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SECURITY OF SUPPLY AND ELECTRICITY NETWORK FLOWS AFTER A PHASE-OUT OF GERMANY'S NUCLEAR PLANTS: ANY TROUBLE AHEAD?

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Abstract

This paper, which examines the impacts of phasing out nuclear power in Germany, is the first to include an analysis of energy supply security and critical line flows in both the German and Central European electricity networks. The technical-economic model of the European electricity market, ELMOD, is used to simulate alternative power plant dispatch, imports, exports, and network use for a representative winter day. The results suggest that the shutdown of Germany's nuclear plants will result in higher net imports, especially from the Netherlands, Austria, and Poland, and that electricity generation from fossil fuels will increase slightly in Germany and in Central Europe. We find that no additional imports will come from nuclear plants since they are already fully utilized in the merit order, and that electricity prices will rise on average by a few Euros per MWh. We conclude that closing the seven nuclear power plants within the government's moratorium will cause no significant supply security issues or network constraints and an eventual full phase-out seem to be possible due to the completion of several new conventional power plants now under construction. Finally, we suggest that a nuclear phase-out in Germany within the next 3-7 years will not undermine security of supply and network stability in Germany and Central Europe.

Keywords

Electricity, Germany

JEL-code: L94

1. Introduction[*]

Shortly after the Fukushima disaster in March, the federal government of Germany announced a three-month moratorium during which the country's seven oldest nuclear plants would be taken offline for examination. To date, a few academic studies have examined the generation needs, potential price increases, and emission impacts in the case of a phase-out. Matthes et al. (2011)[1] conclude that the seven oldest plants could be shut down immediately, and another five in the near term with some compensation through capacity construction and demand management. The German regulator, Bundesnetzagentur (2011)[2] has stated that backup capacities should be sufficient, but that Germany would lose its position as a stable provider of supply security in the European context. Other studies include r2b (2011), Prognos (2011) and Umweltbundesamt (2011).[3] We note, however, that all of these analyses neglect the interaction of generation and network conditions.

Therefore, this paper will examine the impacts of the government moratorium and a complete phase-out by utilizing a network model of the European electricity market that evaluates alternative power plant dispatch, imports, exports, prices, and network use. The simulations will be based on ELMOD, a model of the European electricity market developed at the Chair of Energy Economics and Public Sector Management (EE^2) at the Dresden University of Technology (Leuthold, Weigt and von Hirschhausen, 2011).[4] Two scenarios will be simulated: First, the government moratorium (shut-down of the seven oldest plants); in this case the overall impact on market prices and network conditions is relatively modest as Germany imports more and exports less electricity to and from its European neighbors. Second, a complete phase-out without further adjustments in German and European power plant capacities; in this case, the model is unable to satisfy peak load demand by approximately 1 GW despite increased imports, i.e. a full phase-out requires some additional fossil and/or renewable energy. Both simulations suggest that the expected net capacity growth of fossil fuel capacity, approximately 9.5 GW over the next three years, will be more than sufficient to meet demand.

The remainder of this paper is organized as follows. The next section presents the model and the underlying data, Section 3 describes the two simulations and presents the results, and Section 4 concludes.

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* This paper is part of a longer-term research program on electricity markets; see www.electricity.ee2.biz. Friedrich Kunz acknowledges support of the RWE fellowship program (RWE Studienförderung). The authors thank Jan Abrell for comments, and the usual disclaimer applies.

1 Matthes, Felix, Ralph O. Harthan und Charlotte Loreck (2011a): Schneller Ausstieg aus der Kernenergie in Deutschland. Kurzfristige Ersatzoptionen, Strom- und CO2-Preiseffekte. Berlin; Kurzanalyse für die Umweltstiftung WWF Deutschland.

2 Bundesnetzagentur (2011): Fortschreibung des Berichts der Bundesnetzagentur zu den Auswirkungen des Kernkraftwerks-Moratoriums auf die Übertragungsnetze und die Versorgungssicherheit. Bonn, 27. Mai.

3 Prognos (2011): Das energiewirtschaftliche Gesamtkonzept – Konsequenzen eines beschleunigten Ausstiegs aus der Kernenergie in Deutschland. München; Eine Studie im Auftrag der vbw – Vereinigung der Bayerischen Wirtschaft e. V; r2b (2011): Energieökonomische Analyse eines Ausstiegs aus der Kernenergie in Deutschland bis zum Jahr 2017. Köln, Studie im Auftrag des BDI; Umweltbundesamt (2011): Umstrukturierung der Stromversorgung in Deutschland. Dessau.

4 Leuthold, Florian U., Hannes Weigt, and Christian von Hirschhausen (2011): A Large-Scale Spatial Optimization Model of the European Electricity Market. In: *Journal of Network and Spatial Economics*, doi:10.1007/s11067-010-9148-1. The reference also provides a detailed model description, database presentation, and applications.

2. Model

ELMOD, a technical-economic market model of the European electricity market including power flows and network restrictions, allows simulations of the optimal unit commitment and power plant dispatch subject to transmission restrictions. For the purpose of our analysis we adjust the basic model (see Leuthold, Weigt and von Hirschhausen, 2011) by restricting the geographic coverage to Central Europe and the time frame to one reference day, a typical winter day. The basic mathematical model is:

$$\min \ costs = \sum_{n,s,t} c_{n,s} g_{n,s,t} \tag{1}$$

N.B.:

$$\sum_{s} g_{n,s,t} + wi_{n,t} + PSP_{n,t}^{down} - PSP_{n,t}^{up} - d_{n,t} = ni_{n,t} \tag{2}$$

$$on_{n,s}^{t} \cdot g_{n,s}^{\min} \leq g_{n,s,t} \leq on_{n,s}^{t} \cdot g_{n,s}^{\max} \tag{3}$$

$$\left| P_l \right| \leq P_l^{\max} \tag{4}$$

Our objective is to determine the optimal plant dispatch given generation costs *c* of the different plants *s* (equation 1) subject to three technical constraints:

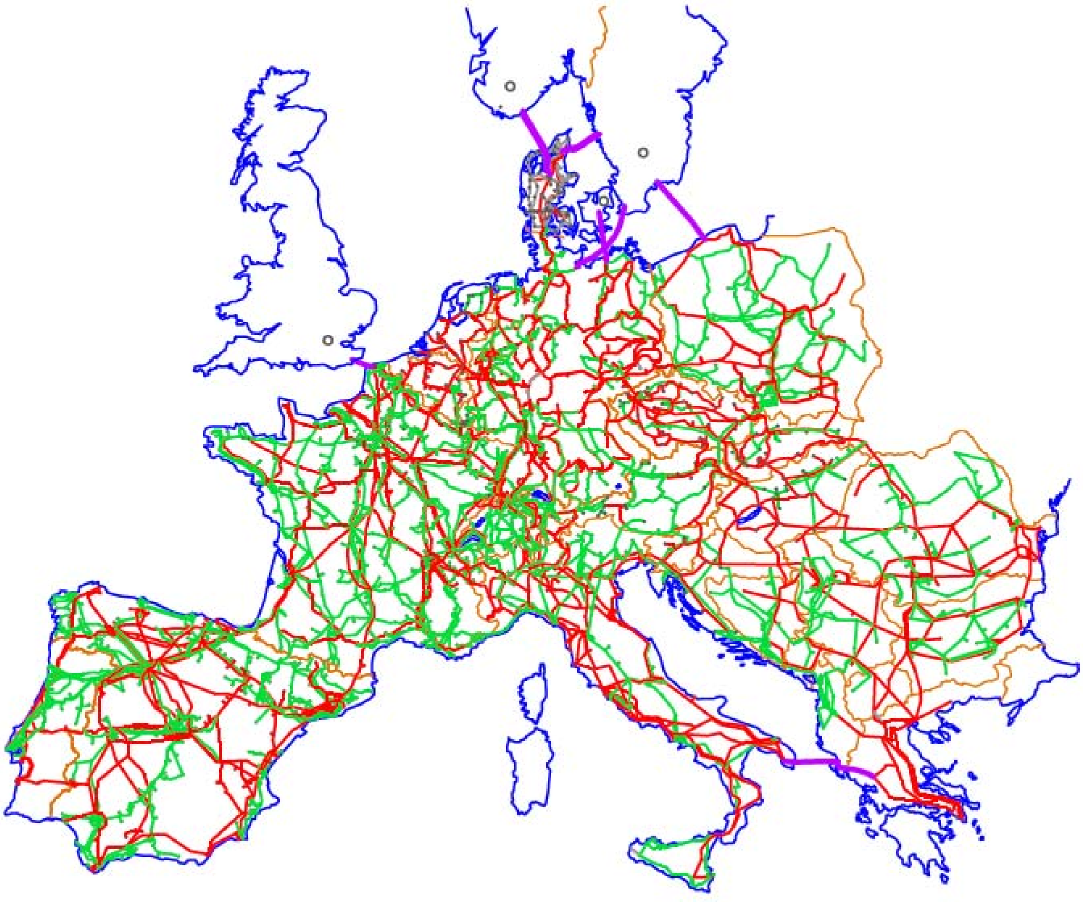
- Demand *d* and generation *g* has to be equal to the net injection (or withdrawal) *ni* at any node *n* of the system for every considered hour *t* (equation 2). In addition an externally defined wind injection *wi* is given for each node *n* and hour *t*. The dispatch can be optimized over the periods via pump-storage plants. During off-peak hours the storage can be filled (PSP^{up}), and in peak hours the stored water can be used to generate electricity (PSP^{down}).
- Unit commitment restricts plant dispatch. When a plant is running (*on=1*), the output has to be within the minimum (g^{min}) and maximum (g^{max}) capacity of the plant (equation 3). Further constraints restrict the start-up possibilities of the different plant types.
- The model considers power flows within the European electricity high voltage grid based on the DC-Load-Flow method presented in Schweppe et al. (1988). Power flow *P* on any line *l* has to remain within the power limit P^{max} in both directions (equation 4). The maximum transmission capacity is reduced by 25% to approximate the n-1 criterion.

Generation costs, the CO_2 emission allowance price and the plant availability of other generators are kept constant (ceteris paribus assumption). The reference for fuel prices, allowance prices, and demand is the twenty-four hours of November 17, 2010.[5] The model includes the entire European transmission network on a nodal scale (Figure 1), but considers only the Central European countries within the plant dispatch optimization.[6] Hourly demand is externally given for every node and is not price-elastic.

[5] This reference has been chosen as a representative winter day, and for which data availability is provided: ENTSO-E publishes hourly load values for each country within the network for the third Wednesday of every month. Furthermore the demand level on a weekday during winter is higher and consequently the resulting plant dispatch and network conditions are more critical.

[6] Austria, Belgium, Croatia, Czech Republic, Denmark, France, Germany, Hungary, Italy, Luxemburg, the Netherlands, Poland, Slovakia, Slovenia, Switzerland.

Figure 1: European network representation



3. Calibration, Scenarios, and Results

3.1 Calibration and scenario definition: moratorium and phase-out

The model is first calibrated to represent the status quo of the European electricity system in November 2011, i.e. "Status Quo" represents the previous electricity market with all nuclear plants available according to regular scheduled maintenance. Figure 2 shows the calibrated model data and the real cross-border flows and Figure 3 shows the modeled market and the observed price data for the 24 hours of November 17, 2010; note the high degree of convergence in both figures. During this period, Germany is slightly a net importer of electricity, with exports to Switzerland, the Netherlands, and Poland, and imports from France, Austria, and the Czech Republic (Figure 2). Figure 3 shows the price development throughout November 17, with lower prices during off-peak hours and a price peak in the evening.[7]

[7] Differences between the simulated quantities and prices and the real observations are unavoidable. The model lets Germany export slightly more and import less than in reality; the off-peak price is about € 5/MWh too low; and the peak price is about € 17/MWh too low. The discrepancies are mostly due to the assumption of European-wide optimal

Figure 2: Comparison of cross-border flows in the model calibration

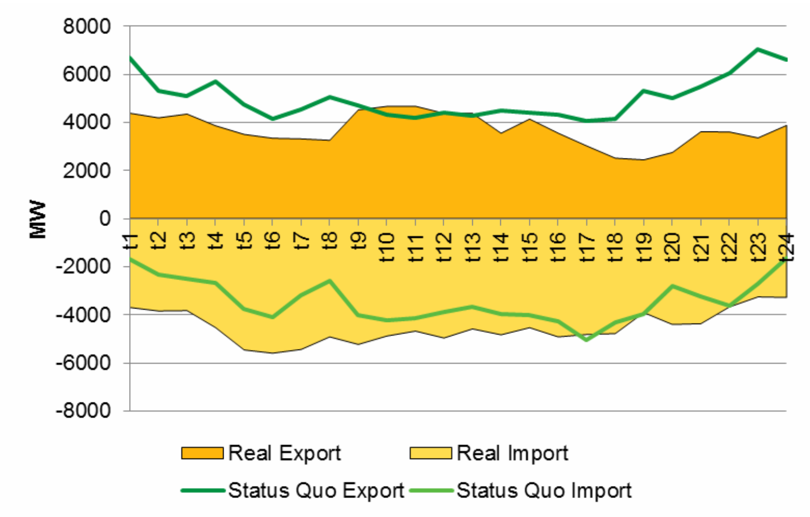
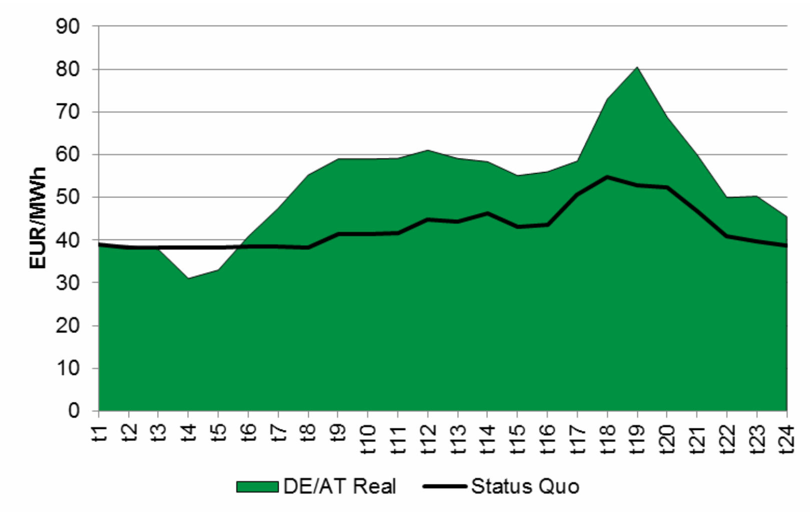


Figure 3: Comparison of market prices in the model calibration



We model two different scenarios:

- The moratorium scenario corresponds to the continuation of the moratorium on nuclear energy of March 14, 2011 when the German government decided to take the seven oldest nuclear plants offline;[8] we add the plant in Krümmel, which had been taken offline due to previous technical obstacles;
- The phase-out scenario where all 17 German nuclear power plants are taken out of service; allows us to compare the observed shortfalls of electricity to the projected capacity extensions of conventional fossil power plants and renewables

(Contd.)

dispatch, the deterministic approach neglecting uncertainty, and perfect competition. Since these assumptions are maintained throughout this paper, the interpretation in terms of relative changes is robust.

8 Isar 1, Neckarwestheim 1, Philippsburg 1, Biblis 1 and 2, Brunsbüttel, Unterweser.

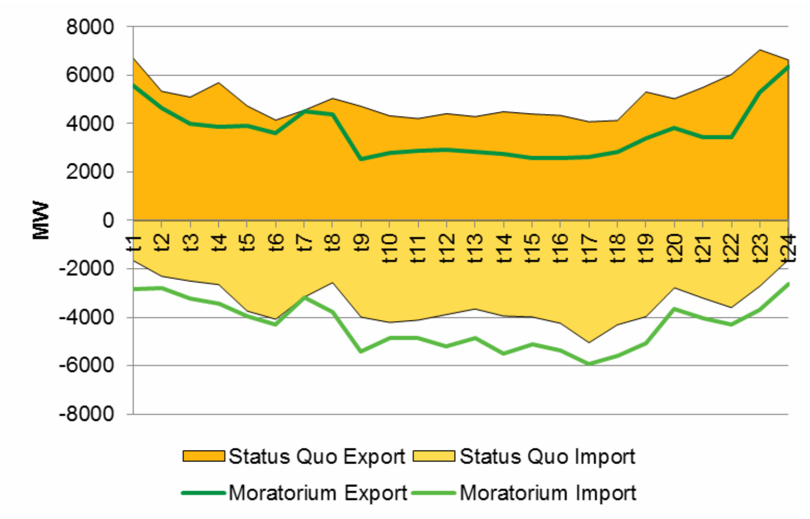
3.2 Imports/exports

Both simulations with reduced nuclear electricity generation lead to a reduction of exports and increasing imports. Figure 4 shows that in the moratorium scenario the total exports drop by approximately 25% and the imports increase by about the same. In the phase-out scenario the total exports drop to 20% of the previous levels and the imports almost double.

With respect to country-specifics we observe that in the moratorium scenario imports from France and the Czech Republic increase by 20%. On the other hand, German exports to neighboring countries drop, particularly to the Netherlands and Austria. This trend strengthens in the phase-out scenario, where physical exports are further reduced, occurring only to Poland and Switzerland. All other countries become exporters to Germany – even the Netherlands and Austria whose net trade balances shift from importer to exporter.

The change in trade flows also relies on the spatial positioning of the nuclear plants. Thus, cross-border flows to France and the Netherlands are largely determined by plant closures nearest to the French and the Dutch borders, which have a higher impact than the generation capacities within these countries.

Figure 4: Cross-border flows: Status Quo and moratorium scenario



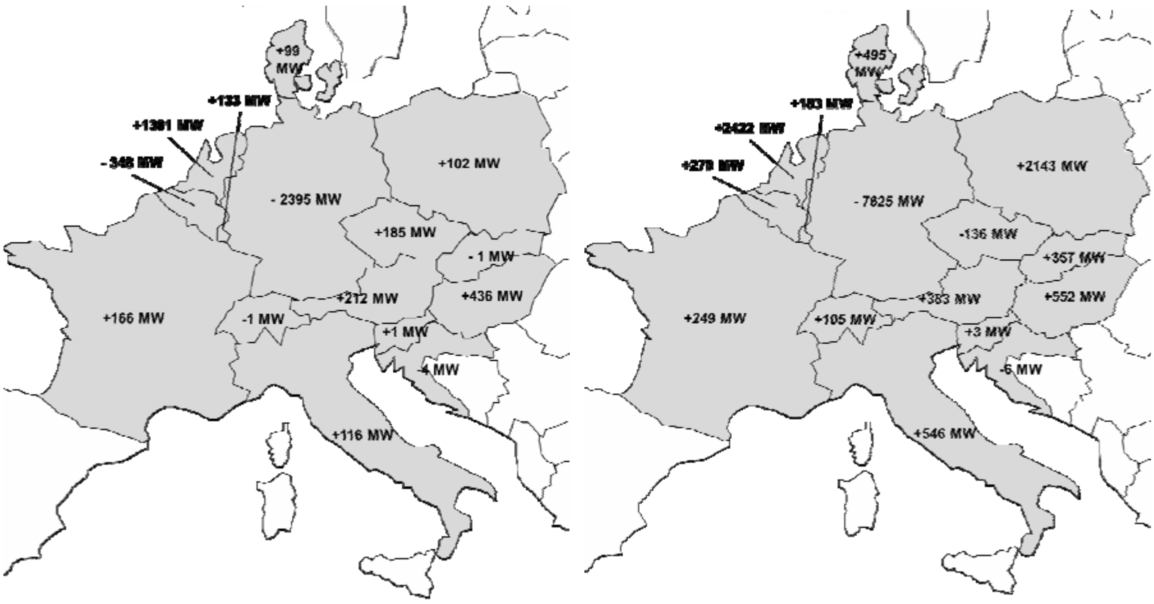
3.3 Generation dispatch and network restrictions

The shifted generation mix in Germany and the neighboring countries changes the cross-border flows and domestic flows as well. In the moratorium scenario there is a higher share of coal and natural gas fired units in Germany (Figure 5, left). Note that intermittent resources are already dispatched with priority in the Status Quo, so, ceteris paribus, they do not immediately contribute to increased electricity requirements. During off-peak hours marginal additional quantities of electricity are generated in the Netherlands, France, Italy, Poland, and Hungary to replace imports from Germany. In the peak hours when the German coal power plants are already close to maximum capacity utilization, natural gas units supply the additional generation.

In the phase-out scenario the lack of nuclear capacity is partially compensated by coal and natural gas plants in the off-peak hours (Figure 5, right). Additional plants from neighboring countries e.g., Poland and the Czech Republic, are also used. Italy increases its electricity generation from natural gas and oil plants to compensate for the lack of imports. During peak hours, mainly between 9am-9 pm, total load in Germany cannot be served with domestic or imported electricity. Although there is sufficient generation capacity in the European market, local network constraints block some imports to satisfy domestic demand.

Thus, we observe a tight market in selected hours under the phase-out scenario. However, when considering the dynamics of expected growth in the generation mix, the estimated shortage of about 1 GW seem to be negligible when compared with the ongoing conventional fossil and renewable projects that are expected to come online in the next two years. BNetzA (2011, p. 7) estimates the net generation increase as high as 9.5 GW until 2013 (of which 1.8 GW in 2011, 1.6 GW in 2012, and 6.1 GW in 2013); according to the national renewable expansion plan (NREAP) submitted by the German government to the European Commission, output of renewable electricity generators will increase from about 100 TWh in 2010 to 135 TWh in 2013.

Figure 5: Average dispatch change compared to the Status Quo in case of moratorium (left) and phase-out (right)

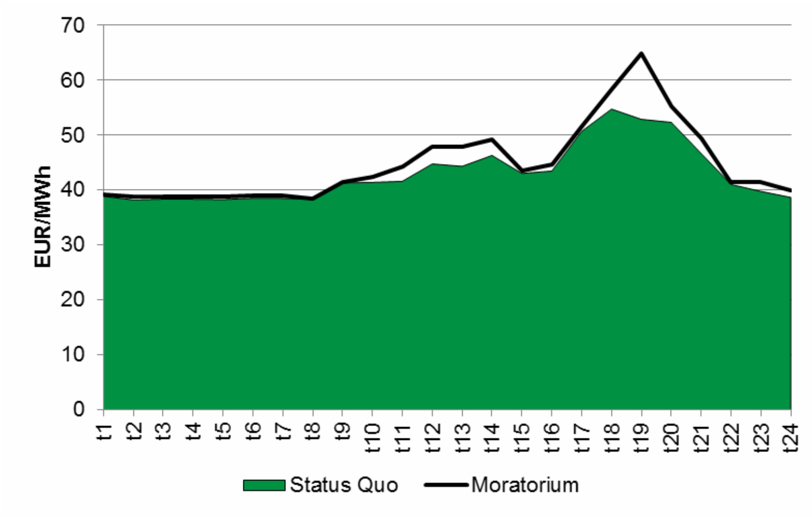


3.4 Prices

In the short term, the changing electricity mix to replace nuclear energy is based on existing fossil fuels, mainly natural gas and coal. The nuclear plants in France and in the Czech Republic do not contribute to the increased imports in Germany, since they already operate under full load in the Status Quo. According to the type of replacement capacity, slightly higher CO_2 emissions are observed in the Central European electricity sector, rising by about 0.1 mn. t (moratorium scenario) to 0.3 mn. t (phase-out scenario) within the modeling period (24h). Given the cap on total amount of emissions under the European ETS, it suggests that a slightly increased CO_2 price will result rather than additional emissions.

Figure 6 compares the development of electricity prices in the moratorium scenario with the Status Quo. The differences are minor; in particular, no significant price increase is observed in the off-peak period, whereas the European capacities are sufficient to meet demand. Off-peak prices are on average 1 €/MWh higher in the moratorium scenario and € 5/MWh higher in the phase-out scenario (not shown in Figure 6). Only in the evening peak, around 7 pm, we do observe a notable deviation of prices due to the need to switch to more expensive peaker capacity. The average off-peak price premium in the moratorium scenario is € 3/MWh.

Figure 6: Price effect in moratorium scenario



4. Conclusion

This paper has examined the impact of the German federal government's nuclear phase-out on the German and the Central European electricity system. Our analysis is the first to consider the effects on electricity generation *and* line flows by using a technical-economic model of the European electricity market. While closure of Germany's nuclear plants will lead to higher net imports, particularly in trade with the Netherlands, Austria, and Poland, the additional imports will not come from nuclear plants, since they are already fully utilized in the merit order. Electricity generation from fossil fuels will increase slightly both in Germany and in Central Europe. Electricity prices will increase on average by only a few Euros per MWh. The results indicate that closing Germany's seven oldest nuclear plants within the federal government's moratorium will cause no significant supply security issues or network constraints and that a complete phase-out in the mid term is possible, given the significant projects coming online in the next years.

We conclude that a nuclear phase-out within the next 3 to 7 years will not undermine security of supply and network stability in Germany or Central Europe. Additional research should extend this analysis beyond the typical day we have used as well as consider the specific effects of fluctuating wind and solar generation.

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