MODEL-BASED EVALUATION OF DECENTRALISED ELECTRICITY MARKETS AT DIFFERENT PHASES OF THE GERMAN ENERGY TRANSITION

APPENDIX DOCUMENT

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Appendix A

Data availability

The below described data sets are available under creative commons license on Zenodo: https://zenodo.org/record/4727354

Table 1: Available input and output data

Data	Data type	Geo scope	Transformation level	Unit	Input/Output
Demand	Hourly profiles	Europe	A and B	MWh	Input
Variable RES-E	Hourly profiles	Europe	A and B	MWh	Input
Power plant fleet	Capacities	Europe	A and B	MW	Input
NTCs	Capacities	Europe	A and B	MW	Input
Electricity generation	Annual data	Europe	A and B	TWh	Output
CO_2 emissions	Annual data	Europe	A and B	Mt	Output
Variable costs of electricity generation	Annual data	Germany	A and B	€/MWh	Output
Self-supply rate	Annual data	Germany	A and B	%	Output
RES-E curtailment	Annual data	Germany	A and B	TWh	Output
Storage losses	Annual data	Germany	A and B	TWh	Output
Grid congestion	Annual data	Germany	A	TWh	Output
Grid expansion	Annual data	Germany	A	Km	Output

Input data for Germany

The following table shows the capacities installed for Germany in transformation levels A and B. The data is mainly based on Klimaschutzszenario 95 from Repenning et al. (2015), including an adjustment towards a stronger decentralised generation as described in Kühnbach et al. (2020). While the capacities of wind onshore, wind offshore and photovoltaics roughly double between level A and level B, lignite and hard coal almost completely lose their role in level B. The capacities of gas-fired power plants remain at roughly the same level between the two transformation levels. However, it must be seen that the gas capacities in level B include approx. 25 GW of back-up capacities that only run at a low utilisation rate (approx. 1,000 full load hours).

Table 2: Generation capacities [GW] installed in Germany

	Level A	Level B
Lignite	1.2	0.0
Hard coal	9.3	2.7
Gas	27.9	28.9
Nuclear	0.0	0.0
Other fossil	4.9	4.4
Hydro	5.5	5.8
Wind Onshore	64.6	122.1
Wind Offshore	15.1	37.7
Solar energy	104.7	237.1
Biomass	4.4	0.4
Other RES-E	0.6	1.9

Source: Repenning et al. (2015); Kühnbach et al. (2020)

Table 3 shows the values used for the different flexibility options in Germany for transformation levels A and B. The data for battery storage, pumped hydro storage and demand response is based on Rippel et al. (2019), while the values for electrolysers, electro mobility and power-to-heat are taken from Repenning et al. (2015).

Table 3: Flexibility options in Germany

	Unit	Level A	Level B
Battery storage	GW	6	21
Pumped hydro storage	GW	9	16
Demand response	GW	4	8
Electrolysers	GW	0	42
Flexible el. mobility demand	TWh	11	80
Flexible Power-to-Heat demand	TWh	20	57

Source: Repenning et al. (2015); Rippel et al. (2019)

In Table 4 fuel costs and CO_2 prices for transformation levels A and B are listed. These values are based on Repenning et al. (2015).

Table 4: Fuel costs and CO_2 price

	Unit	Level A	Level B
Crude oil	€/GJ	16.4	25
Fossil gas	€/GJ	9.4	13.9
Hard coal	€/GJ	3.3	4.5
Lignite	€/GJ	1.7	1.7
CO_2	€/t CO_2	87	200

Source: Repenning et al. (2015)

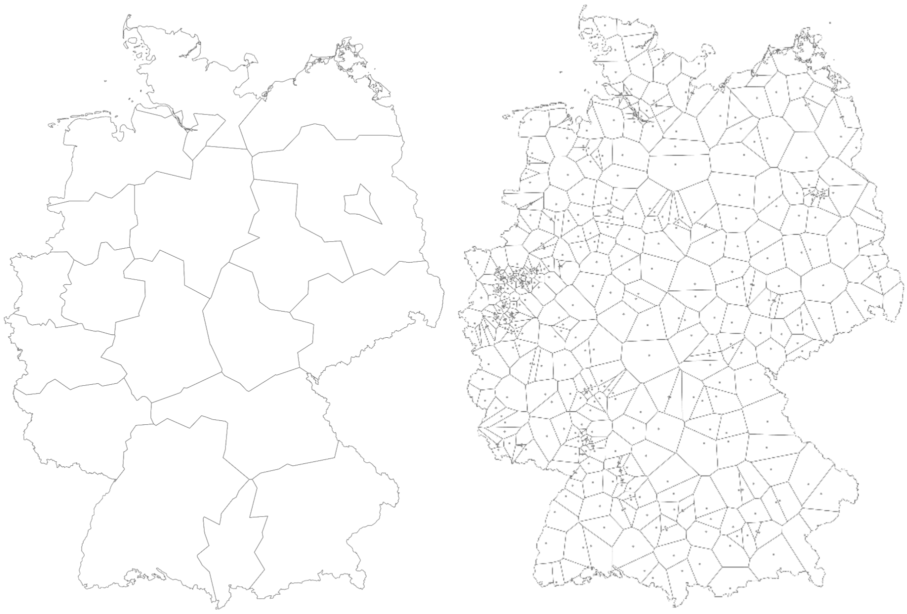
Table 5 shows the keys used for the regionalisation of the input parameters for the German electricity system. Most of the input data used is available on a national level and has to be distributed to the transmission grid nodes by appropriate factors. The procedure for the distribution of RES-E capacities is adapted from the method used in 50 Hertz Transmission et al. (2019a).

Table 5: Regionalisation keys

Input parameter	Regionalisation keys
Wind onshore expansion	Step 1 - Distribution to federal states: Federal state distribution from 50 Hertz Transmission et al. (2019a) Step 2 – Distribution to nodes: ½ Current distribution (repowering) ½ generation potentials
Wind offshore	Distribution from 50 Hertz Transmission et al. (2019a)
PV expansion	Step 1 - Distribution to federal states: Federal state distribution from 50 Hertz Transmission et al. (2019a) Step 2 – Distribution to nodes: Suitable sites for PV installations
Run-of-river	Installed capacity from Bundesnetzagentur (2019)
Power plants	Location if known (Bundesnetzagentur 2019) Additional power plants: Own assumptions
Decentralised power plants (esp. biogas and fossil gas CHPs)	Equal distribution to all nodes
Electricity demand	Industrial load: locations of electricity-intensive industry Remaining load: Population density
Electric vehicles	Population density
PV battery storage	Future distribution of installed capacity from PV plants whose subsidies have ended + installed capacity of PV expansion (cf. Matthes et al. 2018)
DSM	Population density
Electrolysers	Wind onshore electricity generation

Figure 1 shows the structure of the two different configurations for the size of the decentralised markets, with the ‘Reg’ case on the left side and the ‘Area’ case on the ride side. Their derivation is described in chapter 3.1 of the main document.

Figure 1: Structure of the 20 regions (left side) and 457 areas (right side)



Appendix B

Indicator derivation

Self-supply rate:

The capped ratio of local generation to local load if local load exists is derived as follows:

- $g_{r,t}$: generation in region r at time t
- $l_{r,t}$: load in region r at time t
- $s_{r,t}$: $regional$ self-supply ratio $= \begin{cases} 1\,, & l_{r,t} = 0 \; or \; g_{r,t} > l_{r,t} \\ \frac{g_{r,t}}{l_{r,t}}, & else \end{cases}$

Grid congestion:

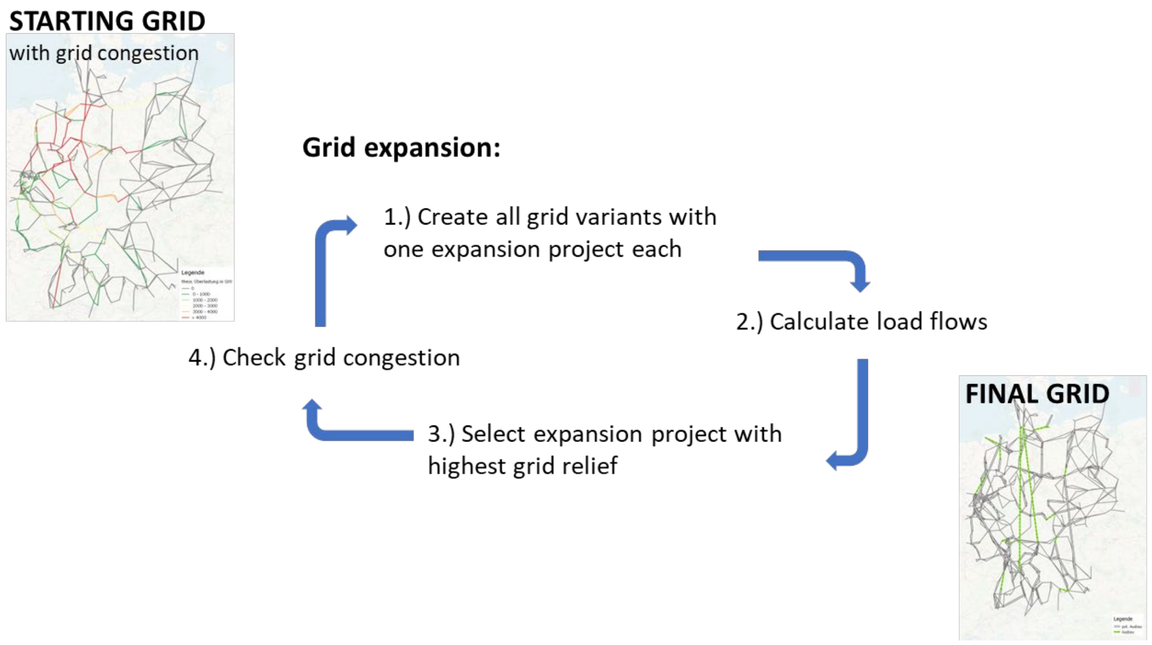
Every hourly line load that would exceed line capacity if no redispatch was applied, is cumulated to yearly values and aggregated to a national value as follows.

- c_l: capacity of line l
- $l_{l,t}$: load on line l at time t
- C: total congestion $= \sum_{l,t} max(l_{l,t} - c_l,\; 0)$

Grid expansion:

Figure 2 shows the scheme of the iterative grid expansion that we used for this analysis.

Figure 2: Scheme of the iterative grid expansion



As shown in Figure 2, the initial point for the iterative grid expansion is a starting grid with its grid congestion. In this case the base grid before expansion is modelled on the starting grid (Startnetz) from the 2019 first draft of the German grid development plan (50 Hertz Transmission et al. 2019b). This grid already incorporates some future power lines where the planning process has reached an advanced stage. The second data set needed is the pool of additional potential lines for the grid expansion algorithm. This data set comes from a model grid provided by the German Federal Network Agency (BNetzA) for the year 2025. Based on the grid congestion of the starting grid the first step of the iterative process is started, where all grid variants that consider one expansion project are created. In the second step the load flows and resulting congestion for all these grid variants are calculated. The expansion projects with the highest grid relief are selected in the third step (we keep more than one configuration for the next step to avoid path dependency in a local minimum). The last step of the grid expansion process comprises checking whether grid congestion for the chosen grid configuration is still above the termination criterion for the iterative process, which was set at 1 TWh of total congestion work. If it is still above, the procedure is continued. If the criterion is met, the last result is used as the final grid.

To quantify the line lengths of the required grid expansion, we us a factor of 2.2 applied to the length of a straight line to estimate actual line length as the real geometry of a future line is not known. This factor was determined from a comparison with the expansion measures in NEP 2019 (50 Hertz Transmission et al. 2019a).

Appendix C

Supplementary illustrations of results

Figure 3 shows for transformation level A the average self-supply rates in the case where all power plants are allowed to participate in the 457 decentralised markets in Germany. For areas with high RES-E potentials or/and low electricity demand high self-supply rates result (green areas), while areas with high demand and low potentials (e.g. large cities or locations with electricity-intensive industry) can only achieve very low degrees of self-supply (red areas).

Figure 3: Average self-supply rates in the 457 areas for level A in the case All – Area

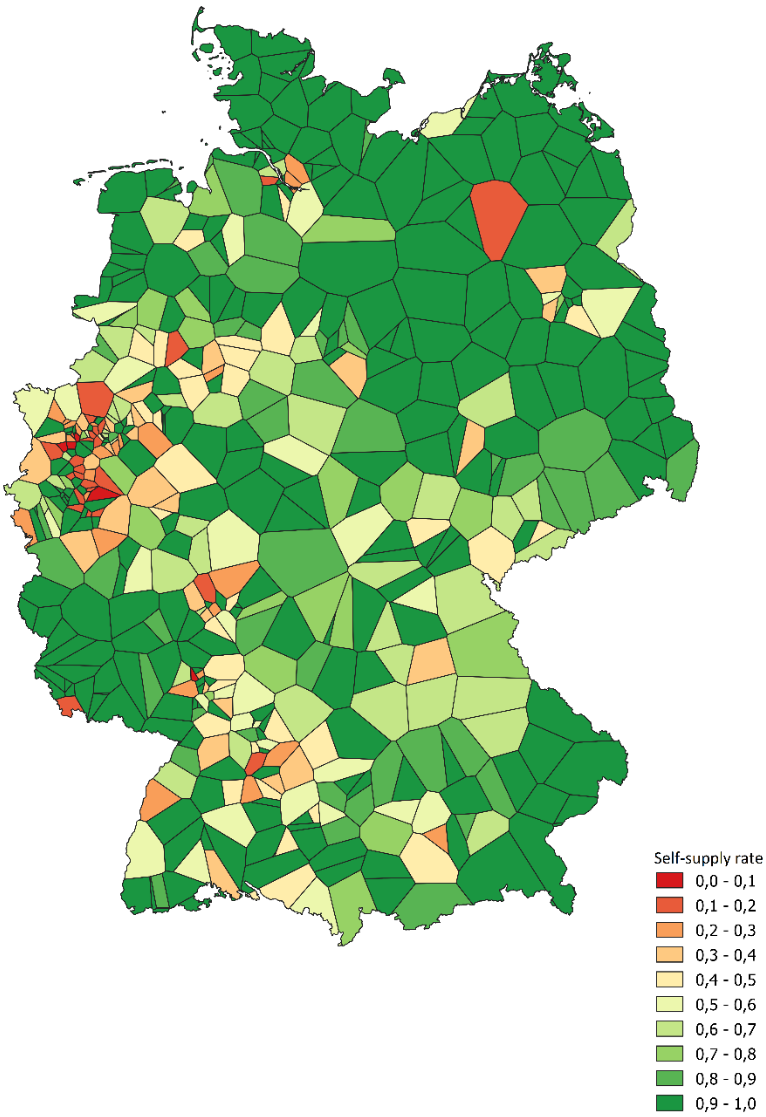


Figure 4 shows the average capacity utilisation of the transmission grid lines for the three cases with the strongest difference of grid usage (Reference, All – Area and All – Reg.). In this illustration, the hours of the year are not arranged chronologically, but according to the size of the parameter value (annual duration curve). The capacity utilisation is estimated after grid expansion and shows the hourly average values of all lines. The content of the figure is discussed in chapter 4 of the main document .

Figure 4: **Average capacity utilisation of the transmission grid lines for level A**