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Evaluation of load flow and grid expansion in a unit-commitment and expansion optimization model

SciGRID International Conference on Power Grid Modelling

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Abstract. Energy system models serve as a basis for long term system planning. Joint optimization of electricity generating technologies, storage systems and the electricity grid leads to lower total system cost compared to an approach in which the grid expansion follows a given technology portfolio and their distribution. Modelers often face the problem of finding a good tradeoff between computational time and the level of detail that can be modeled. This paper analyses the differences between a transport model and a DC load flow model to evaluate the validity of using a simple but faster transport model within the system optimization model in terms of system reliability. The main findings in this paper are that a higher regional resolution of a system leads to better results compared to an approach in which regions are clustered as more overloads can be detected. An aggregation of lines between two model regions compared to a line sharp representation has little influence on grid expansion within a system optimizer. In a DC load flow model overloads can be detected in a line sharp case, which is therefore preferred. Overall the regions that need to reinforce the grid are identified within the system optimizer. Finally the paper recommends the usage of a load-flow model to test the validity of the model results.

1. Introduction

In the Paris agreement, 195 countries adopted the first ever legally binding global climate agreement. The goal is to keep the global average temperature well below 2 degree Celsius (European Commission, 2016). The latest official document of the German government is the “Klimaschutzplan 2050” [1], which confirms the targets of the “Energiekonzept” of 2010 [2] and sets additional CO2-reduction targets for each sector. To reduce the CO2-emissions and to increase the share of renewable energies, energy system models can add value in developing a strategy for the system planning, in providing possible pathways. The models are able to take the costs of the technologies, the different local potentials as well as the existing infrastructure into account. The energy system model ENTIGRIS for example integrates the unit-commitment, transmission and expansion planning of generating technologies, storage systems as well as grid expansion into a cost minimal optimization. Disregarding the grid would lead to different transformation pathways, compared to an approach where the grid expansion is optimized endogenously with the technology and storage systems. This will additionally lead to higher system costs [3]. The challenge for the model set up is to find a good trade-off between computing time and the level of detail. The level of detail is mainly characterized by

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number of regions, in which the system is clustered, number of optimized time steps and years that are calculated, the aggregation of single power plants as well as the detailing of the grid. This paper therefore analyses the performance of the energy system optimizer ENTIGRIS in terms of grid representation using a comparison to a DC load flow model. Within this paper the use case of Baden-Württemberg was chosen to analyse the effect of grid representation within the highly meshed overlaying grid (see Figure 4). Different levels of detail concerning the number of regions as well as an aggregation of grid lines compared to a line sharp approach will be discussed, regarding the root mean squared error (rmse) of line usage, the rmse of power flows as well as the grid expansion and cases of overload.

2. State of the art

The approach of combining long-term system optimization with grid expansion was evaluated in studies like [3] or [4]. Positive benefits like lower system costs and higher system stability related to a more equally distribution of the generation technologies and therefore lower congestion can be attained in joint system planning. There are different approaches to represent the load flow. [3, 4] point out the relation between the model fidelity and the computational time and efforts. They defined three categories of representing the load flow, which differ in the degree of accuracy:
The **AC optimal power flow** represents the real and reactive power flows abiding physical laws. These are represented in non-linear functions. It is the most challenging method but also the one with the best fidelity. The problem can be formulated as a mixed integer non-linear problem (MINLP). The **decoupled load flow (DC)** model is used as a typical market and planning application. It has two parts, the real power flow (directly proportional to angle differences) and reactive power flow (directly proportional to bus voltage differences). For planning a system with minimal system cost the problem is focused on real power flow represented as a linear problem. Calculating the expansion of a grid for a meshed network like the German overlaying grid Kirchhoff's voltage law turns the optimization problem into a MINLP. Using binary variables instead of integer variables the problem can be formulated as a mixed integer linear problem (MILP). But these problems also require high computational times and cause inaccuracies which violate the voltage criteria. These violations cannot be detected using this methodology. The third approach is the **transshipment model** or simple transport model, which has the advantage that computational times are better. The disadvantage is that the model fidelity decreases due to neglecting the voltage variables and the relationship of real power transfers with bus angle differences and line impedances. This can result in an unfeasible system in reality. Energy system models like Remix and Power ACE use a transport model to represent the high voltage DC lines for Europe (each country represented by one node) [5] [6]. A benefit of this approach is that the computational time is applicable also for large scale optimization problems. Another approach is the **one node model** or "Copper-plate" approach, which neglects the grid in the energy system. The assumption is that grid congestion is not an issue [6].
[3] suggest that the expansion results of the transshipment models need to be checked with a DC or AC model, to ensure the security of the network. [7] present(s) a methodology to couple an electricity market model with a power flow model in order to jointly optimize both power generation and transmission grid infrastructures under flow-based market coupling using an iterative approach based on power transfer distribution factors (PTDFs)." Having the non-linear dependence of the impedances [7] suggests an update of the matrix after each grid reinforcement. In contrast to this paper [7] uses the partial equilibrium model DIMENSION, which takes the shares and the mix of RE technologies as an input. For the European system the approach converges after 5 iteration steps. For the ENTIGRIS Model optimizing unit-commitment of all power plants, storage, transport between the regions and power plant and storage as well as grid expansion at the same time in a non-myopic set up, an iterative approach would lead to extreme high computational times (e.g. using around 4000 hours and 50 nodes for Germany result in one optimization run of several weeks). Therefore the authors chose to use a transshipment model within the ENTIGRIS optimization model and validate the results based on a DC load flow approach presented by [12] (described in 3.3.), which is similar to the approach of [7] as it

updates the impedances after each iteration but formulates the problem with voltage angles, whereas [7] uses PTDF matrices

3. Methodology
According to [3] for using an AC approach high computational effort is needed and also data on control devices is necessary. As the target is to optimize the long term development of an energy system like Germany in the highest resolution possible, the power generators in a model region are aggregated. Therefore there is a lack of data on generator capability curves and the AC optimal flow is hence not applicable. The preferable model framework in the context of long-term system planning, takes high regional resolution and high number of time steps into account. As this level of detail will increase the computational time, a DC load flow approach within the optimization model would further increase the computational effort considerably. Hence, the authors choose to combine two models. One model being the ENTIGRIS optimization model (see chapter 3.2.) which optimizes the unit-commitment of renewables, short and long-term storage technologies and the im- and exports between regions as well as the expansion of all available technologies (including grid expansion). The resulting nodal transmission balance and the new grid infrastructure are then transferred into a load flow and grid expansion model based on [12], referred to as DC-load flow model. The DC model provides expansion or upgrade suggestions in the case of overloads, if a potential to do so exists. The DC load flow model therefore ensures that the ENTIGRIS optimization ensures a stable system (in the cases without overloads). Additionally the DC load flow model serves as a benchmark for the calculated load flows and the grid expansion within the ENTIGRIS model as the DC model is more accurately in physical load flow than the simple transport model. Different approaches of grid representation are tested in order to obtain good results. In doing so, following research questions are defined.

3.1. Research Questions
The following research questions are defined within this paper:

- What is the effect of the level of regional resolution (using the highest regional resolution possible and clustering different regions to one model region)?
- What is the effect of a detailed grid representation (representation of each line between regions) compared to a simplified grid (aggregation of lines between regions) within a system optimizer?
- What is the effect of the representation of the load flow by the reactance or the line length within the optimization model?
- How accurate is the performance of ENTIGRIS grid expansion validated by DC load flow?

3.2. Description of the ENTIGRIS optimization model
The objective of ENTIGRIS is to minimize the total system costs of the electric power sector by considering the unit-commitment of power plants and storage systems under the restriction of the grid infrastructure and the power plant expansion (including renewable technologies, storage systems and the electric transmission grid). The description of the main methodology can be found in [8], [9] and [10]. The model considers the electricity sector and the following technologies: Wind power plants, photovoltaics, biogas, CCGT, OCGT, lignite and hard coal, nuclear, hydropower as well as storage technologies (pump storage, batteries). The renewable energy potential is available in NUTS3 level. The 220 and 380 kV voltage grid is integrated in the model. Costs for load change as well as load change constraints are formulated linearly in the model. The power plants of similar types are aggregated within one model region (assuming an average efficiency in dependence of the age of the power plants). The main model scope is displayed in (Figure 1). The annuity costs are broken down to the annuity that occurs for each modelled time step. The annuity payments that have to be undertaken after the last optimization year for an investment that was undertaken within the optimization time are cut off. This enables the model to have the correct ratio of fix to variable costs, even if not all hours of

the year are considered. The sum of the annuity costs per optimization year are discounted by a pre-calculated discount factor, including the life time per technology and taking into account that only selected years are optimized (e.g. 2020, 2030, 2040, 2050). This enables the model to minimize the cost for all chosen time steps and optimization years simultaneously.

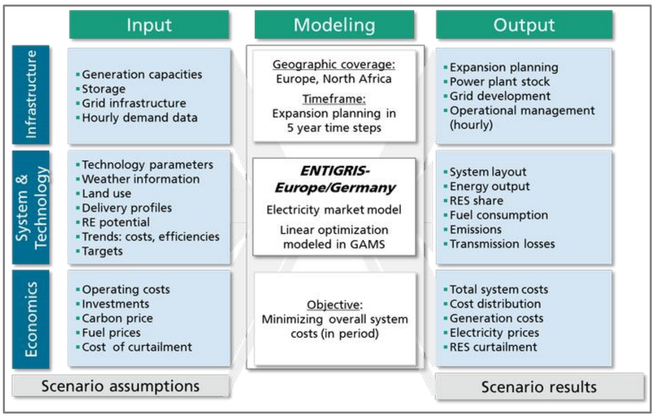

Figure 1: Scheme of ENTIGRIS expansion and unit-commitment optimization model

The balance equation ensures that the sum of generation, storage charge discharge, import and export energy in each node (model region) has to be congruent with the electrical demand, which follows the theory of nodal pricing, as the unit-commitment is restricted by the given grid infrastructure.

The electricity balance equation is used in different forms in this paper. A reference case is calculated for both regional variations (compare 3.4.1.) using the ENTIGRIS optimization for the whole infrastructure (generation, storage, grid) while the grid expansion being switched off for 2020 to ensure a standard case for comparison between the DC load flow and ENTIGRIS. Different variations (explained in 3.4.) are then optimized related to power-flows and grid expansion. Therefore a fixed generation time series is used from a reference scenario, to be able to analyze the effects of the variations directly, without a changing optimal generation portfolio.

To restrict the load flow in the model, a constraint that limits the possible transfer to the given or optimized line capacity including a security factor of 0.7, representing the n-1 criteria, is used. The grid expansion is represented as a mixed integer linear problem (MILP). The following options are integrated: A 220 kV line can be upgraded to a 380kV line and new 380 kV lines can be installed. Different investment costs (€/km) are associated with the two options. The potential is given by a maximum number of systems of two that can be installed on a power line corridor (link between two regions with a given length). If lines are aggregated the potential sums up accordingly. The construction of new corridors is not included in the calculations for this paper. The results presented in this paper display the minimal system cost under the constraint to fulfill a renewable energy share of 20% in 2020, 40% in 2030, 60% in 2040 and 80% in 2050 of the electricity demand in sum over all modeled regions. The system optimization results in an increase of the wind capacities from 9.6 to 18 GW whereas the PV capacities are decreasing from 12.5 to 7 GW between 2020 and 2050. Only those regions that are displayed in Figure 4 are optimized and were treated as an island system for this analysis.

3.3. *The DC load-flow model.*

The DC load-flow methodology is chosen to calculate grid states since there is not enough information of the grid available for a more accurate AC load-flow calculation. Assumptions made for the DC load flow model are that voltage magnitudes at each node are equal to the nominal voltage and resulting power-flow and only depend on line reactances [11]. [12] shows that this problem may also be formulated as linear optimization problem which allows to implement grid reinforcement options. The optimization problem proposed in [12] is applied for this paper. In the case of overload a line is upgraded or expanded, if there is a remaining potential. The decision if a line is upgraded or a new line is build is based on minimal cost, ensuring that the capacity needed is provided. Having a case of overload at two different grid corridors both corridors will be reinforced. If no potential exists, in the case of overload no possible optimization solution can be provided. In order to hold linearity, changes in line properties due to line upgrades are not integrated in the optimization problem. If line reinforcement was chosen by the optimizer the grid parameter are recalculated according to the new structure and a iteration is performed.

3.4. Description of the reference cases

Three criteria with different variants are identified in order to answer the research questions. The target is to evaluate the performance of the ENTIGRIS model in terms of valid grid expansion. The grid in both models is represented according to the ELMOD-DE model [13].

3.4.1. Variation 1: Clustering of area. The highest regional resolution for this paper, in which the necessary data for power system optimization are fully available, is NUTS 3 level (small administrative units according to the nomenclature of territorial units for statistics [14]. The number of regions has a direct impact on the calculation time of the model. Two cases are selected for this paper. Both have the regional coverage of Baden-Württemberg and its neighboring regions (compare Figure 4). Case one, referred to as BaWü-Nuts3_c, is a slightly simplified presentation of the regional resolution, in which regions are clustered to neighboring regions that have no own node to the ultra-high voltage transmission grid. 63 model regions represent that case. The second case, referred to as BaWü-HVTSO represents a cluster of the regions based on the high voltage transmission system operators, resulting in nine regions. The grid needs to be clustered for this case by using a cross border approach, considering only the lines that cross two regions. The power lines within the clustered region are neglected.

3.4.2. Variation 2: Level of detail of the grid representation. Two different levels of grid detail are implemented in both models: On the one hand, all lines that stretch from one region to another are aggregated. The line length (which is important for calculating the costs of grid expansion) is aggregated by using the arithmetic mean. This approach is defined as the aggregated case, only representing one virtual corridor between two regions for each voltage level), resulting in 21 corridors for HVTSO and 99 corridors for NUTS3_c. On the other hand, the line-sharp case represents aggregates only the lines that have the same voltage level and line length, resulting in 48 lines for HVTSO and 127 lines for NUTS3_c. For all cases just one node (represented by demand and supply) per region is assumed.

3.4.3. Variation 3: Representation of the load flow in the optimization model. A variation of the side constraint of transmission cost is conducted. In one case line length and in the second the line reactance is used for calculating the transmission cost in order to evaluate the load flows and grid expansion in the ENTIGRIS model. Both parameters will be normalized to its maximum value in the reference system and then multiplied with variable costs of 0.1 €/kWh and with the transported electricity (kWh).

3.4.4. Criteria for the analysis. The focus of the analysis is twofold. Firstly, the **load-flow** of both scenarios according to respective models is analyzed. In doing so, the degree of usage of each power line is determined. The root-mean-square-error (RMSE) of the degree of usage is then calculated compared to the DC load flow model. This is conducted for the optimization year of 2020, where no expansion takes place. Critical power lines and the frequency of occurrence are determined by identifying the load-flow in power lines that exceeds the permissible capacity in the DC load flow model. Secondly, the **expansion** of the power grid lines for the optimization years of 2030, 2040 and 2050 is analyzed for both models. The amount and capacity of upgraded lines as well as the deployment of new lines are compared. If the DC load flow model has no expansion suggestions, the system stability is ensured. However, if any expansion is suggested, then the grid capacity of at least one line in the simple transport model is insufficient.

4. Results

Figure 2 shows the RMSE of the power flows between the described scenarios. It can be observed that the aggregated scenarios for both regional resolutions have lower outliers than the detailed case. This can be explained by the existence of only one corridor between two regions in the aggregated case. Therefore in the detailed case the deviations can be very high due to the fact that other lines from different corridors are used within the optimization model than in the DC load flow model. In the case of a higher regional resolution the overall deviation is lower than that in the HVTSO case, whereas the median is around 200 MW in both the NUTS3 and the HVTSO detailed case. The load flow of the optimization model and the DC load flow deviate in all cases in the range of 30 to 1200 MW.

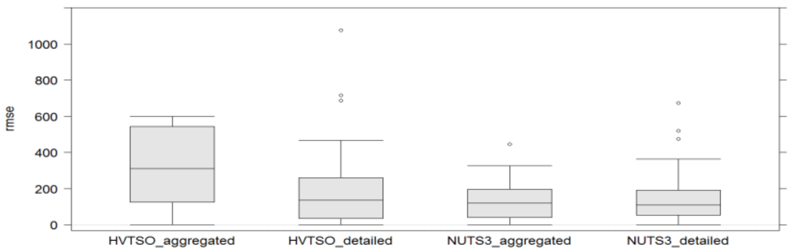

Figure 2: RMSE of power flows per grid line (detailed case) and corridor (aggregated) in MW

Figure 3 shows the degree of usage of each power line in all scenarios. The degree of usage in the detailed scenarios is more scattered than their respective counterparts. This is due to the higher possibilities of lines in the detailed case. The highest outlier is 70% in the HVTSO detailed scenario. The mean deviation in all scenarios is around 10%. This means that an aggregation of lines between regions is comparable to the detailed representations of the power lines. A parameter variation is conducted by varying the variable costs and the line impedance in order to further reduce the deviations between both models. However, no significant trends are observed as the load flows are only minimally affected.

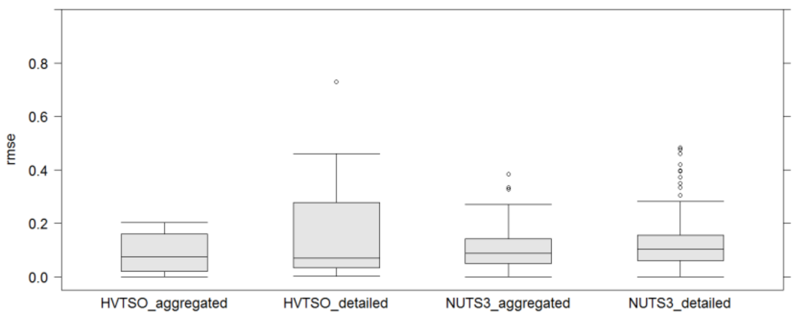

Figure 3: RMSE between DC load flow and transport model of line usage for the four scenarios'

The second part of the analysis concentrates on the validity of the ENTIGRIS results, represented by the cases of overload that occur in the DC load flow model, using the calculated grid by ENTIGRIS. In the HVTSO case the aggregated modelling result in one occurrence of overload in 2020. A reinforcement on this corridor result in a valid system. The expansions by ENTIGRIS in the following optimization years result in a valid system, because the critical line was expanded by ENTIGRIS. In contrast to that the line sharp case (see Figure 4) result in an overload on the same corridor in 2020 but the corresponding rather short line cannot be expended due to potential restrictions. The expansions that were calculated by ENTIGRIS in 2030 for that line is not valid for the DC load-flow; again cases of overload occur in 2030, 2040 and 2050. In 2040 an additional corridor faces the case of overload. The bottleneck effect of a small line within a meshed network is better represented using the line sharp model and cannot be detected using aggregated lines, in the DC load-flow.

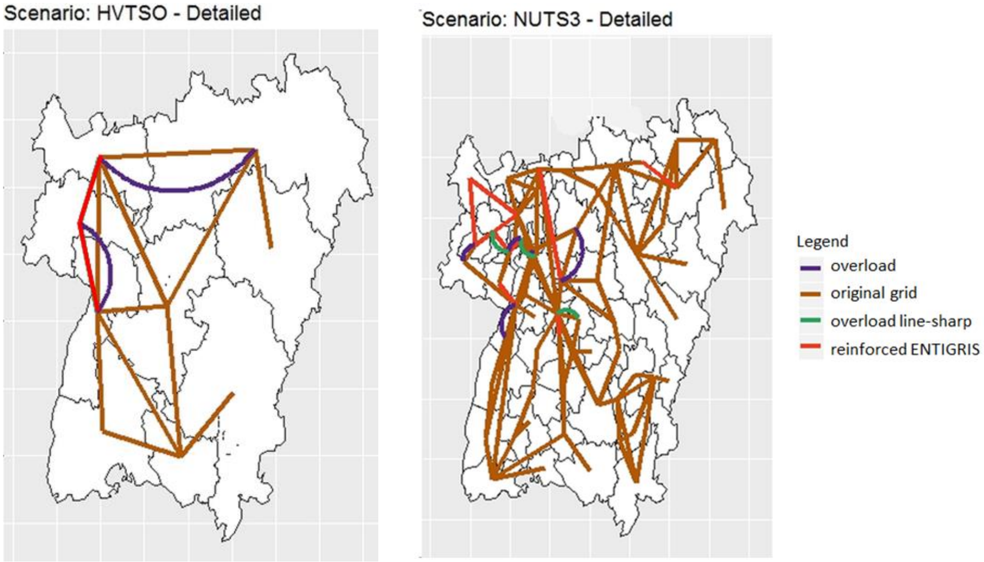

Figure 4: Grid expansions and detected overloads of DC load-flow model for the line sharp calculation of HVTSO (left and NUTS3_c right)

In the NUTS3_c calculation for both (aggregated and line sharp) cases, 10 upgrades are undertaken until 2050 in the ENTIGRIS model (marked in red). In comparison to the NUTS3_c case within the HVTSO case, 7 necessary grid upgrades were not detected because of the lower regional resolution in the optimization. Only in the aggregated model the years 2020 and 2030 result in a valid system. In all years of the line sharp case and in 2040 and 2050 in the aggregated case overloads occur that cannot be solved, because the line potentials are reached with the used model setup. Additionally three additional corridors are identified in the line sharp case in comparison to the aggregated case. In all calculated cases the expansions and the overloads occur in the North-West and in the North-East, in those corridors that were also expanded by the ENTIGRIS model.

5. Conclusion and Outlook

The paper shows that there are significant differences between a simple transport model and a DC load flow model. While the transport model optimizes the transportation by minimizing the costs, the DC load flow minimizes the electrical transport distance. The power flow on each represented line of both models deviate around 100 to 300 MW, with very rare occasions of more than 1 GW. The deviation of the line usage varies by around 10 %. The representation of transmission cost via normalized line length or reactance did not show an influence on the model results. Both approaches can be used.

Important for long term system planning is the grid expansion and the detection of critical lines. It can be concluded that an integral approach of optimizing the generation capacities, flexibilities and the grid infrastructure within one optimization problem is very beneficial because the social welfare can be increased using this approach. The analysis of the results shows that the ENTIGIS optimizer is able to identify most corridors that need reinforcement measures. The DC load flow approach can validate those results and specify which exact lines are critical. It was found that critical lines often occur when they are rather short in a meshed structure. For a long term system planning the approach seems reasonable.

Overall it can be concluded that the validation of the ENTIGRIS system optimizer with a DC load flow model are very valuable. Special attention need to be payed on the level of regional aggregation. A low regional resolution can give rough hints on necessary grid expansion measures whereas the accuracy increases by having a higher resolution. More specific expansion measures and cases of overload can be detected and dealt with. While the DC load flow model should represent each single line in an investigated system, it is sufficient to use aggregated lines within the system optimizer. Further research needs to be done in defining for example time span as well as level of acceptable grid overload without upgrading the grid, as targeted redispatch measures for example are not considered within the DC load flow model. Additionally the accuracy of the model is also very dependent on the method that is used to cluster the grid. Methods of optimizing the overall system without the need of iterating need to be tested, to stay within acceptable computational times.

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