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High Resolution Modeling of the Impacts of Exogenous Factors on Power Systems—Case Study of Germany

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Abstract: In order to reliably design the planning and operation of large interconnected power systems that can incorporate a high penetration of renewables, it is necessary to have a detailed knowledge of the potential impacts of exogenous factors on individual components within the systems. Previously, the assessment has often been conducted with nodes that are aggregated at the country or regional scale; this makes it impossible to reliably extrapolate the impact of higher penetration of renewables on individual transmission lines and/or power plants within an aggregated node. In order to be able to develop robust power systems this study demonstrates an integrated framework that employs high resolution spatial and temporal, physical modeling of power generation, electricity transmission and electricity demand, across the scale of a continent or country. Using Germany as a test case, an assessment of the impacts of exogenous factors, including local changes in ambient weather conditions, effect of timely implementation of policy, and contingency for scenarios in 2020 are demonstrated. It is shown that with the increased penetration of renewables, while the power production opportunities of conventional power plants are reduced, these power plants are required during periods of low renewables production due to the inherent variability of renewables. While the planned reinforcements in Germany, including high voltage direct current lines, reduce congestion on the grid and alleviate the differentials in power price across the country, on the other hand the reinforcements make the interconnected transmission system more vulnerable as local perturbations have a more widespread impact.

Keywords: energy systems modeling; renewables; energy policy

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1. Introduction

The European Commission's Renewables Directive 2009/28/EC targets an EU-wide increase in the share of renewables to 20% of total energy production by 2020 [1]. As a consequence of this directive, it is necessary to increase security of supply, provide access to cheaper power, and to reduce the green house gas emissions. However, this increased penetration of renewables, primarily wind and solar, could adversely impact the efficiency of interconnected power system.

In Germany, most wind power generators are concentrated in the more windy geographical regions in northern Germany and in offshore Exclusive Economic Zones in the North Sea; this is foreseen to continue [2,3]. More than two-thirds of wind turbines in Germany are installed in the five northernmost states of the country and generate upto 45% of total wind power. Due to the high concentration of wind production in the region, occurrences of congestion in the transmission grid along the north-south corridor of Germany have been reported, as a significant portion of power demand is in southern Germany. This high penetration of wind power, coupled with photovoltaic power generation, which is more uniformly distributed across Germany, increases the variability and uncertainty in the generation schedules of conventional power plants, and in the operation of the transmission system infrastructure. As a consequence there are many difficulties and challenges for producers of electricity and for grid operators [3–7]. For example, the increased penetration of renewables has reduced the financial viability of operating conventional power plants as opportunities for production are becoming limited. Nevertheless conventional power plants continue to be required as the availability of renewables power and power demand are not closely coupled. It is anticipated that in order to provide security of supply there will be further reductions in equivalent operating hours of conventional power plants due to the increased cycling in their operation [8]. An increase in the penetration of renewable generated electricity has technical and economic impacts on power transmission systems because of the variability of renewables. Studies carried out by the German Energy Agency [9] assessed the plans for the further development of Germany's power system for connecting and integrating renewable energy sources in conjunction with the cost-efficient use of conventional power stations. The key recommendation of the study is the development by 2023 of new transmission system infrastructure consisting of 2650 km of lines in Germany including High Voltage Direct Current Lines (HVDC). In particular, two high-voltage direct-current transmission lines, the SuedLink between Wilster (near Hamburg) and Grafenrheinfeld in Bavaria, and the Gleichstrompassage Süd-Ost line from Saxony-Anhalt to Bavaria, are seen as essential to transport wind power from north to south. However, the construction of these HVDC lines has yet to begin. It is foreseen that continued growth of renewables in absence of these grid developments, will adversely impact the operation of power generators, transmission lines and the power market in Germany.

Several studies [9–13] have assessed the impacts of increased penetration of renewables, contingencies, and policy design on the power system in Europe. While these studies provide a general assessment of power flows across Europe, these prior studies use an aggregation of the large area power systems on the scale of a country or lumped control region. Therefore, it is not possible to quantitatively assess the impacts of increased penetrations of renewable generation on individual thermal power plants or transmission lines within the geographically widespread power system. However, analyses with details at the level of the individual components of highly interconnected and complex power system are required to assess the system's resilience. In contrast to previous studies [5,9] that have modeled a single country in detail, in the present work the whole region of central, eastern Europe is modeled, whilst the analyses focus on Germany; thus both the local and system wide impacts of the increased penetration of renewable generation can be quantitatively assessed. Another novel aspect of the present work is the simulation framework. Other studies use a peak winter hour and a peak summer hour as representative time periods for their assessments. In contrast, in the present work, hourly chronological simulations of the interconnected and complex power system are made for the whole year—that is 8,760 simulations per year for a given scenario. Thus, the assessments in this work account for the hourly, diurnal, synoptic and seasonal variations of the renewable generation.

The paper is organised as follows. In Section 2, the framework for the high-resolution simulations of power systems is described. Then in Section 3, the impact of exogenous factors on power generation, transmission and pricing in Germany are discussed. The paper concludes in Section 4 with a summary of key findings of this work.

2. Methodology

The simulation tool that is used in this work is EnerPol, an integrated simulation framework that has been developed at the Laboratory for Energy Conversion since 2009, and that provides system-wide, bottom-to-top, assessments of power generation mix, electricity transmission infrastructure, and market performance, [14–16]. In [14], the development of the integrated approach for modeling geographically indexed production, transmission and demand for large-area power systems is described for the test case of Switzerland. The formulations of renewable generation models that account for temporal and geographic variations and demand models that differentiate between the different end-use sectors are described in [15]. The adequacy of capacity in the planned upgrades to the grid in Germany for increases in the penetrations of renewables is examined in [16]. As described above, the present work extends these prior works by examining the impacts of exogenous factors on the individual components of large interconnected transmission systems. In EnerPol the hourly chronological generation, transmission and demand of electricity are modeled, at the level of substations, with dispatch that is optimised on the basis of physical constraints and economic considerations. In regards to generation, both conventional and renewable power plants are considered. The individual units of fossil-fuel power plants—coal, lignite, gas, and oil—are modeled in EnerPol. The operational constraints on the cycling of these individual units, including starts-stops, minimum load operation, and load following ramps, are also modeled as the recent operational histories of the units are tracked in the series of chronological simulations. The cost of electricity for the fossil-fuel power plants accounts for fuel, maintenance, fixed O&M and cycling costs. Nuclear power plants are generally modeled to operate as base load, and their seasonal shutdown for maintenance is also accounted for. Hydro power plants, that is run-of-river and pumped storage plants, are modeled on the basis of natural water inflows and flow rates. The modeling of the generation from wind and solar power plants is described below. In regards to transmission, the power flows in AC and DC transmission lines are modeled using the capabilities of MATPOWER, the Optimal Power Flow (OPF) simulation tool [17], which is integrated within the EnerPol framework. The locations, voltage levels, and electrical properties of all individual transmission lines are included in the transmission lines model. Lastly, in regards to demand, the monthly, daily and hourly electricity demand profiles of the commercial, household, industrial and transportation sectors are differentiated in the simulation framework.

The power flow simulations of Central Europe presented in this paper simulate the operation of more than 1000 substations, 70,000 km of high-voltage transmission lines, 160 transformers and 3000 power generators. The locations and voltage levels of transmission lines are extracted from the grid map of the European Network of Transmission System Operators for Electricity (ENTSO-E) [18]. In this study, the power generation and transmission system in Germany, as shown in Figure 1, is investigated. The Geographical Information System (GIS) database of the power systems infrastructure, which comprises all the substations, high-voltage transmission lines, transformers and power generators in Germany, was developed from publicly available sources [19]. Hourly chronological OPF simulations are carried out for the interconnected transmission system in Central Europe [16]. Detailed validations of historical simulations of interconnected Central European power system are presented by the authors in [20].

2.1. Modeling Renewables

For wind and solar power plants, mesoscale weather simulations are performed to determine the hourly renewables generation as function of geographic location. The weather simulations are conducted using the Weather Research and Forecasting (WRF) model [21]. A full-year simulation was conducted for central Europe at 10 km $\times$ 10 km resolution for year 2013. The hourly solar irradiation at ground level and wind speeds at eight heights between 10 m and 150 m were used in the present work. The resulting wind resources are shown in Figure 2 for the simulated region [16]. The hourly power outputs of renewable power plants are then fed-in to the nearest substation. A validation of weather simulations and their utility for power systems analyses is described in [20].

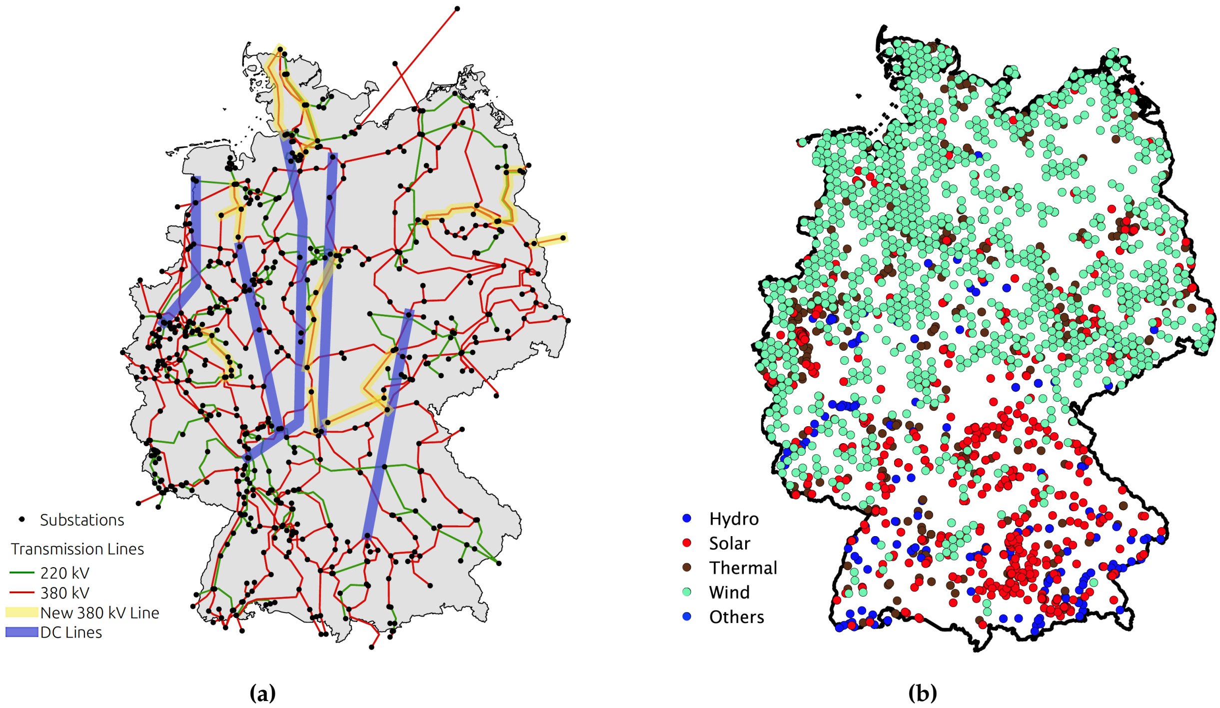


Figure 1. Germany's planned power system infrastructure by 2020. (**a**) Transmission system; (**b**) Generators.

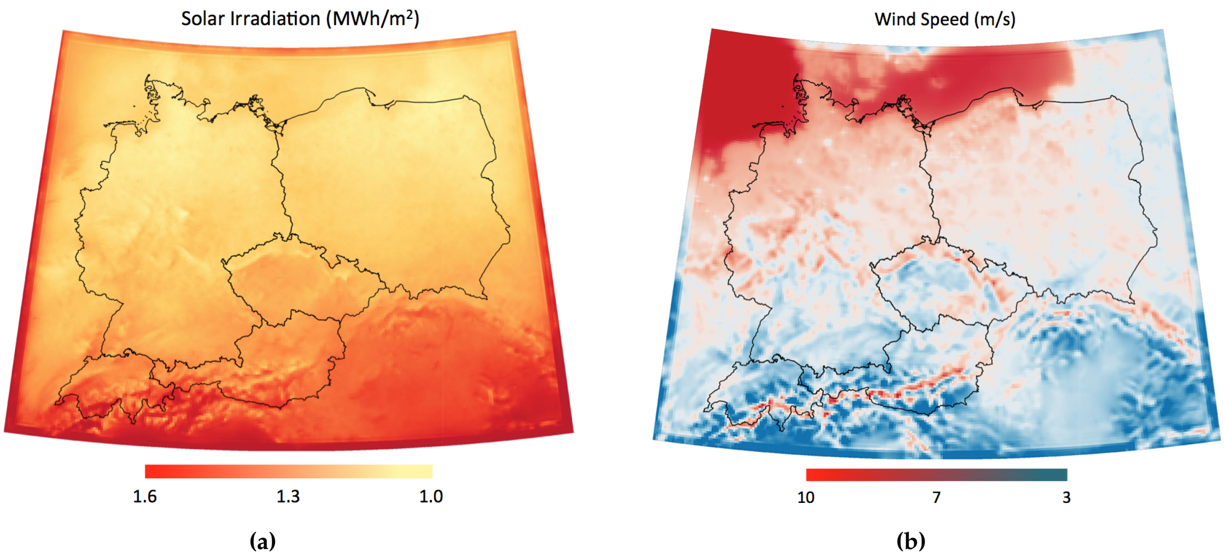


Figure 2. Simulated annual average solar and wind resources for Central Europe (Germany, Austria, Switzerland, Poland, the Czech Republic) in 2013. (**a**) Solar irradiation (ground level); (**b**) Wind speed (100m above ground level).

2.2. Demand Modeling

The hourly vertical power demand is obtained from the 2013 archives of ENTSO-E. The temporal (hourly and seasonal) shares of the demand in the commercial, household, industrial and transportation sectors are determined for every hour using standardised load profiles, for example of the German Association of Energy and Water Industries (BDEW) [22]. As electricity demand is weather dependent, the predicted hourly ambient temperatures, from the mesoscale simulations, are used to scale demand locally. The georeferenced distribution of end-user sectors are based on the Open Street Map project [23]. More details of the demand model are provided by the authors in [15,20]. For the 2020 scenario, due to the population changes and the increased standard of living that tend to increase power demand, and the increased energy efficiency due to demand-side policies and practices that tend to reduce the power demand, the growth of power consumptions are accounted for in the simulations. For the present work, the 2020 demand is assumed to be 5% lower than in 2013, as Germany's population is forecasted to reduce and the end-user efficiency is expected to increase.

2.3. Scenarios

The power systems infrastructure for the 2020 simulations are based on the National Energy Action Plans for Germany [2,3]. Table 1 compares the modeled 2013 and 2020 power generation capacities in Germany. The new renewables power plants for each technology in 2020 scenarios are located at the most economically viable locations, as described by the authors in [24]. The transmission line infrastructure for 2020 are taken from [25].

Table 1. Installed power generation capacity modeled for simulations of Germany in 2013 and 2020.

Generator	Cumulative Installed Capacity (GW)	
	2013	**2020**
Nuclear	12.1	0.0
Lignite	19.8	18.6
Coal	27.2	30.5
Gas	26.0	24.0
Wind	33.6	49.3
Photovoltaic	30.3	47.8
Biomass	5.9	7.5
Hydro	4.4	4.5

In Section 3, the results of three scenarios in Germany are presented. The first scenario assesses the impact of the increased penetration of renewables in 2020. For this scenario, the power system during the periods of peak renewable generation in 2013 and 2020 are compared. The second scenario examines the impact of energy policy. In Germany it is planned to construct HVDC lines along Germany's north-south corridor to facilitate the dispatch of renewables to the demand centers in southern Germany. Therefore, we compare Germany's power system in 2020 with and without the planned HVDC connections. In the third scenario, the impact of a disconnection between offshore wind farms and the onshore transmission system on Germany's power system is assessed.

3. Results and Discussion

3.1. Impact of Increased Variability of Power Generators

In this section, the effect of increasing penetration of variable renewables electricity production is presented for Germany's power system. The simulated renewables generation for the month of December 2013 estimated electricity produced from renewables to vary between 7% to 68% of the total installed renewable power capacity, as shown in Figure 3.

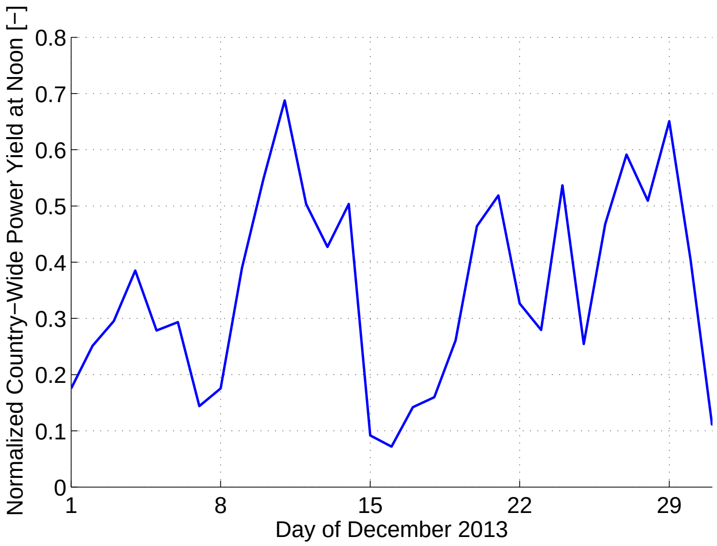


Figure 3. Proportion of renewables generated power in Germany, December 2013.

Figure 4 compares the power production of different generation technologies in Germany at the times of lowest, Figure 4a, and highest, Figure 4b, renewables generation in December 2013 and 2020 respectively.

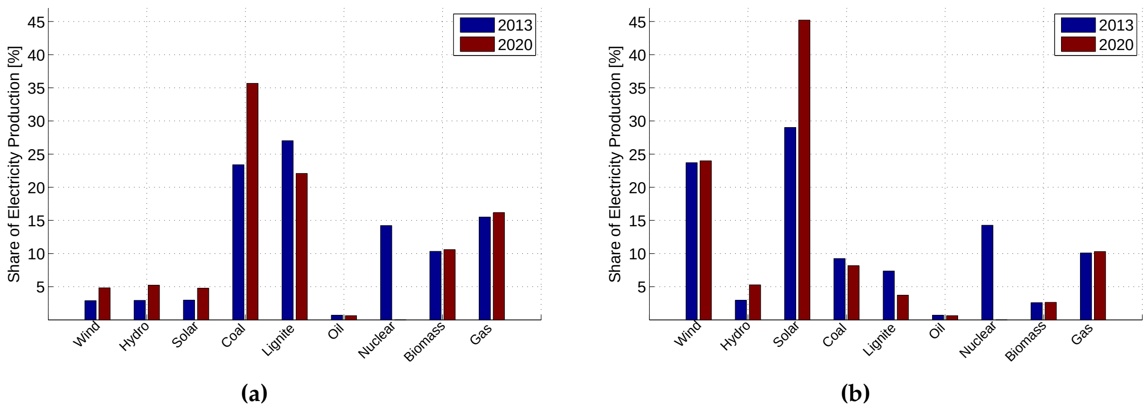


Figure 4. Power generated by different technologies at times of lowest and highest renewables penetrations in December 2013 and 2020. (**a**) 7% penetration of renewables; (**b**) 68% penetration of renewables.

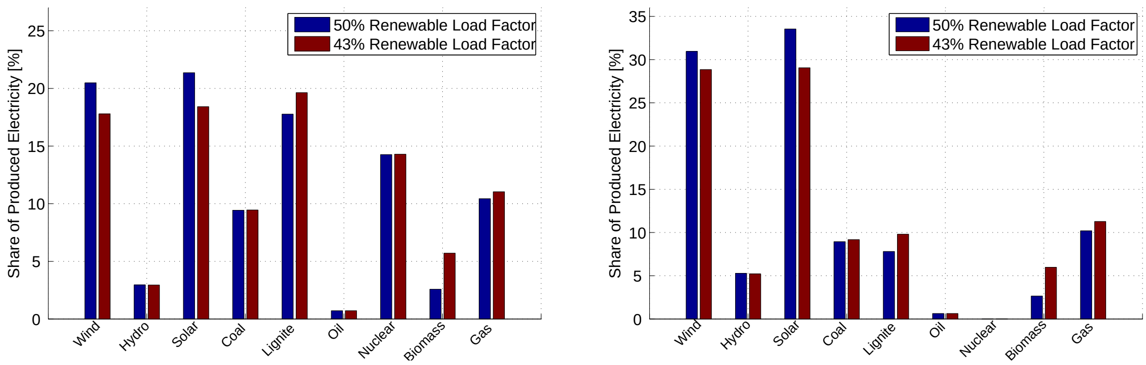
It can be seen in Figure 4a that at the time of lowest renewable generation in 2013, wind and solar each comprise of 3% of the total power produced, whereas from conventional power plants—coal, lignite and gas— produce 65% of total power generated. For 2020, the renewables in-feed increases to 5% each from wind and solar as a result of projected increases in renewables; as nuclear power is phased-out, there is a higher production from the cheaper coal power, which contributes more than 35% of total power generation compared to only 23% in 2013. On the other hand during the period of highest penetration of renewables, shown in Figure 4b, wind and solar power in 2013 contribute 24% and 29% respectively. The contribution of solar in 2020 increases substantially compared to 2013, and accounts for 45% of total power generated in Germany. In comparison to the times of low renewable penetration, Figure 4a, the contributions from conventional power plants are significantly reduced.

The mean electricity prices increase by 9% and 9.5% from 2013 to 2020 at the times of low (7%) and high (68%) penetration of renewables respectively, as more of the conventional power plants are required to operate in place of the phased-out nuclear power. However, the mean prices for the low (7%) renewables penetration are 22.8% and 22.2% higher for 2013 and 2020 respectively compared to the high (68%) renewables penetration, due to the need of operation of conventional power plants in order to balance the power demand. Table 2 summaries the maximum and minimum prices for the low and high renewables. Due to the higher degree of transmission grid congestion at the time of high renewable penetration in 2013 (scenario 3) the spread between maximum and minimum prices is relatively large, while the difference is reduced for the high renewables penetration in 2020 (scenario 4) indicating that grid congestion is alleviated by the planned HVDC lines that transport renewables along the north-south corridor in Germany (discussed in Section 3.2).

Table 2. Maximum and minimum prices as percentage of mean prices for individual scenario.

Scenario	Renewables	Electricity Price (% of Mean)			
		Minimum		Maximum	
		2013	2020	2013	2020
1	7%	91		109	
2	7%		92		110
3	68%	76		110	
4	68%		94		103

If the large penetrations of renewables are to be successfully integrated in the power system infrastructure has to be capable of operating with rapid changes in power generation due to the inherent variability of wind and solar resources. It is estimated from the data analyses that the maximum drop renewables generation in subsequent hour in year 2013 is 7% of the total renewable power capacity. Figure 5 shows the changes in the generation profiles when renewables decrease from 50% of total renewables power capacity to 43% at the same time periods in 2013 and 2020 respectively. It can be seen that in both cases the more expensive and more rapidly deployed lignite, biomass and gas power plants replace the decrease in renewable generation.



(a) (b)

Figure 5. Changes in generation profile when renewables decrease from 50% of total renewables power capacity to 43% at the same time periods in 2013 and 2020. (**a**) 2013; (**b**) 2020.

3.2. Impact of Grid Reinforcement with High Penetration of Renewables

The peak production of wind power in Germany is found to occur at 21 June 2013 at 12:00. This time is used to assess the impact of planned HVDC lines on the operation of transmission grid and pricing in Germany. Due to the planned increase in the installed wind capacity from 30 GW in 2013 to 50 GW in 2020, close to 50% of the total power is generated from wind as shown in Figure 6.

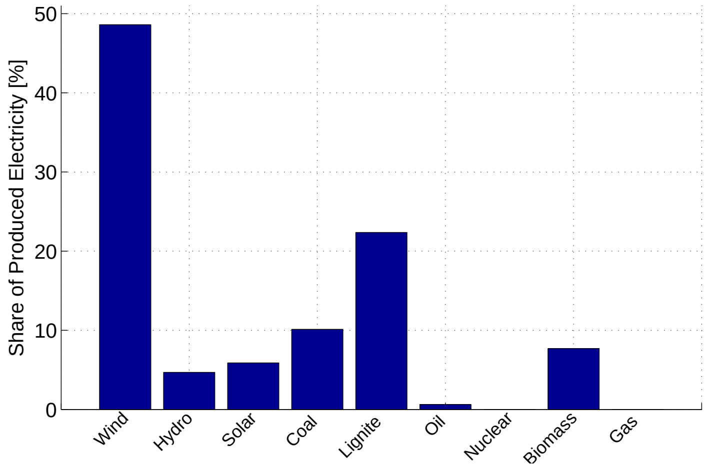


Figure 6. Power production profile for Germany at 12:00 on 21 June 2020; this is the time of the highest wind in-feed.

Figure 7 shows the line loading as a fraction of the line capacity at 12:00 on 21 June 2020 in Germany's transmission system, with and without the planned HVDC reinforcements in the grid. This time corresponds to the highest wind in-feed in 2020. It can be seen in Figure 7a that the transmission lines in Central Germany, traversing from north to south, are operating close to or beyond the transmission reliability margin (that is the mean line loads are 70% or more of the total line capacity), indicating congestion in the network in 2020 if the planned HVDC lines are not brought in to operation. On the other hand, if the HVDC lines are completed, Figure 7b, congestion is alleviated along the north-south corridor as the HVDC transmission lines transport the generated wind power to the demand centres in the south.

Congestion in transmission grid results in losses in transmission and an inability of system to meet demand economically. Figure 8 shows the locational marginal prices at 1200 h on 21 June 2020, the time of highest wind energy production in Germany, with and without the planned HVDC reinforcements in the grid in 2020. Figure 8a shows that there is a large differential in prices from north to south, with prices in the south as much as €10 higher than in north Germany; this is the result of an insufficient transmission capacity along the north-south corridor of Germany. The high demand industrial centres of Germany are located in the south, so the price differenti al may adversely impact Germany's export-oriented economy if the southern region has disadvantageous prices. In Central Germany a price differential can also be seen from east to west, as the relatively inexpensive lignite power plants that are installed in East Germany and more expensive coal power plants in West Germany have to operate in the congested transmission system. In comparison, as shown in the figure Figure 8b, the difference between the maximum and minimum prices is Germany is a factor two small if the HVDC projects are realised by 2020.

3.3. Impact of Contingency on Germany's Transmission System

In next few years, Germany has planned the development of approximately 10 GW of transmission interconnections between the upcoming off-shore wind farms of 10 GW planned capacity and the onshore grid as shown in Figure 9. A contingent disconnection of 2 GW offshore wind to the onshore transmission capacity is simulated for Germany in 2020. The peak demand at 1200 h on 5th December 2013 is used as the representative peak demand time to assess the impact of this contingency.

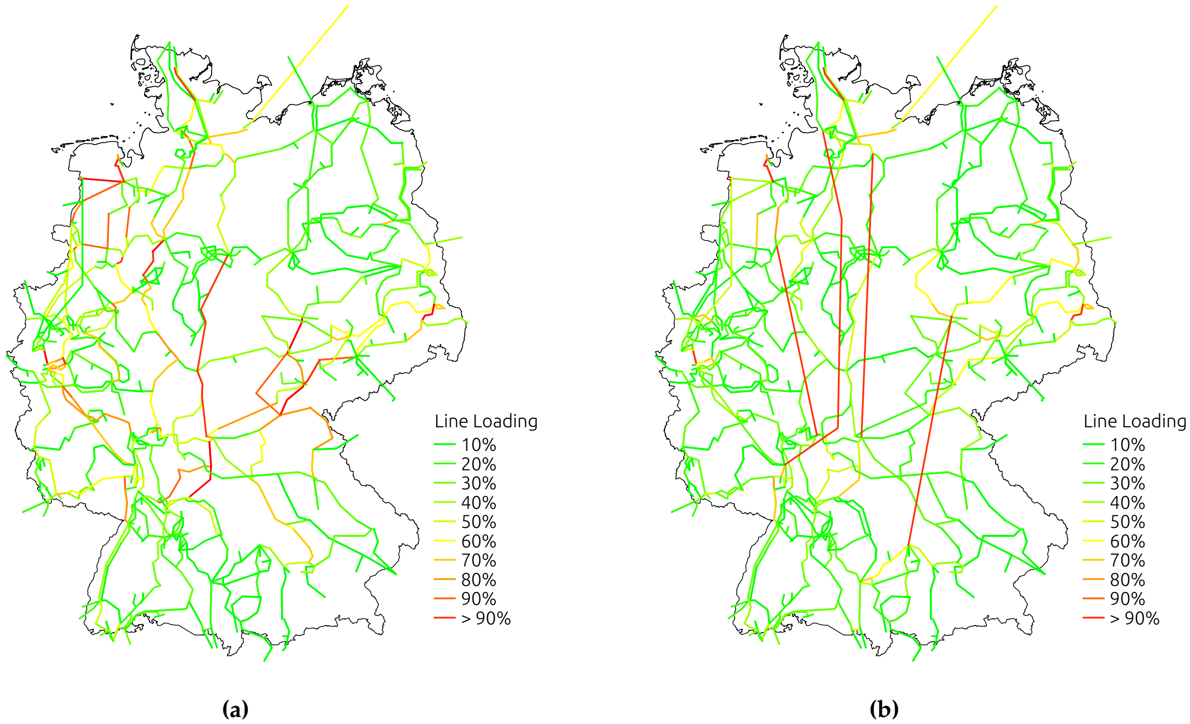


Figure 7. Line loading at 12:00 on 21 June 2020 in Germany's transmission system, with and without the planned High Voltage Direct Current Lines (HVDC) reinforcements in the grid. (**a**) Planned HVDC projects incomplete; (**b**) Planned HVDC projects complete.

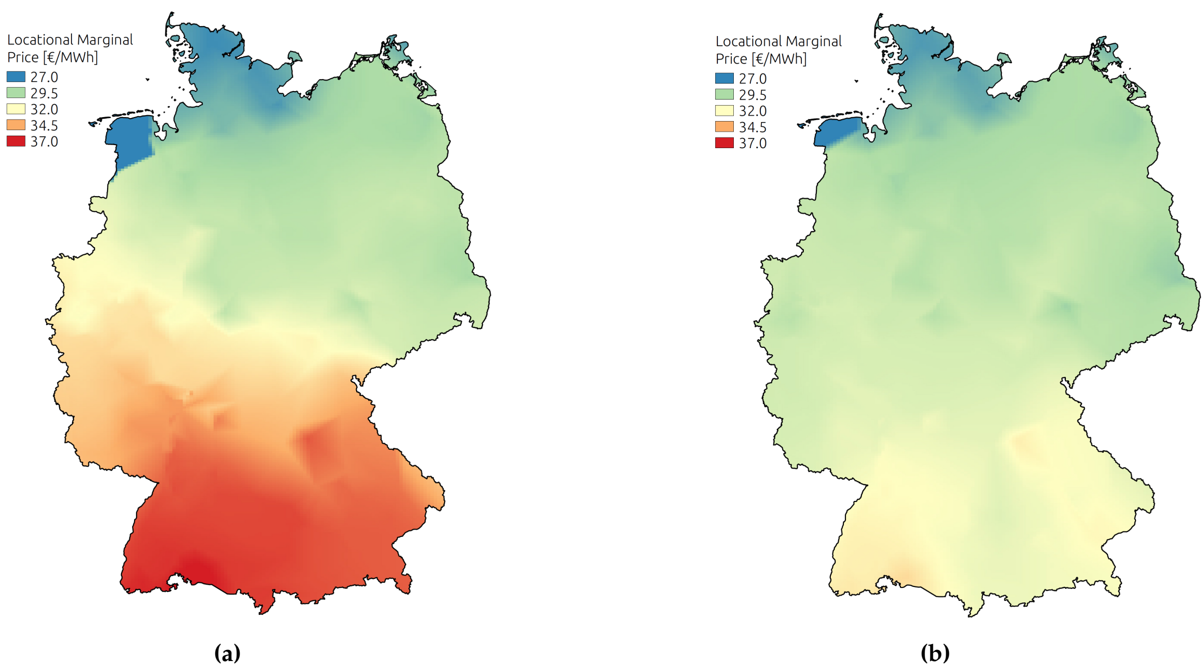


Figure 8. Locational marginal price maps for the hour of high wind energy production in Germany's transmission system, with and without planned HVDC reinforcements in the grid. (**a**) Planned HVDC projects incomplete; (**b**) Planned HVDC projects complete.

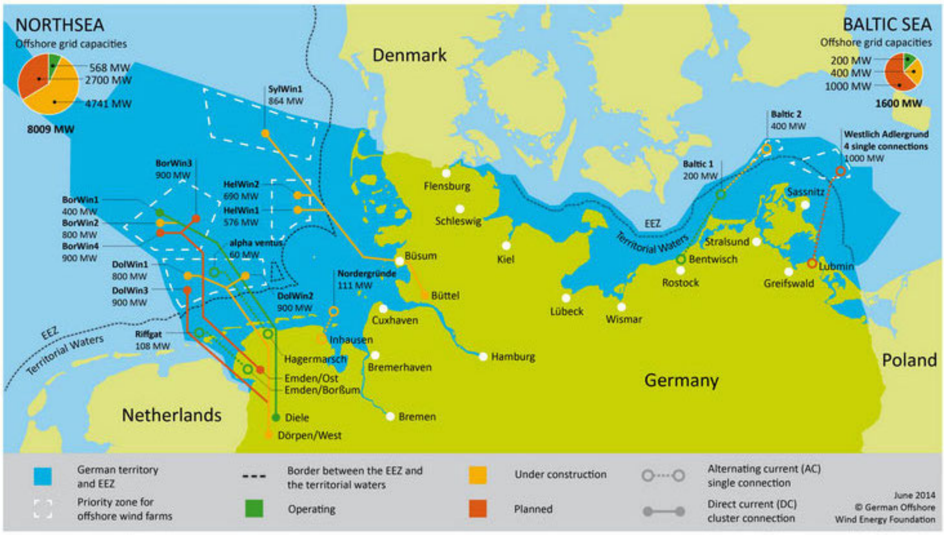


Figure 9. Planned transmission lines development in North Sea and Baltic Sea (Image: [26]).

The changes in the transmission line loads in Germany are shown in Figure 10 with and without the planned HVDC lines. It can be seen in both Figure 10a and Figure 10b that the impacts of the contingent disconnection of the 2 GW of offshore wind capacity are seen in changed line loads across the country; these changes are in response across the interconnected grid. However, one can see that the changed line loads spread across Germany to a greater extent in Figure 10b, which can be attributed to the transport of the perturbations across HVDC lines of the transmission grid to more elements of the grid. Figure 11 shows the relative changes in locational marginal prices for the two cases. As can be seen in Figure 11a, with incomplete HVDC projects, the loss of 2 GW offshore capacity during peak demand hour results in a price increase of up to 2.5% in northern Germany and 5% in the south where a significant portion of the power demand originates. However, with HVDC connections, Figure 11b, the maximum increase in price is reduced to 3.5%, in South Germany. These observations indicate that the effects of the perturbations are rather localised for operation of the grid, but the perturbations, however, could affect the power prices more adversely in absence of the planned HVDC connections.

The results of the hourly chronological simulations for December 2020 with the completed HVDC transmission line in Germany, with and without a 3.25 GW offshore wind to onshore transmission grid interconnection are compared in Figure 12. As the portion of renewables and power demand vary, the locational marginal prices differ. Figure 12 shows that there is a average relative change in prices as function of renewables generation in Germany due to disconnection of 3.25 GW offshore wind power capacity. During periods of high renewables there are larger average relative changes in prices, primarily as due to the large portion of renewables in the overall mix the absolute prices are low, which means that even a small absolute change in prices translates in a relatively large increase. Moreover, if the contingent disconnection occurs during periods of high renewable penetration the lost power capacity has to be compensated for by the more expensive conventional power plants, primarily gas. This is probable reason for high surges in average relative change in prices during the days 21st to 27th of December 2020 as can be seen in Figure 12. Thus it is evident that there will be a high degree of price volatility as Germany's transmission system remains susceptible even with timely completion of planned HVDC projects.

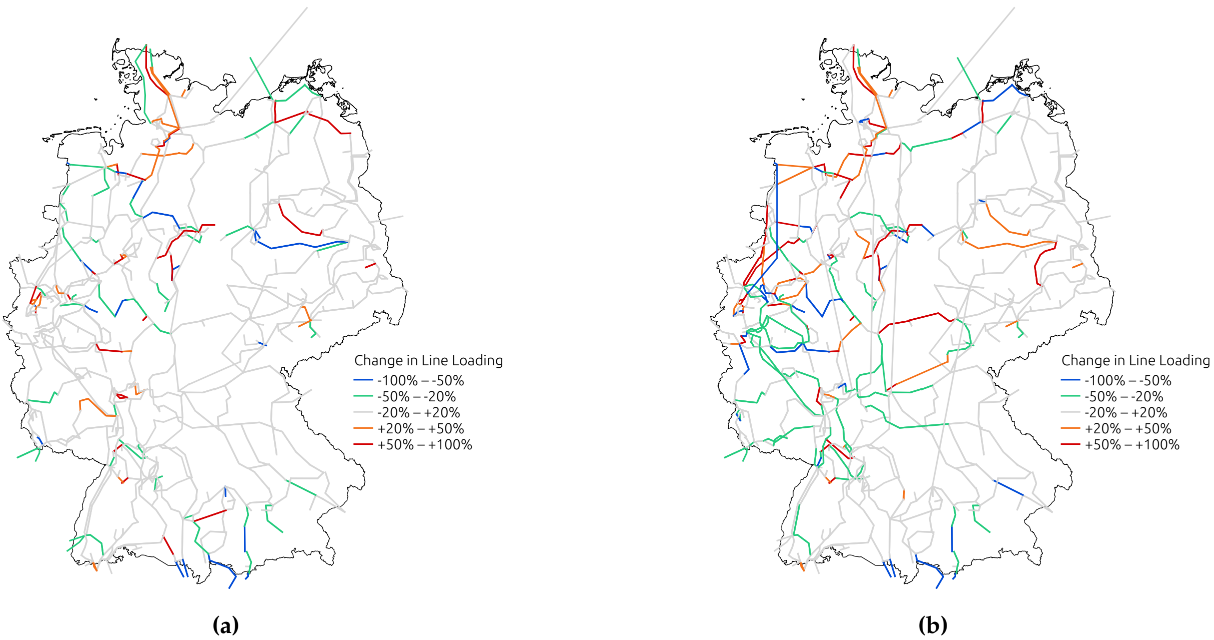


Figure 10. Line loads at 12:00 on 5 December 2020 of contingent disconnection in Germany's transmission system, with and without the planned HVDC reinforcements. (**a**) Planned HVDC projects incomplete; (**b**) Planned HVDC projects complete.

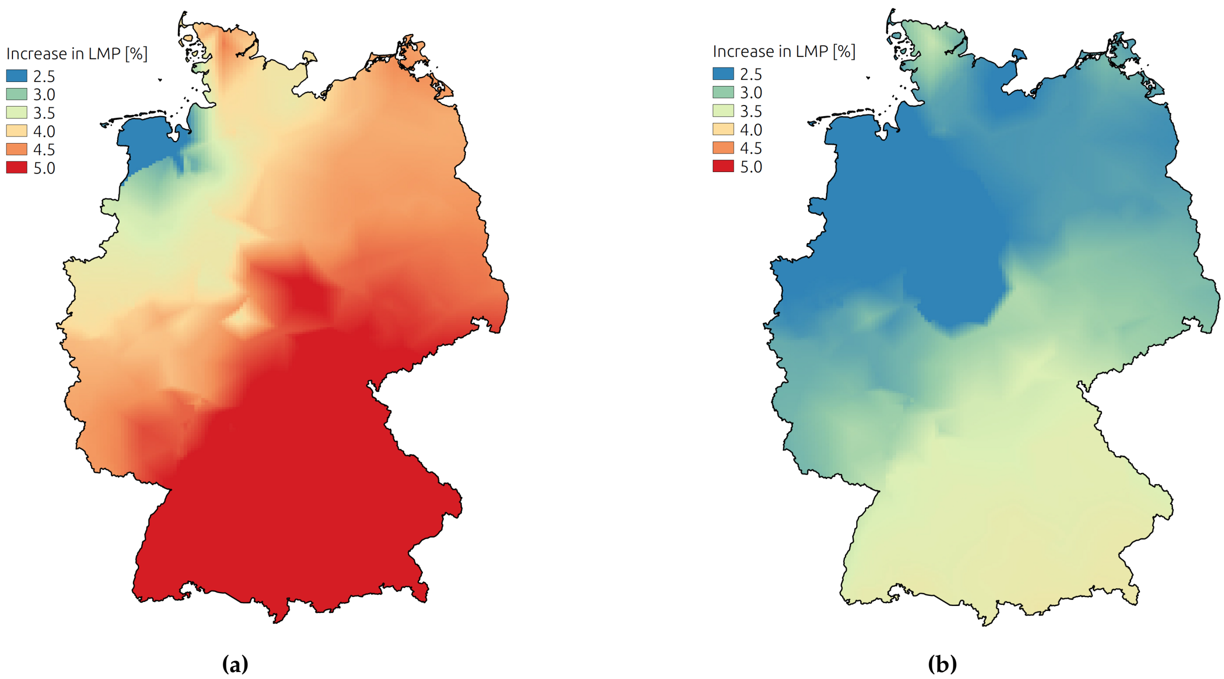


Figure 11. Change in prices at 12:00 on 5 December 2020 of contingent disconnection in Germany's transmission system, with and without the planned HVDC reinforcements. (**a**) Planned HVDC projects incomplete; (**b**) Planned HVDC projects complete.

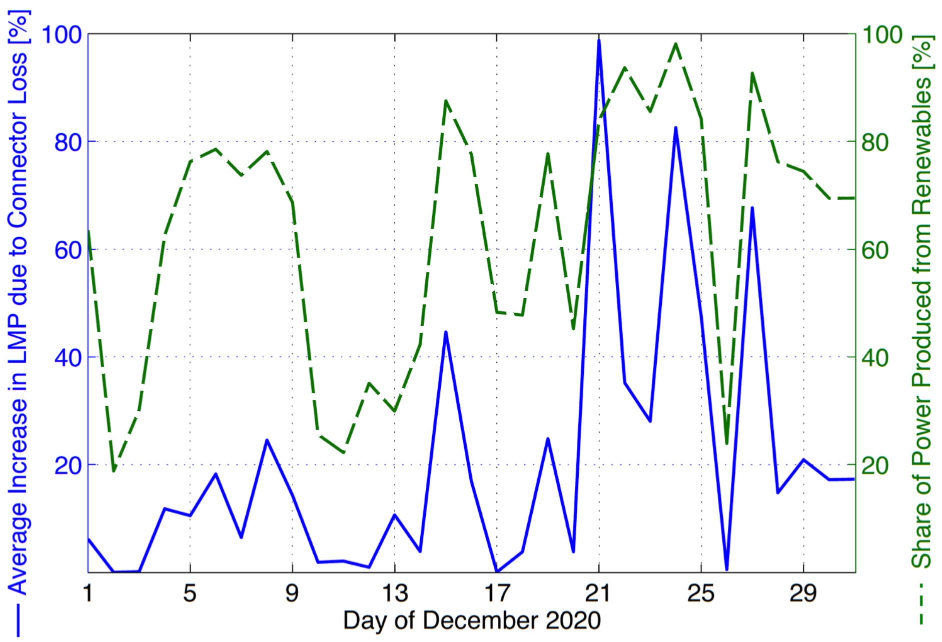


Figure 12. Average relative change in prices as function of renewables generation in Germany due to disconnection of 3.25 GW offshore wind.

4. Conclusions

Exogenous factors such as variable production from renewables generators, implementation of utility policy, and contingent events can result in adverse impacts on the integrity and operation of power system. A novel integrated analyses framework is used to assess the impact of exogenous factors in the complex and interconnected power system of Germany. Unlike the previous approaches in which the power system is approximated at national or regional scales, this novel framework models all the elements of the system spatially and temporally. The German energy transition is already underway, and its generation fleet is expected to see decommissioning of nuclear power plants and growth of renewables, especially solar and wind power. During the periods of high penetration of renewables, all conventional power plants potentially loose production opportunities with the relative share of coal and lignite power decreasing from 24% and 27% in periods of low penetration of renewables to 9% and 7% in 2013. This decrease in the share of production could be larger in 2020 as the portions of coal and lignite power decrease from 36% and 22% during the periods of low penetration of renewables to 8% and 3% during the periods of high penetration of renewables. While this challenges the notion of having the conventional power fleet in Germany, Germany would need to maintain the fleet to meet the power demand in periods of low penetration of renewables (whose share could decrease to as low as 7% of installed capacity). Moreover, the conventional power plants are indispensable for the integration of high penetrations of renewables, which makes it more difficult to address issues of market design that can promote the more profitable operation of conventional power plants. An increase in renewables by 2020, in the absence of adequate transfer capacity due to incompletion of planned HVDC projects, is shown to increase congestion in Germany's transmission system, as lines along the north-south corridor operate close to or above transmission reliability margins. Incompletion of HVDC projects has an adverse impact on price differentials in Germany during high renewables generation hours, as the price varies from €27 to €37 from north to south. This differential could decrease by factor of two if the the wind power transmission is improved through the use of HVDC lines. While HVDC projects are shown to alleviate the grid congestion and price differentials, the HVDC lines expose more elements of transmission system in Germany to contingent perturbations in the system.

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Conflicts of Interest: The authors declare no conflict of interest.

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