it is lower in Conneforde and higher in Voslapp in times of generation surplus and vice versa in times of load surplus. Therefore, more power flows directly through the EHV node in Conneforde than through Voslapp and the EHV line CONN-VOSL. This result indicates that the impedance of the HV grid between Conneforde and Voslapp is lower in the open_eGo grid compared to the DSO model.

The reactive power error is negative in the open_eGo model for each HV-EHV node (see Figure 4b). Hence, the total reactive power error sums up to -90 to -50 MVar. The largest deviation is present by the node in Voslapp. The deviations of the nodes in Emden and Voslapp are nearly constant while the deviation in Conneforde increases with higher negative power.

The deviation are caused by a smaller reactive power consumption in the open_eGo model for lines and MV-HV transformers. As the HV-EHV transformers are modelled equally, their reactive power consumption is nearly the same for both models. In the following section, open_eGo line parameters are applied to the DSO topology to check if the reactive power deviations are caused by deviations in the electrical parameters.

The course of total mean voltage of all HV nodes is comparable in both models but the values of the DSO model are about 0.14 to 0.20 p.u. higher (see Figure 5b). The small deviations of voltages show that the automatic tap changer settings at HV-EHV transformer work as expected. The standard deviation between terminal voltages are higher in the open_eGo model. Hence, a higher voltage drop across the grid in the open_eGo model can be conducted.

3.4 Model variations and aggregation of loads and generation

A comparison of mean absolute error (MAE) and mean biased error (MBE) for variations of the presented model is shown in Figure 6. For explanation of the reactive power deviations, first, the open_eGo line parameters were applied to the topology of the DSO model. The resulting errors of this variation are very small (see Figure 6). Therefore, rather differences in line loadings caused by the parallel topology in the open_eGo model are responsible for the reactive power deviations.

In the second model variation, the offshore cables are considered in the open_eGo model. This variation introduces an even larger error in terms of reactive power due to the capacitive loading of the cables (see Figure 6). In reality, reactive power compensation would be done by static compensators or the connected wind parks, but these components are not included in open_eGo. However, the comparison is done between two models and the errors in reactive power are not weighted as high as active power, as even a match between DSO model and measured values is hard to achieve [24].

Further, the model results are compared to an aggregation of loads and generation to the nearest EHV node, neglecting the HV grid. The aggregation is implemented to classify the model performance of the open_eGo model. Hence, load and generation time series are allocated to the nearest EHV node with regard to shortest line length using a Dijkstra algorithm as suggested by [9]. The resulting MAE of active power is higher for the aggregation than for all grid model approaches (see Figure 6). While the MAE of total active power is

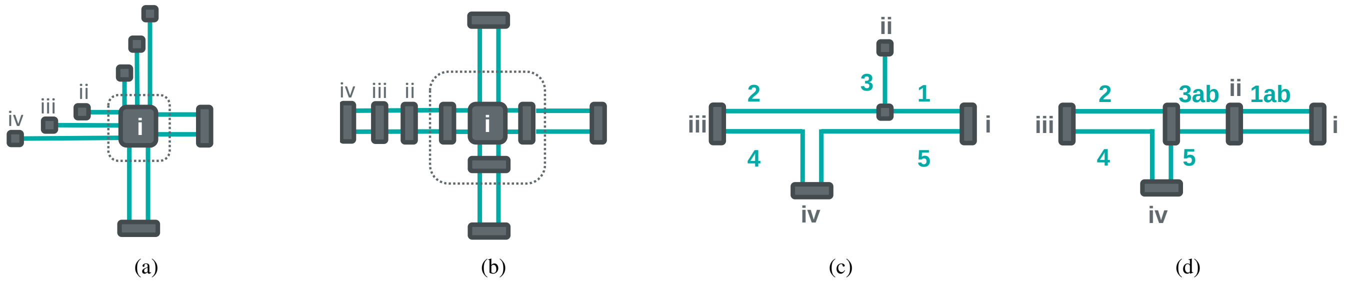


Fig. 3: Grid topology examples: Node with highest degree in DSO model **(a)** and corresponding node in open_eGo model **(b)**; exemplary connection of a wind farm in DSO model **(c)** and open_eGo model **(d)** consisting of five nodes (i-iv) where the fifth node has no load or generation and five links (1-5) where ab denotes two parallel links.

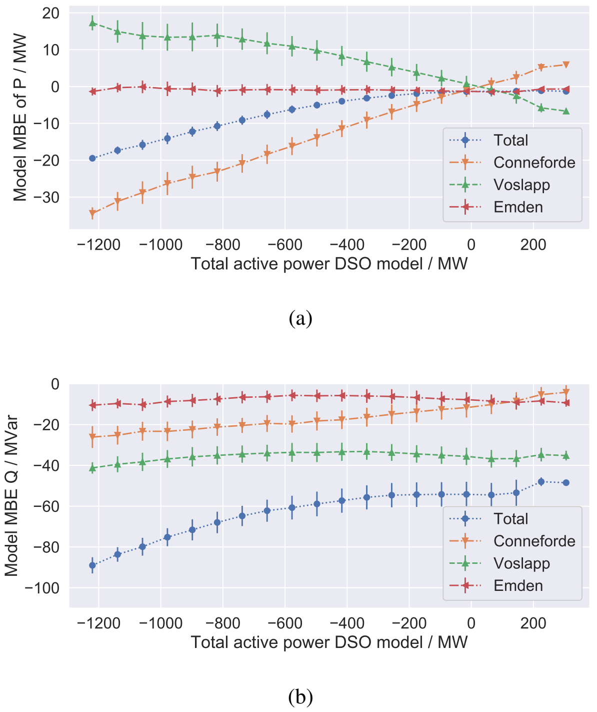


Fig. 4: Mean biased error and standard deviation for **(a)** active power and **(b)** reactive power and binned over the range of active power in the DSO model. The totals of active and reactive power are calculated as the sum of values at all HV-EHV transformers.

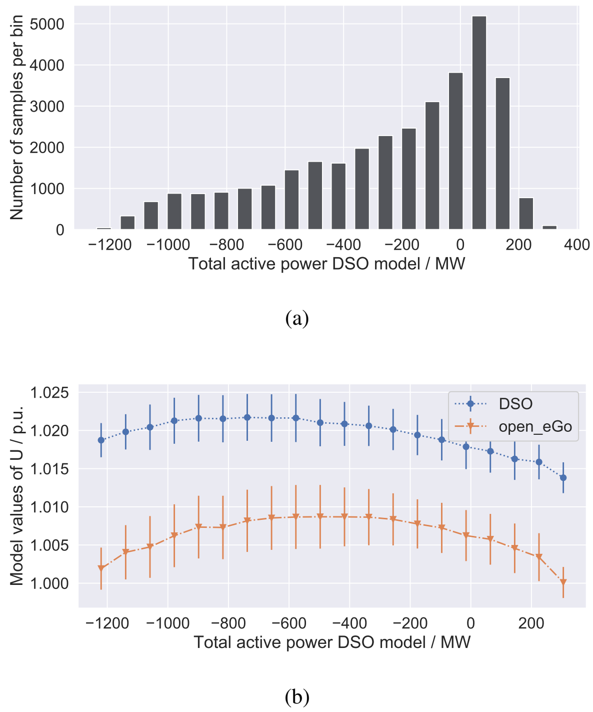


Fig. 5: **(a)** Number of samples per bin of total active power of the DSO model. **(b)** Mean and standard deviation of voltage at HV nodes of both models dependent on total active power.

only 20 MW due to neglected losses, a wrong split of power flow is obtained for the EHV nodes in Emden and Conneforde. In terms of reactive power, there are high errors because the reactive power requirements from grid components e.g. lines and transformers are not represented by this approach.

The EHV line currents were calculated for both models and for the aggregation approach and are shown in Figure 7. The aggregation method will lead to higher maximum EHV line currents unlike the open_eGo model which represents maximum line currents well. Only in case of the line CONN-VOSL, the open_eGo model leads to a false higher minimum line current which is caused by the constant reactive power deviation in times of low loading.

4 Discussion

The open_eGo model for the high voltage grid in a delimited region was validated against the respective proprietary DSO model. The results show, that the open_eGo model is not suitable for the simulation of grid operation on the HV level. Reasons are partly wrong representation of grid topology, missing control devices and knowledge of control schemes. Hence, the local results of the models could not be compared to each other and therefore results of the open_eGo model cannot be used to reproduce and understand DSO grid operation and interventions. Regarding the topology validation based on network criteria, deviations are caused by different modelling of substations and connections of wind farms to the grid. The high number of parallel lines in the open_eGo model leads to more balanced HV line loadings. Hence, the resulting lower line loading influences reactive power consumption and hinders congestion analysis with the model. Reason for the wrongly mapped lines are missing OSM data about connections, switches and other equipment in substations as already stated by [2, 10, 11]. An approach to improve electric connections would be to use a rule set as proposed by [10] where no relations are provided by OSM. In general, improvement of open source models requires further knowledge sharing by the grid operators on their usage of usual equipment, switching states and electrical

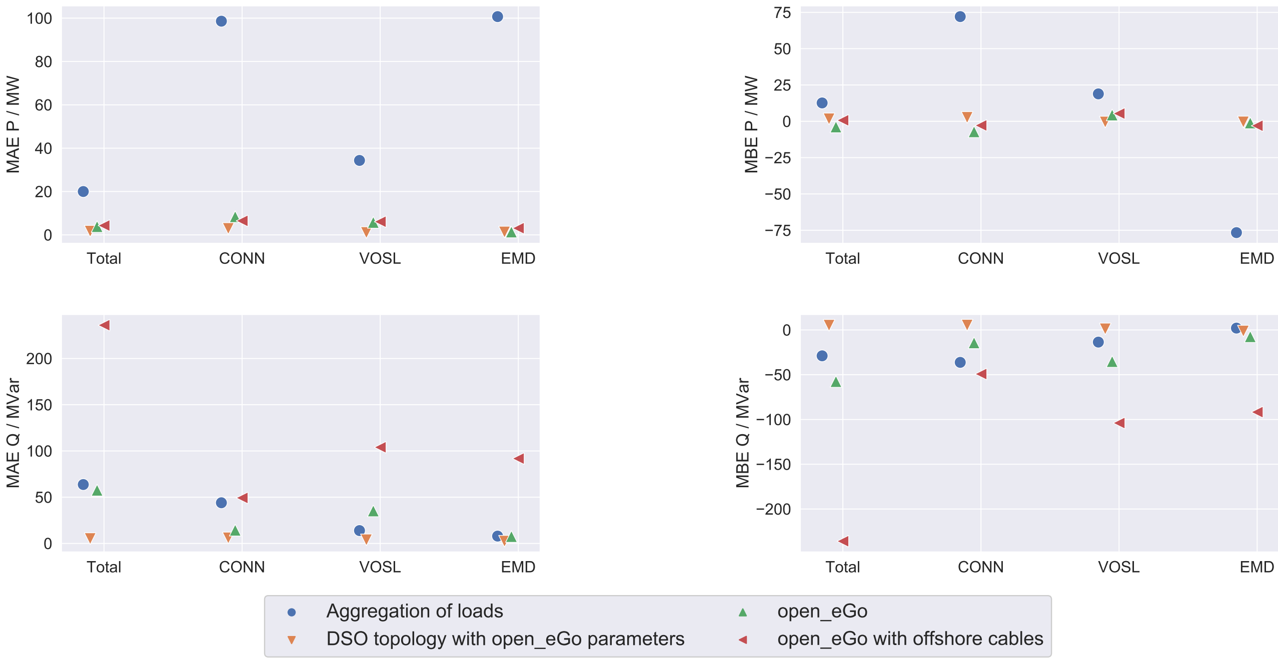
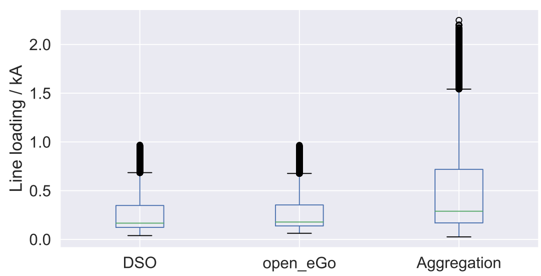
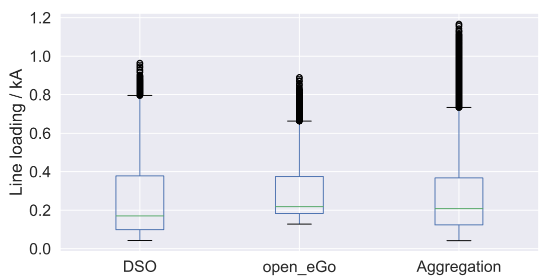


Fig. 6: Mean absolute error (MAE, left column) and mean biased error (MBE, right column) for active power (P, top row) and reactive power (Q, bottom row) compared to results of the DSO model for the following model approaches: aggregation of residual loads to EHV nodes, open_eGo model, open_eGo model considering offshore cables and DSO model using line parameters of open_eGo model.



(a) EHV Line CONN-EMDB



(b) EHV Line CONN-VOSL

Fig. 7: Boxplot of EHV line currents in both models and aggregation method.

connections.

The deviations found for active and reactive power at the EHV nodes are acceptable, consequently the open_eGo model can be used to complement an EHV-only model. Though, the model differences leading to the found deviations could not be clearly identified. No references for the AC results and interpretation can be given due to few open grid model validation approaches which consist mainly of comparing basic network characteristics and visual topology comparisons [1, 2, 10]. AC load flow calculations on a 110 kV grid in Schleswig-Holstein, Germany were conducted in [11] although the only validation was to compare the found congested lines with current network reinforcement planning of the DSO.

The found EHV line currents of the open_eGo model are lower compared to the aggregation of residual loads and fit the DSO model better. Effects of the integration of HV into EHV grid models were also studied in [9, 10, 12] leading to a decrease of EHV line loading due to transit flows through the HV grid. Despite this positive effect, overall negative effects were anticipated in [9] due to more grid restrictions in the HV grid by transit flows. In general, the consideration of the HV grid in EHV grid analysis, even in form of an open source model, yields more reliable results than the use of an aggregation approach.

This work is limited by the DSO model region which was available for validation. The region is rural with low electricity demand and high renewable energy production. Therefore no problems of bad representation due to missing cables in urban areas [10] were encountered. The open_eGo parameters of lines fit well to the DSO parameters in this region while HV-EHV transformer rating and therefore reactance were too high. Especially, reactive power consumption of cables can introduce large errors into the model and should therefore be checked. For further validation approaches, the authors suggest to use regions with different characteristics. Residual time series of the open_eGo model were not validated because measured time series including reactive power were available.

5 Conclusion

In summary, the conducted validation showed that the open_eGo grid model is not yet fit for simulation of grid operation on the HV level. Local analysis like the detection of HV line congestions is likely erroneous and should be compared to supplementary information e.g. network extension plans of the relevant DSO. To enhance open_eGo for this purpose, the network derivation from OSM data has to be improved, for example by connection rule sets for lines.

Further, assumptions for cables and transformers should be validated as their parameters had large deviations from the grid equipment in the assessed region. Additionally, the grid model lacks control devices and the simulation has to be supplemented with control schemes. The data and assumptions which are required to obtain sufficiently precise results with open source models should be subject to further research. However, the validation also showed, that the open_eGo grid model enhances EHV grid analysis compared to the aggregation of loads and generation.

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