Impact of the Nuclear phase-out on the German Electricity System

Techno-economic analysis on changes in grid and market results

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Abstract

The German electricity system has been undergoing an extensive transformation in the last two decades. Next to the introduction of renewable energies into the system, the decision to end the use of nuclear energy and the consequent stepwise shut down of these plants by 2022, pose a complex challenge. As the remaining nuclear plants still account for a large part of electricity generated, and Renewable Energy (RE) infeed is hard to predict, it is not clear how the electricity transmission network itself will cope with these challenges in the future. Likewise it would be interesting to study the effect of nuclear phase out on electricity markets.

To examine these questions a two-fold modeling approach is proposed in this paper. To model the phase out effects on markets, a single zone, i.e. ”copperplate”, dispatch model was built in the Julia language, and to model the effects on the transmission grid, this model was extended to a direct current load flow model. These models were used to simulate scenarios before and after nuclear phase out.

The results show that the transmission system remains stable after phase out. Shutting down the nuclear plants though is accompanied by a significant cost increase. Nuclear energy generation is replaced by conventional, more expansive generation and not by renewable generation. Renewable energy generation does not benefit from phase out, as it remains constrained by the grid.

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Chapter 1

Introduction

Following §7 1a Atomgesetz (AtG) 2020, the last nuclear power plant will stop electricity infeed in Germany on the 31.12 2022. With this date, a long chapter of nuclear power generation will end in Germany. However, the start of the actual phase out [1] has been stated and prolonged for several times. Already in 2002 the government proposed that nuclear power plants will be able to generate another 2673 TWh (Schreurs, 2013), which would have resulted in a stop in the early 2020s. Yet with the argument that Germany needs to reach its climate targets, the new government decided in 2010 the "exit from the exit" stating that power plants will be needed up to mid 2030 to ensure that Germany is capable of reaching its targeted CO_2 emissions (Cho, 2020).
Not far after the AtG amendment 2010, Japan was struck by an Level 9 earthquake, causing a tsunami to flood parts of the northern east coast of Japan. Within the incident the Daiichi nuclear power plant located in Fukushima, which was said to be immune against tsunamis, was flooded which lead to the greatest nuclear tragedy after Chernobyl in 1986 (Schreurs, 2013). As a result the German government decided the "exit from the exit from the exit" passing the 2011 amendment of the AtG with a 83 % 83 support of the German Bundestag (Cho, 2020). Following the Fukushima accident, the eight oldest nuclear power plants built before 1981 were disconnected from the grid. At first for a three-month moratorium and after the amendment for indefinite time (Grossi et al., 2017). Although the share of nuclear power on the electricity mix was reduced by 6 %, stability of electricity supply was not affected (Grossi et al., 2017). Some argue that this was possible due to the fact, that Germany started to increase the share of RE early on in 1990 with feed-in tariffs for RE and the obligation for SO to connect RE to the grid. Further the diversity in the German energy generation in terms of technology usage is beneficial for an nuclear phase out of this quantity (Schreurs, 2013; Grossi et al., 2017).
By now six nuclear power plants are still active: Grohnde, Grundremmingen C and Brokdorf will be phased out by the end of 2021 and Isar 2, Emsland and Neckarwestheim by the end of 2022 (see §7 1a AtG 2020). In 2018, these six nuclear power plants generated around 65 TWh of electricity resulting in around 10 % of the overall electricity generation in Germany (KernD, 2019). Hence between 2021 and 2022 a large portion of dispatchable power generation will leave the German electricity, which raises the following questions:

- Is the German electricity system capable of keeping a stable electricity supply?
- Who is going to benefit from the nuclear phase out?
- Which impact will the nuclear phase out have on the market?

This paper presents a linear model of the German electricity system in order to quantify the impact of

[1] In this paper the term 'phase out' is used as the exit from the nuclear power generation and hence does not cover the long-term consequences such as decommissioning of nuclear power plants and the disposal of nuclear waste. The authors are aware of the fact, that the term nuclear phase out may be misleading but has been chosen due to the wide acceptance of the term and usage in scientific literature.

the nuclear phase out of the remaining six nuclear power plants. Two scenarios (business-as-usual and nuclear phase out) are compared in order to find answers to the research question.
The paper is structured as follows: In Chapter 2 an analysis of already existing literature on this topic is presented. This will also be used to compare results to previous model runs. Next, a presentation of the used data is shown (Chapter 3) followed by the model formulation of the linear problem in Chapter 4. Finally, Chapter 5 contains the result on which the conclusion in Chapter 6 is based on.

Chapter 2

Literature review

Different studies analyse the nuclear phase out in Germany. The following chapter presents different studies focusing on the impact of the nuclear phase out. Literature between 2011 and 2020 is used in order to consider the full horizon since the nuclear phase out plans in 2011.
Knopf et al. (2014) analyse the nuclear phase out in different scenarios. They use a mixed integer cost optimization model (MICOES). The scenarios vary between the actual phase out time (as they call it Exit) covering a span of 2015 to 2038 as well as variation of technology substituting the disconnected generation capacity. They point out that the nuclear phase out itself has in comparison to other model variables such as CO_2 and gas price a rather small impact on the wholesale electricity prices. They also state, that the impact becomes even smaller the longer a nuclear exit is prolonged. This is due to the increase of installed RE power generation especially after 2020. The same observation can be made on CO_2 emission. Since the nuclear capacity is substituted by either gas and/or coal fired power plants, CO_2 emissions rise in the short term. Yet in the long term, Germany is still able to reach its CO_2 emission goal until 2050 with a nuclear phase out in 2022.
Model results by Prognos (2011) underline, that grid stability is only given with additional effort. They point out that in order to use especially wind offshore capacity to substitute nuclear power plants, grid extensions may become necessary. Also, in order to allow enough reserves for any ancillary services, more gas fired power plants located in the south should be considered. This would also increase the import dependency of Germany for natural gas.
The same argument is brought forward by Grave et al. (2012). Although they do not specifically analyse the nuclear phase out, they state that dispatchable power plants, such as nuclear power plants, provide the flexibility needed to increase RE generation while keeping grid stability. With the nuclear phase out the electricity system will rely on other flexibility providers. They conclude that this flexibility may be provided by (not yet available) gas fired power plants. there utilization level might be low though, since they are only needed in peak times.
Nolting and Praktiknjo (2020) analyse the recent years in which nuclear power plants have already been phased out. Using empirical data they show that nuclear power generation has been substituted especially by coal-fired power generation, which has led to higher CO_2 emissions in recent years. In order to analyse the upcoming years (2020-2023) they use a stochastical modelling approach, considering the fluctuational nature of RE electricity generation. They conclude, that the security level of electricity supply decreases, yet still stay on a high (”sufficient”) level. Further they point out that the international electricity market becomes more valuable. A better connection and organisation can increase stability and security of supply.
Grid stability under consideration of curtailment volumes is analysed by Bruninx et al. (2013), using a total of 162 different scenarios (Changes in time, demand profiles, RE generation profiles and import/export scenarios). Interestingly the results show, that the benefits for RE by a nuclear phase out will be small, since the curtailment shows no connection towards a nuclear power generation. Therefore, the

volume of RE in the grid is likely to stay the same, as it is constrained by the grid and not the market capacity. Hence the grid is also the constraining factor in order to reduce CO_2 emissions in future scenarios. Further, nuclear is replaced mainly by coal (both hard coal and lignite), as well as natural gas. Consistency to other studies can be found in a call for further gas-fired generation capacities.
In conclusion we find, that the German grid is capable of handling a nuclear phase out, in case the capacities can be substituted. By now, this substitution is likely to be handled by both coal and gas-fired power generation. This is accompanied by a higher volume of CO_2 emissions, as both technologies show higher CO_2 coefficient in contrast to nuclear. RE on the other hand may be restricted by grid constraints, leading to rather curtailment then higher utilisation in the electricity mix. Increase in wholesale market prices has been reported by many articles including Knopf et al. (2014); Fursch et al. (2012); Grossi et al. (2017). However, literature does compare its results to the status quo in the recent year or in comparison to other scenarios. In this paper the focus is therefore to make a short-term analysis on the last nuclear power plants leaving the electricity generation. The impact is compared to a business-as-usual scenario, allowing to directly link any changes to the nuclear phase out.

Chapter 3

Data

The data for this analysis was provided by courtesy of the Workgroup for Infrastructure Policy from Technische Universität Berlin and represents an aggregation of a plethora of data sources. Several key metrics were precalculated like marginal costs of plants or susceptance of lines, which implies assumptions about fixed fuel and CO_2 abatement costs as well as assumptions about certain aggregation mechanisms. In general, the dataset supplies an abundace of highly granular data, which can be broadly differentiated into nodal specific data and data which describes the topology of the network.

3.1 Nodal Data

The german electricity system is split into 585. About 3124 dispatchable and nondispatchable electricity generators with respective generation capacity and marginal costs are mapped onto these nodes. The generation composition by fuel is shown in Figure 3.1. The remaining nuclear plants make up about 6% of generation capacity. Additionally, wind and solar capacities are high. Other conventional generators, mainly hard coal, lignite and gas, make up about 36 % of the generations mix.

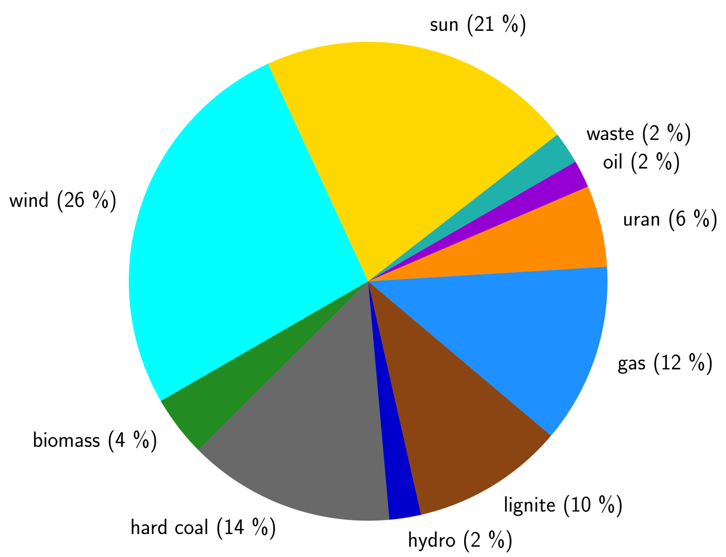

Figure 3.1: Generation capacity mix in Germany
Source: Own illustration

The hourly sharp load timeseries covers the span of a year and is specific for each node. Although balancing the transmission system is a continous process, hourly time series qualify as a good compromise for the sake of computation time. As electricity storages do not play a significant role in a span of a few days, data for storage technologies, mainly pumped hydro storage, was removed from the data set. The nuclear generators which are to be phased out were removed from the data to model the phase out.

The renewable availability percentage constitutes itself as an hourly sharp as well as technology and nodal specific timeseries. With regard to computation time, only an examplary timeframe was analysed. To accomodate for seasonal weather changes and their influence on renewable availability, a typical period of ten days for winter (t0361 - t0601, 2017/01/16 - 2017/01/26) and summer (t3769 - t4009, 2017/06/07 - 2017/06/17) were chosen, along with their corresponding demand. The availability percentages for sun, wind onshore and offshore are shown in Figure 3.2. Especially daily solar peak availability in the summer period is on average almost two times higher than in the winter period. Typical for a summer period are days with high onshore wind availability as well as days with low onshore wind availability. In comparison, the winter period shows quite a low onshore wind availability throughout the week. The offshore wind availability does not reflect any seasonality.

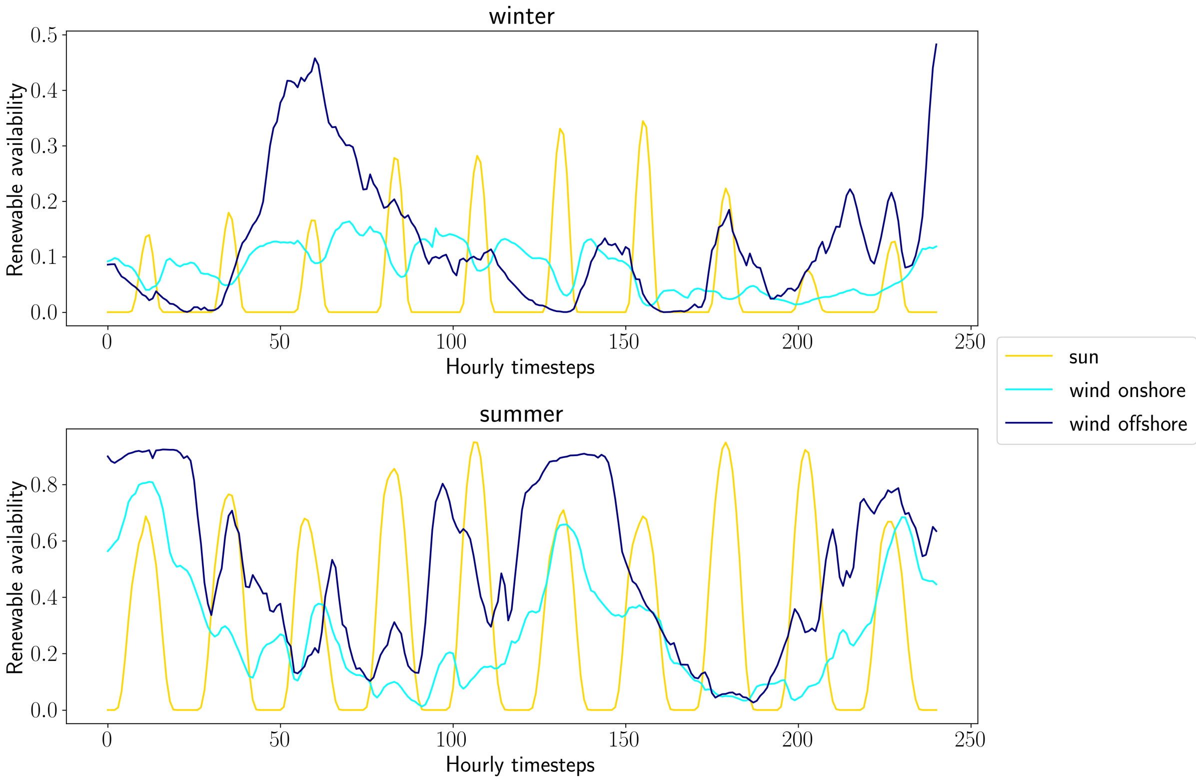

Figure 3.2: Renewable availability in example weeks for two seasons
Source: Own illustration

3.2 Line Data

The input data provides 1343 AC electricity transmission lines connecting the nodes, along with their respective key metrics like length, capacity and voltage as well as susceptance. To ensure a valid transmission network it was made sure that every node is connected to the network. Isolated nodes were dropped. Modeling an AC networks is non-linear and therefore computationally highly complex, so it will be approximated as DC lines in the Direct Current Load Flow (DCLF) model. From these lines one can firstly create the incidence matrix A, which encapsulates the topology of the network. Afterwards A and the susceptance vector b are used to calculate the PTDF matrix, which constraints nodal electricity injections in the DCLF model. The slack node was chosen to be the first node in the data set while making sure that this node belongs to the main network.
The German transmission network along with line voltages is shown in figure 3.3. Lines connecting the grid to offshore wind parks are depicted as well. Transfer capacities from and to neighboring european transmission systems are not part of this analysis and therefore not illustrated.

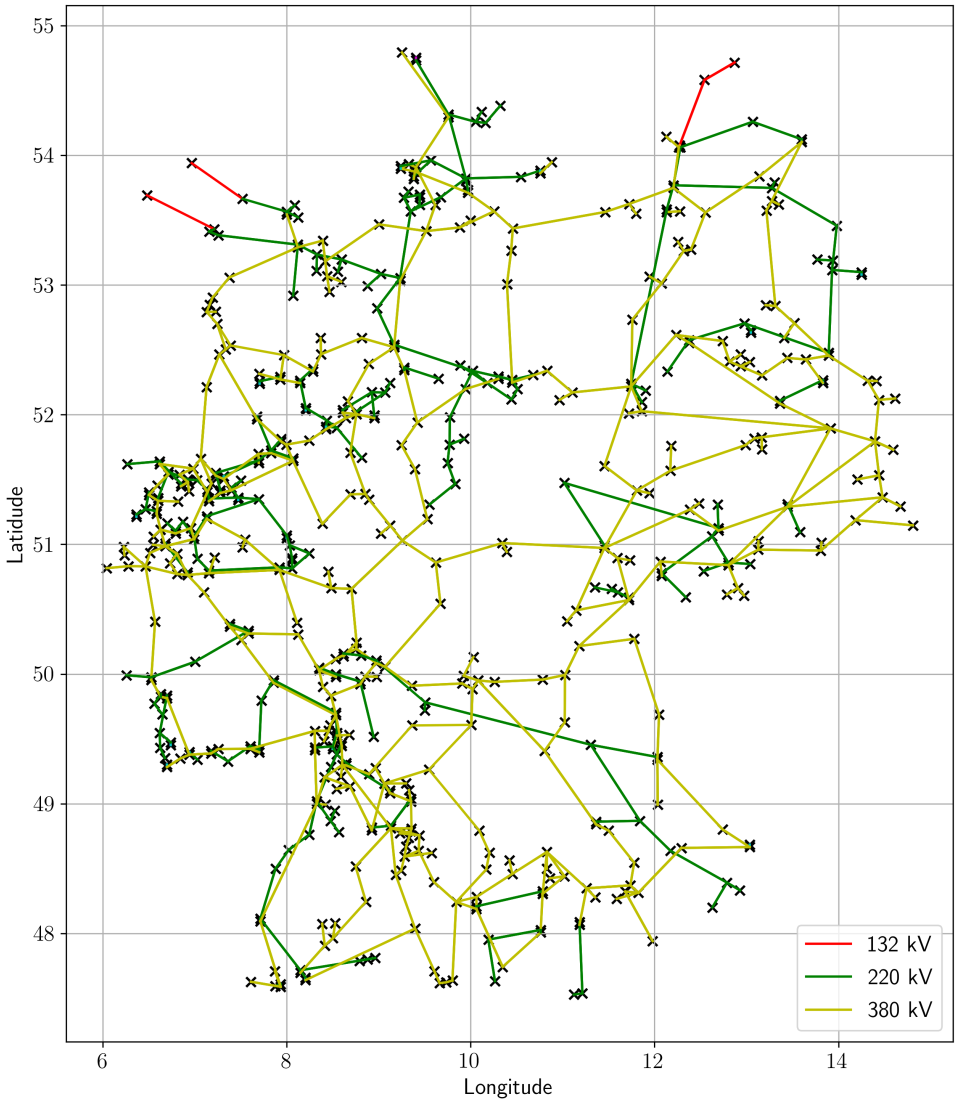

Figure 3.3: Transmission lines in Germany
Source: Own illustration

Chapter 4

Model formulation

The modeling process follows a twofold approach. At first a conventional dispatch model with a single zone, i.e. no transmission constraints, is used to study the effects of the nuclear phase out on the market clearing process. Secondly, a DCLF model is used to compare the effects on the electrical system with regards to transmission and redispatch costs in a multi nodal market. Although the DCLF model is in many ways a continuation of the dispatch model, the two models will be solved independently.
There are some restrictions to the scope of the modeling process. As its focus is the German electricity system, electricity transfers from neighbouring countries will not be part of the model. Furthermore electricity storages will not be part of the model as mentioned in Chapter 3. Additionally ramp-up cost of conventional generators were not included. Although these measures somewhat restrict the the model in its quality and distort the actual output, they where taken to guarantee a reasonable computation time with regard to the high nodal granularity.

4.1 Notation

Variables

1. $G_{p,t} \geq 0$ – Generation of plant p in timestep t (DCLF and Dispatch)
2. $INJ_{n,t}$ – Injection at node n in timestep t (DCLF)
3. $CU_{n,t} \geq 0$ – Curtailment at node n in timestep t (DCLF)
4. $CU_t \geq 0$ – Curtailment in timestep t (Dispatch)

Sets

1. T – Set of all timesteps
2. $PLANTS$ – Set of all plants
3. $DISP \subset PLANTS$ – Set of all dispatchable plants
4. $NDISP \subset PLANTS$ – Set of all non dispatchable plants
5. $NODES$ – Set of all nodes
6. $LINES$ – Set of all transmission lines

Parameters

1. mc_d – Marginal costs of dispatchable plant d
2. $gmax_c$ – Generation max of dispatchable plant d
3. $resfeedin$ – Generation of renewables according to availability
4. $ptdf$ – Power transfer distribution factor matrix of lines l and nodes n
5. $lmax$ – Transmission line capacity of line l
6. $demand$ – Demand

4.2 DC Load Flow Model Equations

The objective function 4.1 minimizes the cost of dispatchable electricity generation $G_{d,t}$ with regard to the marginal costs mc of dispatchable plant d in timestep t. Equation 4.2 constructs an upper limit for each conventional generator at each node n for timestep t.

The energy balance equation 4.3 sets the electricity injection $INJ_{n,t}$ equal to the conventional generation of plant p $G_{n,p,t}$, the renewable feed-in $resfeedin_{n,t}$, and the negative electricity demand $demand_{n,t}$ at node n and timestep t. If too much renewable energy is produced, node specific curtailment $CU_{n,t}$ takes place.

Equations 4.4 and 4.5 guarantee that the electricity injection $INJ_{n,t}$ according to the network topology, which constitutes itself in the $ptdf$ matrix, does not break the transmission line capacity of $lmax$ in both directions. Lastly equation 4.6 ensures Kirchoff's law, that all electricity injections in a single network sum up to 0.

$$min(\sum_{d \in disp, t \in T} mc_d \cdot G_{d,t}) \tag{4.1}$$

s.t.

$$G_{p,t} \leq gmax_{cp} \tag{4.2}$$

$$\forall p \in DISP, t \in T$$

$$G_{n,p,t} - demand_{n,t} + resfeedin_{n,t} - CU_{n,t} = INJ_{n,t} \tag{4.3}$$

$$\forall n \in NODES, t \in T, p \in DISP$$

$$\sum_{n \in NODES, t \in T} ptdf_{l,n} \cdot INJ_{n,t} \leq lmax_l \tag{4.4}$$

$$\forall l \in LINES$$

$$\sum_{n \in NODES, t \in T} ptdf_{l,n} \cdot INJ_{n,t} \geq -lmax_l \tag{4.5}$$

$$\forall l \in LINES$$

$$\sum_n INJ_{n,t} = 0 \tag{4.6}$$

$$\forall t \in T$$

4.3 Dispatch Model Equations

The dispatch model is a simplification of the DCLF model. As it considers a single zone, nodal electricity injections and line constraints are irrelevant. Therefore, there are no line constraints and the electricity injection has been removed from the energy balance 4.9 as well. The demand has been aggregated for all of Germany to result in a single zone timeseries. Otherwise the dispatch model behaves like the DCLF model.

$$min \sum_{d \in disp, t \in T} (mc_d \cdot G_{d,t}) \tag{4.7}$$

s.t.

$$G_{p,t} \leq gmax_{c,p} \tag{4.8}$$

$$\forall p \in DISP, t \in T$$

$$G_{p,t} + resfeedin_{r,t} - CU_t = demand_t \tag{4.9}$$

$$\forall, t \in T, p \in DISP, r \in NDISP$$

Chapter 5

Results

The following chapter shows the results obtained by the model runs. First, the dispatch results are presented, followed by the DCLF model with grid constraints. In both parts, two scenarios are presented, namely with and without nuclear power generation.

5.1 Dispatch

Figure 5.1 shows the results for dispatch for one winter (top) and summer (bottom) period of 10 days. On the left side, the scenario with nuclear power plants (business-as-usal) is illustrates, on the right hand side the dispatch results in a scenario without nuclear power (phase out) can be seen.

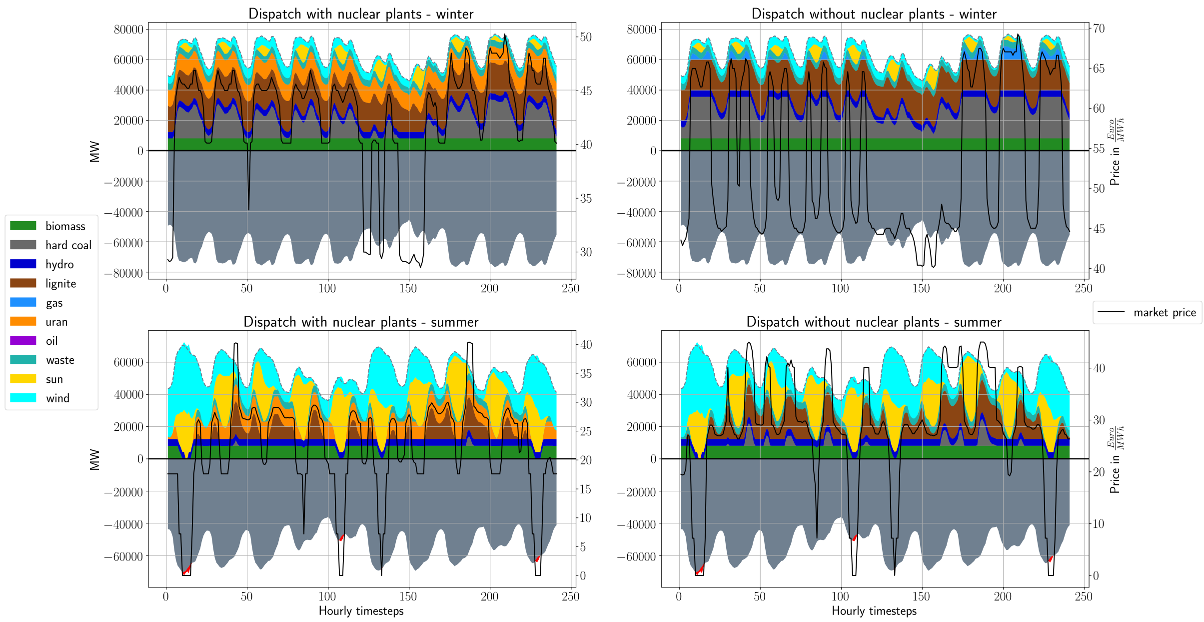

Figure 5.1: Dispatch results
Source: Own illustration

In all cases no grid constraints are accounted for. For every hourly timestep, demand, presented as negative load, has to be matched by supply, which is provided by different electricity generating technologies. In the winter scenario with nuclear power plants demand coverage relies to a large extent on dispatchable power plants. Especially hard coal, lignite and nuclear are covering the demand. In comparison to summer, demand is higher in winter, which should be considered comparing the graphics for summer

and winter.
Both wind and solar power generation is low in the considered winter period. However, solar is especially used in times of high demand, underlying the complementary accuracy of RE in Germany stated by Grossi et al. (2017).
In summer a high RE infeed leads to lower utilisation of dispatchable power generation. In 14 hours, RE generation even exceeds demand, causing curtailment in the model, which in this case is not restricted by any grid constraints but rather by the energy balancing constraint. Apart from RE, mainly lignite and nuclear is used. Generation by gas fired power plants or hard coal can be observed. A higher share of RE has also an impact on the wholesale market price. In times of low RE utilisation, prices increase with a maximum of 50.3 €/MWh in winter. On the contrary, in those times RE is able to meet the full demand, prices decrease to a minimum of 0 €/MWh.

In the second scenario (right hand side of the figure), demand still has to be covered but without the support of nuclear power plants. This has impact on the dispatch of the remaining generation pool. As the results show, nuclear is especially substituted by ramping up hard coal power plants. In times of high demand peaks, gas fired power plants are used to meet demand. But with the additional generation by hard coal and gas fired power plant, higher costs occur on the wholesale market. In contrast to a winter season with nuclear power, the average price rises by 10 €/MWh to around 53 €/MWh. Having said that, the results show, that the price difference varies heavily in summer. In total, the prices are again lower as in winter, which can be traced back to the higher share or RE. However, in times of substitution of nuclear power by lignite, prices increases by up to 32.5 % in timestep 30. Yet the price span between both maxima, i.e. maximum price with and without nuclear, stays around 5 €/MWh. Additionally, all timesteps in the model are feasible, even with reducing the generation capacity by all nuclear power generation. The impact on the load by introducing grid constraints should be further analysed now.

5.2 DCLF

Since Germany is using an ex-post redispatch mechanism, market prices are obtained due to the merit order, without accounting for any grid constraints (Schewe and Schmidt, 2019). Hence the focus of observations using grid constraints does not lie on the wholesale prices but on the actual generation mix and how they are effected also in comparison to the market results. The overall cost allows assumption on whether a nuclear phase out will increase the system costs. In Table 5.1 the business-as-usual (BAU) scenario is compared to the scenarios with nuclear phase out for the seasons winter and summer. In every case, overall cost increase with a nuclear phase out. Overall cost increase by around a factor of 3.5 between the seasons. For the dispatch model it is clear to see that gas fired generation gains importance,

Table 5.1: Comparison of overall costs

Season	**Dispatch** (in Mio. €)		**DCLF** (in Mio. €)	
	BAU	Phase out	BAU	Phase out
winter	336.5	413.8	341.8	439.9
summer	94.2	117.1	96.6	122.5

Source: Own illustration.

when accounting for grid constraints. In winter, its share is increased by 7 % after a nuclear phase out. Further, the share of hard coal is increased, but with 10 % around 4 % lower as observed in the dispatch.

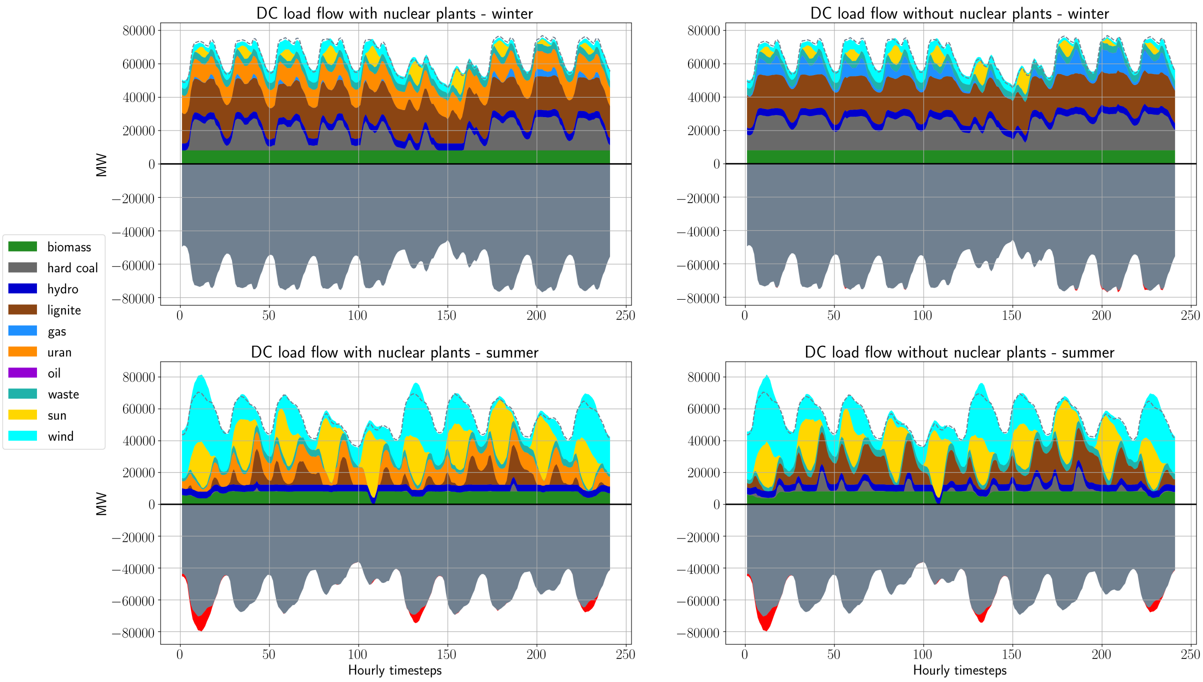

Figure 5.2: Dispatch with grid constraints
Source: Own illustration

During the summer period (see Figure 5.2) , large amounts of RE needs to be curtailed at the beginning of the period, mainly wind offshore. Interestingly, a nuclear phase out does not seem to effect the curtailment volumes, which confirms the results of Bruninx et al. (2013). Due to the curtailment, no higher shares of RE can be achieved in comparison to no nuclear phase out. The total generation mix is also shown in Figure 5.3. As already seen in the dispatch without grid constraints, lignite can benefit from the phase out only in the summer season in which it is able to increase the share by 11 %. Apart from lignite, hard coal is now not only used in winter, but also during the summer period in the phase out scenario, although the share is quite low with 3 %. The increase in conventional power generation with technologies using higher CO_2 coefficents in combination with a constant share or RE does also imply, that CO_2 emissions increase within a nuclear phase out.

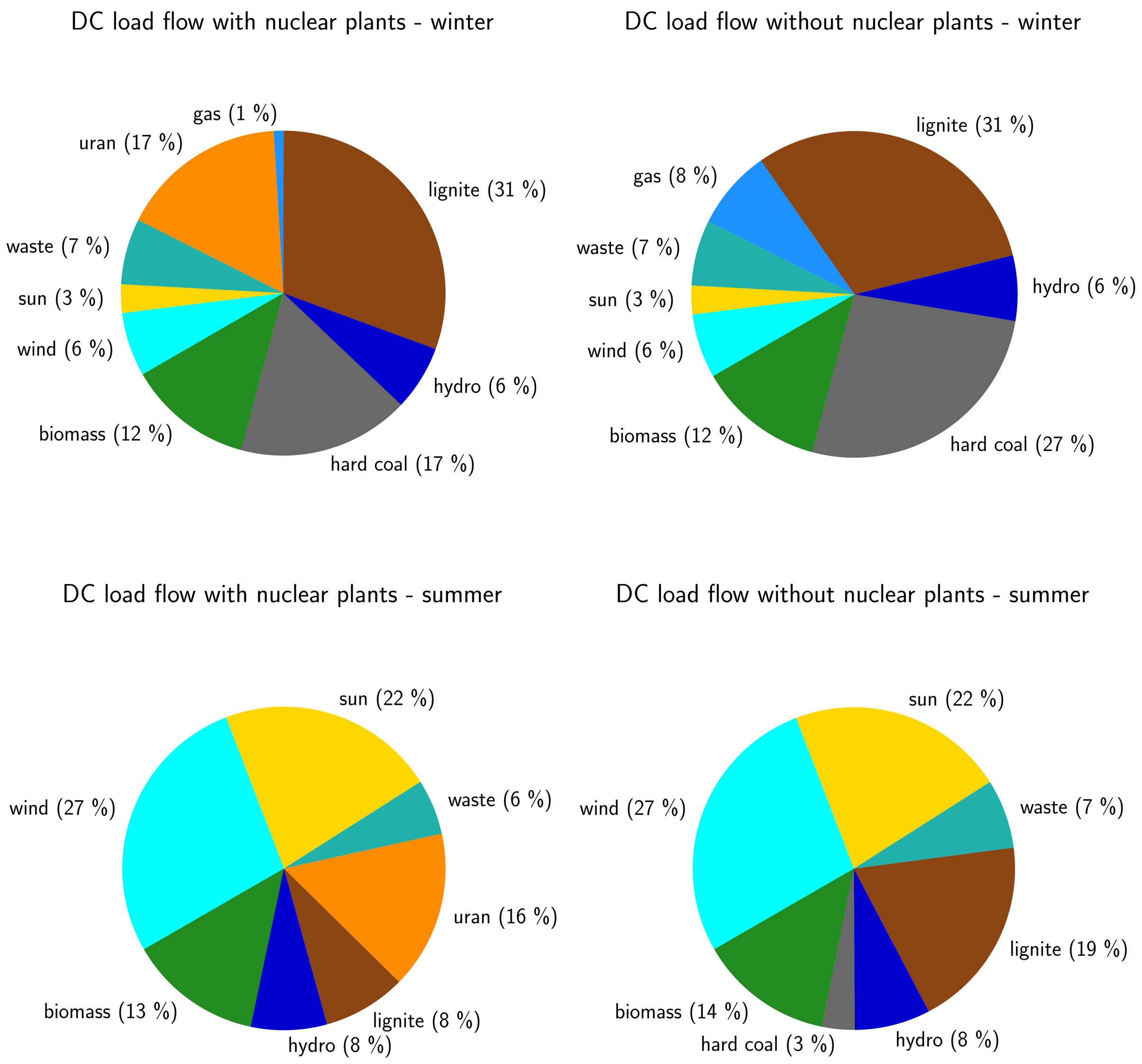

Figure 5.3: Distribution of generation with grid constraints
Source: Own illustration

Figure 5.4 shows the differences of nodal prices between the DCLF with and without nuclear power plants. From the difference the median has been calculated in a second stage to account for comparison. The colour of each node represents its deviation from the median ranging from green (negativ or zero deviation) to red (above 15 €/MWh deviation). Instead of a map, the coordinates in longitude and latitude are shown, yet the shape of Germany becomes clear. Changes in nodal prices are equal to changes in generation at this node. Therefore, changes reveal also the impact of the generation distribution due to the phase out. The result shows that especially in the south nodal prices increase. This may occur due to the higher marginal cost of technology such as gas fired power plants. The figure also illustrates in which areas, new capacities, especially RE generation, would be suitable in order to reduce the impact of grid constraints.

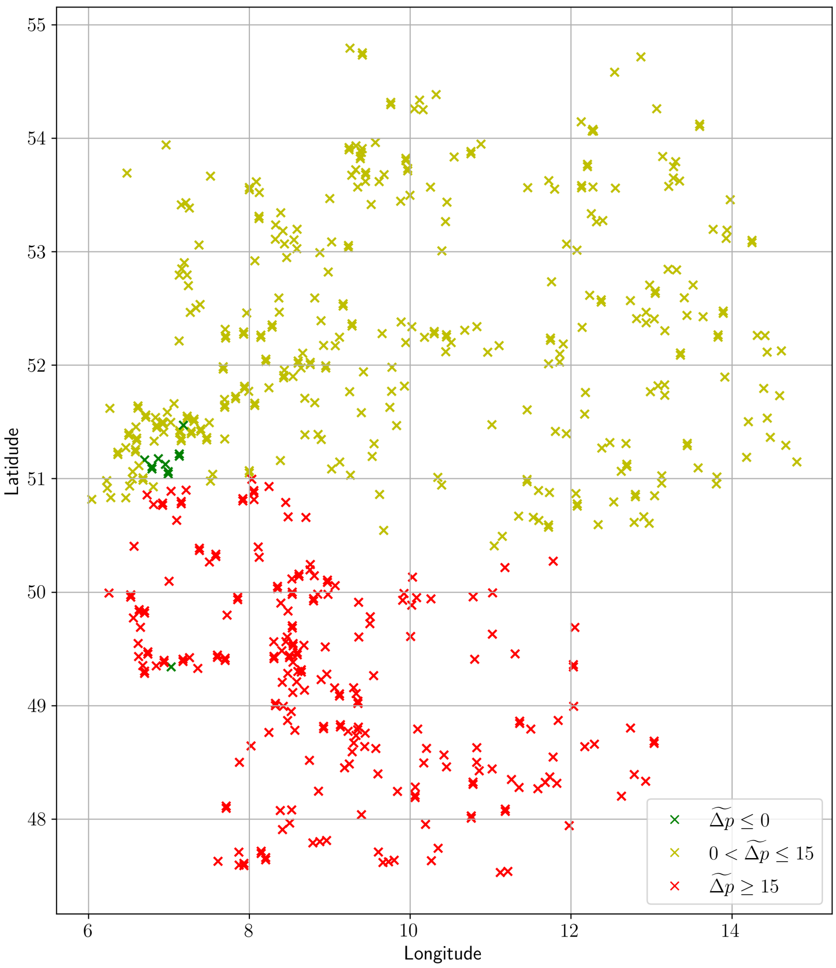

Figure 5.4: Changes in the nodal prices – winter season
Source: Own illustration

Chapter 6

Conclusion

Comparing the results of the single zone dispatch and the DCLF models reveal that grid constraints are decisive for the final generation mix and of course for final costs. Especially flexible, rather small generators like gas-fired plants, see a larger share in the final generation mix under grid constraints. RE on the other hand is limited by grid constraints. This is particularly true for wind offshore with its higher concentration in northern Germany and the resulting north-south division.
The nuclear phase out amplifies these correlations even more. RE generators cannot profit from the phase out at all because they are located on nodes with insufficient grid connection, which results in curtailment of RE. They are therefore still restricted by the transmission network and not by market results. The transport limitation is evident as curtailment practically remains the same. The consequent substitution of nuclear plants with other conventional, CO_2 intensive generators is hardly beneficial with regard to climate goals. Furthermore, because nuclear energy cannot be replaced by cheap RE but by more expansive conventional energy, total costs rise. Although for the market price the grid constraints are irrelevant, they decrease the share of RE drastically. The drawbacks also become clear by the distribution of nodal price differences. While in the south, nodal prices increase, the grid is not able to use the price opportunity given by the nodes in the north.
Having said that, the system is still able to meet demand, although large capacities of nuclear are leaving the electricity generation. In the investigated periods only feasible results in every hour have been obtained. This also means, that generation capacity is sufficient enough. Especially in light of calls for higher gas fired capacity, it has been shown, that gas fired generation is only needed in winter and is already capable of supporting during the peak demand times.
With regard to the questions raised in Chapter 1 it can be stated that the grid stability is not affected by a nuclear phase out. Substitution of nuclear power generation will especially be achieved by higher shares of hard coal and gas fired generation in winter as well as lignite during the summer period, while simultaneously RE capacities cannot be fully utilized under the chosen grid data. The impact of the phase out on the market prices can be explained with the merit order. Since nuclear power is leaving the merit order, more expensive technologies take over the capacity. Prices may be reduced on a medium to long term perspective in case RE capacities are going to increase.

6.1 Critical reflection

This section is dedicated to reflect and inform about limitations and simplifications made during the modeling approach. They can also be seen as future research areas which may be based upon this model.
In the presented model, Germany has been seen as an "island". Interconnectors towards other countries have not been taken into account. Introducing import and export can change market results drastically after a nuclear phase out, and can help to increase grid stability (Nolting and Praktiknjo, 2020). Grid

stability may also be taken into account when speaking of grid expansion. While modelling the nuclear phase out in 2022, no changes to the grid have been made, therefore the grid shows the status quo of 2019. However it is hard to predict, which grid expansion will be available by 2022, since grid expansion faces opposition in the public, which may cause delay in the planning procedures (Kamlage et al., 2020). Apart from grid changes, the installed capacity of RE generation has not been upscaled towards 2022. Higher installed capacity would lead to higher shares of RE in the electricity mix, though, from the result in can be seen, that they are already curtailed with the current data. Yet an upscaled installed capacity may not change the electricity mix after grid constrains, depending on the location of the new installed capacities. Therefore higher installed capacities of RE should only be modelled with grid adaptations. This can lead to a long-term perspective, which would complementing the short-term view, chosen in this paper.

Model framework

We provide our model (Julia), preprocessing and visualisation framework (Python) on GitHub:
https://github.com/rockstaedt/ESM

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