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Drivers of wholesale electricity prices in a small, open economy

Some evidence from the nuclear restart in Belgium

October 2016

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Abstract - In this paper, the impact of a nuclear downtime and subsequent restart on wholesale electricity prices on the Belgian power exchange is investigated by means of a dual methodology. First, publicly available market data is used to construct a stable statistical model that is deployed to examine the effect of nuclear power generation variations on market price outcomes. Quantifying this phenomenon, also called the merit-order effect, with the aid of econometric methods translates into an estimated price decrease of around 10 €/MWh for a nuclear capacity hike of 2.5 GW. The importance and impact of the openness of the Belgian market, that is, its strong reliance on cross-border energy exchanges is highlighted. Next to this empirical evidence, the optimisation tool Crystal Super Grid is used to assess the impact of the resumed availability of the nuclear reactors on several indicators characterising the Belgian and European power landscape. A positive effect on overall welfare, consumer surplus and CO_2 emissions can be noticed. As regards prices, this analysis confirms the negative merit-order effect which is calculated to equal, on average over a year, 3.8 €/MWh. Nevertheless, temporary hourly excesses of 30 €/MWh can occur. The paper then describes the possible causes of divergence between the two approaches.

Our findings have important policy implications as they demonstrate the need to take the downward influence of prolonged nuclear power generation on wholesale prices into consideration when revising the (timetable in the) nuclear phase-out law since it may have a delaying effect on the compulsory energy transition towards a low-carbon economy.

Jel Classification - C51, L94, Q41
Keywords - Energy modelling, nuclear phase-out, electricity wholesale markets, energy transition

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Executive summary

Wholesale power prices nowadays are creating havoc in the European electricity markets. Depressed prices caused by numerous features as diverse as the economic downturn, subsidies granted to variable production technologies, rather successful energy efficiency initiatives, low carbon prices,… together bring about profitability problems for conventional power producers. In this paper, we study another potential source of downward influence on power prices, being the variation in nuclear power generation.

As nuclear electricity comes at relatively low marginal cost, output variations from nuclear reactors tend to shift the relevant part of the aggregated supply curve back and forth (just as output variations from variable renewable energy sources do). In order to get a good grasp of the magnitude of the price impact these movements are inducing, it is necessary to build a merit-order curve for the Belgian market. In doing so, taking cross-border energy exchanges into account is paramount to correctly address the specificities of the Belgian market. Large interconnection capacities and strong reliance on electricity imports do have a significant influence on the shape of the merit-order curve and its variations in time. In this respect, the analysis for a small and rather open market such as the Belgian one diverges from other studies focusing on large electricity markets with little reliance on imports like Germany. Additional complications in the modelling effort are introduced as well as additional sources of uncontrolled variation in the outcomes.

Basically, designing a merit-order curve can be done in two ways: a top-down empirical or a bottom-up optimisation approach. Since the expertise and the instruments to execute both methods reside within the Energy team of the Federal Planning Bureau, it was decided to carry out both analyses and therefore work with a dual methodology. Afterwards, results are compared and differences explained.

In the first approach, publicly available high frequency market data is used to specify a stable, robust statistical model linking prices and demand. This model is subsequently deployed to investigate the effect of nuclear power generation variations on market price outcomes. Quantifying this phenomenon with the aid of econometric methods translates into an estimated price decrease of around 10 €/MWh on average over a year for a nuclear capacity hike of 2.5 GW.

The second approach consists in performing a scenario analysis with the optimisation tool *Crystal Super Grid* using detailed power plant and grid specification data. This analysis confirms the negative merit-order effect for the same capacity change which is calculated to equal, on average over a year, 3.8 €/MWh. Nevertheless, temporary hourly excesses of 30 €/MWh can occur.

Next to prices, this optimal dispatch instrument can also be used to calculate the impact of the resumed availability of the nuclear reactors on other indicators characterising the Belgian and European power landscape. A positive effect on overall welfare, consumer surplus and CO_2 emissions can be noticed. The effect on the producer surplus, on the other hand, is mixed: it increases for the nuclear producers, but it decreases for all other Belgian production technologies. Hence, our findings have important policy implications as they demonstrate the need to take the downward influence of prolonged nuclear power generation on wholesale power prices into consideration when revising the (timetable in the) nuclear

phase-out law, since it may have a delaying effect on the compulsory energy transition towards a low-carbon economy. Urgently needed investments in low-carbon and/or flexible technologies may be postponed or annulled all together because of the diminished selling price prospect.

On a more technical side, differences in the results stemming from the two approaches considered here also pave the way for further research that will augment our understanding of the pricing mechanisms on the Belgian power market.

Synthèse

Les prix de gros de l'électricité perturbent aujourd'hui les marchés européens de l'électricité. La faiblesse des prix, qui s'explique par de nombreux facteurs, aussi divers que le ralentissement économique, le subventionnement des technologies de production variable, des initiatives plutôt réussies en matière d'efficacité énergétique, les prix bas du carbone, etc., met à mal la rentabilité des producteurs d'électricité traditionnels. Dans cette étude, nous examinons une autre source potentielle de pressions à la baisse sur les prix de l'électricité, à savoir les variations dans la production d'électricité nucléaire.

L'électricité d'origine nucléaire étant produite à un coût marginal relativement faible, les variations de production nucléaire tendent à induire des glissements de la partie supérieure de la courbe de demande agrégée (à l'instar des variations de production d'énergies renouvelables, dont le coût marginal est proche de zéro). Pour bien cerner l'importance des effets de ces glissements sur les prix, il est nécessaire de construire une courbe de mérite ('merit-order') pour le marché belge. Dans cet exercice, il est essentiel de prendre en considération les échanges transfrontaliers d'énergie afin de rendre compte correctement des spécificités du marché belge. Ses grandes capacités d'interconnexion et sa forte dépendance aux importations d'électricité influencent sensiblement la forme de la courbe de mérite ainsi que son évolution dans le temps. À cet égard, l'analyse réalisée pour un marché de petite taille mais plutôt ouvert comme celui de la Belgique se différencie d'autres ciblées sur de grands marchés de l'électricité, peu dépendants des importations, comme l'Allemagne. En effet, la modélisation est ici plus complexe et les sources non contrôlées de variation des résultats plus nombreuses.

Fondamentalement, deux approches peuvent être envisagées pour construire la courbe, l'approche top-down empirique et l'approche bottom-up d'optimisation. Puisque l'équipe Énergie du Bureau fédéral du Plan disposait de l'expertise et des instruments pour appliquer les deux approches, elle a fait le choix d'une double méthodologie et a donc mené les deux analyses. Les résultats ont ensuite été comparés et les différences expliquées.

La première approche est fondée sur la spécification d'un modèle statistique robuste et stable qui lie les prix à la demande, estimé au moyen de données publiques de marché observées à haute fréquence. Le modèle est ensuite exploité pour analyser les effets des variations de production d'électricité nucléaire sur les résultats en termes de prix du marché. La quantification de ce phénomène par le biais de méthodes économétriques a révélé une baisse de prix moyenne estimée à 10 €/MWh environ sur une année pour une augmentation de capacité nucléaire de 2,5 GW.

Quant à la deuxième approche, elle est fondée sur une analyse de scénarios au moyen de l'instrument d'optimisation *Crystal Super Grid* et sur la base de données de spécification détaillées sur les centrales électriques et les réseaux haute tension en Europe. Cette analyse confirme l'effet négatif sur les prix pour une même variation de capacité, qui est calculée à 3,8 €/MWh en moyenne sur une année. Toutefois, des pics horaires sont observés avec des valeurs d'impact jusque 30 €/MWh.

Outre les effets sur les prix, cet instrument d'optimisation peut aussi être utilisé pour calculer l'impact de la disponibilité renouvelée des réacteurs nucléaires sur d'autres indicateurs du paysage électrique belge et européen. À titre d'exemples, on observe des effets positifs sur le niveau du bien-être général, la rente du consommateur et les émissions de CO_2. D'autre part, l'effet sur la rente du producteur est plus contrasté : la rente augmente pour les producteurs nucléaires mais, en revanche, diminue pour toutes les autres technologies de production utilisées en Belgique. Par conséquent, nos constatations ont des implications importantes pour les politiques à mener. En effet, elles mettent en lumière la nécessité de tenir compte des pressions à la baisse exercées par une production prolongée d'électricité nucléaire sur les prix de gros de l'électricité au cas où l'on envisagerait de revoir (le calendrier de) la loi sur la sortie du nucléaire. Ces effets sont de nature à retarder la transition énergétique indispensable vers une économie pauvre en carbone. Les investissements requis de manière urgente dans des technologies à faible intensité de carbone et/ou flexibles pourraient être retardés ou annulés compte tenu des perspectives de prix de vente moins favorables.

D'un point de vue plus technique, les différences de résultats entre les deux approches retenues ouvrent la voie à de nouvelles recherches qui nous permettront de mieux comprendre les mécanismes de formation des prix sur le marché belge de l'électricité.

Synthese

De huidige groothandelsprijzen voor elektriciteit zorgen voor heel wat onrust op de Europese elektriciteitsmarkten. Te lage prijzen die te wijten zijn aan uiteenlopende factoren zoals de economische vertraging, subsidies voor elektriciteitsopwekking uit variabele energiebronnen, vrij succesvolle maatregelen op het vlak van energie-efficiëntie, lage koolstofprijzen, enz. leiden tot rendabiliteitsproblemen voor de traditionele energieproducenten. In deze paper bestuderen we een andere mogelijke bron van neerwaartse druk op de elektriciteitsprijzen, namelijk de variatie in de nucleaire elektriciteitsproductie.

Aangezien nucleaire elektriciteit wordt geproduceerd tegen relatief lage marginale kosten doen variaties in de nucleaire productie het relevante deel van de geaggregeerde aanbodcurve heen en weer verschuiven (net zoals de wisselende productie van hernieuwbare energie dat doet). Om een goed beeld te krijgen van de omvang van de prijsimpact die deze bewegingen veroorzaken, is het noodzakelijk om een 'merit-order'-curve voor de Belgische markt op te stellen. Daarbij moet rekening worden gehouden met de grensoverschrijdende energie-uitwisselingen om de specifieke eigenheden van de Belgische markt correct weer te geven. De grote interconnectiecapaciteit van de Belgische markt en haar sterke afhankelijkheid van ingevoerde elektriciteit hebben een grote invloed op de vorm van de 'merit-order'-curve en de variaties ervan in de tijd. In dat opzicht verschilt de analyse voor een kleine, maar vrij open markt zoals de Belgische van andere studies die toegespitst zijn op grote elektriciteitsmarkten die minder afhankelijk zijn van invoer zoals de Duitse. In het model worden bovendien bijkomende complicaties ingebracht, evenals additionele bronnen van ongecontroleerde variatie in de resultaten.

In feite kan een 'merit-order'-curve op twee manieren worden opgesteld: via een top-down empirische benadering of via een bottom-up optimalisatiebenadering. Aangezien de equipe Energie van het Federaal Planbureau beschikt over de expertise en de instrumenten om beide methodes toe te passen, werd beslist om beide analyses uit te voeren en te werken met een duale methodologie. Nadien worden de resultaten vergeleken en de verschillen toegelicht.

In de eerste benadering worden publieke hoge-frequentiemarktgegevens gebruikt om een stabiel en robuust statistisch model op te stellen dat vraag en prijs aan elkaar koppelt. Dit model wordt vervolgens ingezet om het effect te onderzoeken van variaties in nucleaire elektriciteitsopwekking op de marktprijsresultaten. Het kwantificeren van dit fenomeen met behulp van econometrische methodes komt neer op een geschatte prijsdaling van gemiddeld ongeveer 10 €/MWh over een jaar voor een nucleaire capaciteitsverhoging van 2,5 GW.

De tweede benadering bestaat erin een scenarioanalyse uit te voeren met het optimalisatie-instrument *Crystal Super Grid* op basis van gedetailleerde data over de elektriciteitscentrales en het netwerk. De analyse bevestigt het negatieve merit-order effect voor dezelfde capaciteitsverandering die gemiddeld 3,8 €/MWh over een jaar zou bedragen. Er worden evenwel tijdelijke uurverschillen van 30 €/MWh genoteerd.

Naast prijzen kan dit optimalisatie-instrument ook gebruikt worden om de impact te becijferen van de beschikbaarheid van kernreactoren op andere indicatoren die het Belgische en Europese elektriciteitslandschap kenmerken. Zo is er een positief effect merkbaar op de algemene welvaart, het consumentensurplus en de CO_2-emissies. Het effect op het producentensurplus, daarentegen, is gemengd: het verhoogt voor de nucleaire producenten, maar het daalt voor alle andere Belgische productietechnologieën. Onze bevindingen hebben daarom belangrijke beleidsimplicaties omdat ze aantonen dat er rekening moet worden gehouden met de neerwaartse impact van een verlengde nucleaire elektriciteitsopwekking op de groothandelsprijzen voor elektriciteit bij het herzien van (de kalender in) de wet op de kernuitstap aangezien deze de noodzakelijke overschakeling naar een koolstofarme economie kan vertragen. Dringend noodzakelijke investeringen in koolstofarme en/of flexibele technologieën kunnen immers uitgesteld of zelfs helemaal geannuleerd worden omwille van dalende prijsvooruitzichten.

Vanuit een meer technisch oogpunt tonen de verschillen in de resultaten van de twee beschouwde analyses de noodzaak aan van verder onderzoek om een beter begrip te krijgen van de prijsmechanismen die spelen op de Belgische elektriciteitsmarkt.

1. Introduction

1.1. The Belgian context

Belgium disposes of seven nuclear reactors located on two sites, Doel and Tihange. In Doel, four nuclear units are being operated, called D1, D2, D3 and D4. In Tihange, three units are functioning: T1, T2 and T3 (see Table 1). In 2015, the oldest nuclear units (T1, D1 and D2) turned 40 (commissioning year 1975) and hence found themselves subject to the nuclear phase-out law. Back in 2003, the Belgian federal Parliament voted a law on the implementation of a nuclear phase-out programme spanning the period 2015-2025 to gradually close down all nuclear reactors when they reach the age of 40. In 2013, however, this law was revised to grant an operational lifetime extension of 10 years to T1 (within the so-called "Plan Wathelet[1]"). In February 2015, the revised programme went life, shutting down the first unit, D1. Previous to that, however, in the summer of 2012[2], the operations in two nuclear units (D3 and T2) were halted rather abruptly because small hydrogen flakes were found in their reactor vessels. The simultaneous stop of the three nuclear reactors in the year 2015 had a pronounced impact on the Belgian wholesale market, requiring both increases in generation from other energy sources as well as a significant rise in net electricity imports (attaining a level of 27% of the residual load). At the beginning of 2016, the three nuclear reactors were brought back online due to, amongst others, a revision of the (already revised) phase-out law[3], and the Belgian power production park could again count on 5926 MW of nuclear generation capacity.

Table 1 Nuclear assets in Belgium

Power plant	Reactor	Reactor size (MW)	Year of commissioning	Lifetime in 2015
Doel	Doel 1	433	1975	40
	Doel 2	433	1975	40
	Doel 3	1006	1982	33
	Doel 4	1038	1985	30
Tihange	Tihange 1	962	1975	40
	Tihange 2	1008	1983	32
	Tihange 3	1046	1985	30
Total	7 reactors	5926		

Source: ENTSO-E (2016), Nuclear Forum (2016).

Meanwhile, numerous price fluctuations in the wholesale power markets could be spotted. One of them was the clear downward trend in prices which could be detected at the moment the return to the market

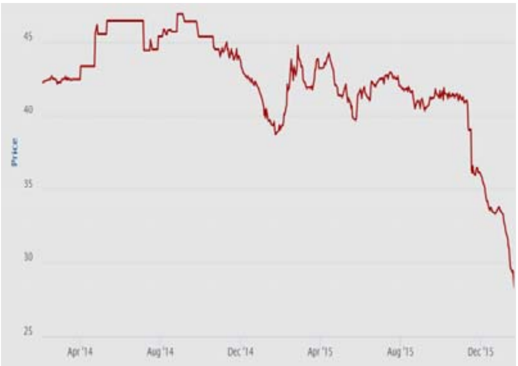
1 In the summer of 2013, the federal government approved a (second) nuclear phase-out plan. This so-called "plan Wathelet" (named after the former Secretary of State for Energy M. Wathelet) not only contains the timing of closure of the different nuclear units, but also some measures to cope with the ensuing lack in controllable capacity.

2 The nuclear power station D3 was shut down for a 10-yearly overhaul on June 2, 2012. During this overhaul, anomalies in the vessel were detected which led to a sustained outage of the unit. On August 16, 2012, T2 was up for its decennial overhaul and the same type of irregularities were found which also caused a prolonged outage. After ample research by numerous (inter)national experts, a common restart was granted in June 2013, but by March 25, 2014, both reactors were stopped once again because of a single test non-conformity.

3 For a detailed overview of the different revisions of the phase-out law and its origins, see Laleman & Albrecht (2016).

of the three nuclear reactors was announced. Graph 1 shows the Cal17[4] for a two-year period spanning 2014, 2015 and the start of 2016.

Graph 1 Belgian Power Base Load Futures, Cal17
€/MWh

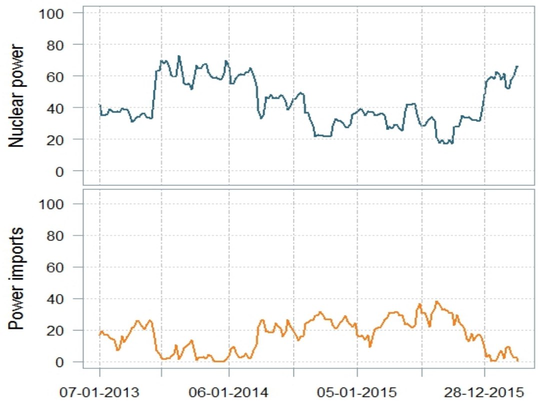


Source: EEX, consulted on 01/29/2016.

This graph illustrates that, at the moment the Federal Agency for Nuclear Control gave its green light for the recouped operation of D3 and T2 (November 17, 2015), the price dropped significantly. A second fall in price can be witnessed end of November, 2015 when the convention between the Belgian federal government and Engie, the utility company owning both power plants, on the extension of the operational lifetime of D1 and D2 was signed.

Since these price movements do not seem to have happened arbitrarily, we thought it to be interesting to scrutinize the extent to which nuclear power generation variations would impact wholesale power price setting in Belgium, knowing that the Belgian electricity landscape is characterised by (at least) two important features: its strong nuclear presence in domestic power production and its highly interconnected nature.

Graph 2 Share of nuclear power and imports in total grid load
%



Source: Elia.

Graph 2 illustrates the significance of both factors: the first graph depicts the importance and volatility of nuclear power generation in Belgium during the period January 2013-March 2016. It is accompanied by a second graph demonstrating the share of net electricity imports in the total Belgian grid load. The latter can reach shares exceeding 25% for sustained periods of time, whilst the former can cover up to 75% of the load, but can also reach lows falling beneath 20%. The title of this paper then reflects these twin traits: *nuclear restart* (nuclear) and *small, open economy* (net imports).

[4] A Cal17 contract prices delivery of baseload power over the calendar year 2017.

1.2. Some literature

Research on the price impact of (announcements of) nuclear phase-outs has been done before, especially (and not surprisingly) in Germany[5]. Matthes et al. (2011a), for example, describe the decision on the nuclear moratorium in 2011 to have increased the German electricity wholesale future prices after the announcement by about 1 eurocent per kWh (or 10 €/MWh), which was partially offset by subsequent price reductions. Kunz et al. (2011) model the impacts of the nuclear moratorium and a complete nuclear phase-out against a status quo scenario in a techno-economic cost minimization framework with a detailed network representation of the German and the central European network. Results are reported for a representative winter week. They come up with an electricity price increase in the off-peak hours between 5 and 25 €/MWh for the moratorium and complete phase-out respectively. With the aid of a dynamic long-term Cournot-Nash equilibrium model of the entire EU electricity sector, Traber and Kemfert (2012) find a price impact ranging from 2 to 6 €/MWh on German electricity prices attributable to the German accelerated[6] nuclear phase-out.

1.3. Design of the paper

This research is novel in its dual approach. In a first phase (described in part 2), data from a variety of public sources are used to examine the impact of the restart on wholesale prices based on an analytical model. These sources include the market operators Belpex, ICE Endex and EEX, the national electricity transmission system operator Elia as well as the European Network of Transmission System Operators ENTSO-E.

In a second phase (described in part 3), the modelling tool *Crystal Super Grid*[7] is deployed. This model in fact minimizes total system production costs whilst aligning demand with supply. It contains an extensive library of both physical and financial assets (thermal power plants, renewable energy sources, power lines, etc.) which allows a fine-grained level of detail for analyses. Powerful optimization solvers are used to calculate the optimal dispatch of generating facilities in interconnected zones. Results cover i.a. imports/exports between zones (countries or regions), marginal costs of electricity generation and CO_2 emissions.

After having described the results of both analyses, part 4 tries to come up with some arguments for diverging results. Part 5 concludes whilst pointing to possible policy implications of this research.

5 For a discussion on German energy policy in general and its position on (phasing out) nuclear power production, a comprehensive overview can be found in Jacobsson and Lauber (2006).

6 The German decision to phase-out its nuclear power production was significantly advanced by the Fukushima Daiichi major nuclear accident (grade 7 in the IAEA INES scale, i.c. the maximum scale value) in March 2011. The German government then agreed to phase out the seven nuclear plants built before 1980 as well as the Krümmel plant. The amount of capacity that was affected by the moratorium was 8.5 GW, out of 20.5 GW, the total nuclear installed capacity in Germany.

7 *Crystal Super Grid* is developed by the French consultancy agency Artelys that is specialised in quantitative methods for optimization, modelling and decision support.

2. The empirical top-down approach

The empirical impact analysis requires a valid price-to-quantity relation to be estimated for the elected market. The focus will be on the day-ahead, spot market for Belgium. Though this market coverage is not ideal, its price still acts as a reference for other transactions and is as such a good price notion for our purpose. The day-ahead market mechanism translates into the merit-order curve (MOC) as a representative supply curve. Demand is considered to be inelastic, which is still a good approximation for today's market. Hence, the MOC should convey all necessary information for our usage.

Basically, estimating MOCs can be done with the aid of two different methodologies. The first possibility is to build the curve bottom up using detailed information on individual power plants, interconnections, outage rates, fuel prices, etc. Using an optimisation technique, the optimal dispatch can be inferred for a given set of conditions, hence a MOC will result. The second option is to derive an analytical formulation of the MOC from observations of market variables and other variables relevant to the pricing issue.

The optimisation method obviously takes advantage of most of the available information, but also requires a number of assumptions, and is fully relying on the theoretical market mechanism to derive a supply curve. It is as such computationally and informationally intensive, and is not linked to observed price quantities. On the other hand, the analytical method requires much less information and is computationally very efficient, relying on standard statistical techniques. It is directly based on observed market outputs. It is, however, much less granular by nature and thus allows to consider only broad aggregate quantities in the analysis. It contains a significant amount of uncertainty due to its statistical nature and limited modelling scope. Additionally, special care has to be taken when performing counterfactual or causal analysis in such frameworks due to non-modelled links between the variables used.

Because both approaches have their own advantages and because the expertise for executing these two analyses is present in the Energy team of the Federal Planning Bureau, it was decided to carry out both analyses and compare them afterwards. The analytical approach is discussed in the rest of this chapter, the optimisation approach is covered in chapter 3. The comparison can then be found in chapter 4.

2.1. A relevant empirical merit-order curve model for Belgium

The merit-order curve (MOC hereafter) is the basic analytical tool for electricity spot markets. It is defined as the supply curve under the hypothesis of marginal cost pricing, that is, under the hypothesis that power plants are called on the grid by increasing order of marginal cost until demand is satisfied. In the case of Belgium, it may help to consider the energy exchanges through interconnections as an additional generator, for which output is positive when the net flow is an import. As mentioned, this generator can cover up to 27% of the load, and thus deserves special attention.

The MOC as broadly defined above would be a suitable price-to-quantity relation to perform impact analyses if it were a stable relation. Indeed, the suitability of empirical methods relies on reproducibility, that is, a sufficient assurance that similar conditions will lead to similar outputs. In our case, that similar loads will lead to similar prices. However, several sources of variation in the output and marginal costs of the generators populating the MOC call for attention to obtain a sufficiently stable function, that is, a function robust to changes in the broad market environment.

First of all, if generators are entered at their nominal capacity in the theoretical definition of the MOC, in reality all generators are intermittent for one or another reason, that is, they cannot always produce their nominal capacity or some other required output level when called for. This is either:

– By *nature*, as their output depends on external factors we cannot control. This is the case of the weather dependent renewable energy sources,

– For *technical reasons*, among which our focus is on outages (planned or unplanned), but other aspects such as ramp-up time or must-run character rank among the causes for output deviating from the optimum,

– For *institutional reasons*, as energy and environmental policy may force to shut down technically available generators.

Not only the output, but also the cost is not constant. This is chiefly attributable to fuel and related costs in the short term. In the case of Belgium, however, this is also due to the special nature of the international exchanges which can be interpreted as generating capacity for which the equivalent marginal cost depends on the market price of the neighbouring countries, hence is highly variable in time.

It is therefore needed to adapt the basic definition of the MOC, at least to include these factors. Other variability factors are being left out but this is proper to the nature of the statistical approach in which the residual sources of variation are modelled by a random error term.

The literature on analytical modelling of the MOC and on estimating merit-order effects provides several alternatives to incorporate these elements into a model of the supply curve. These range from linear models with all variables and some of their interactions included in the regression (e.g. Müller, 2013) to sophisticated varying coefficient semi-parametric models (e.g. Thoenes, 2014). In this paper, the ideas as found in He et al. (2013) which strike a nice balance between interpretability, ease of computation and incorporation of structural relationships between variables, are followed.

As in most of the merit-order effect related work, a residual version of the grid load is used to avoid variability in the price-to-quantity relation stemming from intermittence of low marginal cost generators. In our case, we start from GL, the grid load for the Belgian high voltage grid net of international exchanges and pumping flows, from which we derive a residual load after deduction of the wind infeeds W and the nuclear generation N. Note that solar production is not taken into account as it already appears as a netting out on the demand side in our data[8]. This is almost equivalent to He et al. (2013) where - in the German context - unavailable capacities in nuclear (and lignite) plants are added to the load, instead of subtracting the nuclear production. To tackle the issues stemming from the unknown marginal cost of imports, we for now will also subtract net imports I from the residual load. As a result, our residual load RL corresponds to the demand addressed to local conventional production capacities:

[8] This is due to the fact that these plants typically are not connected to the high voltage grid but to the distribution grid.

$$RL(t) = GL(t) - W(t) - N(t) - I(t) \quad (1)$$

To include the effect of outages in these conventional capacities, the residual load is divided by their availability rate *Av*. As a result, the pricing quantity *NRL* is scaled back to a situation where all capacity is available. This is obviously a proxy as outages in plants with different marginal costs are treated similarly as if the outages were uniformly spread along the plants in this category.

$$NRL(t) = \frac{\mathrm{GL(t) - W(t) - N(t) - I(t)}}{Av(t)} \quad (2)$$

To take the variability in prices of fuels and emission quota into account, we follow the approach in He et al. (2013) in which a fuel adjusted heat-rate model is defined as

$$P_{spot}(t) = P_{fuel}(t) \cdot f\big(Load(t)\big) + \varepsilon(t) \quad (3)$$

In equation (3), the function *f* is an approximate heat-rate function for the market which is an indicator of the efficiency of the power plants in the market.

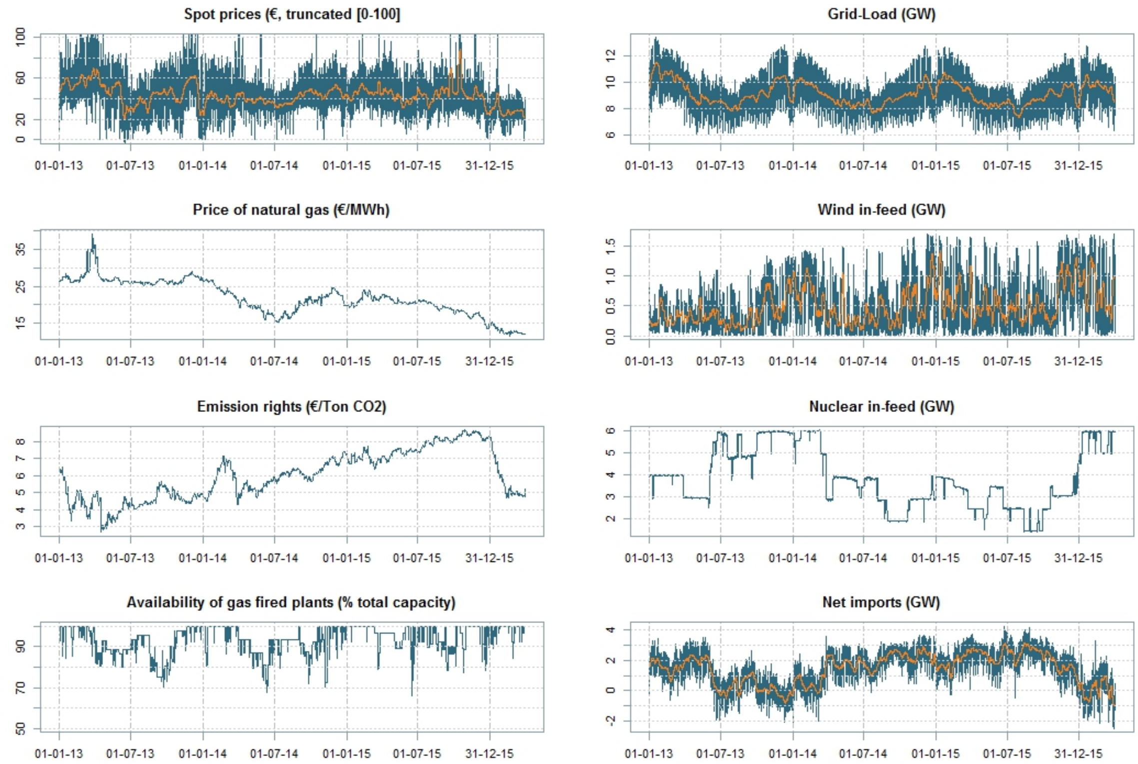
In our case, the fuel price will be taken as the ZTP spot natural gas price. We use only natural gas prices as most of the conventional plants in Belgium are gas fired. To this price, we add a mark-up for the emission rights, based on 0.2 tons of CO_2 per equivalent MWh of natural gas: $P_{fuel} = P_{gas} + 0.2 \cdot P_{CO_2}$. The emission rights are taken as the ECX EUA continuous futures, front month. This allows us to provide the final definition of the function *f* to be estimated:

$$\frac{P_{spot}(t)}{P_{fuel}(t)} = f\left(\frac{GL(t) - W(t) - N(t) - I(t)}{Av(t)}\right) + \varepsilon(t) \quad (4)$$

This function should be a good version of the MOC – actually, a market implied heat-rate curve – for Belgium.

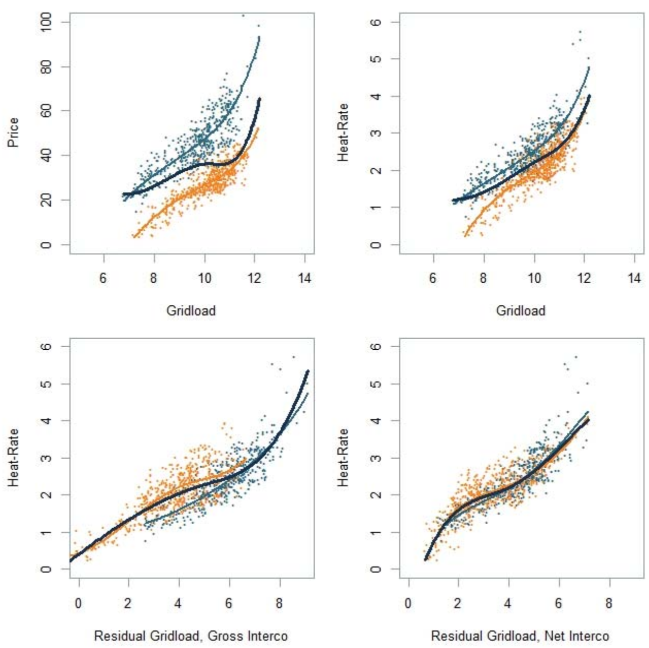
Graph 3 provides an overview of the evolution of the different variables used on the time horizon 1/01/2013 to 31/03/2016.

Graph 3 Overview of market variables and price driving factors, hourly data (in orange: weekly averages)



Source: Elia, ENTSO-E, Belpex, ECX, own calculations.

Graph 4 Effect of adjustments in the MOC definition Nov 2015 (blue) vs. Feb 2016 (orange), weekdays



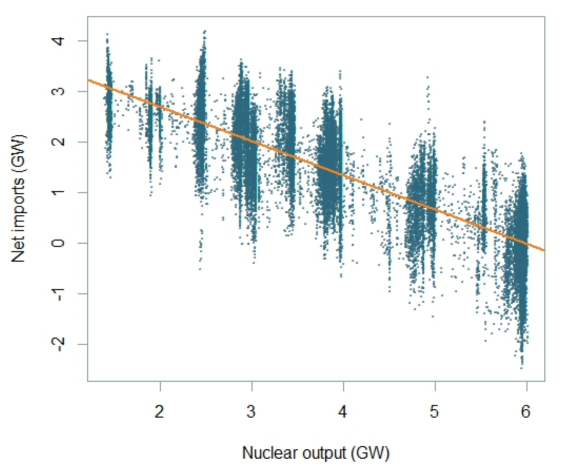
Source: Elia, ENTSO-E, Belpex, ECX, own calculations.

To illustrate the impact of the various adjustments on the stability of the function *f*, Graph 4 provides an example comparing two one-month periods occurring before and after a large increase in the total available nuclear capacity. The effect of the subsequent neutralisation of fuel prices (top right pane), wind and nuclear output (bottom left pane) and net imports (bottom right pane) is clearly visible. Each step in this normalisation process increases the stability of the estimated relation between time periods, with the last pane corresponding to equation 4 providing a visually stable price-to-load relation although the two selected time samples differ substantially along the aforementioned sources of variability. How the model performs globally on the observed data will be described below but first, the topic of impact analysis will be tackled to ensure the model is suitable for its final aim.

2.2. Estimating impacts

Provided the function *f* in equation (4) is specified and being estimated, it apparently conveys a way to assess the contemporaneous impact of a change in nuclear generation capacity on wholesale spot prices of electricity. However, for this to be true, the effect of a change in *N* on all other variables appearing in the equation should also be known. For most of these variables, this is the case as it is reasonable to assume that the fuel price, the availability rate of conventional plants, the grid load and the wind generation are independent of a change in nuclear capacity. The effect of such a change is then null on these variables. However, this is certainly not true for the net imports *I*. On the contrary, it seems logical that additional cheap nuclear capacity would crowd out potentially more expensive imports, or strengthen exports, at least part of the time. This is confirmed by a crude analysis of the observed link between these two variables in our data, as depicted in Graph 5.

Graph 5 Nuclear output and net imports correlation



Source: Elia, ENTSO-E, Belpex, ECX, own calculations.

The substitution relation between nuclear and imports is clearly apparent and a simple linear model offers a very good fit with a parameter around -0.7: hence, the exchanges with neighbouring countries seem on average to compensate for 70% of a change in nuclear production, a result that is confirmed in the optimisation exercise (see below). This crude model is obviously not a causal model as too many variables are omitted.

This is therefore not a sufficient model to correctly account for the link between *N* and *I* in our case. As a consequence, one is led to consider an intermediate version of the model (4) where net imports *I* are kept as a generator in the residual MOC:

$$\frac{P_{spot}(t)}{P_{fuel}(t)} = f\left(\frac{GL(t) - W(t) - N(t)}{Av(t)}\right) + \varepsilon(t) \tag{5}$$

The model in equation (5) is inferior to the model in (4) in two respects: first, it suffers from the variability in *I* for any residual load, blurring the price-to-load relation. Put differently, for a given residual load which is now a demand addressed to Belgian conventional plants and the interconnected foreign markets, one does not know what part of the demand is satisfied by imports. As imports lower the market price, there is an uncertainty about the market price. And second, it applies the availability rate correction based on gas fired plants only also to net imports. If this second point introduces a small bias, the first point has stronger implications. Instead of estimating a heat-rate function, the function *f* now estimates a central version of the collection of heat-rate functions corresponding to the different possible net import price and flows' situations at a given residual load.

With model (5), estimating the impact of a change in nuclear capacity is possible at the expense of some precision in the modelling of the heat-rate curve, thus in the attainable precision of this estimation. Even if model (4) were perfect for the Belgian producers, the uncertainty around import price and capacity translates to the estimates of the impact.

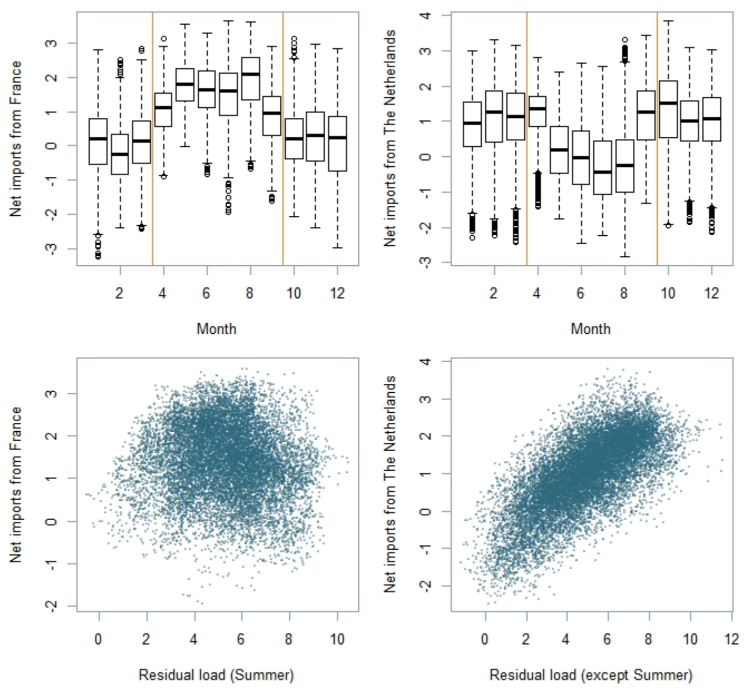
2.3. Additional considerations

Obviously, the sources of variation in the price-to-load relationship mentioned above do not form an exhaustive list. As mentioned, all unaccounted sources will end up in the error term of the statistical model. Below, some other relevant sources of variation are listed as well as some propositions of ways to incorporate them in the statistical model.

– *Forecast errors:* day-ahead prices are based on forecast quantities for the next day. Especially, renewable production and grid load are forecasts when the day-ahead price is determined. In our data, however, renewable production and grid load are the real observed values. This introduces a source of variation in the price/load relationship. One may argue that there is no systematic bias in this additional error – that is, it has zero mean – as such a bias if observed would be corrected in the forecasting models used by market participants. Hence, parameter estimates should remain consistent but with higher variance.

– *Additional seasonality:* due to the specificities of some of the generators, seasonal patterns not present in the load series are expected to be incorporated in the price series. Indeed, at times of low demand (e.g. nights and Saturdays and Sundays) some inflexible or must-run plants will be kept online to avoid extra costs (e.g. shutting-down and start-up costs or ramp-up and ramp-down costs), possibly by bidding below their marginal cost. That is, the market mechanism will be different in these times of low load. This aspect can be partially corrected for by introducing date and time related variables in the model, though this obviously is not structural in any way and hampers any interesting interpretation of the additional estimated parameters. This enhancement is studied at the end of the next section.

Graph 6 Seasonal switch in import sources and behaviour



Source: Elia, ENTSO-E, Belpex, ECX, own calculations.

– *Seasonal regime switching:* the Belgian power market presents a markedly different situation between summer and winter. In summer – actually between April and September – most of the planned outages occur, especially of the nuclear power plants. This aspect is already taken into account in our model. But the use of interconnection capacities is also fairly different between this summer half and the winter half of the year. As can be seen in Graph 6, in the summer half, imports flow mostly from France and are not much correlated to the grid-load. This suggests that in summer, imports are opportunistic and price related, driven by the large over-capacity of the French nuclear plants in that season. By contrast, in the winter half of the year, imports originate mostly from the Netherlands and demonstrate a strong correlation with the grid load. This suggests a peak load import pattern driven by the insufficient capacity of the Belgian local producers. This is not an issue for model (4) where imports are netted out from the residual load, but should be kept in mind when using model (5). A first basic approach to this issue is presented below.

– *Persistence:* other unaccounted market mechanisms, such as the possibility of bidding for a bloc of several hours at a given price, may introduce increased persistence in time for the prices as compared to the load. This would translate into autocorrelated residuals after estimating the models. A possible way of improving the model in this respect, though again it would be of strict statistical nature with no structural information, is to specify a time series model for the residuals that would capture this remaining serial dependence. This approach has been tested but with limited impact on the estimation results and therefore is not presented here.

2.4. Empirical Results

2.4.1. Model estimation

First, we estimate the models (4) and (5) with three different specifications for the function *f*:

– A non-parametric fit, based on cubic splines. This will give us a reference "shape" for the MOC and will help us to validate the parametric models studied below

– A simple linear model

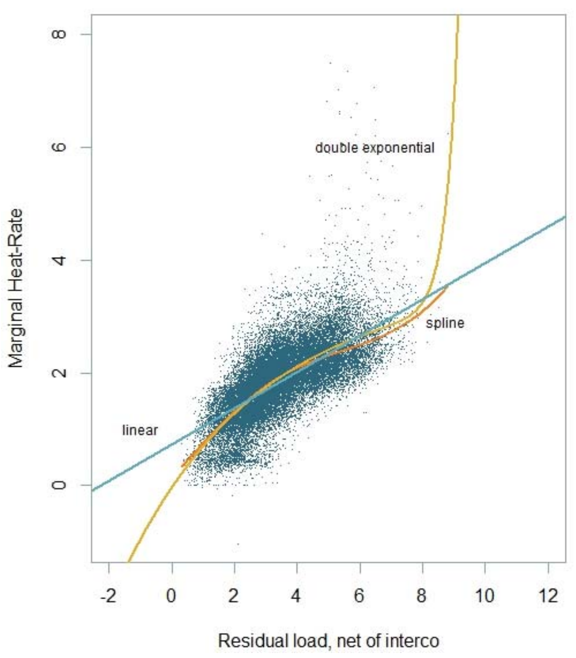
– A double exponential specification following He et al. (2013):

$$f(x) = \frac{e^{\frac{x-a}{b}} - e^{-\frac{x-c}{d}}}{2} + \mu \tag{6}$$

This last function is a smooth sigmoid function with different left and right tail curvatures. This flexible parametric function is well suited to the usual shape of market-data based MOCs, but still simple enough to be easily estimated using non-linear least squares estimation techniques.

Graph 7 represents the data and model estimates for *f* as in equations (4) and (5) on the full dataset, when *f* is taken to be a linear function (light blue), a cubic spline with five degrees of freedom (orange), or a double exponential function (yellow). Estimation is by median regression, except for the double exponential model which is fitted through non-linear least squares. The estimation results can be found in Table 2.

Graph 7 Whole sample, net and gross of interconnection flows



Source: Elia, ENTSO-E, Belpex, ECX, own calculations.

As expected, the right pane showing model (5) presents a less clear structure of the data cloud, as additional volatility due to the interconnection is included in the heat-rate curve, whereas the left pane showing model (4) is more definite, data representing the heat-rate for Belgian conventional producers only. As regards the bulk of the data, the non-parametric and the double exponential model are quite close, meaning that the double exponential is a good parametric model in our case. The linear model is obviously quite far off at the extreme values of the residual load, but seems to fit correctly the core of the sample. This translates into the goodness-of-fit measures in Table 2 and 3, which are based on an estimation sample spanning the period from 1/01/2013 to 31/03/2015, and a test sample spanning the last year of data from 1/04/2015 to 31/03/2016.

Table 2 In-sample goodness-of-fit measures (MAE and RMSE in €/MWh)

model	*f*	R-squared	MAE	RMSE	AIC	BIC
	Linear	0.53	7.85	11.17	4.83	4.83
(4)	Double-exponential	0.56	7.59	10.79	4.76	4.76
	Spline	0.56	7.56	10.82	4.76	4.77
	Linear	0.55	7.86	10.96	4.79	4.79
(5)	Double-exponential	0.57	7.63	10.67	4.73	4.74
	Spline	0.57	7.56	10.67	4.74	4.74

Table 3 Out-of-sample results (MAE and RMSE in €/MWh)

model	*f*	R-squared	MAE	RMSE
	Linear	0.40	8.32	12.83
(4)	Double-exponential	0.41	8.13	12.70
	Spline	0.42	7.96	12.59
	Linear	0.37	9.04	13.16
(5)	Double-exponential	0.36	9.26	13.28
	Spline	0.33	9.47	13.58

In-sample results in Table 2 show that all models perform quite similarly. The adjusted R-squared values around 0.55 are synonymous for reasonable fits but with a significant remaining variance in the error term, which translates into a median error of around 7.5 € on average when estimating the price of one MWh of electricity for a given load. These figures are quite typical of what other published studies achieve in terms of goodness-of-fit. More interesting are the out-of-sample results reported in Table 3. Poorer results for model (5) as compared to model (4) can be observed. This is what could be expected as model (5) suffers from the variability in the imports level and prices for a given load which are netted out in model (4). The double-exponential specification shows the best fit globally but the linear specification is not much worse. As a mean of calibration check, we note that for model (4), the median power plant (the typical marginal plant called for a median load addressed to the conventional plants which is around 3.4 GW in our data) has an estimated heat-rate of around 1.9, which corresponds to an estimated efficiency of 52%[9]. That is indeed a plausible value for a CCGT plant, which forms the bulk of the conventional thermal plants in Belgium.

As the potential imports or exports may partially substitute for the changes in nuclear capacity, the perceived change in demand for the local conventional plants – which constitute the pricing zone of the heat-rate curve – is lower than the nuclear production variation. The interconnection has a dampening effect which can be seen in the more gentle slope of the linear approximation of the heat-curve in Graph 7 (0.21 vs. 0.32). As expected, estimating the impact of such nuclear capacity changes on prices based on the best market model (4) would therefore overestimate this impact. This is particularly obvious in the case of Belgium where the interconnection capacity is significant compared to the size of the market and the reliance on power imports is marked: the interconnection capacity equals about half the total installed capacity of the power plants in our pricing bloc.

2.4.2. Further enhancements

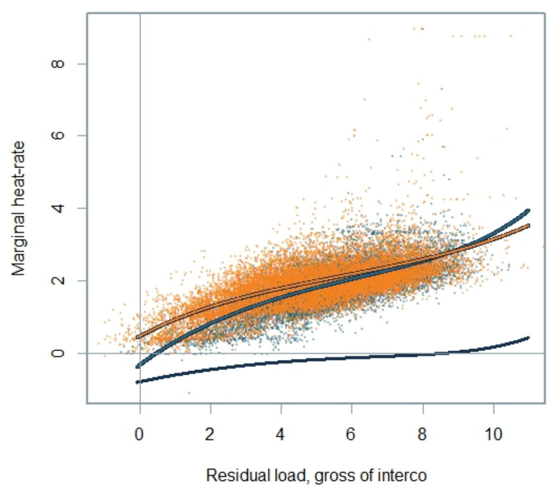
In this section, the models presented above are expanded with additional covariates to capture some of the effects mentioned higher.

To capture the effect of some of the unaccounted seasonality related to low load periods, dummy variables for days in the weekend and holidays (Saturdays, Sundays and official national holidays) and night hours (from 23:00 to 5:59) are included in the model. This choice of dummies has been made based on significance tests over individual days and hours.

[9] As the emission rights are included in the price of gas, this value of 52% is actually an overestimation of the efficiency of the median plant, which only adds to the plausibility of the number.

We also investigate the observed impact of the winter vs. summer regime mentioned above and related to the variable use of the interconnection. Graph 8 represents the full data set for the summer half year (blue) and the winter half year (orange) for the definition of model (5). The dual-exponential estimates of the heat-rate curve for both half years are shown in matching colours. The difference is depicted in black.

Graph 8 Winter vs. Summer regime



Source: Elia, ENTSO-E, Belpex, ECX, own calculations.

One can indeed observe a marked difference between the two half years. Given the shape of the difference, we choose to add a linear function of the residual load to the model for observations in the winter season only to reproduce this shape difference in the heat-rate curve between the two seasons. For model (4), there is no significant difference, as can be expected, since the difference essentially stems from the behaviour of the net imports.

The models thus become:

$$\frac{P_{spot}(t)}{P_{fuel}(t)} = f\left(\frac{GL(t) - W(t) - N(t) - I(t)}{Av(t)}\right) + \beta_1 \cdot D(WE\,\&\,H) + \beta_2 \cdot D(Night) + \varepsilon(t) \qquad (7)$$

$$\frac{P_{spot}(t)}{P_{fuel}(t)} = f\left(\frac{GL(t) - W(t) - N(t)}{Av(t)}\right) + \beta_1 \cdot D(WE\,\&\,H) + \beta_2 \cdot D(Night) + D(Winter) \cdot \left(\beta_3 + \beta_4 \cdot \frac{GL(t) - W(t) - N(t)}{Av(t)}\right) + \varepsilon(t) \qquad (8)$$

In and out of sample estimates for models (7) and (8) above are found in Tables 4 and 5, for the linear, double-exponential, and spline specifications of *f*. The fit measures both in and out of sample significantly improve upon models (4) and (5). While linear and double-exponential specifications remain closely tied out of sample, the spline specification shows some lack of prediction capacity for model (8).

Table 4 In-sample goodness-of-fit measures (MAE and RMSE in €/MWh)

model	*f*	R-squared	MAE	RMSE	AIC	BIC
(7)	Linear	0.56	7.52	10.83	4.77	4.77
	Double-exponential	0.59	7.35	10.47	4.70	4.70
	Spline	0.58	7.31	10.56	4.71	4.72
(8)	Linear	0.61	7.08	10.20	4.64	4.65
	Double-exponential	0.64	6.85	9.80	4.57	4.57
	Spline	0.63	6.77	9.84	4.57	4.58

Table 5 Out-of-sample performance (MAE and RMSE in €/MWh)

model	*f*	R-squared	MAE	RMSE
(7)	Linear	0.43	7.95	12.56
	Double-exponential	0.44	7.80	12.45
	Spline	0.44	7.71	12.41
(8)	Linear	0.43	8.24	12.50
	Double-exponential	0.44	8.23	12.45
	Spline	0.40	8.52	12.86

From this, we can conclude that the double-exponential specification for model (8) provides the best analytical MOC estimated on the data for our purpose. It is the specification with the best out-of-sample properties. This specification also allows some extrapolation outside the range of observed residual loads, which is not really the case for the non-parametric spline, and may be problematic for the linear specification as can be seen in Graph 7.

2.4.3. Impact assessment

With the help of this model, we are now able to compute impact estimates on spot prices for selected events affecting the nuclear generation capacity in Belgium. Results for two scenarios are produced. The first considers the impact of an additional GW of available nuclear capacity at all points in time on our one-year test sample. The second compares estimated prices along the test sample for the full capacity of 5926 MW, to the prices estimated for a reduced capacity of 3479 MW[10]. An average availability rate of 91% is used in both cases. Results are available hour by hour, and an average weighted by total grid load is computed as a proxy for a total demand weighted average.

To implement these scenarios, we simply impact the value of *N(t)*, for *t* in the test sample, in the definition of the reduced load used in model (8):

$$\frac{GL(t) - W(t) - N(t)}{Av(t)}$$

The value of *N(t)* is either augmented by 1 GW, or replaced by the determined fixed value, depending on the scenario.

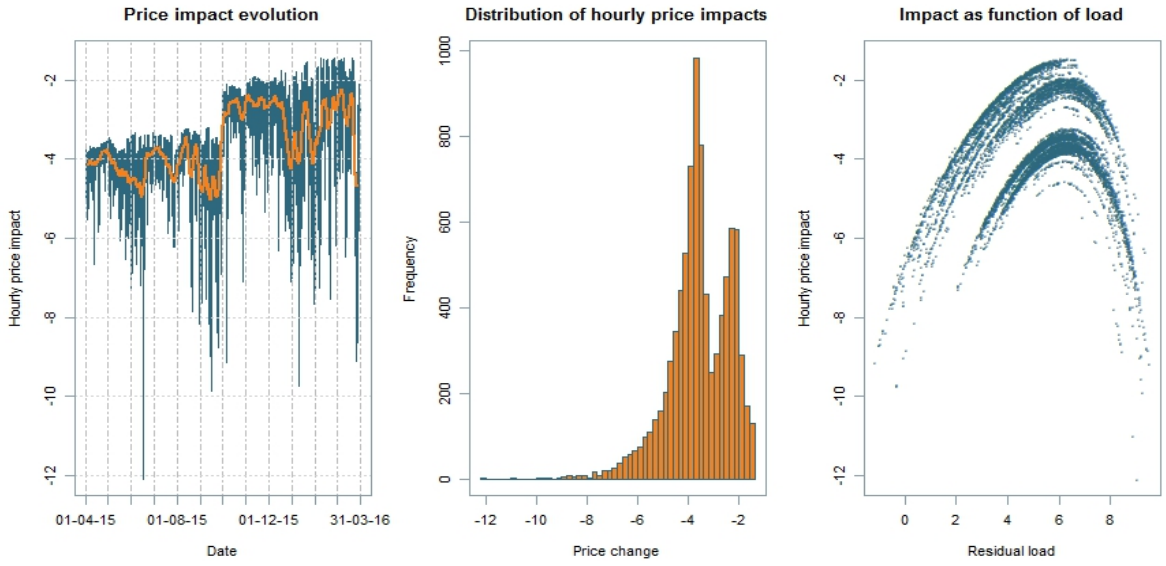
The test sample ranges from April first, 2015 to March 31, 2016. Table 6 provides the computed weighted average price impacts for this 1 GW increase (scenario 1) and the full versus reduced capacity scenario (scenario 2). Graph 9 and Graph 10 give a graphical summary of the hour-by-hour results. It is clearly visible that higher absolute impacts occur for low or high loads, where the slope of the MOC is high, whereas for residual loads around 6 GW, the impact reaches its minimum absolute value. For the second scenario, most of the average impact stems from low load periods. The two seasonal regimes are clearly visible as well.

[10] 5926 MW – 2447 MW equals 3479 MW.

Table 6 Scenario results: Impact on spot prices (€/MWh)

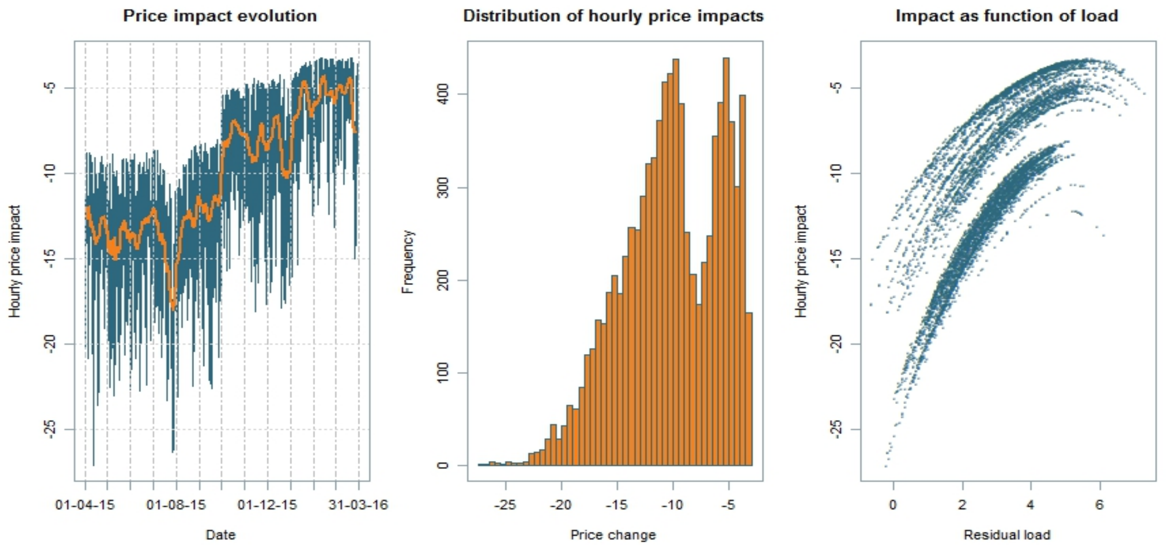
	Average impact	Minimum hourly	Maximum hourly
Scenario 1	-3.43	-1.39	-10.82
Scenario 2	-9.65	-3.24	-27.10

Graph 9 Results for scenario 1



Source: Own calculations.

Graph 10 Results for scenario 2



Source: Own calculations.

The following section then discusses the optimisation based approach of the same problem. Subsequently, comparisons are made before drawing conclusions.

3. The bottom-up optimisation approach

3.1. An economic dispatch model for Belgium

As a second approach to merit-order curve modelling, the optimisation tool *Crystal Super Grid*[11] is deployed. This model in fact minimizes total system production costs whilst aligning demand with supply. It contains an extensive library of both physical and financial assets (thermal power plants, renewable energy sources, power lines, etc.) which allows a fine-grained level of detail for analyses. The data infeed for the model mainly comes from publicly available databases like ENTSO-E and the International Energy Agency (IEA). More specifically, the demand, the installed capacities and the thermal availabilities are obtained from ENTSO-E, the fuel costs from IEA and the detailed capacity descriptions from the European TSO's individual websites. Powerful optimization solvers are used to calculate the optimal dispatch of generating facilities in interconnected zones. Results cover i.a. imports/exports between zones (countries or regions), marginal costs of electricity generation and CO_2 emissions.

Crystal Super Grid runs on JAVA. The computation process is performed by successive optimisation problem resolutions over a rolling horizon. This is done to avoid perfect foresight issues at the end of the projection period. The model computes 14-day period (tactical horizon) problems with 7-day steps (rolling horizon) at each iteration. This way, each new computations' tactical horizon overlaps with the previous one taking into account its decisions and the ensuing state of the system.

In this paper, this electricity market model with hourly load profile, power plant ramp-up and emission trading is applied to the European electricity market to study the case of diverging levels of nuclear power production in Belgium. For this purpose, two scenarios are created within *Crystal Super Grid*. A scenario is a broad description of a state of generating facilities in the countries belonging to the CWE (notably Belgium, France, the Netherlands, Luxemburg and Germany), complemented with the available capacities in 15 other European Member States (such as Spain, Italy and Portugal) and Morocco. The two scenarios differ in the total amount of available capacity: the first one assumes that the entire Belgian nuclear park (5926 MW) is online, the second studies the situation in which three nuclear power reactors (D1, D3 and T2) are taken offline, mimicking what happened during (a large part of) the year 2015[12]. This modelling approach allows sketching the difference in nuclear availability for the period of a whole (statistical) year, which gives an insight in the delta occurring during each hour of each day of each week of that year. It then allows to see which periods of the year are particularly vulnerable to price discrepancies caused by additional nuclear power production (or nuclear outage).

It is important to mention that demand as well as CO_2 emission prices are assumed to be equal in both scenarios. Restarting the three nuclear units is not supposed to provoke a direct impact on demand patterns and the effect of the Belgian policy context regarding nuclear power generation is assumed to not drastically alter the EU price for CO_2 emission quota[13]. Second, power production by variable renewable energy sources is assumed to have priority access on the grid, so all things being equal, the

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11 *Crystal Super Grid* is developed by the French consultancy agency Artelys that is specialised in quantitative methods for optimization, modelling and decision support.

12 These scenarios closely relate to "scenario 2" of the impact assessment described in part 2.4.3.

13 According to Gusbin and Henry (2007), this impact was estimated to not exceed 5%.

production of variable renewable energy is not directly affected by the restart (but its economic situation can be).

3.2. Optimisation Results

According to the results obtained from the modelling exercise, the average annual marginal cost (which is a proxy for the wholesale price) is 3.8 €/MWh lower when the three nuclear reactors (approximating 2.5 GW) are in generating mode. These findings hence seem to confirm the empirical results observed in the wholesale markets although they are estimated to be lower. In part 4, some arguments for this deviation are provided.

Also of importance, the 3.8 €/MWh is an annual average. Since the model has an hourly granularity, it can be further dissected. Overall, the biggest difference in terms of marginal costs between a scenario with and one without D1, D3 and T2 amounts to 30.2 €/MWh, so prices can, at certain moments in time, be around € 30 lower when all nuclear units are generating electricity. This maximum value is in line with the maximum hourly impact of our empirical estimate (see Table 6).

Taking advantage of the higher granularity and the broader spectrum of the optimisation approach, some more results can be obtained with this scenario analysis. From the knowledge of the hourly marginal cost, it is possible to calculate the (loss or gain of) consumer surplus. The consumer surplus is defined as the surface being made up of the demand curve and the horizontal line representing the marginal cost (defined as the intersection between demand and supply). The incremental consumer surplus caused by the restart equals the difference in marginal costs between the scenario with and the one without D1, D3 and T2, multiplied by the total demand (which is assumed to be equal). This is positive and amounts to € 311 million. Although this result seems to be very promising for Belgian electricity users, we should make a distinction as to the type of consumer. First, companies who buy their electricity directly on the power exchange[14] will most certainly feel the downward pressure on prices (hence the increase in their consumer surplus). Residential consumers, on the other hand, will feel less of an impact. According to the Belgian energy regulator CREG (2016a), for residential consumers[15], the commodity only represents around 30% of their total bill. The balance is being made up of transport and distribution tariffs, levies, taxes, etc. This means that even if the price of the commodity decreases, the overall effect on the household's bill is watered down.

Second, the price decrease not only affects the consumers, it will also have an impact on the power producers. For that, it is instructive to have a look at the production surplus, more specifically, at the production surplus per technology. The production surplus is the surface constituted by the horizontal line representing the marginal cost (defined as the intersection between demand and supply) and the supply curve. In fact, this equals the marginal cost of the power system multiplied by the production (generated by different technologies) minus the cost to produce that amount of electricity (consisting of variable fuel costs and, when needed, the purchase of CO_2 emission quota). The overall production

[14] Around 30% of power is traded on Belpex, the Belgian power exchange.
[15] Type Dc with a dual metering system.

surplus (all technologies taken together) when the total nuclear capacity (5926 MW) is operational compared to the situation when three nuclear units (D1, D3 and T2) are not producing, demonstrates a positive difference of € 426 million.

When zooming in on technologies, we see that, although marginal costs (hence, selling price for electricity) decrease when the nuclear units are brought back online, the production surplus for nuclear power plants is positive and amounts to, on an annual basis, € 476 million[16]. This positive surplus indicates that the increase in nuclear power production (by almost 20 TWh) more than compensates the price decline and subsequent potential loss in profit.

This result stands in sharp contrast with the variable renewable technologies which, although their production is not directly affected by the surplus nuclear production, will suffer the consequences of the decrease in marginal cost, hence, the price at which they can sell their energy. Because of this merit-order effect induced by the renewed operation of the three nuclear reactors, the solar surplus is estimated to diminish by € 12 million, the wind production surplus by € 20 million. This finding can have an impact on potential investments in renewable energy sources for power generation, as systems in which fixed feed-in premia are installed, become less interesting. This could even provoke a delaying effect on the energy transition as investments in low-carbon technologies in Belgium which are urgently required (Devogelaer and Gusbin, 2015), will suffer from this lower ROI calculation and will be postponed or even cancelled all together.

Adding up the consumer and producer surplus already gives an idea of the variation in total welfare. To precisely calculate the total welfare, the sum of the congestion revenues divided by 2[17] should be added. In order to estimate the congestion revenues, it is important to know both the flows from country A (Belgium) to country B (interconnected neighbour) as well as the difference in marginal costs between country A and country B, and this for all the "country B's" with which Belgium is interconnected. For that, we should first get a grasp of the flows, more specifically, of the change in net imports between Belgium and its connected "country B".

The operational restart of the nuclear units not only has an impact on the operations of the remaining power generating facilities in Belgium but also on its interconnection capacities. The regained nuclear production seems to, ceteris paribus, replace, on an annual basis, 14.2 TWh of net electricity imports into Belgium and 5.2 TWh of electricity being produced domestically by natural gas fired power plants. In other words, the "lost" nuclear power when the three reactors were idle was being replaced by net imports (73%) and domestic natural gas fired power plants (27%). These imports generate congestion revenues, hence if net imports decrease, congestion revenues decrease, in this case by € 30 million.

All in all, we see that the welfare in Belgium (defined as the sum of consumer surplus, production surplus and congestion revenues) by recouping the nuclear operation increases by € 722 million.

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16 This value is highly sensitive to the hypothesis taken on the production cost of nuclear power generation. In order to take that aspect into account, a sensitivity analysis was run in which the nuclear production cost was supposed to be higher (20 €/MWh). The ensuing surplus then decreases to € 359 million.

17 Assuming that the revenues are equally distributed between the respective national TSO's.

The decrease in marginal costs (i.e. wholesale prices) can also be felt in other (foreign) markets (Traber and Kemfert, 2012, Phan and Roques, 2015). The price impact of the increase in Belgian nuclear power production on the neighbouring (interconnected) markets is significant and may reach up to 90% of the price impact observed in Belgium, whilst price effects in more distant Member States are rather marginal (but not non-existing). We see for example that the marginal cost diminishes by 3.7 €/MWh in France and by 2.5 €/MWh in the Netherlands, against a mere 0.2 €/MWh in Spain.

Finally, the impact of the restart on CO_2 emissions is scrutinized. The power sector is part of the EU ETS which is a cap-and-trade system. Nevertheless, it is instructive to see how much of the CO_2 emissions can be avoided by restarting the nuclear power plants in Belgium. According to the model results, this boils down to 2.2 Mt CO_2 in Belgium[18]. Interestingly, this decrease in CO_2 emissions in Belgium is not the end of the story. Since the restart leads to a decrease in both power generation from natural gas fired power plants by 5.2 TWh (hence, the decrease in CO_2 emissions in Belgium) and net imports, the renewed operation also has an influence on total emissions in Europe through the levels produced (and inherently, the electricity mix chosen) in the exporting countries (or the emissions originating in the country from which Belgium imports electricity). A restart then leads to an overall CO_2 emission reduction in Europe by 11.2 Mt. The biggest impacts can be seen in both Germany and the Netherlands, two countries from which we import[19] and which, by restarting the three Belgian nuclear plants, can decrease both their coal-fired (by 5 and 2 TWh respectively) and gas-fired power production (by 0.8 and 0.2 TWh respectively).

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[18] In 2013, the total net CO_2 emissions in Belgium amounted to 97.8 Mt of which 16.5 Mt were emitted by the public production of electricity and heat (UNFCCC). CO_2 emissions represent around 85% of total GHG emissions in Belgium.

[19] Technically, Belgium is not (yet) connected to Germany, hence the flows originating from Germany run through the Netherlands (and France).

4. Comparison between the two approaches

With the aid of the dual methodology described in the previous parts, the impact of nuclear power variations on wholesale power prices is scrutinised. When comparing the results of the two analyses, we see a similar but consistently higher price impact estimate in the empirical analysis. This can be chiefly ascribed to the fact that the optimisation model generates the long-term marginal costs instead of the real observed price data that are imputed in the empirical analysis. In theory, bidding strategies are based on the marginal cost[20] but in practice, there may be a substantial difference due to various reasons.

For one, the marginal production cost as calculated in the optimisation model is in fact based on historical production cost averages as taken from IEA publications. Observed prices on the spot market (and used in the empirical analysis) may (and will) deviate because of the complexity of indexation on i.a. highly volatile fuel (and CO_2) prices. The optimisation model also assumes that the market is perfect (no oligopoly) although in practice, it is not (always). The use of market power cannot be entirely excluded and certain (physical or virtual) constraints in regular power markets or exchanges, e.g. inflexible power plants that cannot be shut down for 1 hour, minimum running time of power plants, structural 4-hour block bids, influence price setting. Last, the model is not equipped to simulate the interior network within the country, so redispatching (impacting prices) cannot be captivated in the optimisation results. For all these reasons, it is not surprising that price effects are estimated to be lower in the optimisation exercise.

Another important point relates to the error margin of the empirical analysis. MAE or RMSE values reported above provide an idea of the magnitude of the potential error of prediction of our empirical model. Further research on the empirical approach should help to reduce this margin, for example by allowing fluctuations in the shape of the MOC using functional analysis techniques such as in Liebl (2013). Additional investigations regarding the way the interconnections with France and the Netherlands are used, will provide a clearer understanding of these issues as well since significant differences between the optimisation results and the observed data may occur. Nonetheless, the important lesson to be learnt from both analyses is that nuclear power production variations cause significant price fluctuations.

[20] Which explains why this indicator was chosen as a proxy for the calculation of the wholesale power price impact in the optimisation model setting.

5. Concluding remarks

The operational recapitulation of three Belgian nuclear baseload reactors representing 2447 MW has an undeniable influence on a number of national and international indicators. Since Belgium is, both physically and virtually (through market coupling), a highly interconnected EU Member State, consequences of changes in its nuclear production can be felt all over Europe. According to the model results, the restart seems to be, both in Belgium as on an aggregated European level, positive in terms of overall welfare, consumer surplus and CO_2 emissions. Both analyses also reveal an undeniable effect on prices. This downward effect on prices has to be seen in a context of increasing shares of variable renewable energy sources as part of the energy transition, coupled with a stable to decreasing (peak) demand (CREG, 2016b).

Renewable energy sources constitute the subject of Directive 2009/28/EC and can be perceived as an indispensable part of the required energy transition towards a low-carbon economy[21] (European Commission, 2011, IEA, 2016). They do possess, however, the characteristic of having a short-run marginal cost close to zero which, in energy-only markets, depresses average prices and leads to an increasing proportion of low priced periods (Sensfuss et al., 2008, Phan and Roques, 2015, European Commission, 2015). An incremental reduction in prices through the adding of low cost baseload to the power system further dampens the business case for current utilities and potential investors, whether in renewables or in centralised production, and therefore has to be carefully screened for its potential consequences on generation adequacy and, more generally, security of electricity supply. This challenge is all the more daunting because an enormous amount of investments in the Belgian utility sector is required (Devogelaer and Gusbin, 2015) and low commodity prices will not attract the much needed investments. Our findings therefore have important policy implications as they demonstrate the need to take the downward influence of prolonged nuclear power generation on wholesale prices into consideration when revising the (timetable in the) nuclear phase-out law since it could have a delaying effect on the compulsory energy transition.

[21] According to the IEA projections for OECD economies, the average CO_2 intensity of electricity needs to fall from 411 g/kWh in 2015 to 15 g/kWh by 2050 to achieve the goal of limiting the global increase in temperature to 2°C (IEA, 2016).

6. References

Artelys France (2015), Artelys Crystal Super Grid documentation.

CREG (2016a), De componenten van de elektriciteits-en aardgasprijzen, STUDIE (F)160309-CDC-1516.

CREG (2016b), De opvallende evoluties op de Belgische groothandelsmarkten elektriciteit en gas in 2015, Nota (Z)160114-CDC-1506.

Davis, L. and Hausman, C. (2014), The value of transmission in electricity markets: Evidence from a nuclear power plant closure, Energy Institute at Haas, Working Paper 248.

Devogelaer, D. and Gusbin, D. (2015), 2030 Climate and Energy Framework for Belgium - Impact assessment of a selection of policy scenarios up to 2050, Federal Planning Bureau, Working Paper 3-15.

ENTSO-E (2016), Transparency Platform, https://transparency.entsoe.eu/dashboard/show, [Accessed March 2016].

European Commission (2011), A Roadmap for moving to a competitive low carbon economy in 2050, Impact Assessment, COM(2011) 112 final, SEC(2011) 289 final, March.

European Commission, DG Energy (2015), Quarterly Report on European Electricity Markets, Market Observatory for Energy, Volume 8, Issue 1, first quarter.

Gusbin, D. and Henry, A. (2007), Toelichting bij enkele uitdagingen voor het Belgische energiebeleid geconfronteerd met de klimaatproblematiek, Federal Planning Bureau, Working Paper 1-07.

He, Y., Hildmann, M., Herzog, F. and Andersson, G. (2013), Modeling the Merit-order Curve of the European Energy Exchange Power Market in Germany, IEEE Transactions on Power Systems, 28(3), 3155-3164

IEA (2011), World Energy Outlook 2011.

IEA (2016), Re-powering markets, Market design and regulation during the transition to low-carbon power systems.

Jacobsson, S. and Lauber, V. (2006), The politics and policy of energy system transformation—explaining the German diffusion of renewable energy technology, Energy Policy, 34(3), 256-276.

Knittel, C.R. and Roberts, M.R. (2005), An empirical examination of restructured electricity prices, Energy Economics, 27(5), 791-817.

Kunz, F., Hirschausen, C., Möst, D. and Weigt, H. (2011), Nachfragesicherung und Lastflüsse nach dem Abschalten von Kernkraftwerken in Deutschland Sind Engpässe zu befürchten?, TU Dresden, Electricity Markets Working Papers, WP-EM-44.

Laleman, R. and Albrecht, J. (2016), Belgian blackout? Estimations of the reserve margin during the nuclear phase-out, International Journal of Electrical Power & Energy Systems, Volume 81, 416-426.

Liebl, D. (2013), Modeling and Forecasting Electricity Spot Prices: A Functional Data Perspective, The Annals of Applied Statistics, 7(3), 1562-1592.

Matthes, F., Harthan, R. and Loreck, C. (2011a), Schneller Ausstieg aus der Kernenergie in Deutschland. Kurzfristige Ersatzoptionen, Strom- und CO_2-Preiseffekte, Kurzanalyse fr die Umweltstiftung WWF Deutschland, Ökoinstitut, Berlin.

Matthes, F., Harthan, R. and Loreck, C. (2011b), Atomstrom aus Frankreich? Kurzfristige Abschaltungen deutscher Kernkraftwerke und die Entwicklung des Strom-Austauschs mit dem Ausland, Kurzanalyse fr die Umweltstiftung WWF Deutschland, Ökoinstitut, Berlin.

Müller, J., (2013) Stochastic Modeling of the Spot Price of Electricity Incorporating Commodities and Renewables as Exogenous Factors, Universität Siegen Dissertation, Siegen, 2013

Nuclear Forum (2016), De elektriciteitsproductie op basis van kernenergie, https://www.nucleairforum.be/energie/de-elektriciteitsproductie-op-basis-van-kernenergie, [Accessed March 2016].

OIES 2016, Electricity markets are broken – can they be fixed?, Keay, M., OIES paper EL17, January.

Phan, S. and Roques, F. (2015), Is the depressive effect of renewables on power prices contagious?, CEEM, Working Paper 2015-16.

Sensfuss, F., Ragwitz, M. and Genoese, M. (2008), The merit-order effect: a detailed analysis of the price effect of renewable electricity generation on spot market prices in Germany, Energy Policy, 36(8), 3086-3094.

Traber, T. and Kemfer, C. (2012), German Nuclear Phase-out Policy Effects on European Electricity Wholesale Prices, Emission Prices, Conventional Power Plant Investments and Electricity Trade, DIW Berlin, Discussion Paper 1219.

Thoenes, S., (2014), Understanding the Determinants of electricity Prices and the Impact of the German Nuclear Moratorium in 2011, The Energy Journal, 35(4).