Germany's nuclear phase-out: Sensitivities and impacts on electricity prices and CO_2 emissions

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Abstract

Following the nuclear meltdown in Fukushima Daiichi, in summer 2011 the German parliament decided to phase-out nuclear power by 2022. When this decision was taken, a number of model-based analyses investigated the influence this decision would have on electricity prices and CO_2 emissions. They concluded that CO_2 emissions would be kept at levels that are in line with national reduction targets but that the phase-out would result in an increase in wholesale electricity prices. We show by means of a sensitivity analysis that results crucially hinge on some fundamental model assumptions. These particularly include the development of fossil fuel and CO_2 prices, which have a much larger influence on the electricity price than the nuclear phase-out itself. Since the decision of the nuclear phase-out, CO_2 prices have decreased and deployment of renewables increased ever since. This partly counteracts the negative effect of the nuclear phase-out on electricity prices, but on the other hand challenges the mitigation of CO_2 emissions and security of supply. This underlines the importance of sensitivity analyses and suggests that policy-makers need to consider scenarios that analyze the whole range of possible future developments.

Keywords: Nuclear policy, Climate protection, Renewable energy, Electricity market modeling, Energiewende

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1 Introduction

Following the nuclear reactor accident in Fukushima Daiichi, the German Parliament decided in summer 2011 to phase-out nuclear power by 2022. This involved a controversial public discussion (e.g. Ethics Commission 2011) and the decision also raised a lot of interest on the international level (e.g. The Economist 2011, New York Times 2011, Nature News 2011). But the phase-out in 2011 was not the first decision to withdraw from nuclear power. In 2002, the former Government already agreed to phase-out nuclear through the "nuclear consensus" between the Federal Government and the industry. Based on an average operational life-time of 32 years for a nuclear power plant, a phase-out was agreed upon with the last nuclear power plant to go off the grid by around 2023. However, in 2010, the new conservative Government opted for a life-time extension of nuclear power up to 2038 as a "bridging technology" in order to facilitate the "road into the age of renewable energies" (Federal Government 2010), i.e. the energy transition (Energiewende). In that sense, the second decision on the phase-out in 2011 constituted (again) a strategic reversal. Without discussing the details of this decision and the potential political reasons for the life-time extension, this leaves the question not only on the influence of the phase-out on prices and emissions but also if the now earlier phase-out might imply serious challenges for the overall energy transition compared to the previously mandated prolongation. In this paper, we analyze different pathways for the nuclear phase-out and narrow our scope by looking at its impacts regarding the originally envisaged role, i.e. to curb the increase of electricity prices and to decrease CO_2 emissions. Although already a number of analysis of the nuclear phase-out are available (e.g. enervis energy advisors (2011), Prognos/EWI/GWS (2011), IER/RWI/ZEW (2010), r2b energy consulting/EEFA (2010), Nestle 2012, Samadi et al. 2011, Fürsch et al. 2012) the added value of this paper is to explore a range of sensitivities, including a model comparison, and to provide a fresh perspective of the model results in light of current developments.

The first part of the analysis looks back at the time before the nuclear prolongation was revoked and allows us to evaluate the different policy options that were discussed then. Besides the precise date of exit from nuclear energy, an important and long-term political discussion concerns the possible replacement options of nuclear power. We identify how much generation capacity needs to be replaced and use a power market model to analyze the differences in prices and emissions between early (2015 and 2020), the currently decreed (2022) and the previously planned (2038) phase-out. In that context, a range of different replacement options (for example, giving priority to coal or gas-fired power plants) is evaluated. As model results depend heavily on input assumptions, these paths are tested for their robustness in sensitivity analyses in which individual assumptions are varied. In this way, a range of alternative scenarios is explored. This sensitivity analysis is completed by a comparison with electricity prices from other model-based studies that evaluate the difference between a phase-out in 2022 and a life-time extension until 2038.

While the model-based analyses concentrates on the effect of the nuclear phase-out on wholesale electricity prices and CO_2 emissions, in the second part of the analysis we relate the model-based analysis to the current situation. The comparison of different studies in combination with the results from the sensitivity analysis allows us to assess the range of results for the situation-as-is and their potential underlying causes and to distil some policy implications over the whole portfolio of available scenarios. We widen the perspective from the isolated effect of the nuclear phase-out towards the challenges of the overall Energiewende (see e.g. Nature 2013).

The paper is organized as follows. In Section 2, we present the scenario set-up, the applied electricity market model and evaluate the effect of the nuclear phase-out on electricity prices and CO_2 emissions. In Section 3, we accomplish this with a sensitivity analysis and a comparison with results from other studies. Section 4 reviews the modeling results in view of current developments and derives some policy implications. Section 5 concludes.

2 Impact on electricity prices and CO_2 emissions

2.1 Scenario definition and model description

For exploring the different pathways, an assessment of different scenarios is required. We define them along two dimensions: the year of the nuclear phase-out and the different technologies by which nuclear capacities are to be replaced, i.e. gas or coal power plants. Both aspects were most heavily debated at the time shortly after the nuclear accident in Fukushima Daiichi in March 2011. The full set of scenarios is shown in Table 1.

Regarding the development of renewable capacities, we assume the deployment path described in Nitsch et al. (2010) for all scenarios. It breaks down to an increase in renewable energies from 165 TWh in 2015 to 360 TWh in 2030 leading to a share of renewable energies in the electricity mix of 65% by 2030. Our assumptions for electricity demand, electricity production from renewable energy sources (RES), fossil fuel and CO_2 prices are based on the same study (price path B). The full set of assumptions is shown in Table 2.

Table 1: Scenario definition

Scenario Name	Exit year	Replacement by conventional power plants based on …
Exit2015-gas	2015	gas
Exit2015-coal	2015	coal
Exit2020-gas	2020	gas
Exit2020-coal	2020	coal
Exit2022	2022	combination of gas and coal
Exit2038	2038	combination of gas and coal

All scenarios are analysed with regard to the development of electricity prices and CO_2 emissions using the MICOES (Mixed Integer Cost Optimization Energy System) model. MICOES is a bottom-up electricity market model for power plant scheduling based on Theofilidi (2008) with an extension by Kondziella et al. (2011), Bruckner et al. (2010), Harthan et al. (2011). From a methodical point of view, MICOES is a mixed-integer optimization model that is capable to consider short-term marginal cost, start-up and shut-down costs as well as limited ramp rates. It uses a least-cost approach to optimise the hourly scheduling of the conventional fleet of power plants in the market. Going beyond a simple merit order approach, it is therefore able to take into account the constrained flexibility of conventional power plants.

Table 2: Exogenous input assumptions to the model. *The gas price refers to the border price.

	2015	2020	2025	2030
Gas price* [€/MWh]	27.4	30.6	34.2	37.1
Coal price (hard coal) [€/MWh]	12.6	14.4	15.8	16.9
CO_2 price [€/tCO_2]	26.0	31.2	34.3	36.4
Electricity production from RES [TWh/yr]	165	227	293	360
Gross electricity consumption [TWh/yr]	575	560	550	550

The input to the model stems from a database with fossil-fired power plants in operation in Germany (block by block for a unit capacity of greater than 100 MW, aggregates for smaller units). For each power plant, installed net capacity and electric efficiency are available (or estimated from literature). Furthermore, technical restrictions of thermal power plants such as minimum load, load change ratios, minimum downtime, minimum uptime, etc., are incorporated in the model. Renewable generation serves as an exogenous input and hourly fluctuations by intermittent sources like wind and solar power are taken into account.

For this analysis we assumed that Germany has to manage the nuclear phase-out with own capabilities. However, the model is able to utilise an additional supply opportunity (import) at a very high price (300€/MWh). This additional degree of freedom is used by the model only in a limited number of hours. More details concerning the input assumptions and the modeling approach are given in Knopf et al. (2011a) and Knopf et al. (2011b).

2.2 Projection of conventional replacement capacity

A complete withdrawal from nuclear energy in Germany means that 21 GW in net power plant capacity have to be replaced until 2022 that equals 21 % of the total conventional capacity. The first eight out of 17 nuclear power plants that were taken off the grid by March 2011 (the so-called "Moratorium on nuclear energy", Federal Government 2011) so that around 10 GW in power plant capacity were out of operation in mid-2011. This capacity was replaced by making use of existing overcapacity as well as by reducing net electricity exports. Furthermore, according to the German Association of Energy and Water (BDEW) (BDEW 2013a), a series of fossil fuel-fired power plants are under construction whose capacity of around 9.2 GW, mainly coal-fired power plants, will be available by 2015. Another net extension of 2 GW was already commissioned between 2011 and 2013. This was taken into account by the model-based analysis. In this way, the capacity of the nuclear power plants could be completely replaced by 2015. However, it is also planned to shut down 14 GW in power plant capacity from old fossil fuel-fired power plants. And by 2020, a further 13 GW in fossil fuel-fired power plant capacity are to be shut down because they reach the end of their technical lifetime. This means that, in addition to the exit from nuclear energy, a total of 27 GW in fossil fuel-fired power plants will have to be replaced within the next decade. The options primarily deployed in our model for filling this gap include the expansion of renewable energy and of (centralized and decentralised) cogeneration capacity, the reduction of electricity demand by increasing energy efficiency and the import (although only for a limited number of hours per year) of electricity from other European countries. Apart from these replacement options the construction of fossil fuel-fired power plants or the refurbishment of older fossil fuel plants has to be considered. Based on economic considerations and our model-based analysis, 8 GW of additional conventional capacity is required (see Figure 1).

The scheduling of the capacity expansion can be deferred further into the future depending on the date of exit (Figure 1). This means, e.g. in the case of a nuclear exit in 2020, not only all the power plant capacities currently under construction need to be ready, but that further fossil fuel-fired power plants currently planned or to be planned will have to be put into service. Alternatively, a prolonged use of older coal-fired power plants may be considered. An even earlier exit in 2015 would represent an even greater challenge and would probably endanger energy security. This involves many other open questions and assumptions requiring further investigation that is beyond the scope of this paper (see discussion in Section 4).

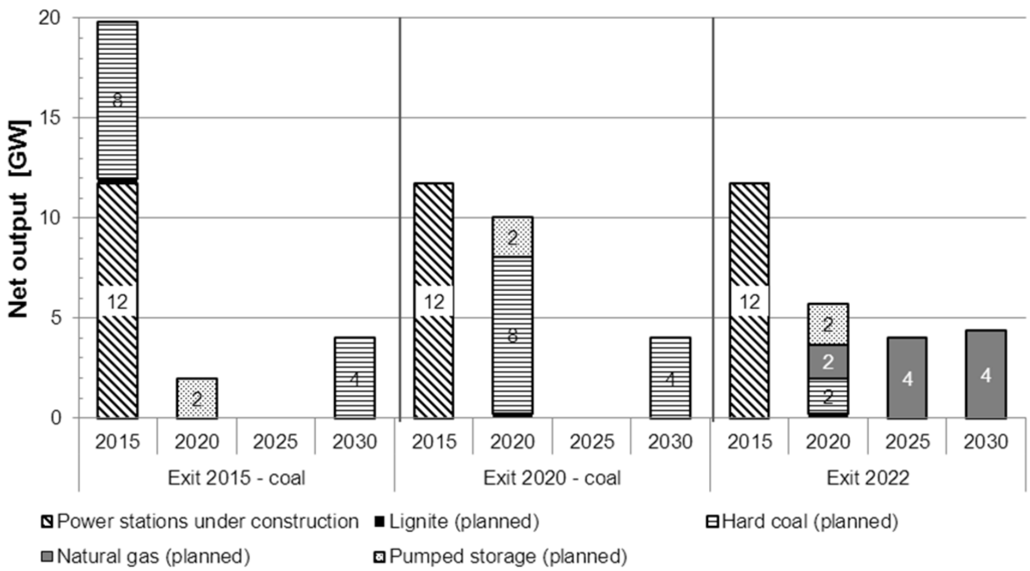

Figure 1: Replacement capacity required in conventional power plants. Comparison of scenarios *Exit2015-coal, Exit2020-coal* and *Exit2022*

2.3 Impact on electricity prices

Within liberalised electricity markets, spot market prices are based on the supply-cost curve (merit order) of all plants in the market. The marginal plant, i.e. the plant with the highest (short-term) generation costs still needed to meet a given demand, establishes the spot market price. Accordingly, nuclear energy, with low generation costs, would be the economically preferred technology within the merit order followed by lignite, hard coal and gas-fired power plants.

If nuclear power plants are to be decommissioned, the spot market price will rise in average in response, at least temporarily, since then gas fuelled power plants will set the marginal price due to the shift of the supply curve to the left. The increasing proportion of renewable energy in the German electricity mix (23% in 2012 (BDEW 2013b), and envisaged at 40 % in 2020 and 65 % in 2030 according to the Government's decision (Federal Government, 2010)) will work in the opposite direction, bringing about a long-term fall in the spot market price level by shifting the supply curve to the right. The reason is that, in accordance with the feed-in-tariff system (and the low short-term generation cost), renewable energy must be supplied at “negative” cost at the wholesale market in order to be able to ensure the obligation of grid operators to purchase all renewable energy and sell it to the market. As a result, the spot market price will rise until 2020 but then fall again to below the initial level by 2030 due to the ever increasing proportion of renewable energy (Figure 2).

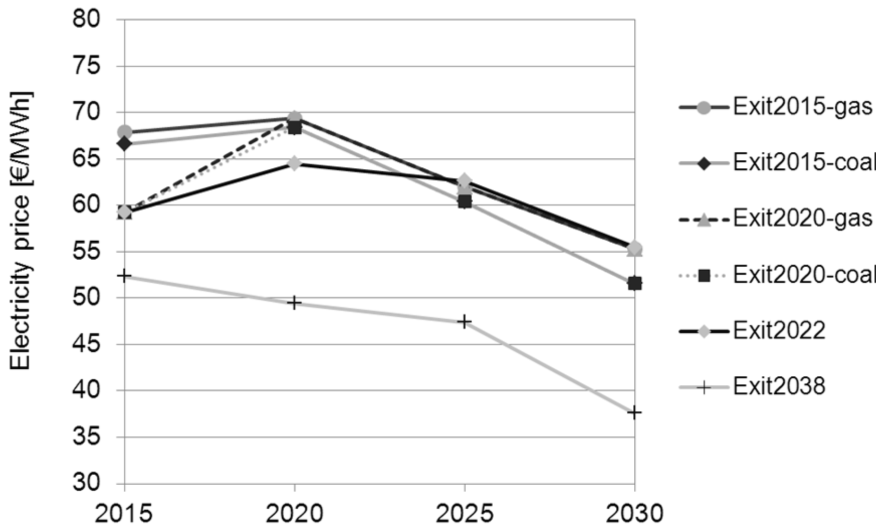

Figure 2: Development of the electricity price at the spot market (baseload). For comparison: The average price at the spot market (baseload) was 56 €/MWh in 2011

For the scenario *Exit2015-coal*, the spot market price in that year would be 67 €/MWh and thus 8 €/MWh higher than the price in the corresponding year in the case of an exit in 2020 or 2022. The reason for this is the need to draw on cost-intensive replacement capacities ahead of time. However, prices in the *Exit2015-coal* scenario are not higher in 2020 than those of the *Exit2020-coal* scenario since replacements only occur a few years later but still before 2020 (cf. Figure 1). In the case of *Exit2022*, replacements are put back a bit further so that the prices in 2020 will be 4 €/MWh lower. Long-term spot market prices, however, remain slightly lower in the case of an early exit with coal (*Exit2020-coal*) as the replacement option than under the *Exit2022* scenario. This is due to the intensified expansion of gas-fired power plants in the case of *Exit 2022* (Figure 2) which have a slightly higher cost level.

Furthermore, the results show that prices will reach nearly equal levels if nuclear power plants are replaced by either gas or coal-fired power plants. The reason is that, on the basis of the assumed fuel and CO_2 prices, electricity production costs for both technologies are approximately equal. Accordingly, if – apart from the projects under construction – exclusively gas-fired power plants are built instead of coal-fired power plants, for the scenario *Exit2020-gas* the spot market prices in 2020 will be only around 1 €/MWh higher than those under the scenario involving intensified expansion of coal-fired power plants *Exit2020-coal*.

Figure 2 also makes clear that a life-time extension of nuclear power (*Exit2038*) would have led to much lower wholesale prices and would thus have indeed facilitated the energy transition in Germany by reducing costs. In numbers, there is a price increase of 11% between *Exit2038* and *Exit2022* in 2015 and 23% in 2020.

The prices for household consumers are determined only to a minor extent by the wholesale market price and the distribution that together currently make up only about 30% of the overall consumer price (BDEW 2013c), while taxes and other expenses are responsible for 50%, while grid charges account for another 20%. From these 50% the feed-in-tariff (FIT) levy is the most important component which makes up around 19% of the consumer price. The German FIT levy which is paid by all electricity consumers with some exceptions for electricity-intensive industries is based on the difference between compensation under the FIT system and the average electricity procurement costs on the electricity exchange. Thus, a price increase on the spot market is compensated by a reduced FIT levy for the end consumers and vice versa. The largest influence on the consumer prices is therefore determined by the interplay between spot market prices and renewables deployment. As the latter is given exogenously in the model, it is not subject of the model-based analysis and will be discussed in Section 4.

2.4 Impacts on CO_2 emissions

The year of the nuclear phase-out has a clear impact on CO_2 emissions (see Figure 3) as the substitution with coal-fired power plants or gas-fired power plants the CO_2 emissions of the electricity generation sector would increase. The earlier the phase-out, the higher are the emission at least until 2025. In the long term, however, for the scenarios *Exit2015*, *Exit2020* and *Exit2022*, the emissions would be similar. An exit in 2020 instead of 2022 would of course mark only a short-term rise in CO_2 emissions (Figure 3). Nonetheless, a complete exit in 2015 would increase CO_2 emissions: In 2015, they would be 64 $MtCO_2$ higher than in the case of *Exit2020* or *Exit2022*. The additional emissions could be reduced by 20 % if the expansion of gas-fired power plants was pursued instead of coal-fired power plants. An increase of 64 $MtCO_2$ would raise German CO_2 emissions of the electricity sector by almost a quarter in 2015.

A life-time extension of nuclear power until 2038 would have reduced emissions in Germany by 45 to 70 $MtCO_2$ between 2015 and 2030 but the *Exit2022* scenario still reaches roughly 70% reduction against 1990 by 2030 solely in the power sector. In fact, the German nuclear energy phase-out in 2022, as consensually enacted in 2011, only means a return to the old “status quo” before the prolongation of the operational life of nuclear power plants in autumn 2010. Climate protection is not endangered by the earlier phase-out since the total quantity of emissions in the European electricity sector is limited by the cap of the EU emissions trading system that was set up in 2005 when the decision on the first nuclear phase-out in Germany was already taken. In that sense, the nuclear phase-out has no effect on the overall CO_2 emissions of the EU. This means that larger emissions in one region are offset with lower emissions in a different region. This may indeed affect the regional distribution of CO_2 emissions across the EU but not the overall emissions.

Nevertheless, increasing emissions can lead to an increase in CO_2 prices. This is not considered here but is topic of the sensitivity analysis in Section 3. Increasing CO_2 prices would mean that across Europe, power plants would be utilised that emit less CO_2. Since nuclear power plants have lower marginal costs, their capacities are, as a rule, already fully utilised within the framework of the existing possibilities. Rising CO_2 prices would therefore lead mainly to the utilization of more efficient fossil fuel-fired power plants across Europe.

Our analysis solely focuses on the electricity sector but the emission path is very much in line with that of the Nitsch et al. (2010) that reaches an economy-wide emission reduction of 85% by 2050 with CO_2 emissions from the electricity sector accounting for 213 $MtCO_2$ in 2020 and 105 $MtCO_2$ in 2030 compared to 188 and 113 $MtCO_2$ in our scenario *Exit2022*.

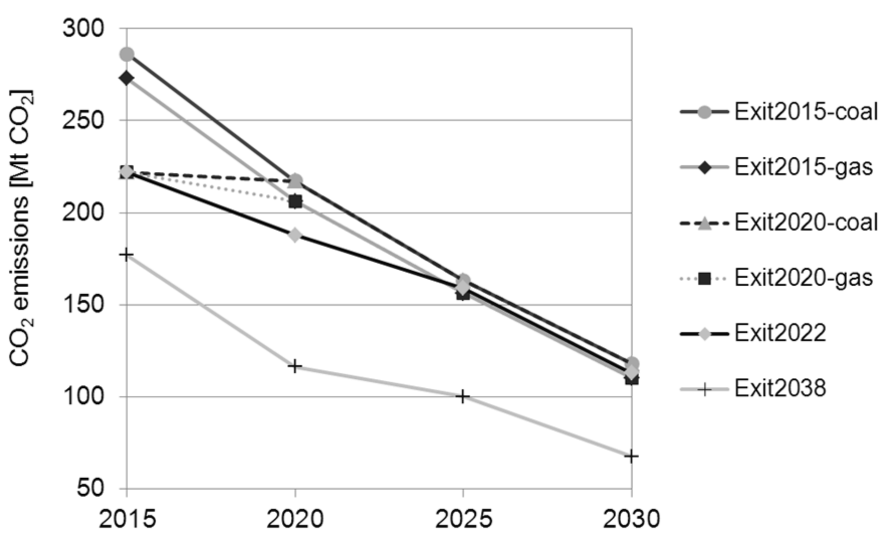

Figure 3: CO_2 emissions from conventional power plants 2015–2030

3 Sensitivity analysis and comparison with other studies

In this Section we analyze how the results depend on come critical modeling input assumptions and how our results compare to other studies in terms of outcome and assumptions. Within the framework of a sensitivity analysis the following assumptions were considered (for the numbers see overview in Table 3):

Table 3: Model parameters for the sensitivity analysis for 2020.

	Reference	Sensitivity	Difference
a) Higher fuel and CO_2 prices			
Gas [cts_{2007}/kWh]	3.86	4.85	26%
Hard coal [cts_{2007}/kWh]	2.59	3.30	27%
Lignite [cts_{2007}/kWh]	1.70	2.09	23%
CO_2 [€/t]	31.17	40.52	30%
b) Constant instead of decreasing electricity consumtion [TWh]	560.0	587.0	5%
c) Only modest expansion of decentralised cogeneration [TWh]	63.8	49.5	-22%
d) More rapid expansion of renewable energy [TWh]	227.0	267.0	18%
e) Additional system flexibility		5 GW and 30 GWh	

a) Stronger increase of fuel and CO_2-Prices

The reference scenario assumes a moderate increase of the input prices according to the "Lead study 2010" (price scenario B) of the German environmental ministry (Nitsch et al., 2010). That price scenario relates to price forecast of the WEO 2007. Due to optimistic assumptions the price scenario B turns out to be at the bottom line of the future price trend. The sensitivity of a stronger increase of future input prices according to price scenario A of the "Lead study" is analysed for the scenario "Exit 2020" in the year 2020. That stronger increase of fuel prices is derived from oil price forecasts of the WEO 2009.

b) Constant instead of decreasing electricity consumption

The reference scenario assumes a slight decrease of gross electricity consumption for Germany from 587 TWh (2010) to 550 TWh (2030) due to economic and demographic forecasts (Nitsch et al. 2010). Hence the increase of the annual primary energy productivity has to reach 2.7 % relating to efficiency targets of the federal government (for comparison: the average value is 1.8 % for the period 1991-2008). The sensitivity analysis investigates a failure of the efficiency target and keeps the gross electricity consumption at a constant level.

c) Only modest expansion of decentralized cogeneration

According to the reference case the contribution of decentralised cogeneration units to electricity demand is doubled until 2030. For the sensitivity analysis in 2020 we regard a temporal failure of capacity extension targets about five years. Comparing to the reference case the capacity is reduced by 3 GW (14.3 TWh) that has to be substituted by conventional generation.

d) More rapid expansion of renewable energy

The share of renewable energies in the German electricity market is expected to reach 40% by 2020 in the reference scenario (Nitsch et al. 2010) that is equivalent to an electricity generation of 227 TWh. Recent projections have frequently underestimated the extension path that is triggered by the German feed-in-tariff-system. Therefore in this sensitivity analysis renewable extension targets are pushed up by three years, i.e., in 2020 we assume the renewable capacity available in 2023 for the reference case, leading to additional supply from renewable generation of about 40 TWh in 2020.

e) Effect of additional system flexibility

The integration of large amounts of fluctuating renewable energies requires a flexible energy system to match supply and demand instantaneously. One option assumed in the model is pumped-hydro storage. The installed capacity in Germany is about 7 GW and 40 GWh. The sensitivity analysis assumes an additional flexibility of 5 GW and 30 GWh. This can be seen as a proxy for other flexibility options, such as demand-side-management or grid expansion.

For these five sensitivities, we take the scenario *Exit2020-gas* as the reference and compare results for the year 2020. The largest influence on spot market prices is exercised by the assumption about the future development of increasing fossil fuel and CO_2 prices which lead to a 25 % increase from 69 to 86 €/MWh in 2020. The reason for the large influence of the fossil fuel price and especially the gas price lies in the merit order (see section 2.3). As in most cases, the power plant with the highest (short-term) generation costs is a gas turbine, the gas price therefore has a large influence on the spot price.

The assumption of not fulfilling energy efficiency improvements also exerts a big influence. If electricity consumption, contrary to policy targets, remains at its current level, wholesale prices will increase by 10 %. The influence of these assumptions on the electricity price is thus similar to or even greater than the timing of the exit itself, compare Figure 2. In contrast, the impact of load shifting measures (demand-side management) can reduce prices only slightly: Likewise less cogeneration has also a relatively low impact on prices. Again, as already explained in Section 2.3 the influence on the price for households is very limited, the spread is between 22.3 ct/kWh (with DSM) and 23.5 ct/kWh (for high fossil fuel and CO_2 prices), i.e. only an increase of 4%.

Table 4: Sensitivities in relation to spot market prices (baseload) in 2020 with regard to the scenario *Exit2020-gas*.

	Spot market price (baseload) in 2020 [€/MWh]
Reference scenario: Exit2020-gas	69
Sensitivities:	
Higher fuel and CO_2 prices	*86 (25%)*
Constant instead of decreasing electricity consumption	*76 (10%)*
Only modest expansion of decentralised cogeneration	*72 (4%)*
More rapid expansion of renewable energy	*66 (-4%)*
Additional system flexibility	*68 (-1%)*

As the sensitivity analysis shows, the assumptions have a strong influence on the electricity prices that is even stronger than the exact year of the phase-out. Therefore, it can be expected that other studies likely differ in their projected price paths – given different assumptions. We compare our results (labelled as PIK/IIRM in Figure 4) with results from other studies that analyze a phase-out in 2022 compared to a phase-out in 2038 and that have been performed in the years 2010 and 2011 to inform the discussion about the life-time expansion of nuclear power. These studies are enervis energy advisors (2011), Prognos/EWI/GWS (2011), IER/RWI/ZEW (2010) and r2b energy consulting/EEFA (2010)[2].

Whereas the difference between a phase-out in 2022 and a life-time extension until 2038 leads to differences in wholesale prices between 6 €/MWh in 2015 and 17 €/MWh in 2030 (see Figure 4, cf. also German Council of Economic Experts (2011)), the absolute numbers show a very large divergence between the studies (see Figure 5a) as large as 26 €/MWh already in 2015. This means that the differences in absolute price levels between the different studies are much larger than the relative differences between the scenarios with and without a life-time extension of nuclear power.

[2]) The models in these studies differ in terms of regional and temporal resolution or investment decisions are modeled, but this kind of analysis is beyond the scope of the paper.

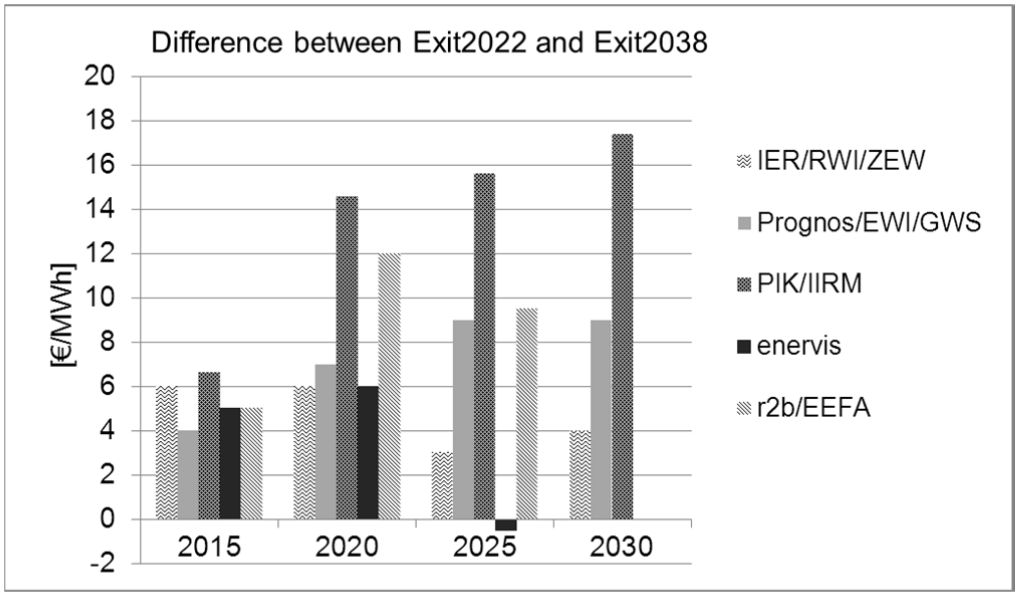

Figure 4: Difference in wholesale prices between a nuclear phase-out in 2022 and 2038 for different studies. For enervis a comparison between 2020 and 2038 is shown. PIK/IIRM refers to this publication.

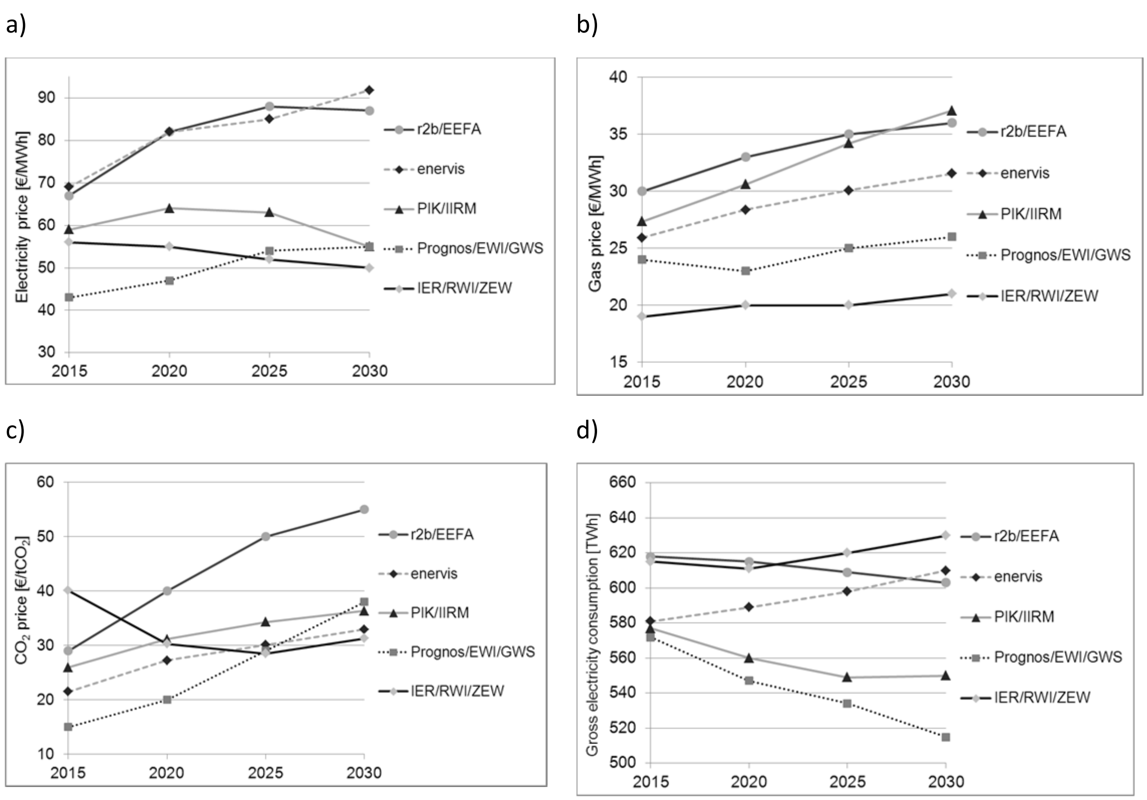

Figure 5: Results and assumptions from different studies. a) Wholesale prices for a nuclear phase-out in 2022, and input assumptions for b) gas prices, c) CO_2 prices and d) gross electricity consumption. PIK/IIRM refers to this publication. Enervis assumes a phase-out by 2020.

The electricity price path for the different studies does not only show a large divergence in absolute numbers but also the tendency of increasing (in three studies) or decreasing prices (in two studies) is not clear. In Knopf et al. (2012), the reasons for these differences are analysed in more detail. It turns out that the studies are based on very different assumptions concerning i) fossil fuel and CO_2 prices, ii) the future electricity demand and iii) the deployment path of renewable energies and, see Figure 5b-d.

It is not astonishing that electricity prices are so different given the widely differing assumptions on the future gas price and CO_2 price development (see Figure 5b and c). As seen in the sensitivity analysis, energy efficiency - represented by the reduction of electricity demand - is also an important driver for the electricity prices. Whereas the demand decreases in three studies (PIK/IIRM, Prognos/EWI/GWS and r2/EEFA), it increases in the two others (IER/RWI/ZEW and enervis), see Figure 5d. This partly explains the low prices for PIK/IIRM and Prognos/EWI/GWS. The decreasing prices in the PIK/IIRM scenario can mainly be explained by the assumption of a very ambitious deployment path for renewable energies along the numbers in Nitsch et al. (2010) that reaches 360 TWh in 2030, whereas in the other studies only between 212 to 267 TWh (not shown here).

The sensitivity analysis and the comparison show that many other factors besides the decision of the nuclear phase-out determine the electricity prices. These driving factors are often exogenous assumptions in the models and can only to a certain degree be influenced by political decisions and regulatory frameworks. We will elaborate on the policy implications of this in the next section.

4 Policy implications of the modeling results

The model-based analyses were mainly performed in the years 2010 and 2011, so the results are based on core assumptions that reflect the expectation of that time, namely the development of renewable capacities and the development of CO_2 prices. Do the assumptions of that time hold in the current debate about the Energiewende? And what can we learn from these modeling results today and for the future, retrospectively, around two years after the decision on the nuclear phase-out was taken? In the following, we relate the policy implications of this analysis to the three energy policy goals of competitiveness, environmental effectiveness and security of supply. We compare model results with de facto developments and trace back the differences to model assumptions.

The model-based studies concentrated mainly on the aspect of *competitiveness* in terms of the magnitude of spot market prices, as increasing prices might potentially challenge the competitiveness of the German industry (e.g. dpa 2011, Handelsblatt 2012, Manager-Magazin 2012). Most models show increasing spot market prices, while at the moment the opposite is observed. The modeling studies all assumed increasing fossil fuel prices and, more importantly, increasing CO_2 prices (except in one study). However the situation today is very different: we are a long way off the assumed starting price of at least 15 €/tCO_2 in 2015 (see Figure 5c), and currently face the lowest prices since 2008 at 3€/tCO_2 in May 2013 (EEX 2013). This, inter alia, has an effect on the spot market price which at 32€/MWh as a monthly average in May 2013 is at its lowest level since 2009 (IWR 2013). In addition, fossil fuel prices have increased only slightly between 2011 and 2012 and currently show a decreasing trend (BDEW 2013c). These two developments – together with the merit-order effect of renewables (see below) – explain why retail prices for industrial consumers (excluding taxes and FIT levy) have been stable between 2009 and 2012 and are decreasing in 2013 (BDEW 2013c). Thus the expected effect of the nuclear phase-out on the spot market price has been partly compensated for, and the burden for the German industry from the nuclear phase-out is in fact smaller than projected by the model-based analyses. This emphasizes that nuclear energy is mainly important for curbing the increase of electricity prices when CO_2 prices are high. In response to the low spot market prices the FIT levy increased considerably from 3.6 ct/kWh in 2012 to 5.3 ct/kWh in October 2013, due to the counteracting effect of both price components described in Section 2.3. As a result, the most debated issue in the context of the Energiewende is currently the increase in consumer electricity prices and the related distributional issue (Neuhoff et al. 2013), but this goes beyond the model analysis.

Environmental effectiveness, i.e. the influence of the nuclear phase-out on CO_2 emissions, was not the key aspect of the modeling studies. However, it is becoming increasingly important in Germany and Europe, due to the decreasing CO_2 allowance price. This not only affects the spot market price directly, but also via the merit order, so that coal will be more cost competitive in comparison to gas (see Section 2.3). However, since coal is more emission intensive than gas, this would result in an increase in total CO_2 emissions. This has important implications both in the short-term and the long-term. In the short-term, as argued in Section 2.4, emissions are capped at the EU level. However, this could endanger the national target of 40% GHG emission reduction by 2020 (Ziesing 2013). In this context it is important to note that energy related CO_2 emissions have increased slightly in 2012, partly due to a colder winter and more heating demand, but also due to higher emissions from hard coal and lignite (AGEB 2013). For the long-term, a low CO_2 price sets problematic incentives: if investments into coal capacities instead of gas power plant are incentivised, this has an effect on future CO_2 emissions. In Figure 3 we have shown, based on the model results, that a switch from coal to gas could decrease the emissions, which would not happen at low CO_2 prices. For the future, the low CO_2 price at the European level and a switch from gas to coal could endanger not only Germany's emissions targets, but also European emissions, especially if no clear signal for a GHG reduction target at 2030 is provided. Therefore, the discussion about a new EU framework for 2030 is of considerable importance (European Commission 2013). Otherwise a lock-in into coal-based power plants might occur in Germany and in the EU, driven by the combination of the nuclear phase-out and a low CO_2 price (see Pahle et al. 2013) that reflects the lack of a reliable future framework and targets.

Security of supply is not directly addressed by the models, but it is implicitly assumed that enough replacement capacities are available. This might be the strongest (model) assumption and – besides increasing consumer prices - currently one of the most debated and crucial issues in the nuclear phase-out discussion (BMWi 2013). As assumed in the models and as planned during the first decision of the nuclear phase-out, fossil fuel replacement capacities are indeed being built, see Section 2.2. In addition, the increase in renewable capacities have greatly exceeded expectations. The models in Section 3 assume that electricity generation from renewables will account for about 130-165 TWh in 2015. In fact, renewables were already generating 135 TWh in 2012 (BDEW 2013b), so that expected deployment by 2015 will be higher than assumed by the models. In general, this has a positive effect on the security of supply, but it also comes with some drawbacks.

First, renewables are not necessarily deployed where nuclear power plants are taken off the grid. Current transfer capacity is limited or is under construction (Bundesnetzagentur 2012) and is often not yet available. This might lead to regional supply problems, especially in Southern Germany. Many observers expect this to become apparent when the nuclear power plant in Grafenrheinfeld in Bavaria is switched off in 2015 with no available (regional) replacement capacities or new power grids (BMWi 2013). This problem is exacerbated by the current price developments (see above), which cause gas power plants to become increasingly unprofitable and go offline. While this is not worrying from the overall market perspective, the plants located in the south are deemed relevant for system stability. Largely for this reason, there is currently a political debate as to whether an energy only market can provide the relevant price signals, or whether specific capacity mechanisms are needed (see Agora Energiewende (2013) for an overview of different proposals). However, from an economic point of view, such a market-wide long-term mechanism is clearly the wrong solution for a transitory and regional problem (Cramton and Ockenfels 2012). Moreover, if such a mechanism is to be set up, it should be considered, for efficiency reasons, in the framework of the European internal energy market. This requires European coordination.

To conclude, model projections differ from current observations because some crucial assumptions of the model-based analysis have not held. This implies that it is not possible to isolate the effect of the phase-out decision on electricity prices and CO_2 emissions. In such a context it is important to note that the results stem from partial electricity sector models that only investigate the influence of the phase-out on some central variables, such as the electricity price. In all of these models the deployment of renewables is given exogenously. Therefore, they miss the (positive or negative) welfare effects of the expansion of renewable energy (Edenhofer et al. 2013) and the interplay with the nuclear phase-out. The deployment of renewables has largely grown through policy intervention and the justification and the degree of subsidies for renewables is part of the current debate. These questions are beyond the modeling frameworks and need further research. This is in addition to the analysis of the interaction of renewable supporting schemes with other instruments, such as the EU ETS (Kalkuhl et al. 2012).

5 Conclusions

In this paper we have reconsidered modeling studies that were performed to analyze the German nuclear-phase out of 2011. The core of the modeling exercise, with the electricity market model MICOES, was an extensive sensitivity analysis on critical input assumptions, such as fossil fuel prices, CO_2 prices and the development of renewable energy deployment. By comparing our model results to those of other studies, we have concentrated on the crucial drivers behind the results and have deduced some policy implications for the situation-as-is.

The model-based analysis shows that the nuclear phase-out has a visible effect on the wholesale electricity prices. On the other hand, uncertainty in some input assumptions, such as the development of the gas price or energy efficiency, has a stronger effect than the timing of the nuclear phase-out. This implies that exogenous drivers and assumptions determine the electricity prices to a much greater extent than the phase-out itself. From comparison with other studies, we can conclude that different assumptions lead to a variety of developments of the electricity price which implies that the future development of electricity prices in Germany is highly unpredictable. For the period between 2015 and 2030, three out of five models show an increase in electricity prices while two show a decrease. We make the point that crucial assumptions at that time, for example concerning increasing CO_2 prices, have developed differently. This partly counteracts the negative effect of the nuclear phase-out on electricity prices, but on the other hand challenges the mitigation of CO_2 emissions.

The sensitivity analysis has revealed that some assumptions have a substantial influence on the model output, i.e. the electricity price. Whereas some of these assumptions, for example the expansion of renewables or developments regarding energy efficiency, can be addressed by policy measures, some others, for example the gas price, are independent of national policies. This implies that policy-makers need to consider scenarios that analyze the whole range of possible future developments. For this task, a structured model comparison with harmonized input assumptions is required. Robust pathways that are valid under a range of assumptions and across a range of models could be identified from such an analysis.

The modeling studies presented have tried to isolate the effect of the nuclear phase-out by reflecting other important drivers through exogenous assumptions. Two years after the decision to phase-out nuclear it turns out that some assumptions valid at that time have changed and that the nuclear phase-out cannot be assessed in isolation from the broader context. This context incorporates other developments such as the European CO_2 price or the development of renewable capacities. Some of these aspects point towards a European solution (Fischer and Geden 2011). The EU ETS should be considered as crucial element for a German mitigation strategy and more effort should be put on re-strengthening this instrument. With a well-functioning EU ETS, CO_2 is avoided where emission reduction is cheapest, thus enabling cost reduction of mitigation in Germany and all other European countries. The further development of the EU emissions trading system is extremely important for future climate and energy policy, although it might be difficult to implement a scheme with a high enough carbon price and one that is able to cover all emissions. With this in mind, an early agreement on a European GHG reduction target for 2030 should be an urgent issue on the policy maker's agenda. The security of supply also needs to be considered in a European perspective to avoid lock-ins into national mechanisms considered necessary to ensure adequate capacity. It goes without saying that this requires European coordination beyond the current extent.

As initially indicated, we concentrated solely on the effect of the nuclear phase-out on electricity prices for industry and on CO_2 emissions. Most modeling studies failed to investigate some of the most relevant factors in the current context, for example the decrease of CO_2 prices, the rapid increase of renewables and the aspect of security of supply. But the sensitivity analysis and the policy implications that we deduced from that indicates that the different interacting instruments of renewable supporting schemes, emission pricing and capacity mechanisms for ensuring the security of supply emerge as the future challenges that have to be tackled today. However these are the challenges of the entire "Energiewende", i.e. the transformation towards a "road into the age of renewables". The influence of the nuclear phase-out on this strategy seems to be only one of several challenges – and probably a small one at that.

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