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The impact of the German response to the Fukushima earthquake☆

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ABSTRACT

The German response to the Fukushima nuclear power plant incident was possibly the most significant change of policy towards nuclear power outside Japan, leading to a sudden and very substantial shift in the underlying power generation structure in Germany, an enthusiastic leading proponent of renewable power. This provides a very useful experiment on the impact of a supply shock in the context of increasing relative generation by renewable compared to conventional fuel inputs into power production. Our quasi-experimental exploration of a modified demand-supply framework finds that despite the swift, unpredicted change in nuclear power, the main impact was a significant average increase in prices, surprisingly particularly at low residual load levels.

1. Introduction

The German "Atomausstieg" decision to have a nuclear moratorium following the Fukushima nuclear disaster in Japan in March 2011 was sudden, unexpected, decisive and significant internationally (Joskow and Parsons, 2012). Immediate closure for testing in March 2011, confirmed by end-May 2011 as a permanent shutdown, of 6 of the 17 plants producing nuclear energy (as well as two that were offline at the time) was instituted. As a result, whereas in 2010 over 22% of its power was from nuclear sources, this decreased to less than 16% in 2012 (BDEW, 2014). Removing this amount of capacity from the system in such an unplanned manner would be infeasible in some other countries; for example in Britain it would likely cause complete collapse.[1] This did not happen in Germany, because it is relatively well-endowed with power plants, it is well-connected with other countries (it remains a significant net power exporter) and it has invested heavily in renewables. However, what did happen was a sudden switch to a less controllable system; essentially base-load generation was removed whilst, through a separate policy process, there was a significant increase in intermittent sources. We investigate the impact of the sudden change in nuclear policy in terms of effects on load and prices.

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[1] National grid scenarios do not encompass such a major drop in capacity.

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Reductions in the nuclear fleet can be expected to increase spot prices, since nuclear plants produce power at low marginal cost and therefore operate as baseload. Some observers would predict the largest rises would occur at peak times (Poyry, 2010). However our estimates show something that at first blush might seem surprising: the major price impacts are felt in the dead of night, as a result of necessary movements up the merit order curve (i.e. the supply side ordered from lowest to highest marginal cost generation unit representing the economic order in which plant is brought onstream as load increases) once a significant part of the nuclear fleet had been taken off-line. In part as a result of this, despite increasing electricity generation from renewables by over 1/3 between 2010 and 2012, Germany *increased* its CO_2 emissions from power plants by around 3.9% over these two years, whilst generating slightly less electricity in total in 2012 as a result of increased use of coal and lignite plants.[2] This means that the CO_2 emissions per unit of residual demand generated were 13% higher in 2012 than in 2010, going against the German policy of Energiegewende.[3] This provides a wider context to our analysis of price effects.

The data we have enable us to document in detail, over hours of the day and throughout levels of residual load, the impact of the decision on supply, spot prices and, to some extent, on generation mix.[4] Our approach to the topic utilises a detailed hourly dataset on prices and load over four years, using a broad supply-demand framework tailored to the German case. Specific features include detailed disaggregated temperatures across the country, information on all key import and export interconnections and a specially calibrated residual supply index so that market power effects due to tighter supply can be separated from the direct influence of the Atomausstieg. Econometrically, we are careful to set out our identification assumptions and instrumentation strategy. We explore a variety of approaches, using a range of techniques, on the supply side to check robustness and to identify the separate impacts at different times of day and generation levels.

To preview our results, we confirm that whilst there is no evidence equilibrium quantity was negatively impacted by the sudden decision, there is a clear significant impact on price - a movement up the supply curve, other things equal, resulting from the use of higher cost fuel sources.[5] We estimate an average price increase of around 8.7% and calibrate the net impact on German consumers at approximately 1.75 Bn € per year. Our estimates find the price increase to be partly driven by increased market power - scarcity price markups become more common - in addition to a general leftward shift in the merit order. Furthermore, the closure of the 6 GW nuclear capacity was partially absorbed by cross-border trade. Our results contribute to the ongoing analysis of whether electricity prices would have been lower with extended nuclear plants life spans (Nestle, 2012), as well as permitting some more general lessons to be drawn.

Fig. 1 charts the data we later investigate in some detail, simply taking mean prices and mean load into account. Comparing complete years before (average of 2009 and 2010) and after (2012) the Atomausstieg decision, we observe an average price increase in off-peak periods but the reverse impact on the early afternoon hours where

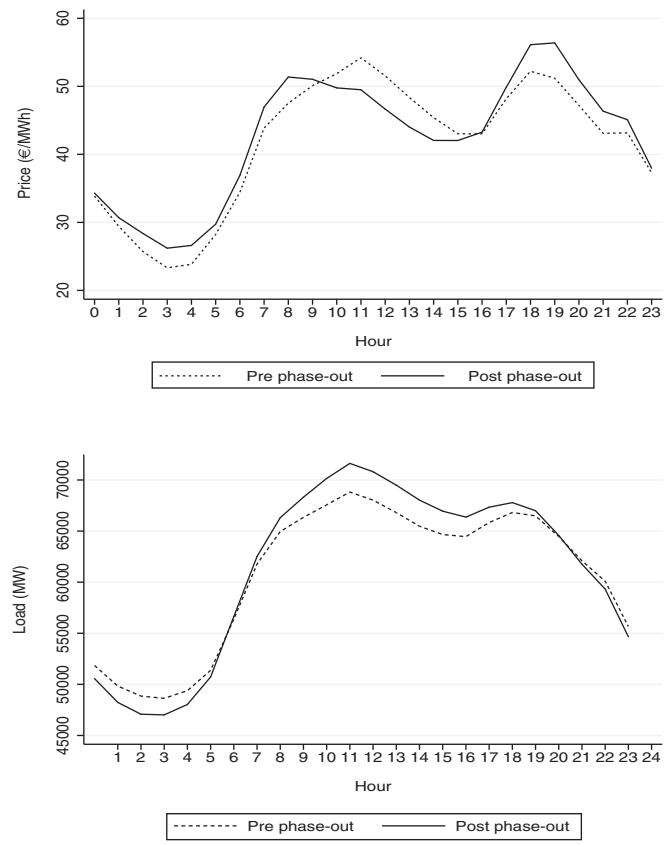

Fig. 1. Mean hourly spot price and load (average of 2009 and 2010) and after (2012) the Atomausstieg decision.

significantly augmented solar power has its greatest impact. With regard to load we observe a decrease in the morning hours and an increase during the day. A figure illustrating these patterns split into summer and winter is available in Appendix A. For comparison we also report figures on prices and load for the British market since the market shares no direct interconnectors with the German market in Appendix A.

Many authors have looked at the impact of the German decision to date (e.g. Betzer et al., 2013; Ferstl et al., 2012; Thoenes, 2014) focussing on event studies in order to infer profitability impacts, not the arguably more important effects on consumers, although Thoenes (2014) investigates futures prices. A more relevant paper is Kunz and Weigt (2014), which surveys some early model-based predictions of the effects on prices, amongst other things, summarizing that prices will rise up to 10 €/MWh in the short term. This is surprisingly close to what we find. However, although the finding that the outage causes a price rise is unsurprising, we are able to show big price rises particularly in low demand periods whilst the impact on price is insignificant during peak load. To our knowledge, this is something that was not predicted.

The closest study to ours is a recent paper (Davis and Hausman, 2016), that also examines market reaction to an unanticipated nuclear outage through a before and after experiment. In their case it is the sudden unexpected closure of a nuclear power plant in California which had an impact on Californian generation capacity of similar relative magnitude to the German decision on German capacity. Davis and Hausman's main goal is to evaluate the consequence of the plant closure on generation mix, generation costs and emissions in the first 12 months after the closure. Given the observed natural gas generation, they aim to measure how much of

[2] Source: http://de.statista.com/statistik/daten/studie/38893/umfrage/co2-emissionen-durch-stromerzeugung-in-deutschland-seit-1990/.

[3] For further information on the carbon abating potential from nuclear see Davis and Wolfram (2012). Of course, not all of the 13% can be assigned to the nuclear outage; we should not neglect that lower coal prices lead to relatively more generation by coal as opposed to gas. On the issue of CO_2 emission sensitivity to alternative scenarios regarding fuel prices, see Knopf et al. (2014).

[4] Unlike some other countries such as Spain (Fabra and Reguant, 2014) in Germany, plant-level generation data are not available.

[5] If there had been selective disconnection or "brown-outs" then we would expect to see these in the empirical estimates for load through a reduction in expected load given exogenous parameter values. There is no hard evidence that they occurred; on this see later.

the increase was a direct consequence of the nuclear plant closure. To this end, they define and estimate semi-parametric regression models to identify the marginal generating unit at each time. The models are estimated separately in the periods before and after plant closure using as independent variables a series of indicator variables defined by different levels of total system demand. Hence they isolate two effects: the predicted change as the non-marginal shift in net demand faced by each unit in each hour, and the residual change given by the difference between predicted and actual generation caused by grid congestion or the exercise of market power. They find a smaller overall impact than we do. There are probably many reasons for this. However, one we would point to is the markedly different price of natural gas in the two countries; the German price is more than double the US price (source: International Energy Authority). In a broader sense, our paper can be placed in a stream of literature investigating, econometrically, the impact of external events on deregulated electricity markets and in particular on the price formation mechanism (see, a recent paper by Hurn et al., 2016).

Of course we accept that the German position in electricity is different from that in other European countries. Nevertheless, because we are able to uncover substantial detail on the German response to Fukushima, we can draw certain more general lessons for the development of renewables, in particular relating to the large night-time price rises. The underlying reason for the most significant effect being on off-peak period prices is that a reduction in the nuclear fleet implies a cut in cheap baseload provision. Times when baseload could be supplied by nuclear or lignite as the marginal technology shrink, meaning that higher cost plants commonly swing into operation especially in the quietest periods. The impact of such technology jumps is better absorbed in peak hours because the replacement of baseload plants by renewables also includes solar generation. More generally, this suggests that the appropriate portfolio for a country's wind and solar power will depend in part on the time characteristics of demand.

Alongside the rise in prices, this episode casts indirect light on the underlying mechanisms that will come into play as other European countries move to increased renewable provision. Beyond the price rises, in our opinion this policy decision is one with wider ramifications. We can view the sudden change in German policy as an experiment. It caused a quicker than anticipated move to a structure for power supply based on resources that are far more intermittent, in which Germany is playing a key role. It also has implications for the impact of an individual country's policies on its neighbours' energy costs and the European policy on interconnection. We incorporate the impact on Germany's most inter-connected neighbour, Austria, finding clear increases in Austrian power prices as a result.

Our plan in the paper is as follows. We first describe the event (Section 2). Then in Section 3 we develop our theoretical and econometric model of the German system, including discussion of variables and the data we use. We then present and discuss the results in Section 4. Finally, Section 5 offers some concluding remarks.

2. German reaction to the Fukushima earthquake in context

Angela Merkel, the German Chancellor, had prior to the Fukushima earthquake been an advocate of nuclear power. A previous plan from 2002 under Gerhardt Schroeder to phase out nuclear plants entirely by 2022 had been delayed in 2010 against Red-Green opposition, with the lives of some plants extended until 2036 at the latest. However, following a dramatic change of mind by Merkel, the Fukushima accident resulted in all the eight pre-1981 plants being closed down permanently (hence, this has been described as an "Ausstieg vom Ausstieg vom Ausstieg", the first decision being the previous 2022 moratorium, the second the Merkel extension, the third the Merkel U-turn!). Clearly, this final decision - the so called "Energiewende" (Energy Turnaround) - was unexpected (opposed to the 2010 extension) and equally clearly, if Fukushima had not happened, the decision to close pre-1981 plants immediately would not have been made. Hence, this is a natural experiment - we measure the outcome of a completely unexpected event relative to the prior situation. It was an event of some significance: 6.3 GW of capacity, around 7% of installed conventional capacity or 12% of German average supply, was permanently removed from the system at a stroke, with significant impacts on nuclear plant output, as shown in Fig. 2.[6]

The context is important: Germany is one of the world's pioneers in renewable energy from wind and solar sources (Borenstein, 2012) with clear ambitions to generate followers.[7] Indeed, many other countries decided to follow a similar path hoping to benefit from lessons learned from Germany (see e.g. Campbell, 2015; McMahon, 2015, also EPA, 2015). Germany has by far the largest installed base of solar capacity and the third largest installed base of wind capacity in the world (International Energy Agency, 2014, 2015). Capacity in these areas has been growing rapidly, boosted by significant subsidies.[8] Wind capacity at end 2011 reached almost 30 GW and photovoltaic power capacity reached 25 GW, out of a total system listed capacity of 175 GW (source: BMWi, 2014). As a result, between end 2010 and end 2011, more capacity had been added through renewables (wind, 1.9 GW, solar, 7.5 GW) than had been removed by the Atomausstieg. Capacity is one thing; clearly wind and photovoltaic capacity figures are potentially misleading in two senses - first these sources are nowhere near being used as intensively as conventional sources, nor are they "controllable" in the same way that coal, gas and pumped hydro plants are (Joskow, 2011). Thus whilst on average thermal plants provide around 50% of their total theoretical capacity over a year, wind hovers around 20% and photovoltaic only around 11%.[9] Taking average utilisation of nuclear plants conservatively to be around 75%, the 6.3 GW of capacity that closed as a result would have produced 41 TWh over a typical year. The increased capacity in wind and photovoltaic, on the other hand, would on average produce only just over 10.5 TWh over the year. Thus in terms of production, there is a big net loss across these fuels and Germany is more likely to be on the upward sloping part of the supply schedule, despite the increased capacity.[10]

Examining these patterns in more detail, we should also take into account the "must-take" nature of wind and solar (under current conventions in Germany).[11] Hence, it becomes of importance what impact wind and solar plants have on the remainder of the system (Lechtenböhmer and Samadi, 2013). Here there is some positive impact - German demand is characterised by a high point in the middle of the day (particularly in summer; winter months have a high again around 19.00) which is nicely matched to the high point

[6] We should note that two of the eight plants were not in production at the time of the decision. Considering these two plants increases capacity removed to 8.4 GW.

[7] This is clearly seen in Angela Merkel's rhetoric: "the world is looking at us with a mix of incomprehension and curiosity to see if it is possible for us to accomplish this energy transition and if so, how. If we succeed, it will become - and I am convinced of this - another prominent German export." (Translation from Steinbacher and Pahle, 2015).

[8] Here a key decision regarding the "Energiewende" came in September 2010, prior to the Fukushima earthquake, with the publication of a German Government strategy document (BMWi, 2010) on development of a renewable energy system.

[9] Authors' calculations from Bundesnetzagentur (2012), comparing theoretical maximum output given capacities with actual output produced.

[10] This is not a complete comparison: Biomass production, which is rather intensively used, grew a little between these years, as did Brown Coal capacity. Overall, however, the gross additions of conventional generation over our period are certainly modest by comparison with the fall in nuclear capacity and the growth in renewable capacity, amounting in total over the three years to around 1.5 GW (source, Bundesnetzagentur power plant list). A figure on installed capacity and generation for each technology over time can be found in Appendix A.

[11] We will discuss properties of the German EEG (*Erneuerbare Energien Gesetz*; translated Renewable Energy Act) in some more detail later.

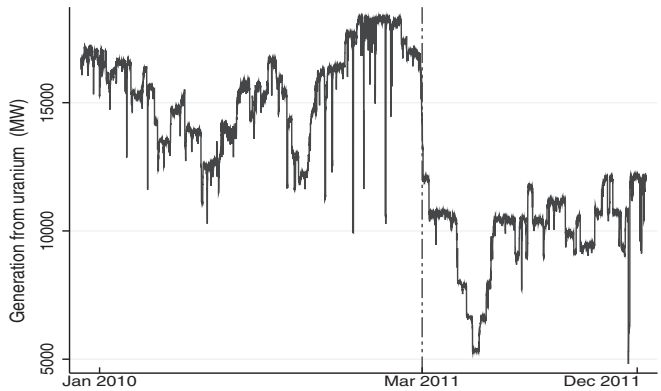

Fig. 2. Generation from nuclear power plants before and after the Atomausstieg decision.

of solar production, as shown in the example for July 2012 in the upper panel Fig. 3. However, there is also bad news: in the period after the Atomausstieg, the standard deviation of the German residual load (i.e. load after "must-take" elements have been accounted for) has increased, particularly in winter, as compared with the same period in 2010, whether measured by daily average or hourly average. In other words, the task required of the conventional generators is more variable, which is likely to add to costs.

3. Modelling the German electricity market

We model the German day-ahead wholesale power market, the main transaction point for electrical power.[12] Here expected system load and price are determined simultaneously in the market through the bids received by the system operator for each hour of the day matched against anticipated demand. Any shortfalls or over-supply within the day are handled through shorter-term mechanisms that we do not consider. Slightly more formally, our assumptions are that the day-ahead market captures the expectations regarding each day's load and generation and that the sophisticated players who engage in the day-ahead market hold unbiased (rational) expectations regarding the subsequent adjustments. Thus what matters to price in this market are forecasts of demand values for the next day, not the actual values, which will instead impact on the intraday activities. Since intraday corrections depend on stochastic criteria like small adjustments in renewables forecasts and short-term plant failures and, thus, intraday trade accounts for only a very small fraction of traded electricity compared the day ahead traded volume, the focus on day-ahead prices will not introduce bias in our analysis.[13]

In the main analysis reported here, we model residual demand and price after anticipated wind and solar power have been subtracted (hereinafter referred to as residual load), because, according to the Renewable Energy Act (EEG), these get paid a fixed feed-in tariff and obtain priority feed-in to the grid, which means in effect that they are always bid into the system and the wholesale market

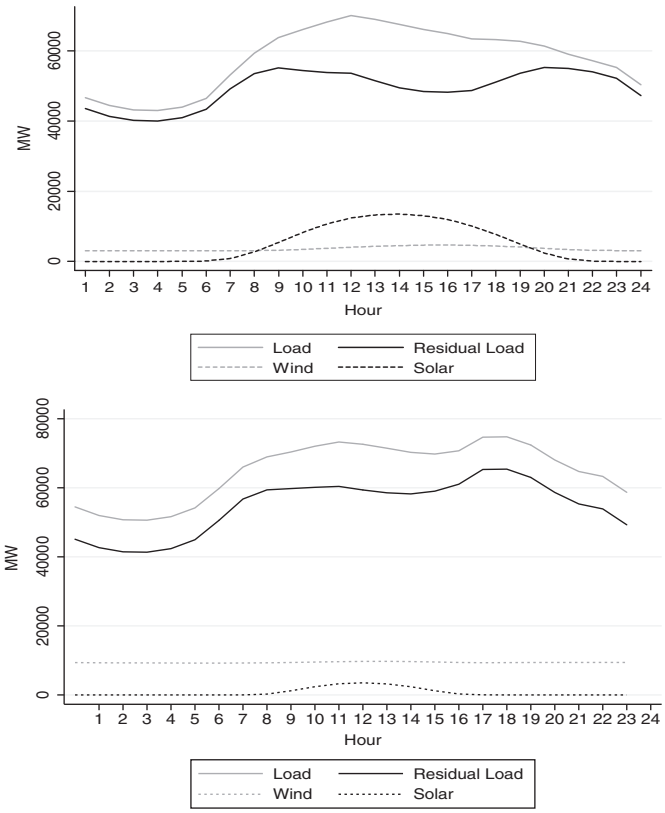

Fig. 3. Comparison of load and uncontrollable supply for July 2012 (upper panel) and January 2012 (lower panel); total hourly data.

price is set by the equation of the remainder of the generation and demand.[14] This feature of the EEG design has a significant advantage in our case because it enables us to easily disentangle the coincidental impact on the market of increased renewables from the Atomausstieg event.

3.1. Demand and supply framework

Under normal operation, a key feature of the electrical system is that generation and demand are tightly in balance, so on the day-ahead market expected loads are balanced within each hour. Thus, we aim to explain the behaviour of German plus Austrian residual

[12] In addition, there are various futures markets, most notably the year-ahead futures market, which does experience some similar movements to those we describe; see Thoenes (2014) for evidence on this. There are also nearer-time markets involving corrections on the day in question.

[13] Because renewables are "must-take", these plants do not formally bid into the system and cannot therefore act as strategic players (compare Spain, Ito and Reguant, 2014).

[14] The Renewable Energies Act (EEG) is a promotion tool for renewable energy technologies which equips suppliers of renewable energies with a 20-year fixed feed-in tariff and unlimited priority feed-in into the grid. In other words, maximum possible generation from renewables will be produced regardless of actual demand and the fixed feed-in tariff is paid instead of a market-based spot price. The system operators manage the process of selling renewables at the spot market and bid forecasted renewables into the day-ahead spot market at the lowest price (which can be zero or negative). The clearing system is via uniform-price which system operators receive for each kW from renewables. A result of this process is the yearly adjusted EEG surcharge. It is primarily calculated as the forecasted yearly difference between expected revenues from renewables at the spot market and expected expenditures from the fixed feed-in-tariff payments (e.g. forecasted revenues from renewables in 2013 were 3.1 billion € and forecasted expenditures were 22.9 billion €) plus the error from the last year's calculation. These costs build the basis of the EEG surcharge and a price per kWh is calculated which is to be paid by the end-consumers as a component of the retail price. However, electricity-intensive industries are essentially exempted from the EEG surcharge.

load and wholesale market price, which are jointly determined.[15,16] Each is measured hourly over the period 1 January 2009 to 31 December 2012 and so is instrumented in the equation in which they appear as an explanatory variable. Our key hypothesis is that

$$E[(P_A - P_B)|\, RL] > 0 \tag{1}$$

where P_A and P_B are prices after and before the earthquake, respectively and RL is the residual load, with the price gap varying across hours.

Our basic estimating equations, one for residual load and one for wholesale price may be written as

$$RL_t = \beta_{01} + \beta_{11}AUS_t + \beta_{21}P_t + \beta_{31}RE_t + \beta_{41}IP_t + \beta_{51}DL_t + \sum \gamma_{i1}Temp_{i,t} + \sum \delta_{j1}Cal_{j,t} + Trend_t + \varepsilon_{1t} \tag{2}$$

and

$$P_t = \beta_{02} + \beta_{12}AUS_t + \beta_{22}RL_t + \beta_{32}RE_t + \beta_{42}RSI_t + \sum \gamma_{i2}X_{i,t} + \sum \gamma_{j2}CI_{j,t} + \sum \theta_k Riv_{k,t} + \sum \varphi_l Cal_{l,t} + \varepsilon_{2t} \tag{3}$$

Not shown above for simplicity, we engage in various interactions and introduce some non-linearities into Eqs. (2) and (3) in order to take account of known non-additive elements discussed in the Results section.

All variables are time series collected from January 1st 2009 to December 31st 2012. Prices P_t are measured hourly in €/MWh. They have been obtained from the day-ahead auctions of the European Power Exchange (EPEX). Residual load data are the sum of German and Austrian loads gathered from the European Network of Transmission System Operators for Electricity (ENTSOE) website minus wind and solar forecasts.[17]

Factors affecting load and so residual load are, for the most part, well known and to a significant extent exogenous in the short run. Temperature (*Temp*) is a key influence: low temperatures call forth demand for heating power, whilst high temperatures may increase demand due to demand for cooling, so the effects are nonlinear. Lack of daylight (*DL*) also increases demand for lighting purposes. The level of economic activity, represented here by industrial production (IP), is another key influence. Demand evolves over the day, over the week and over the year (hence the Cal variables relating to hours, days and months). Wholesale price of course has an influence, particularly in cases where there are alternatives to electricity. Amongst the factors that change on an annual basis is the increase in energy efficiency as well as the EEG-Umlage (renewable energy surcharge) affecting final consumer price and through this, potentially, wholesale demand. Both the increase in final consumer prices due an increase of the EEG-Umlage resulting from growing renewables as well as the increase in energy efficiency likely decrease final consumer demand for electricity. We therefore simply model it through a Trend term that takes the value 1 for each day in the first year, 2 in the second year, and so on. For above mentioned reasons one would naturally expect the trend to be negative. Forecasted generation of wind and solar power renewables (*RE*) will affect the relationship between load and residual load. Finally, we should allow for the possibility that the Atomausstieg decision led to situations where demand exceeded supply at the market price, resulting in black-out or brown-out. This will manifest itself in the model as an unexpectedly low load given temperature, etc. so we model it through a dummy variable (*AUS*) in the load equation, which takes the value 1 after the event. As an alternative, we model the effect of the decision in two different ways to check robustness. First, we used the SAIDI index[18], in which case we drop the yearly trend variable, since the correlation between them is around 0.99. Second, we modelled demand without including the AUS index.

The main independent variable above that does not vary by the hour is industrial production. Monthly industrial production indices for Germany and Austria are adjusted by working days.[19] Temperature is measured hourly across a number of major population sites in both Germany and Austria. We get an overall average temperature index weighting by local population. We experimented with some variants of the temperature variable, for example a quadratic formulation and cooling and heating degree days.[20] Daylight hours is a binary variable taking the value 1 where the sun has already risen or set in a period where within the year the hour is sometimes dark and sometimes light. Thus it is always zero in night time hours, but also always zero in the middle of the day (e.g. between 12.00 and 13.00). It takes on the value 1 only when the hour is between sunrise and sunset on that date, but would be outside that period at other times of year (e.g. between 17.00 and 18.00). All the weather and daylight variables are naturally considered exogenous, being determined by nature.

Turning to the supply side, given the anticipated residual demand, supply price will be set at the level that equates generators' bids with that load. The composition of these bids will be affected by several factors, again for the most part well-known.

In Eq. (3), X is a set of control variables including input prices for coal and gas[21], carbon emission right prices, *CI* contains import and export congestion indices and *Riv* represents "low river level" and "high river temperature" variables. *RSI* is a market power measure. Lastly, *Cal* is a set of calendar dummies (hour, weekday, national holiday and months).

Conceptually, we may think of a merit order curve, where low marginal cost but high fixed cost plants bid in under virtually all circumstances. Then at successively higher demands, successively higher marginal cost plants bid into the system to determine the clearing price to give a (non-strictly) convex supply curve. Admittedly, the merit order curve is most straightforward in a closed system of controllable plants and the concept loses some relevance in

[15] Germany and Austria can be considered as being fully integrated since there is no congestion observed at this border.

[16] Both supply and demand quantities depend on price, so we have a simultaneous system. Since supply is assumed always to equal demand load, we model the system directly in terms of a load equation and a price equation, the latter model being discussed below.

[17] Data on wind and solar forecasts are obtained from the Transparency Platform of the European Energy Exchange (EEX) and the commercial forecast service Eurowind.

[18] Here we are forced to use the annual SAIDI indicator. The Bundesnetzagentur, who publish the annual data, clearly have more detailed information available, but our request for these more detailed data was refused.

[19] Industrial production is downloaded from Eurostat. We use this in preference to GDP since GDP is only available on a quarterly basis. Also,despite the lower frequency for GDP both variables are highly correlated (0.7). However, the AUS dummy remains insignificant regardless whether we use GDP or industrial production. Furthermore, as suggested by one anonymous referee we have also experimented with interactions of industrial production and the trend variable as well as GDP and the trend variables. In all cases the impact of AUS remains insignificant.

[20] Hourly temperatures are from the Federal Ministry of Transport, Building and Urban Development in Germany; Austrian temperatures are downloaded from Mathematica 9. The original values are in degrees Celsius, but because of the introduction of a quadratic term in the demand equation we transformed them in degrees Fahrenheit to avoid problems with mathematical transformations of negative values. The alternative temperature variables are defined as follows: a Heating Degree Day (HDD) or in our case hour, is the extent to which air temperature is below 18 °C, whilst a Cooling Degree Day (CDD) is the extent to which 22 °C is exceeded.

[21] We do not include a price for lignite, because this is obtained local to the power station and is therefore not exogenous. Also, the lignite index that is produced by the Federal Statistical Office (https://www.destatis.de/DE/Publikationen/Thematisch/Preise/Energiepreise/EnergyPriceTrends.html) has only very little variation (standard deviation of 6.8% over the observed 48 months). It is thus already partially captured in the included constant term and for this reasons excluded from the regressions.

the context of increased uncontrollable (largely renewable) generation and greater interconnection. Nevertheless, conventional factors such as coal, gas and carbon emission rights prices are all likely to have a positive influence on the prices bid in. Here, we have the carbon price index, computed daily, plus import prices for natural gas and for hard coal at the German border reported monthly.[22] We treat all these as exogenous to the German system, given that their prices are determined on supra-national (European or world) bases. Of course, some German power stations are fuelled by lignite; its price cannot be considered exogenous.[23]

Because water in significantly large quantity is required not only in run-of-river hydro generation plants but also for cooling purposes for conventional plants, low river levels and high river temperatures may have the effect of uplifting prices since they curtail some operation, as shown by McDermott and Nilsen (2014). The variables (*RivT* and *RivL*) relate to river temperature and river level.[24] High temperatures can cause scarcity of cooling water for generators. Low river levels reduce production from run-of-river generation plants. Both these are measured daily for each of the major navigational rivers. The "high river temperature" variable *RivT* is defined as an index measuring the extent to which river water temperatures exceeds 23 °C, the legally envisaged threshold that, if exceeded, forces power plants to decrease generation on grounds relating to the protection of the environment. Following McDermott and Nilsen (2014) the "low river level" variable RivL indicates whether river levels fall below their 15% percentile.[25] *RE* is again forecasted generation from renewables and should have an impact since high fluctuating renewables increase marginal costs of the conventional plant fleet due to higher ramping costs.

In addition, there are three other sets of variables of potential importance, each of which is outlined below then discussed in more detail in Section 3.2.

First, imports and exports of power (represented in Eq. (3) by *CI*, two congestion indices) will also have an impact since Germany is in the middle of Europe and shares interconnectors with Austria, Switzerland, France, the Netherlands, both Danish price zones, Sweden, Poland and the Czech Republic.[26] When prices in Germany are high relative to those of its neighbours, power will flow in from neighbours *so long as the interconnectors are uncongested*. If prices in Germany's neighbours are high, power will flow in the opposite direction, subject to the same proviso.[27] If there was no congestion in interconnectors, as is the case between Germany and Austria, then prices across the countries would be equated. However, the remaining interconnectors are all modest in size, at least so far as Germany is concerned.

Second, it has widely been found that market power in generation can allow large bidders to manipulate the system (Wolfram, 1999; Borenstein et al., 2002; Wolak, 2003). Because bids are prices, market power is likely to have an effect if a bidder is in a situation where it can act as residual supplier once all other operators' bids have been accepted.[28] Due to the decrease of conventional capacity it is likely that situations in which a certain supplier is essential to meet demand will appear more frequently after the shutdown of 6 GW baseload capacity, i.e. the likelihood for a supplier to be pivotal increases. Thus it is common that the Residual Supply Index (RSI) is used as a measure of market power, a convention we adopt here.[29] The RSI is in general defined as[30]

$$RSI_i = \frac{\textit{Total Capacity} \text{ less } i\text{'s } \textit{Relevant Capacity}}{\textit{Total Demand}} = \frac{\sum_{i \neq j}(k_j + x_i)}{D} \quad (4)$$

where *TotalCapacity* is the total regional supply capacity plus total net imports, *i's RelevantCapacity* is company *i's* capacity, k_i, less company *i's* contract obligations taken as x_i, and *TotalDemand*, *D*, is metered load plus purchased ancillary services.

Finally, but most importantly given the subject of our paper, we investigate the impact of the Atomausstieg decision through a dummy variable system influencing the price equation. The Atomausstieg dummy AUS is fixed equal to 1 from March 18th 2011 when the "Atom Moratorium" was decided. The effect is to remove a portion of the lower parts of the merit order curve. Given the probable nonlinearities in this curve for reasons discussed in Section 3.2, we adopt several frameworks for estimation, including non-parametric modelling and polynomials.

It will be observed that the system as a whole is overidentified given our exogeneity assumptions, so that we experiment with optimal sets of instruments to identify the endogenous variables of interest.

In Table 1 we report mean values and standard deviations (in parentheses) of our key variables. If we consider the whole observation period the EPEX spot price is around 44.26 €/MWh on average, however, it is approximately 9% higher after March 18th 2011 than it was before. By contrast, load remains quite stable. Generation from renewable energies (wind and solar) provides about 12% of total demand in the full sample with an increase from 10% to 15% if we consider the pre- and post-Fukushima periods separately. This is mainly a result of increased solar generation which tripled in the post-Fukushima sample and increased its share of total generation from 1.7% to 5.3% compared to the pre-Fukushima period. Concerning market power, the RSI variable increased by almost 50% from 0.019 to 0.032, which indicates that market power plays a bigger role after the nuclear plants have been shutdown. Interpreting import and export congestion is less straightforward as there have been several changes in the operation of interconnectors on several borders in recent years aiming to allocate cross-border capacity more efficiently (for instance, coordination of explicit auctions between a couple of countries, replacements of explicit auctions in favour of implicit auctions and market coupling arrangements). River levels have been around 13% higher in the pre-Fukushima sample, which is of importance as we will show later. At the foot of the table, we list the various components of capacity, noticing that there have been no major changes in the amount of other renewable capacity such as Biomass over the period.

[22] Carbon prices are from Thomson Reuters Datastream, prices for natural gas and coal are obtained from the Federal Statistical Office of Germany.

[23] There is no reasonable price series on lignite because the prices vary extremely from power plant to power plant and lignite is not traded, it is produced by the lignite power plants directly. Therefore, there is no market for lignite. Thus, even if we would use a lignite price series we would have endogeneity problems. This can also be seen from the data published by the German Federal Statistical Office which provides an import price index for hard coal but only a producer price index for lignite. In addition, this price index is also very flat, e.g. the variation between October 2011 and October 2012 is only between 112.6 and 112.7. Hence, using the lignite index would also cause multicollinearity problems.

[24] The data is obtained on daily basis from the German Federal Waterways and Shipping Administration (WSV).

[25] Rivers considered for the river variables are the main German rivers for shipping transport Donau, Rhein, Main, Elbe, Mosel, Neckar, Weser, Spree and Ems.

[26] Germany is also partly indirectly connected with some more countries through interconnectors of the directly connected neighbours by so called market coupling and coordinated auctions, i.e. with Belgium and Slovakia.

[27] The existence of common trends between prices in Germany and in its neighbours has been studied by Bosco et al. (2010).

[28] Such bidders are called pivotal suppliers (Brandts et al., 2014).

[29] See Sheffrin (2002), Twomey et al. (2005), London Economics (2007) and Newbery (2008) for a discussion of this index, which is commonly used to measure market power in electricity in preference to more standard measures. An additional justification is given in Appendix B.

[30] E.g. Newbery (2008) or Twomey et al. (2005).

Table 1
Summary statistics.

	Pre-Atomausstieg		Post-Atomausstieg		Full sample	
Dependent variables						
EEX spot price (€/MWh)	42.58	(17.12)	46.33	(17.09)	44.26	(17.21)
Residual load (MW)	55,990	(10,840)	53,470	(11,420)	54,860	(11,180)
Supply side variables						
RSI (0–1)	0.019	(0.054)	0.032	(0.075)	0.025	(0.064)
Coal price index	181.68	(19.93)	175.9	(8.15)	179.09	(16.04)
Gas price index	136.15	(20.31)	181.35	(9.59)	156.41	(27.82)
Carbon price index	11.95	(0.94)	6.01	(3.79)	9.29	(3.95)
Import congestion index (0–1)	0.27	(0.32)	0.23	(0.22)	0.25	(0.28)
Export congestion index (0–1)	0.41	(0.34)	0.26	(0.26)	0.34	(0.31)
Low river level index (0–1)	0.09	(0.19)	0.23	(0.26)	0.15	(0.24)
High river temp. index (0–1)	0.03	(0.24)	0	(0.00)	0.02	(0.18)
Residual demand side variables						
Renewables (MW)	5361	(3873)	8117	(5691)	6596	(4967)
Temperature index (C°)	8.83	(8.27)	11.2	(7.38)	9.89	(7.97)
HDD (C°)	9.7	(7.44)	7.42	(6.52)	8.68	(7.13)
CDD (C°)	0.15	(0.84)	0.14	(0.72)	0.15	(0.79)
Industrial production index	95.22	(8.67)	108.26	(5.63)	101.06	(9.89)
Daylight (0–1)	0.29	(0.45)	0.37	(0.48)	0.33	(0.47)
Information on auxiliary variables						
Load (MW)	61,355	(11,147)	61,586	(11,819)	61,459	(11,452)
Solar (MW)	943	(1560)	2899	(4285)	1820	(3243)
Wind (MW)	4418	(3676)	5218	(4292)	4777	(3984)
Avail. import capacity (MW)	12,723	(1046)	11,714	(897)	12,271	(1103)
Avail. export capacity (MW)	6690	(1239)	6830	(812)	6753	(1071)
Avail. conventional capacity (MW)	87,370	(7760)	80,000	(7220)	84,070	(8370)
#Obs.	35,064	19,344	15,720			

Note: This table reports the mean values of the variables. Standard deviations are in parentheses to the right. The first sample includes the period from January 1st, 2009 to the closure of the nuclear power plants on March 18th, 2011. The second sample includes the period afterwards. The third sample includes the whole period from January 1st, 2009 to December 31st, 2012.

3.2. Further discussion of supply side variables

Our discussion in Section 2 suggests that the Atomausstieg event potentially has effects both due to the impact of lower capacity and due to the impact of increased variance. This latter effect leads to a lower level of baseload via nuclear power and a higher level of "must-take" intermittent power. Let us examine the increased variance issue in more detail. Assume, for simplicity, the supply schedule is convex, with the upper part (beyond baseload) strictly convex. We commence with an endowment N of baseload nuclear capacity that, again for simplicity, provides a constant flow nt of power. This endowment is reduced exogenously at a point in time, A, to θN with the flow reducing to θnt. Assume that nt is the lowest value taken by load. The lost endowment is replaced at A by an endowment R of must-run renewable generation capacity providing a flow rt of power. Assume that $E(rt) = (1-\theta)\cdot nt$, and that rt is symmetrically and uniformly distributed between 0 and $2\cdot(1-\theta)\cdot nt$. Thus the total baseload plus must-run supply is distributed symmetrically and uniformly between $\theta\cdot nt$ and $nt + (1-\theta)\cdot nt$, and the mean of this distribution is nt. Supplying the lowest value of load, nt, is on average more expensive after time A than before, because of the strict convexity of the supply schedule. By an extension of the same argument reliant on (non-strict) convexity, supplying any load greater than nt is also no less expensive in expected value terms after time A. Clearly, this argument makes a number of simplifying assumptions, but the key assumption, convexity of the supply schedule above some low level, is well-established empirically, for nations with many power plants. This suggests that the impact of the Atomausstieg will differ depending upon the location of the intersection of demand along the supply curve. Therefore, in order to capture the effect of the Atomausstieg, we explore both a dummy that has a constant impact following the initial decision, and dummies that separate this effect into different impacts as well as other nonlinear approaches.

Turning to the *CI* variables, we measure congestion in Germany's import and export interconnectors on an hourly basis. In order to identify congestion we use spot price differences between Germany and the relevant neighbouring country to generate dummies ($D^{Imp(Exp)}$). To capture exchange rate errors and to reflect the fact that on some borders allocation of interconnector capacity takes place via explicit auctions, we allow for small price differences up to 1 €. By doing this we hope to adjust for most of the explicit auctions' expectation errors.[31] These hourly dummies for congestion at each border are multiplied by border and direction-specific available transfer capacity (ATC) to weight interconnectors by their maximum possible trade volume in a congested hour. Thus the capacity index may be written as

$$CI_t^{Imp(Exp)} = \frac{\sum_{i=1}^{N}\left(D_{t,i}^{Imp(Exp)} \times ATC_{t,i}^{Imp(Exp)}\right)}{\sum_{i=1}^{N} ATC_{t,i}^{Imp(Exp)}} \tag{5}$$

[31] In explicit auctions arbitrageurs submit bids for interconnector capacity in the direction from the low price to the high price country which reflect the expected price. Due to uncertainties with respect to the expectation of price differences, small price differences can occur in explicit auctions even if transmission capacity between countries is not fully utilised (see Gebhardt and Höffler, 2013). By contrast in implicit auctions, there are no bids for interconnector capacities but auction offices collect the national spot exchanges' aggregated order books and optimize cross-border capacity allocation. Thus, price differences cannot occur when interconnector capacities are fully utilised in the implicit auction. The 1 € price difference is arbitrary but we compared results from different specifications (no price difference, price differences of 1% and 10%, respectively); results are robust and only marginally sensitive to these changes.

with

$$D_{t,i}^{Imp} = \begin{cases} 1 & if \quad P_{t,G} - P_{t,i} > 1 \\ 0 & if \quad P_{t,G} - P_{t,i} \leq 1 \end{cases}$$

and

$$D_{t,i}^{Exp} = \begin{cases} 1 & if \quad P_{t,i} - P_{t,G} > 1 \\ 0 & if \quad P_{t,i} - P_{t,G} \leq 1 \end{cases}$$

$P_{t,i}$ and $P_{t,G}$, respectively, denote spot prices in the N neighbouring countries i and Germany (G) in hour t.

We acknowledge that endogeneity from simultaneity may be a concern, since the German electricity market is well connected with the neighbouring country markets. However, with the exception of the Austrian border (which we treat as a part of the German market), available interconnector capacity is limited and varies daily and even hourly. Of the remaining interconnector countries, each has relatively low capacity when compared with the German load; in other words they are likely to make little difference to prices in Germany. Neither, in the short run, can interconnector capacities be enhanced in response to price movements.[32] Expansion of interconnector capacity is a long-term matter and the variation in the transfer capacity is based on technical calculations according to the ENTSO-E method and reflects the physical realities of the grid adjusted by a (varying) security margin.[33] We also assume national generation capacities to be exogenous and unaffected by the event in the short-term. In particular, it is important that whilst other countries (e.g. Switzerland) changed their strategies towards future scrappage dates for nuclear plants, none closed plants as a result of Fukushima in the way Germany did. Hence, endogeneity from reverse causality should not be a particular issue.

Market power is measured hourly through the residual supply index (RSI) and is treated as endogenous because it involves dynamic changes on the demand side. Hence, we instrument for it where it is used. The market RSI takes available capacity (after adjusting for trade) for the largest firm (RWE) and relates it to residual load, with a low value for the index indicating tightness of the gap between plants available from other providers and residual load, thereby indicating the potential for RWE to exercise market power.[34] As shown in the general RSI formula in Eq. (4), RWE's actually available capacity is of relevance rather than total installed capacity owned. Hence, we deduct capacity contracted in the reserve power market since reserve power auctions take place prior to the spot market auctions, making this capacity unavailable for spot trade. Since reserve power auctions are anonymous we multiply reserve capacity by the aggregated market shares of all suppliers except RWE and subtract it from the system's total capacity. We proceed analogously with the system's capacity that is not available e.g. due to failure or maintenance.[35]

The calculation formula is as follows:[36]

$$RSI_{t,RWE} = \frac{\sum_{k=1}^{K}(IC_{t,k} - UC_{t,k}) + \sum_{i=1}^{N} Imp_{t,i} - \left(\sum_{i=1}^{N} Exp_{t,i} + RP_t\right) \times (1 - S_{t,RWE})}{L_t - RE_t} \tag{6}$$

with

$$Imp(Exp)_{t,i} = \sum_{i=1}^{N} \left(D_{t,i}^{Imp(Exp)} \times ATC_{t,i}^{Imp(Exp)}\right)$$

$IC_{t,k}$ is firm k's installed capacity with $k = 1, \cdots, K$ and $k \neq RWE$. UC_t is unavailable capacity.[37] Exp_i and Imp_i is the maximum export and import capacity from/to country $i = 1, \cdots, N$. RP denotes the contracted reserve power capacity in t. Again, L_t is the equilibrium quantity and RE_t is generation from renewable sources wind and solar. S_{RWE} is RWE's market share, that is

$$S_{RWE} = \frac{IC_{t,RWE}}{\sum_{k=1}^{K} IC_{t,k} + IC_{t,RWE}}.$$

Then, the RSI variable in our model is constructed as $(1 - RSI) \times I^{RSI<1}$. Here, $I^{RSI<1}$ is an indicator which is equal to one if the RSI is less than 1.

4. Results

We now present the results of the estimated models. We start by investigating the Atomausstieg's impact on (residual) demand in order to check we can rule out a structural simultaneous shift on residual load, alternatively interpreted, in the ability of supply to serve demand, other things equal.[38] Having reassured ourselves on this score, we indulge in an extensive range of estimations on the supply side, to capture the several nuances of the impact on price and to check robustness.

4.1. Demand

Whilst electricity demand is commonly considered as being perfectly inelastic in the short-term, hence exogenous, the increase of real-time response makes it unlikely that this assumption still

[32] We have also experimented with instrumental variables for the congestion variables in addition to the load variables. In these estimations we used temperatures in neighbouring countries and/or technical availability of cross-border capacity (ATC) to predict import and export congestions. Unfortunately, the instruments were not very strong (Kleibergen-Paap statistic of around 4). However, a Durbin-Wu-Hausman Test did not reject the null hypotheses that import and export congestion variables can be considered as exogenous regressors.

[33] A detailed description of the calculation procedure is provided by ENTSO-E, see http://www.amprion.net/sites/default/files/pdf/Approved%20capacity%20calculation%20scheme.pdf.

[34] Following Twomey et al. (2005) we define the market's RSI as "lowest company RSI amongst all the companies in the market" which in our case is always RWE. With approximately 25% of the total conventional capacity in the German-Austrian market before Fukushima and 24% after Fukushima, RWE is the biggest supplier, followed by EON (20% before and 19% after Fukushima). Vattenfall is the number three with 15% market share before Fukushima and 14% afterwards. The Southern-German electricity supplier EnBW was hit hardest by the Atomausstieg decision: its market share decreased from 10.6% to 8.5%.

[35] Reserve power, also called balancing power or control power, is an ancillary service required to stabilize the system if deviations between electricity fed into and withdrawn from the grid occur. Data on reserve power auctions are downloaded from regelleistung.net.

[36] Cross-border trade is treated as follows: exports reduce the available capacity, but ownership ratios remain unchanged whilst, against the background that the German giants RWE and EON only play a minor role in neighbouring countries' electricity generation, imports reduce the ownership ratios of the available capacity. Hence, available export capacity and available import capacity have to be treated in different ways. Therefore, available export capacities from countries with higher prices are multiplied by the aggregated market shares of all suppliers, except RWE, and afterwards subtracted from total installed capacity. By contrast, available import capacity is just added if import congestion is observed.

[37] Plant and ownership information is from the EEX power plant master data, information on unavailable capacity for each hour is from the EEX Transparency Platform.

[38] Note that we already control for coincidental general improvements of demand side management over time through the inclusion of a linear trend whilst an increase in involuntary load shedding and brown- or blackouts should be captured by the Atomausstieg indicator variable.

reflects reality.[39] Accordingly, we use an instrumental variable (IV) approach to ensure consistency of the estimated parameters. The estimation is performed using an IV GMM estimator. In the (residual) demand side estimates, price indices of natural *Gas* and *Coal* are deployed to instrument for the spot price. In the basic supply side estimates we present, instruments for residual load are *Temperature*, *Temperature*^{2}, *Industrial Production Index* and *Daylight Hours*[40]. Since the Angrist-Pischke first stage *F* statistics always exceeds the critical Stock and Yogo (2005) values for weak identification, the instruments seem to work properly.

As shown by the estimates in Table 2, residual demand is relatively inelastic with respect to price, at mean values the elasticity is 0.15 in absolute terms. The demand estimations only differ slightly whether we use Temperature and its square or *HDD* and *CDD* variables and demand is minimized at a temperature of 66 °F (19 °C, column 1), other things equal, which is almost exactly what would be expected. Industrial production and lack of daylight are also very important in affecting demand positively. With regard to the estimations in columns 1 and 2, a 1 MW increase of generation from renewables should naturally decrease residual load by 1 MW which is what we find since coefficients on renewables are insignificantly different from −1. In columns 3 and 4 the dependent variable is Load rather than Residual Load and Renewables are used as an additional instrument for (wholesale) Price. The estimates presented in Table 2 confirm that there is no evidence for an impact of the "Atomausstieg" reduction in generation capacity on average residual demand, i.e. there was no appreciable rationing as a result.[41] This might be because the German Federal Network Agency (Bundesnetzagentur) contractually ensured 2.5 GW so called "cold reserves" power plants (e.g. old and already decommissioned oil plants in Austria) in order to be prepared for the increased risk of outages. These German and Austrian reserve power plants were called upon on more than one occasion in winter (Bundesnetzagentur, 2012). Our experiments where we dropped the AUS index, and where we replaced it with the SAIDI index, are reported in the Appendix (Tables C.2 and C.3). The results remain rather similar across the alternative specifications.

4.2. Overall impact on wholesale price

We now turn to the supply side. Because the shape of the supply curve is unknown and in order to model it as flexibly as possible we propose a semi-parametric partially linear model and estimate it by Robinson's (1988) double residual method. The model can be written as

$$P = \theta_0 + Z\theta + m(RL) + \varepsilon \tag{7}$$

where P represents the wholesale price, θ_0 is the intercept term. $m(RL)$ is an unspecified function of residual load (RL) that may be non-linear and Z is a $K \times 1$ vector containing all remaining covariates (including the Atomausstieg dummy *AUS*) from Eq. (3) which enter the model linearly. ε is the error term, for the moment assumed to follow an independent random distribution with $E(\varepsilon|RL) = 0$. The double residual methodology applies conditional expectation on both sides leading to

$$E(P|RL) = \theta_0 + E(Z|RL)\theta + m(RL) \tag{8}$$

and through subtracting Eq. (8) from Eq. (7), we get

$$P - E(P|RL) = [Z - E(Z|RL)]\theta + \varepsilon \tag{9}$$

where $P - E(P|RL) = \varepsilon_1$ and $Z - E(Z|RL) = \varepsilon_2$ reflect the two residuals. In a two-step procedure we first obtain estimates of the conditional expectations $E_n(P|RL)$ and $E_n(Z|RL)$ from some non-parametric kernel estimations of the form $P_i = m_P(RL) + \varepsilon_1$ and $Z_k = m_{Z_k}(RL) + \varepsilon_{2k}$ with $k = 1, \ldots, K$ indexing the control variables entering the model parametrically. After inserting the estimated conditional expectations in Eq. (9), the Robinson method enables us to estimate the parameter vector θ consistently without explicitly modelling $m(RL)$: using a standard non-intercept least square regression we obtain $\hat{\theta} = (\hat{\varepsilon}_2'\hat{\varepsilon}_2)^{-1}(\hat{\varepsilon}_2'\hat{\varepsilon}_1)$. Finally, $m(RL)$ is estimated by regressing $(P - Z\hat{\theta})$ on RL non-parametrically.

The reverse causal relation between the non-parametric term RL and the dependent variable P however, may yield $E(\varepsilon|L) \neq 0$. As standard IV-techniques such as 2-SLS and GMM are not feasible in the context of endogenous variables that are non-linear in parameters, we apply a two-stage residual inclusion (2SRI) control function (CF). Thus, we first conduct a reduced form estimation of RL and add the residuals ν_t from that estimation as control function for endogeneity to the semi-parametric regression model (see Blundell and Powell, 2004 and Imbens and Wooldridge, 2009, respectively). *Temperature, Temperature*^{2}, *Industrial Production Index* and *Hours with Daylight* provide sufficiently strong instruments as shown by the first-stage *F*-statistics. We then have $\varepsilon = \rho\nu + \eta$ with ν being the error from the reduced form estimation of RL. Because RL is a linear function of exogenous covariates and ν we have RL also uncorrelated with η. The adjustment of standard errors needed due to the inclusion of the generated variable $\hat{\nu}$ is through a block bootstrap procedure which is conducted on blocks of 24 h in order to consider serial correlation.

In Table 3 we report estimates of our basic supply side models prior to developing variants. The significant coefficient for the control function indicates that treating residual load as an endogenous variable is reasonable. The general tenor of the results in Table 3 is as expected across all models, both in terms of coefficient signs and magnitudes. Supply price is related to most of the key variables. Signs on renewables are positive - due to their fluctuating nature high renewables increase operational costs of the conventional power plant fleet as they require frequent adjustments to rapid load changes.[42] Input prices on gas, carbon, and coal take their expected positive value. Gas prices have the most important quantitative impact compared to coal in terms of standardized coefficients because combined cycle plants are significantly more efficient and near to time of consumption.[43] Low river levels lead to higher prices, because plants' generation is then constrained, whereas the river temperature variable remains insignificant. It is possible that plants

[39] As will be shown later the Durbin-Wu-Hausman F test also clearly rejects the null hypothesis of price and residual load, respectively, being exogenous regressors in the corresponding estimations.

[40] Daylight hours also have an impact on price through its impact on solar production. Solar in turn has an impact on price as it decreases residual load, i.e. solar shifts the (residual) demand curve to the left. In addition, solar also may have a direct impact on prices as high variation in solar increases ramping costs. However, as we directly control for production from renewables in the regression, endogeneity is not a concern and $Cov(DaylightHours|e)$ is expected to be zero therefore.

[41] This result is robust to a non-parametric specification of price in a semi-parametric partially linear regression model. The models are estimated by Robinson's (1988) double residual method with price entering the model according to a non-binding and potentially non-linear function. In order to consider the reverse causality we apply a control function (CF) approach. The general method is explained in detail in the subsequent section; estimation results can be found in Table C.4 in the Appendix.

[42] Note that the main impact of renewables on price is a price decrease as they decrease required generation from conventional plants (residual load). However, this is already reflected in our residual load variable which is load minus renewables. Furthermore, following a suggestion from an anonymous referee we have also estimated models where we use the daily variation in generation from renewables in order to proxy ramping costs as an alternative to hourly generation from renewables. The results remain unchanged to the second decimal place (see Table C.5).

[43] Standardized coefficients, computed as coefficient of regressor x × (standard deviation of x/standard deviation of regressandy) are 0.17 for gas, 0.15 for carbon emission right prices and 0.03 for coal.

Table 2
IV estimates of residual load and total load.

Dependent variable is	(1) Residual load	(2) Residual load	(3) Total load	(4) Total load
Price	−188.7**	−231.3***	−93.69***	−92.48***
	(80.19)	(87.07)	(16.72)	(16.98)
Atomausstieg (AUS)	150.1	660.4	−435	−263.4
	(591.6)	(676.2)	(321.3)	(326.1)
Renewables	−1.121***	−1.177***		
	(0.0985)	(0.107)		
Temperature (F°)	−705.3***		−609.2***	
	(92.86)		(45.13)	
Temperature^2 (F°)	5.515***		4.723***	
	(0.774)		(0.385)	
HDD		489.8***		405.1***
		(61.96)		(30.35)
CDD		687.5***		504.4***
		(142)		(77.35)
Industrial production	630.6***	694.4***	502.9***	506.2***
	(110.8)	(121.4)	(31.11)	(31.68)
Daylight hours	−632.8***	−409.7*	−530.5***	−310.9*
	(209.7)	(218.4)	(172.7)	(177.8)
Weekend/bank holiday	−14,062.0***	−14,501.7***	−13,013.9***	−12,977.6***
	(906.3)	(975.6)	(275.7)	(277)
Trend	−2577.8***	−3025.4***	−1903.9***	−1998.7***
	(619.5)	(699)	(248.5)	(255.5)
Angrist-Pischke first stage *F* test	25.25	22.39	25.25	22.39
Stock-Yogo weak ID test critical values (10%)	19.93	19.93	19.93	19.93
Durbin-Wu-Hausman test for endogeneity	0	0	0	0
#Obs.	35,064	35,064	35,064	35,064

Note: Newey-West standard errors are in parentheses. Estimation is by IV GMM. Endogenous variable is price (*P*). Instruments in (1) and (2) are (index) prices of the generation inputs *Coal* and *Gas*; in (3) and (4) renewables serve as additional instrument. Relevance of the instruments tested by Angrist and Pischke's (2009) first-stage *F* test. Critical values therefore are from Stock and Yogo (2005). Dummies for months, days of the week and hours and constant term are not reported. Significant for * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 3
Semi-parametric estimates of the supply side.

	(1) No cong.	(2) Basic	(3) Market power	(4) Feb. 2012	(5) Restr. sample
Dependent variable is price					
Atomausstieg (AUS)	4.189***	3.715***	3.383***	3.089***	4.788***
	(0.573)	(0.612)	(0.642)	(0.681)	(0.930)
Residual load (RL)	Non-para.	Non-para.	Non-para.	Non-para.	Non-para.
Import cong. index		7.278***	7.083***	7.980***	6.654***
		(0.506)	(0.418)	(0.474)	(0.458)
Export cong. index		−4.200***	−4.618***	−4.484***	−4.603***
		(0.455)	(0.452)	(0.463)	(0.464)
RSI			3.473*		
			(1.906)		
Feb-12				4.983***	4.983***
				(1.545)	(1.545)
Low river level	4.739***	4.161***	4.303***	4.603***	2.358***
	(0.678)	(0.845)	(0.835)	(0.811)	(0.514)
High river temp.	0.171	0.68	0.773	0.552	2.487***
	(427)	(0.557)	(0.475)	(0.441)	(0.783)
Renewables	0.001***	0.001***	0.001***	0.001***	0.001***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
Gas price	0.127***	0.107***	0.123***	0.117***	0.096**
	(0.015)	(0.015)	(0.015)	(0.013)	(0.029)
Coal price	0.037**	0.032***	0.015	0.025*	−0.007
	(0.012)	(0.014)	(0.012)	(0.013)	(0.029)
Carbon price	0.772***	0.675***	0.751***	0.709***	1.013***
	(0.071)	(0.075)	(0.075)	(0.074)	(0.125)
Control function	−0.001***	−0.001***	−0.001***	−0.001***	−0.001***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
First stage F test (RL)	80.01	80.66	74.15	85.40	49.53
Angrist-Pischke first stage F test (RSI)			45.23		
Stock-Yogo weak ID test critic. val. (10%)	10.27	10.27	9.92	10.27	10.27
#Obs.	35,064	35,064	35,064	35,064	35,064

Note: Standard errors adjusted by block bootstrap with blocks of 24 h in parentheses. Estimation is by Robinson's (1988) double residual method. *RL* is estimated non-parametrically and is endogenous which is considered through a two-stage residual inclusion (2SRI) control function. Instruments for *RL* are *temperature*, *temperature*^{2}, *industrial production index* and *hours with daylight*. Statistics significant for * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Dummies for months, days of the week and hours and the constant term are not reported.

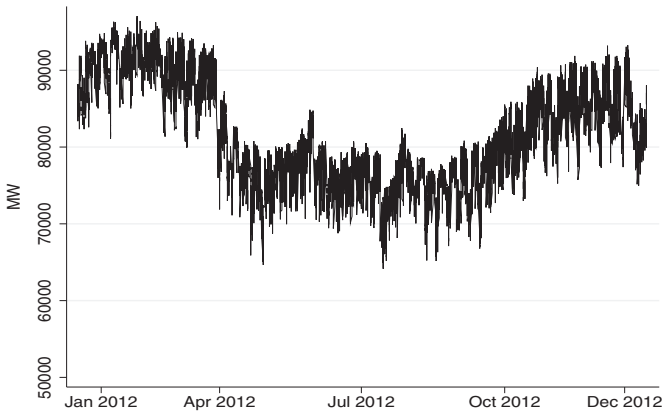

Fig. 4. Available residual capacity from conventional power plants in 2012. Available export and import capacities are considered.

have already been ramped down in situations when the 23°C threshold is exceeded.

Most important for our purposes is the effect of the Atomausstieg (*AUS*). We estimate several models in Table 3 in order to investigate the impact of the Atomausstieg decision on prices. In the first model in column 1 we do not control for the existence of congestion. In this model the coefficient of the *AUS* dummy is highest.[44] Subsequently, we include import and export index variables to control for cross-border trade congestion in all remaining columns. These take the expected signs; we would naturally expect that exports take place when the price in Germany is low relative to its neighbours, and imports when it is relatively high. If interconnectors for import activities are congested then prices cannot be moderated any more through cross-border trade and thus will rise un-damped, and vice versa for the case of congestion in the opposite direction. Our column 2 estimates suggest that the sudden shutdown of a significant share of the nuclear power plant fleet after the Atomausstieg has created, on average, approximately 8.7% (3.72 €/MWh) uplift on supply prices, ceteris paribus. The small difference between the estimates in models 1 and 2 suggests that Germany is already well integrated with its neighbours and the impact is only marginally higher (10%) when interconnectors are congested.

Because firms with market power may incorporate their ability to influence prices in their bid functions we investigate whether increased unilateral market power plays a role in explaining prices by including the *RSI* into the estimated model (column 3). Given the probable endogeneity of *RSI* (recall from formula (6) that *RL* is in the denominator), we instrument for it by adding the hourly available capacity of the conventional power plant fleet to the set of instruments. We then estimate the first stage residuals and include them as the control function for endogeneity in the second stage. As Fig. 4 reveals, there is sufficient variation in available residual capacity resulting from planned maintenance and unplanned outages plus variation in the available interconnector capacities to identify the *RSI*, as the Angrist-Pischke first stage *F*-test confirms. We can now separate the Atomausstieg's impact on prices into two components. The first is the price increase from a general left shift of the merit order due to higher marginal costs of generation, here referred to as "technology jumps". The second is the potential impact on prices through higher frequency and intensity of temporary market power in the post-Fukushima period. Our estimates suggest that market power has a significantly positive impact on prices since including the *RSI* reduces the Atomausstieg dummy's coefficient by 9%. Hence, the price increase is mostly but not entirely a result of a general shift in the merit order.

In column 4 we investigate a particular case: the German electricity market slid into a critical situation during a cold spell in February 2012. As most of the closed nuclear plants were located in the south (4.95 GW out of 6.3 GW) the German grid could not manage to transport sufficient electricity from north to south to satisfy demand. Furthermore, some gas plants were forced to close during this period due to a lack of gas availability from Russia. As a result the German Federal Network agency additionally had to call expensive electricity from contracted "cold reserve" power plants in southern Germany and Austria. We test to what extent the post-Fukushima price increase was caused by this particular situation by including an indicator variable for February 2012. The estimation indicates that approximately 17% (1–3.089/3.715) of the price increase took place during the February crisis. However, the impact of the Atomausstieg dummy remains positive even after controlling for this special grid situation. Moreover, it is clear that this crisis was intensified by the earlier Atomausstieg decision. Finally, in column 5 we re-estimate the model from column 2 on a restricted sample using the period 18 March 2010 to 17 March 2012 which is exactly one year before to one year after the Fukushima accident. Essentially, and unsurprisingly, the Atomausstieg effect is larger when we examine this shorter period - the February 2012 effect looms larger and the economy has had less time to adjust. Also the effect of the short-term shutdown of additional nuclear plants for testing directly after the incident has a higher weight on the shorter sample.

4.3. Price impact throughout the supply curve

We are interested in more than the average impact of the phase-out. For future investments in storage technologies or in peak load plants it matters a good deal where in the supply curve the most significant structural changes are observed. To investigate this issue in depth and to reveal potential non-linearities of the phase-out's impact we engage in several model specifications and interactions in this section. First we apply a parametric approximation of the non-parametric fit of *RL* in order to analyze the impact throughout the supply curve. Subsequently, we examine the typical differentiation in electricity markets between peak-load and off-peak-load hours and evaluate the impact in different hours of the day. The first approach requires interacting the supply function with the Atomausstieg dummy. Because we are interested in the parameters we now have to make assumptions on its shape. The non-parametric fit from the estimations in Table 3 (column 2) is illustrated in Fig. 5.

Though eyeballing the trimmed range indicates a linear specification of the supply curve to be a reasonable choice, the application of Hardle and Mammen's (1993) specification test (based on squared deviations between parametric and non-parametric regressions) suggests that the non-parametric fit should be approximated by a polynomial parametric adjustment of (at least) order 2. Critical values are simulated values obtained by wild bootstrap. Based upon that, we first estimate the models from Table 3 parametrically with a quadratic function of residual load (*RL*). Whilst *temperature, temperature*^{2}, *industrial production* and *hours with daylight* instrument for *RL* as above, we use the square of the fitted residual load values ($\widehat{RL}^2$) from the first stage regression to instrument for RL^2. The model is always identified as shown by the high Kleibergen-Paap rk Wald statistic for weak identification which always exceeds the Stock and Yogo (2005) critical values. The estimation results only differ slightly from their semi-parametrically estimated counterparts in Table 3 and are reported in Table C.6 in the Appendix.

[44] One could argue that we do not disentangle the impact of the Atomausstieg from post-recession adjustments after the Global Financial Crisis (GFC). It is true that demand increased again in the post-recession period. However, as we control for electricity consumption in all estimations this adjustment is already captured by our models.

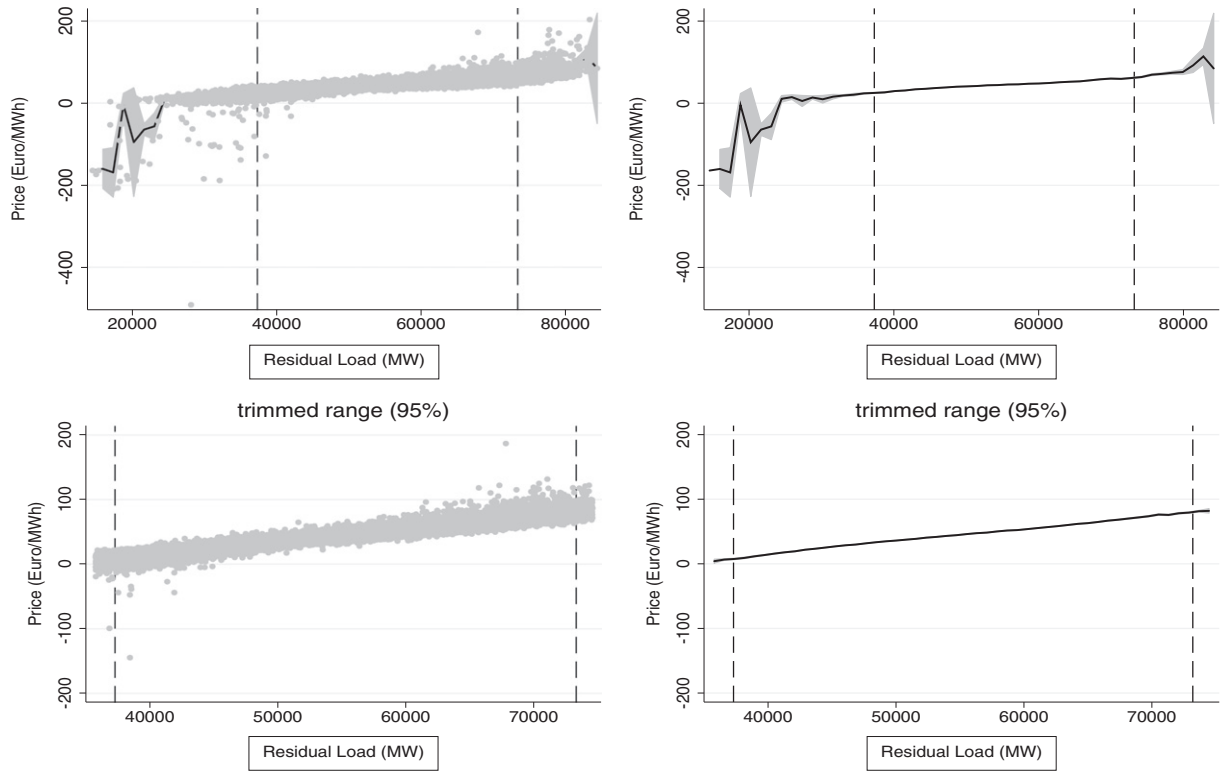

Fig. 5. Non-parametric fit of the supply curve. Note: The figure represents the non-parametric fit of the supply curve estimated by Robinson's (1988) semiparametric method in Table 3 model 2; vertical lines represent 5% (38,000 MW) and 95% percentiles (73,000 MW) of residual load (*RL*). Dots represent actual observed prices. For better illustration of the fit actual observed prices are suppressed in the right hand figures. The lower images present the fit from estimations on a trimmed range of *RL* which excludes the highest and lowest values of *RL*.

In the next step we allow for a non-linear impact of the phase-out by adding interactions of residual load and squared residual load with the Atomausstieg dummy ($AUS \times RL$ and $AUS \times RL^2$). *RL* and RL^2 are instrumented as before and the interaction term of residual load and the Atomausstieg dummy ($AUS \times RL$) is instrumented by interacting the residual load instruments with the Atomausstieg dummy. The instrument for the interaction between squared residual load and the Atomausstieg dummy ($AUS \times RL^2$) is the interaction between $\hat{RL}^2$ and the Atomausstieg dummy ($\hat{RL}^2 \times AUS$). In contrast to the alternative of including squared values of all instruments for residual load and their interaction with the Atomausstieg dummy, this approach reduces the additional number of instruments from

Table 4
Estimation of the supply side with a quadratic function and market power.

	(1) Quadratic interactions		(2) Quadratic interactions with RSI	
Dependent variable is price				
Residual load (RL)	0.558*,***	(0.087)	0.587***	(0.087)
RL^2	−2.93e−08***	(6.78e−09)	−3.22e−08***	(6.79e−09)
AUS × RL	−0.00323***	(0.001)	−0.00353***	(0.001)
AUS × RL^2	2.64e−08**	(1.10e−08)	2.87e−08***	(1.10e−08)
Atomausstieg (AUS)	99.52***	(33.31)	107.8***	(33.45)
RSI			26.70**	(11.87)
#Endogenous variables	4		5	
#Instruments	10		11	
Kleibergen-Paap Wald rk F-statistic	22.21		20.16	
Stock-Yogo weak ID test critical value (10%)	n/a		n/a	
#Obs.	35,064		35,064	

Note: Newey-West standard errors are in parentheses. Estimation is by IV GMM. Endogenous variables are *RL*, RL^2, $AUS \times RL$ and $AUS \times RL^2$. Instruments for *RL* are *temperature*, *temperature*^{2}, *industrial production index* and *hours with daylight*. Instruments for $AUS \times RL$ are interactions of the *RL* instruments and the Atomausstieg dummy *AUS*. The additional instrument for RL^2 is the square of the fitted *RL* values from the reduced form estimation ($\hat{RL}^2$); the additional instrument for $AUS \times RL^2$ is $AUS \times \hat{RL}^2$. As instrument for *RSI* we employ the aggregated *available capacity* from thermal power plants. The estimation includes all control variables as in Table 3 column 2. Significant for $^*p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

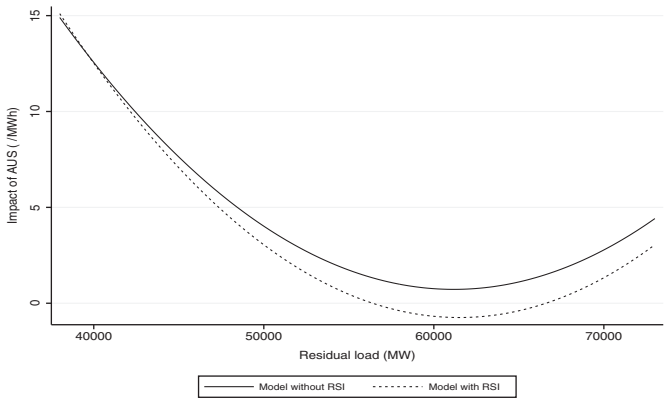

Fig. 6. Estimated impact of *AUS* dummy on prices across residual load before and after controlling for market power. Note: The figure illustrates relationships between the impact of the nuclear plants closure (*AUS*) on prices across residual load (*RL*) from the models (1) and (2) reported in Table 4. The solid line represents the estimated impact from model (1) and dashed line reflects model (2) where we additionally control for market power through the inclusion of the (instrumented) *RSI* variable. Minimum and maximum values of the x-axis are restricted to 5% percentile (38,000 MWh) and 95% percentile (73,000 MWh).

8 to 2, which increases efficiency of the IV estimator. The results are reported in Table 4. Model 2 additionally contains the *RSI* variable, instrumented as above. The estimated impacts are illustrated in Fig. 6. We find a U shaped impact of *AUS* which is highest in situations with very low levels of *RL* and decreases for mid-residual load and high *RL* levels with a slight increase when residual load reaches its maximum. As can be seen, unilateral market power plays the main role in explaining price increases when residual load is high. However over the entire range of residual load and especially when residual load is low the overall price increase is still dominated by technology jumps. An alternative representation of the same phenomenon is shown in Fig. C.1, where we examine the impact based upon a variant model where we interact the *AUS* dummy with each of 5% increasing GW of load. The figure shows the largest impact at the lowest load levels, with the lowest being at medium load levels and a lesser increase at high load levels, presumably related to the market power effects we have identified.

Given a convex supply schedule it is somewhat unexpected at first sight that the price impact is not highest in hours with high residual load. To add intuition on these results, we can think of the supply function as being made up of a series of separate sections relating to particular technologies and different efficiencies of the same technology. The results then suggest that in high demand periods on the whole the marginal technology is less changed by the shrinkage in nuclear provision. However, in the low demand periods, where nuclear anyway contributes a higher proportion of supply, the marginal plant has on average been replaced by more expensive technologies or less efficient plants of the same technology further to the right in the merit order. To examine this we have estimated model (2) of Table 3 incorporating interactions between the Atomausstieg dummy and each hour of the day. The average development of the Atomausstieg dummy's coefficient across the hours of a day is illustrated in the upper panel of Fig. 7. As can be seen, the Atomausstieg dummy's coefficient is highest during night hours which illustrates the technology jump in the merit order following the closure of the nuclear plants. For hours before sunrise in the morning and after sunset in the evening a significantly positive impact is also detected, although it is clearly lower.[45] Moreover, we have estimated models where we interact the Atomausstieg dummy with dummies for peak and off-peak periods as well as seasons. Peak periods are defined as the time between 8 a.m and 8 p.m. on working days. Again, we find that the impact of the Atomausstieg is highest in the off-peak period when residual load is low (see Table C.7 in the Appendix). There is no substantial difference across seasons with winter being the exception, potentially due to the February 2012 crisis. The table containing these estimates is available in the Appendix (Table C.8).

Residual load is significantly higher in the evening hours when people cook, watch TV and enjoy their evening and there is commonly no generation from solar, whilst it is much lower in the early morning when most people are asleep. In Fig. 7 it can be observed that the price increase is negatively correlated with residual load in off-peak hours.[46] To make the causal relation clearer we average available baseload capacity from nuclear, biomass, water and lignite for the years 2009/2010 and then 2012 and compare them with residual load. As the lower panel in Fig. 7 reveals, capacity from baseload technologies was sufficient to cover residual load in the night and early morning hours before the Atomausstieg but this was not the case afterwards on average. As a result the higher coefficients of the Atomausstieg dummy in the night and early morning are caused by a technology jump from lignite to hard coal, whilst they are driven by the use of less efficient plants of the same technology in the evening. Moreover the price increase can be partly explained by more frequent situations with market power in the late morning and early evening as shown above. To summarize, market power plays a role in explaining price increases for those hours in which total demand is already high but generation from solar is not and as a result, residual demand is not reduced through increased renewables in these hours.

To further examine our findings we have constructed the marginal costs from technical data using fuel costs and efficiency of each power plant in the German-Austrian market (Fig. 8).[47] From that we build the averaged merit order for 2010 and 2012 and report their curves along with spot price means plotted against the corresponding residual load means. To be more precise, the distribution of residual load has been split into 20 classes defined by the corresponding percentiles. Within each class the means of spot prices and residual load have been computed. The merit order curve and price means before the Atomausstieg decision are represented by the continuous line and solid black circles, respectively. The high impact for low residual load levels can clearly be detected in the graphical representation. The gap between both merit order curves is highest for residual load below the median which represents the technical jumps from lignite to coal. Of course, fuel prices are flexible, meaning that the figure is only a representation of what is happening. But the important point is that price changes are not sufficient to upset the merit order - in terms of increasing marginal costs, the order is {nuclear, lignite, coal and gas} throughout the period.[48]

Given this pattern, we revisit the cases in our data which are near to the jump in costs, to see whether market power effects may come in additionally here, since firms with baseload plants may realise

[45] Estimation results are reported in Table C.7.

[46] For robustness check, a similar plot obtained with a IV-GMM estimator is shown in Fig. C.2.

[47] The necessary data for the fundamental construction of the merit order are gathered from annual reports and the EEX master data; fuel prices used to proxy marginal costs are future prices for gas and coal (TTF and ARA) and per plant efficiency levels are adjusted by year of the plant's installation. Fig. 8 is for illustrative purposes only. We adopt the 2010 fuel and carbon prices for both merit order curves in constructing the figure.

[48] Looking at the summary statistics of Table 1 it might appear that the merit order changed after the Atomausstieg. According to these figures, the mean of the coal price index is higher than the mean of the gas price index pre-Atomausstieg, whereas the opposite is true post-Atomausstieg. However, notice that coal and gas prices in the table are indices with a base year, not actual prices. In fact, although there has been differential growth in the indices, the ranking of coal and gas price levels is unchanged over our period.

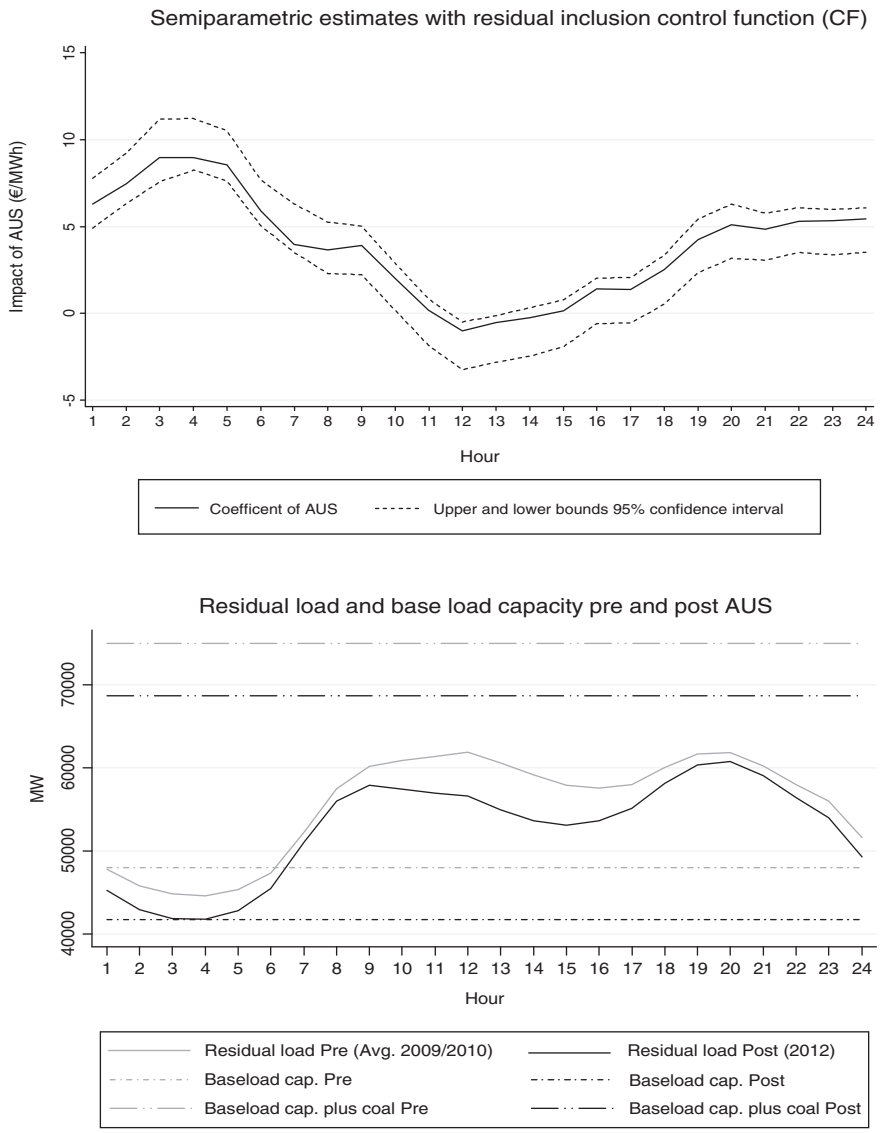

Fig. 7. (Upper panel) Price increase on hourly basis (€/MWh); coefficients and standard errors can be found in Table C.6. (Lower panel) Comparison of residual load and average available capacity from baseload technologies in 2010 and 2012.

that marginal bids well above marginal cost will not trigger higher cost plants. However, we find little evidence of such strategies being played out in our sample.

An additional impact of the price increase is on the EEG surcharge which is computed from the yearly difference between aggregated fixed feed-in payments for renewables and the revenues from selling them on the spot market (broadly speaking). Hence, the spot price increase actually decreases the EEG surcharge which is charged at the retail level. In this context it is worth noting that the spot price increase hits energy intensive industries much more than households since industry is virtually exempted from the EEG surcharge whereas the EEG surcharge accounts for more than 20% of the electricity retail price for households. Therefore, the EEG surcharge can be considered as a subsidy to industry which decreased through the phase-out decision.[49]

[49] Actually, the issue remains open since the Commission opened an in-depth inquiry into support for industry benefitting from a reduced renewables surcharge in December 2013 (http://europa.eu/rapid/press-release_IP-13-1283_en.htm).

5. Conclusions

In deciding, almost on the spur of the moment, to close a substantial proportion of its nuclear power plant fleet as the result of a chance event in Japan, far away, Germany made a bold decision; almost certainly this was the most extreme reaction to Fukushima outside Japan. Germany's unexpected political U-turn did not lead to a disaster.

This outcome is assisted by Germany being relatively well connected with other European countries in terms of exports/imports. Taking the impact on Germany alone, an implication of the average 8.7% uplift on wholesale prices is that German consumers face an annual cost, assuming unchanged conditions otherwise, of around 1.75 Bn €, according to our estimates in Table 3. The calculation is as follows: Mean load is 53.8 GW, which on average is uplifted in price by 3.715 €/MWh, so on an annual basis is $53800 \times 365 \times 24 \times 3.715$ €. Estimates from Table 4 may be calculated similarly, but of course applied only to the relevant time periods. This exceeds 20 €per year per person, net of any EEG impact. The various robustness checks we have engaged in also suggest a similar magnitude. However,

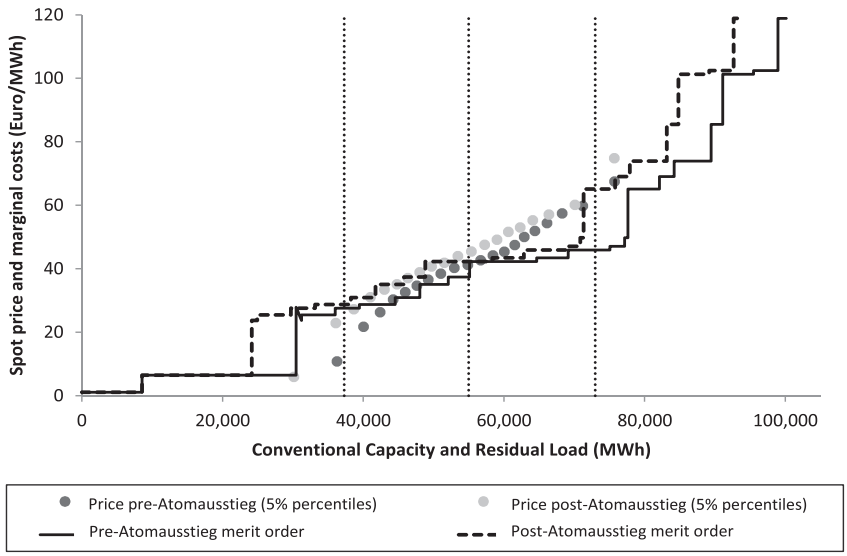

Fig. 8. Marginal costs and prices throughout residual load. Note: For better interpretation, the vertical lines present residual load percentiles 5, 50 and 95, respectively.

this chance German decision also gave a glimpse into the future, where non-controllable renewables will play a much larger part in the power markets than hitherto, whilst nuclear power will have a lesser role. Germany is well ahead of the curve in implementing changes to the electrical power industry to favour renewables, and these often take the form of experimental moves, although we have yet to see any of the planned impact on reducing carbon emissions (Auffhammer, 2015) that Germany, like California, is promising. Energy prices are expected to rise as a result (as have the EEG payments).

We are able to draw a number of further lessons from this. First, Germany is in the fortunate position that solar power matches well with peak demand. Indeed, it is remarkable how complementary the generation from wind and solar plants is in Germany, with wind speed higher when solar output is lower, and vice versa (see Fig. A.4 in the Appendix). Countries such as Britain will not be so fortunate. The other side of this coin is that doubt is cast on the common assumption that electric vehicles charged overnight will provide useful storage. At least, given current wind production relative to solar, our estimates suggest this would be precisely the opposite of an appropriate strategy in Germany, although it may be well-suited to the Irish situation, which has significant wind. More generally, where the impact of a future cut in conventional generation falls most significantly will depend on the particular features of the market, and in the German case these push towards most of the effect taking place in low demand periods, where baseload plants have been removed. This particular result on the impact of a move to higher renewables can be generalised to a certain extent since many countries have similar generation structures with significant reliance on a nuclear power fleet that is in the process of being phased out, for example Spain and Belgium and US states, e.g. California.

Typically a fraction of baseload capacity sets the marginal price during off-peak followed by a significantly more expensive large swathe of mid-merit plants and a bigger jump in marginal costs to a small fraction of peak plants. This is demonstrated nicely in our results where we separate out seasonal and peak effects. We can infer that the marginal impact of the nuclear moratorium on price is larger in summer than in winter due to the increased probability of moving to the next production technology. Hence a significant cost jump from baseload to mid-merit plants may be expected as nuclear baseload declines. Furthermore, our finding is important in terms of expected future investments in conventional plants and hence the possible requirement of providing security of supply through capacity markets for conventional plants. The price increase in off-peak along with largely unchanged prices in peak periods squeezes the gap between peak and off-peak prices. This will arguably reduce German incentives to invest in new storage technologies and decrease profitability of pumped storage, where these technologies rely financially on arbitrage between periods when prices are low to input energy and periods when prices are high to generate electricity. However, flexible conventional sources like open-cycle gas turbine plants and more novel storage plants will be required in future to handle periods when renewable generation is low. In fact, one issue that our study reveals is the desirability of a strategic combination of renewable energy technology investments in order to minimize the potential increased variance in requirements from conventional generation. More does not necessarily mean better. Different countries will face different issues and solutions will need to be tailored to these situations.

There is a more general political dimension to our analysis. There is no doubt that significantly electrically interconnected countries benefit in many ways from this interconnection in terms of power smoothing and the resultant smoothing in prices; evaluating this benefit is beyond the scope of our paper. But there is also a downside to this interconnection, as observed here most clearly in the case of Austria. The German political decision to phase out nuclear plants cost Austrian consumers approximately 0.25 Bn €per annum, almost 30 € each.[50] Interconnection does imply that political decisions in one country can have significant ramifications on energy prices in another, even between friends.

Appendix. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.eneco.2017.07.010.

[50] With an average load of 7.75 GW for Austria, the corresponding calculation is 7750 × 24 × 365 × 3.715 €.

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