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Published in:
Economics of Energy & Environmental Policy

DOI:
[10.5547/2160-5890.6.2.mmul](https://doi.org/10.5547/2160-5890.6.2.mmul)

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Document Version
Publisher's PDF, also known as Version of record

Publication date:
2017

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

Mulder, M., & Pangan, M. (2017). Influence of climate policy and market forces on coal-fired power plants: Evidence on the Dutch market over 2006-2014. *Economics of Energy & Environmental Policy*, 6(2), 87-110. <https://doi.org/10.5547/2160-5890.6.2.mmul>

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Influence of climate policy and market forces on coal-fired power plants: Evidence on the Dutch market over 2006–2014

MACHIEL MULDER^{a,b} and MELBOY PANGAN^c

ABSTRACT

Many governments aim to reduce the dependence on coal-fired generation to decrease carbon emissions. At the same time power markets with competition between independently operating power firms have been created which leave the actual decisions concerning electricity production to these firms. This paper analyzes the interaction between climate policies and policies to foster power markets. Using hourly plant-level data on the Dutch power market over 2006–2014, we find that the dispatch of fossil-fuel power plants is strongly influenced by relative fuel prices, despite the existence of several climate policy measures. Coal-fired power plants have become more important in the Dutch market since 2006, not only in share of total production, but also as provider of flexibility. Examining the short-term dispatch decisions and the past volatility in relative fuel prices, the maximum CO₂ price which was needed to provide incentives for power producers to dispatch a gas-fired plant instead of a coal-fired plant was 43 euro/ton. We conclude that internalizing the external (CO₂) costs by raising the CO₂ price is a more appropriate measure than a forced closure of coal-fired power plants to align the principles of a market-based power industry and the wish to implement effective climate-policy measures at relatively low costs.

Keywords: Coal-fired power plants, electricity market, dispatch, climate policy

<https://doi.org/10.5547/2160-5890.6.2.mmul>

1. INTRODUCTION

Because of climate concerns, governments aim to reduce carbon emissions in the power sector by a range of measures varying from pollution-control measures for coal-fired power plants to support schemes for renewable electricity production (Jaraitė and Di Maria 2012). Governments in large emitting regions such as the European Union, the United States and China have formulated targets to strongly reduce carbon emissions in the near future. In order to reach these ambitious targets, the portfolio of generation techniques within power markets needs to change. More specifically, governments are stimulating renewable energy, while discouraging the role of coal-fired power plants. The realization of these objectives, however, is seriously challenged by the transformation of the centralized electricity systems into electricity markets with decentralized decision making. Preceding the 1990s, the dispatch of power plants was primarily characterized by centrally coordinated decision-making.

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Since then, energy markets have been created, resulting in a decentralized process of decision making based on competition (Pollitt 2012). Yet, the liberalization of energy markets implies that individual electricity producers themselves decide to what extent particular types of power plants are utilized. This firm-level decision-making process regarding the electricity portfolio on the one hand and the societal policy ambitions regarding the generation mix on the other, creates challenges for government policies. The interaction between climate policies and policies to foster competition is the topic of this paper.

Recently, due to intensified climate policies, electricity generation by coal-fired power plants has stagnated, but has remained the dominant source of electricity generation worldwide. Coal-fired power plants accounted for approximately 41% of the total supply of electricity in 2014 (IEA 2016b). Moreover, global demand for coal is expected to experience rather sluggish growth of 0.6% on average between 2015 and 2021 (IEA 2016a; IEA 2016c). An essential factor that recently hampers the effectiveness of climate policies is the worldwide declining trend in coal prices (EURACOAL 2016; IEA 2016b). Therefore, in order to realize the transition of the power sector towards less-polluting generation techniques, effective climate policies are needed which are directed at reducing carbon emissions by discouraging the incentives for power firms to use coal-fired power plants (Newbery 2016).

This paper analyzes the tension between the climate policy objectives and the policies to foster competition in power markets, using hourly plant-level data on the Dutch power market over 2006–2014. We focus on the Dutch market since this market has faced many changes in the economic and policy environment over the past decade. The Dutch electricity supply is heavily based on thermal electricity generation. Furthermore, it moved from a centralized system, with coordinated decisions on investments, dispatch and prices, to a market system at the end of 1990s (Tanrisever, Derinkuyu, and Jongen 2015). The Dutch market is increasingly integrated with the neighboring countries (Germany, Belgium, UK and Norway) through extensions of the cross-border transport capacity and more efficient usage of this capacity (Mulder 2015). Over the past decade, the Dutch government has implemented a number of climate policy measures to influence the decisions of energy producers and consumers, such as stringent regulations on air pollution, taxes on energy consumption, subsidies promoting renewable electricity generation, and making the electricity industry subject to the EU Emission Trading System (ETS). In 2013, the Dutch government and a large number of societal stakeholders, including the electricity producers, concluded the so-called ‘Energy Deal’, which is an agreement to foster energy efficiency, renewable-energy and emission reduction.¹ As part of this agreement, the Dutch government introduced stricter energy-efficiency standards which resulted in the closure of the old coal-fired power plants. In response to a request by the Dutch parliament to introduce legislation to close all remaining power plants (including three recently built plants), the Dutch government is currently exploring the role of coal-fired power plants in the electricity market as well as in the energy transition.² Remarkably, the coal-fired power plants contribute to the realization of the renewable-energy targets, as these plants are able to use biomass as an input next to coal: closing coal-fired plants may consequently result in a decreasing share of renewable

1. Social Economic Council. 2013. “Energy Agreement for Sustainable Growth.” <http://www.ser.nl/-/media/files/internet/talen/engels/2013/energy-agreement-sustainable-growth-summary>

2. EZ. 2015. “Kamerbrief over Het Uitsfaseren van de Kolencentrales in Nederland.” <https://www.rijksoverheid.nl/documenten/kamerstukken/2015/12/18/kamerbrief-over-het-uitsfaseren-van-de-kolencentrales-in-nederland>.

energy.³ Keeping these plants running would therefore help to realize the renewable-energy targets. In order to reduce the carbon emissions by the coal-fired power plants, the Dutch government wants to test the feasibility of Carbon Capture and Storage (CCS). Nevertheless, in the Dutch society a broad support exists to close all coal-fired power plants. The final policy decision regarding the role of these plants has, however, not yet been taken. As a contribution to that debate, this paper analyses the role of coal-fired power plants in the recent history and to what extent their dispatch was determined by market forces as opposed to policy measures.

Using a unique data set containing hourly plant-level data on the Dutch electricity market, we examine whether the measures based on climate policy objectives have affected the utilization of coal-fired power plants over 2006–2014. In this paper, we restrict our analysis to the effectiveness of climate policy measures directed at CO₂ emissions, while we do not address policies to reduce the emissions of other contaminants (such as sulfur dioxide, nitrogen oxides and mercury) or policy measures directed at other greenhouse gases. We also restrict ourselves by only examining short-term dispatch decisions of plants which already have been installed. Hence, we do not address how climate policies affect investments in power plants.

We find that the dispatch of power plants was strongly influenced by relative fuel prices. Despite its low levels during the period of analysis, our findings also show that the price of CO₂ in the European Emissions Trading Scheme exhibited a negative effect on the dispatch of coal-fired power plants and a positive effect on the dispatch of gas-fired power plants. In spite of the implementation of a number of climate policy measures, coal-fired power plants have become more important in the Dutch market since 2006, not only in share in total production, but also as provider of flexibility. While the government aimed to reduce the use of coal-fired power plants in order to reduce carbon emissions, market forces have been more powerful resulting in a larger role of these plants in the Dutch supply of electricity. An alternative policy currently considered in several countries is a forced closure of coal-fired power plants, but such a policy is at odds with the idea to have decentralized decision making in the power industry. A policy which is more in line with the existence of power markets is raising the costs of CO₂ emissions. Examining the short-term dispatch decisions and the past volatility in relative fuel prices, the maximum CO₂ price needed to provide robust incentives for power producers to dispatch a gas-fired plant instead of a coal-fired plant was 43 euro/ton.

The rest of this paper is structured as follows. Section 2 starts by briefly describing power markets and climate policies regarding the power market in a number of OECD countries. This section also presents the indicators that measure the role of coal-fired power plants in the electricity market from different angles. Section 3 presents and discusses the results, while Section 4 offers the conclusions.

3. The Energy Research Centre of the Netherlands (ECN 2015) concludes that closure of all coal-fired power plants would imply that the share of renewables in the Dutch energy consumption will decline from 11.9 to 10.8 % in 2020, while the policy target is 14%. As co-fuelling with biomass would not be possible anymore, the government would annually save approximately 0.5 billion Euro on subsidies, which could be used for subsidizing other types of renewable-energy projects. The challenge, however, is to find these other projects, as the growth in renewable energy projects appears not to be hindered by a lack of financial means but other factors, such as spatial-planning procedures and social resistance towards in particular onshore wind parks.

2. METHOD

2.1 Power markets and climate policy

In many countries over the past decades, the electricity industry has been restructured from systems characterized by monopolies and coordinated decisions on investments, dispatch and prices towards liberalized markets where independent decision-making units (i.e. firms) make their own decisions based on information from market prices (Pollitt 2012). In addition, national markets have been integrated into regional markets. Within the EU, the policies have been directed at fostering market efficiency and cross-border trade through removing barriers for international trade, resulting in a number of regional European markets. A similar process has occurred in the US where the electricity market now consists of eight regions with three nation-wide interconnected networks, namely the Eastern, Western and Texas Interconnected System.

Various climate policies have been developed around the globe to reduce the environmental burden of electricity generation. In 2007, the European Union decided to counter climate change by adopting EU-wide objectives for 2020, namely their ‘2020 climate and energy package’ (IEA 2014a). Relative to 1990, GHG emission ought to be decreased by 20%, while the share of renewable energy consumption as a proportion of gross energy consumption should increase up to 20%. In addition, total primary energy consumption ought to be cut down by 20% compared to the projected use of energy in 2020. Currently, however, coal is still a key source of total electricity generation. On a global scale, in 2015, 195 countries embraced the Paris Agreement aimed at accelerating cooperative climate action to limit global warming to below 2 degrees Celsius compared to pre-industrial levels.⁴ A key element of the policies to realize this climate-policy objective refers to the use of coal. In order to understand how countries struggle with the role of coal in their energy supply, we briefly summarize recent developments in the policies on coal in the US, UK, Germany and the Netherlands. We will observe that in all of these countries except the Netherlands the share of coal-fired generation has been reduced since 2000.

In the United States, the ‘Blueprint for a Secure Energy Future’ was developed in 2011 as an integral part of the US energy policy (IEA 2014b). Its main objectives included fostering domestic energy supplies, decreasing dependence on fossil fuels and funding research to develop innovative clean technologies. In 2013, the US launched the Climate Action Plan in 2013, meant to, amongst others, reduce domestic CO₂ emissions by enforcing stricter emission regulation on new and existing power plants. Currently, coal is the primary input for electricity generation in the US, accounting for approximately 40% of total electricity generation in 2014 (Figure 1). Nonetheless, a transition is taking place towards more natural gas as a result of the relatively low gas prices. Dropping coal demands in the US can also be seen in the decline of coal production by 23% between 2008 and 2015, while natural gas production exhibited an increase of 51% and while the role of renewable energy has become more prevalent (Culver and Hong 2016).

In the United Kingdom, a Climate Change Act was implemented in 2008, stating environmental targets for the year of 2050.⁵ Furthermore, in 2013, a carbon price floor (CPF) was

4. UNFCCC. 2015. “Paris Agreement.” http://unfccc.int/paris_agreement/items/9485.php.

5. UK Government. 2008. “Climate Change Act 2008.” The National Archives on behalf of HM Government. http://www.legislation.gov.uk/ukpga/2008/27/pdfs/ukpga_20080027_en.pdf

Source: www.iea.org/statistics

FIGURE 1

Share of coal-fired power generation in Germany, the Netherlands, UK and USA, 2000 and 2014.

introduced which influences the costs of carbon by taxing fossil fuels used to generate electricity by businesses.⁶ The share of coal-fired generation in the UK decreased slightly over the past years to 36% (Figure 1). In 2016, the United Kingdom announced that they committed to the Paris Agreement in which they continue to strive for reducing GHG emissions by 20% in 2020 and to an EU wide emissions reduction to at least 40% by 2030.⁷ The Energy and Climate Change Secretary has proposed to shut down all coal-fired power plants in the United Kingdom by 2025 and to rely more on electricity generation by gas-fired power plants.⁸ Moreover, in 2016, 4.9 GW of coal plant had been closed, namely Longannet, Ferrybridge and Rugeley, while Drax unit 3 was converted to biomass (Agora Energiewende and Sandbag 2017). To achieve the 2050 targets, the Act imposes carbon budgets for succeeding periods of five years.

Germany started policies to stimulate renewable energy in 1991, by implementing feed-in-tariffs for wind power in 1991 (Hitaj 2013). Since the Fukushima nuclear disaster in 2011, the German policies towards the power sector were considerably intensified. It was aimed at phasing out nuclear power plants and coal-fired power plants (0.6 GW of coal plants in 2016), strongly increasing the share of renewables and setting GHG emissions targets (Hirschhausen 2014; Agora Energiewende and Sandbag 2017). The objectives are to increase the share of renewables to 50% in 2030 and 80% in 2050. In 2014, about 25% of total electricity produc-

6. UK Government. 2013. “Excise Notice CCL1/6: A Guide to Carbon Price Floor.” <https://www.gov.uk/government/publications/excise-notice-ccl16-a-guide-to-carbon-price-floor/excise-notice-ccl16-a-guide-to-carbon-price-floor#introduction>.

7. UK Government. 2016. “The Paris Agreement proves that the transition to a climate-neutral and climate-resilient world is happening.” <https://www.gov.uk/government/speeches/the-paris-agreement-proves-that-the-transition-to-a-climate-neutral-and-climate-resilient-world-is-happening>.

8. DECC. 2015. “Government Announces Plans to Close Coal Power Stations by 2025.” UK Government. <https://www.gov.uk/government/news/government-announces-plans-to-close-coal-power-stations-by-2025>.

tion came from renewable energy sources (mainly wind, biomass and solar), while this share was no more than 7% in 2000. The share of nuclear power has reduced to about 15% in 2014, while the share of coal-fired generation reduced to about 45% (Figure 1).

In line with the EU '2020 climate and energy package', the Netherlands has committed to the objectives to decrease their GHG emission by 16%, to increase energy efficiency savings by 1.5% per year while renewable energy need to constitute 14% of total energy consumption by 2020. The Netherlands charges relatively high environmental taxes, accounting for approximately 9% of total government tax revenues. The use of fossil fuels in energy-intensive industries, however, is not taxed.

The Dutch electricity generation portfolio is still predominantly characterized by the use of fossil fuel resources, namely natural gas and coal (Table 1). While the share of coal-fired generation declined in Germany, the UK and the USA, in the Netherlands it remained stable at slightly above 30% (Figure 1). This development may be related to a specific policy measure regarding coal-fired power plants which is the reduction of tax burden on coal use by electricity producers. Although recently a number of new power plants have been added to the installed capacity, the Dutch government has implemented environmental restrictions meant to close older coal-fired power plants.⁹ Related to this, in 2016, 1.6 GW of coal plants was shut down, namely Amer 8, Borssele 12 and Gelderland (Agora Energiewende and Sandbag 2017). In this paper, we focus on how the role of coal-fired power plants has evolved in the Dutch market in response to market developments as well as climate policies.

2.2 Indicators, model and data

To analyze the influence of markets forces and climate policy on the utilization of coal-fired power plants in the Netherlands over 2006–2014, we use a number of indicators. In order to quantify these indicators we use a unique data set containing hourly plant-level data regarding production levels and available capacity for each generation unit above 50 MW.¹⁰ For 2006, this database of Dutch portfolio of power plants includes 8 coal-fired power plants and 33 gas-fired power plants. The average available generation capacity of the coal-fired plants was 520 MW, while the average capacity of the gas-fired plants was 190 MW. For 2014, the database includes 10 coal-fired plants and 48 gas-fired power plants. This data is obtained from the Authority for Consumers and Markets (ACM).¹¹ In addition, data from Bloomberg on market prices is used.¹²

First of all, we analyze aggregated numbers on the annual contribution of coal and gas-fired power plants to the Dutch market. Next, we analyze to what extent coal-fired power plants were dispatched compared to gas-fired power plants. Using hourly plant-level data, we examine how often coal and gas-fired power plants were yearly dispatched.¹³ Furthermore, we investigate how coal-fired power plants are used as providers of base load and flexibility. As a

9. EZ. 2015. "Kamerbrief over Het Uitsfaseren van de Kolencentrales in Nederland." <https://www.rijksoverheid.nl/documenten/kamerstukken/2015/12/18/kamerbrief-over-het-uitsfaseren-van-de-kolencentrales-in-nederland>.

10. The available capacity per plant refers to the capacity which is really available for production, corrected for maintenance periods. This data is based on what the electricity companies have to submit to the TSO one day before real time.

11. Electricity firms in the Dutch market are legally obliged to submit data on the hourly production and available capacity per power plant to the ACM. For a more extensive description of this data set, see NMa (2010) and Mulder (2015). For a detailed and up-to-date description of all Dutch power plants, see https://nl.wikipedia.org/wiki/Lijst_van_elektriciteitscentrales_in_Nederland. Note that there is no official source available providing this kind of detailed data on power plants in the Dutch market.

12. See www.bloomberg.com.

13. By dispatch we mean that the hourly production is above zero.

TABLE 1
Key Indicators of the Dutch power market in 2006–2014 (annual averages)

	2006	2010	2014
<i>Number of power plants</i>			
total	95	96	98
gas-fired	33	40	48
coal-fired	8	8	10
biomass	1	2	2
nuclear	1	1	1
waste	2	3	5
<i>Installed capacity of power plants (GW)</i>			
centralized total	16.7	18.5	23.9
gas-fired	12.2	13.7	16.9
coal-fired	4.2	4.2	6.2
biomass	0.0	0.0	0.0
nuclear	0.5	0.5	0.5
waste	0.1	0.0	0.2
<i>Domestic Production (TWh)</i>			
total	91.6	109.6	93.2
gas-fired	57.1	73.6	51.4
coal-fired	23.1	21.9	28.8
biomass	5.2	7.1	5.9*
nuclear	3.5	4.0	4.1
waste	2.8	3.1	3.0*
Import (TWh)	27	16	33
Export (TWh)	6	13	18
Domestic consumption (TWh)	120	121	118
Import capacity (GW)	3.6	4.3	5.2

Sources: number and size of power plants: ACM database; production, import, export, domestic consumption and installed capacity: CBS; import capacity: TenneT.

Note: *due to unavailable data in 2014, data for 2013 have been used.

result of the increase of intermittent supply by renewable sources, more supply of flexibility is needed. We use duration curves of the annual production by coal and gas-fired power plants to analyze which role these two types of plants play and whether these respective roles have changed since 2006. Duration curves are generally used as indicators to measure the degree of flexibility of power supply (de Jonghe et al. 2011; Korpaas, Holen, and Hildrum 2003). We test whether a change in the supply of flexibility can be observed between coal and gas-fired power plants in 2006, 2010 and 2014.

As the dispatch of power plants is strongly related to the marginal costs of production, we calculate these costs for all plants on a daily basis, using information on the technical characteristics per plant and daily data on gas, coal and CO₂ prices. In addition, we conduct a panel regression on the hourly dispatch of gas-fired and coal-fired power plants to explain the hourly dispatch levels.¹⁴ We hypothesize that the hourly dispatch of a power plant depends

14. The panel regression is conducted on those plants which were running during the full period 2006–2014. See Appendix A for the results of the statistical tests on serial correlation, multicollinearity, stationarity and fixed/random effects. Based on

on the marginal generation costs as well as factors determining the total load (McGuinness and Ellerman 2008). Regarding the former, we include the prices of gas, coal and CO₂ in the regression model. Although power firms sell significant parts of the production in the forward market, for the actual production decisions the power prices closer to real time are relevant and therefore we use the day-ahead prices.¹⁵ As variables measuring the impact of changes in load, we include the total centralized generation, the hourly weather temperature and the supply of electricity by renewable sources. The latter is assumed to be related to climate policy: the more effective this policy is, the higher the supply by renewable sources (cet. par.).¹⁶ We also include renewable supply in Germany since the Dutch market is closely connected to the German market, while the surge in the supply of renewable energy in Germany has strongly affected their market (Mulder 2015). As only high-frequency data on German wind energy is available for our full period of analysis, we only include German wind energy. Note that the price of CO₂ is also related to the impact of climate policies, as this price originates from the European ETS. We test whether the price of CO₂ as well as the supply of renewable energy affects the production by coal and gas-fired power plants. Hence, the regression model to be tested is the following:

$$G_{i,t} = \beta_{i,0} + \beta_1 G_{i,t-1} + \beta_2 P_{g,t} + \beta_3 P_{c,t} + \beta_4 P_{CO_2,t} + \beta_5 L_t + \beta_6 T_t + \beta_7 RES_{NL,t} + \beta_8 W_{GER,t} + \varepsilon_t \quad [1]$$

where $G_{i,t}$ is generation per plant i per hour t , P_g is the price of gas, P_c is the price of coal, P_{CO_2} is the price of CO₂, L is total load served by the centralized power plants, T is the average daily temperature, RES_{NL} is the supply of renewable energy in the Netherlands, W_{GER} is the supply of wind energy in Germany, while ε refers to the error term of the equation.

Next, we examine a scenario in which coal-fired power plants are non-existent and how this absence of coal-fired power plants may influence the electricity price. We use the actual merit-order in the Dutch market to examine the effect on system-marginal costs if coal-fired power plants would be excluded from supplying power as is currently subject to debate in the Netherlands as well as in several other countries.

Finally, we go more into depth in the role of the price of CO₂. We calculate the break-even price of CO₂, which is the price of CO₂ where electricity producers are indifferent between dispatching a coal-fired or gas-fired plant.¹⁷ This break-even price of CO₂ is a short-term price which is predominantly influenced by relative gas and coal prices, given the current technical efficiencies of coal and gas-fired power plants. To determine the annual break-even price of

these results, we include the lag of the dependent variable in order to control for serial correlation. In addition, we take the first difference of the (annual) Dutch supply of renewable energy because of the presence of a unit root in this time series. Moreover, we estimate the model in fixed effects. Finally, we include hourly, daily and quarterly dummies to control for time patterns in the data. The full results of the regression model are presented in table A.7.

15. Although power firms buy their fuel inputs on the forward market in order to match the duration of the fuel contracts with the duration of forward electricity contracts, the daily prices on both markets are still relevant for the dispatch of plants. For instance, if the gas price on the spot market is much higher than the gas price in the forward contract, the power firm has an incentive to resell the gas in the spot market and to buy electricity in the spot market, instead of producing itself, in order to fulfil its commitments.

16. The supply of renewable energy also depends on other factors, in particular weather conditions, but in general one can state that the more effective climate policy is, the more investments in renewable capacity are made and the higher the production of renewable energy.

17. See also Newbery (2016) who calculates the break-even CO₂ price for gas-fired power plants versus renewable generation techniques.

CO₂, the average marginal costs of coal-fired plants are set equal to the average marginal costs of gas-fired plants.¹⁸ The marginal costs per type of plant are calculated as follows:

$$MC_f = \left(\frac{1}{e_f} \right) (P_f + P_{CO_2} CO_2 rate_f) + VC_f \quad [2]$$

where MC_f is marginal costs (euro/MWh) per type of generation plant (f), e_f is the technical efficiency per type of generation plant, P_f is the fuel price, CO₂ rate is the content of CO₂ per kWh electricity generated per type of plant and VC_f are the remaining variable costs per type of plant. Equating the marginal costs for gas-fired and coal-fired power plants, we find the following equation for the break-even value of the CO₂ price ($P_{CO_2}^{BE}$), where g stands for gas and c for coal:

$$P_{CO_2}^{BE} = \frac{\left(\frac{P_g}{e_g} - \frac{P_c}{e_c} \right) + (VC_g - VC_c)}{\left(\frac{1}{e_c} CO_2 rate_c \right) - \left(\frac{1}{e_g} CO_2 rate_g \right)} \quad [3]$$

Eq. (3) shows that the minimum CO₂ price needed to replace coal-fired electricity by gas-fired electricity strongly depends on the relative prices of gas and coal. Therefore, we calculate the break-even price of CO₂ for each year since 2006, a period in which the relative fuel prices changed significantly.

3. RESULTS AND DISCUSSION

The Dutch power market is strongly related to the markets in the neighboring countries. Until 2010, the average hourly import used to be about 30% of the average hourly domestic production by conventional power plants (Figure 2). Since 2011, the aggregated level of domestic production declined gradually, while the imports increased. This is in particular due to the low power prices in Germany resulting from the increase of renewable energy (Mulder and Scholtens 2016).

Figure 2 also shows that the seasonal pattern in domestic load: as electricity is relatively strongly used for lighting (compared to many other countries) the total load peaks in December and January and reaches the lowest levels during June and July.

The centralized domestic production within the Dutch market is primarily characterized by relatively high levels of production by coal-fired and gas-fired power plants (Figure 3). The production by gas-fired power plants largely dominated coal-fired power plants production in 2006, while the levels of production of these two types of power plants have reached rather similar levels in 2014.

The generation capacity in the Dutch electricity market has increased significantly since 2006. The aggregated size of installed centralized capacity increased from approximately 17 GW in 2006 to 24 GW in 2014 (Table 1). The size of the capacity of the gas-fired power plants increased by approximately 40%, while the coal-fired power plants capacity grew by

18. For the sake of simplicity, we ignore the fixed start-up costs. Furthermore, we assume that the power producers cannot pass on an increase in the CO₂ price into the electricity price, implying that this price is treated as a fully exogenous cost driver, see also Delarue et al. (2008).

FIGURE 2

Centralized production, imports and exports in the Dutch market, 2006–2014, per hour.

FIGURE 3

Aggregated average hourly centralized production in the Dutch market by type of plant, 2006–2014.

almost 50%. In the period after 2010, the contribution of total domestic production to serving total load, however, declined whereas the share of import increased strongly. This increase in cross-border flows was enabled by the increase in the import capacity from 3.6 GW in 2006

Source: ACM database, own calculations

FIGURE 4

Number of hours of dispatch of coal and gas-fired power plants in the Dutch power market, 2006, 2010 and 2014.

to 5.2 GW in 2014. Based on these aggregate numbers, we observe that the coal-fired power plants have become more important to the Dutch market over the period of analysis.

Figure 4 shows the annual number of hours of dispatch of all plants ranked from the lowest number to the highest number of hours for 2006, 2010 and 2014.¹⁹ For gas-fired power plants, it can be seen that the hours of dispatch curve in 2014 is well below that of 2006 and 2010, indicating that most plants were used less intensively. For approximately 2000 MW, gas-fired power plants were not dispatched at all in 2014. Also for coal-fired power plants, it can be observed that the number of hours of dispatch declined between 2006 and 2014, yet to a lesser degree than gas-fired power plants. For most coal-fired plants, the number of hours of dispatch in 2014 is comparable to those in 2006.

To examine the role of coal-fired power plants as providers of flexibility, we investigate the duration curves of production by coal and gas-fired plants (Figure 5). We observe that the coal-fired power plants increasingly provide flexibility as the duration curve in 2014 is much steeper than in the previous years. We also see that the production by gas-

19. By dispatch, we mean that the hourly production is above zero. The horizontal axis in this figure is based on the available capacity of plants which can be much smaller than the technical installed capacity due to maintenance or mothballing.

FIGURE 5

Duration curves of hourly production by coal and gas-fired power plants in the Dutch power market, 2006, 2010 and 2014.

fired power plants decreased over the past decade, which is indicated by a leftward shift of the curve.²⁰ Yet, the flexibility of gas production has remained rather similar.

Another clear indication of the increased flexibility of coal-fired power plants is given by Figure 6. The hourly variation has increased strongly from 2006 to 2014. However, the hourly variation by gas-fired plants did not really change. Figure 7 shows that the levels of production by these plants reduced in this period, but that the flexibility remains fairly similar.

Figure 8 shows that the coal-fired production is clearly positively related to German wind production, while for gas hardly a relationship exists. This indicates that the coal-fired plants respond to German wind production. The mechanism here is that increasing levels of German wind production reduces the available cross-border capacity because of uncontrolled loop flows, which hinders import from Germany (Hulshof, van der Maat, and Mulder 2016; TenneT 2014). These loop flows result from congestions within the German grid when high amounts of wind in Northern Germany are fed into the grid while the major load centers are located in the West and South. In response, the Dutch TSO has to reserve a larger part of the cross-border capacity for loop flows, which reduces the cross-border capacity available for commercial trade.²¹ Consequently, the import from Germany is reduced, which increases the need

20. Note that the maximum realised production of gas fired plants is much smaller than the installed capacity (see Table 1).

21. Until May 2015, the cross-border capacity allocation was based on Available Transmission Capacities (ATC) per border, but since then a flow-based approach has been introduced. This means that the capacity allocated to the market is now based on

FIGURE 6

Production by coal-fired power plants in the Dutch power market, 2006, 2010 and 2014, per hour.

FIGURE 7

Production by gas-fired power plants in the Dutch power market, 2006, 2010 and 2014, per hour.

Source: ACM database, own calculations

Note: Lines are fitted based on OLS regression plus 95% confidence interval

FIGURE 8

Dutch domestic production per plant type, Dutch import and German production by wind turbines, hourly observations over 2014.

for domestic production. From the data, it appears that the import from Germany is indeed negatively related to the German production by wind turbines (Figure 8). For Germany, this means that the export demand is lower, which reduces the residual demand for the German conventional plants. Overall, there might be a net reduction in CO₂ emissions because of the differences in CO₂ intensity between the Dutch coal-fired plants and the German lignite plants. However, given the existence of the ETS this effect is neutralized and, hence, no net effect on emissions occurs.

Closely examining the average daily marginal costs of coal and gas-fired power plants in the Dutch electricity market, Figure 9 shows that their marginal costs (which are based on fuel costs, CO₂ costs, technical efficiency per plant and remaining variable costs (see Eq. 2)) hovered around similar levels until 2010, but afterwards they show a larger spread. Since 2010, coal-fired power plants operated at significantly lower marginal costs, whereas the marginal costs of gas-fired power plants were characterized by an increasing trend from 2010 onwards.

Conducting a panel analysis, it appears that the hourly dispatch of the gas and coal-fired plants is significantly related to the fuel prices, but in the opposite direction (Table 2). The higher the gas price, the lower the production by gas-fired plants and the higher the production of coal-fired plants, and vice versa for the coal price. It appears that the dispatch of coal-fired

all factors affecting the flows in all critical grid elements in the whole region of Central Western Europe (CWE) (ELIA, 2015). As a result, the capacity available for market transactions in the region is larger, increasing the potential for international trade. Nevertheless, high levels of expected wind generation may still negatively affect the capacity for international trade as TSOs will require a higher reliability margin.

FIGURE 9

Marginal costs of gas and coal-fired power plants in the Dutch power market, 2006–2014 (average per plant type per day).

power plants is sensitive to both fuel prices.²² The price of CO₂ in the ETS also has an opposite effect on the production of both types of plants: the higher this price, the more gas-fired plants are dispatched, while the coal-fired plants are less dispatched.²³ Hence, the price of CO₂ triggers substitution from coal-fired to gas-fired generation.

Both types of plants respond positively to an increase in total domestic load. We also observe that the outside temperature has a significant impact on the level of production. Note that this variable also covers the influence of daylight because of the close relationship between these environmental variables.

Dutch power plants, both gas and coal-fired, positively respond to the level of production by German wind turbines. The more wind electricity is produced in Germany, the more the Dutch conventional plants produce. The production of the conventional power plants shows also strong time patterns (see Table A.7). The regression results confirm that coal-fired power plants are also used for short-term (i.e. within-day) flexibility.

Closing coal-fired power plants, a policy option that is currently considered in the Netherlands²⁴ would have a significant effect on the merit order and, hence, the system-marginal

22. A change in the price of gas by 1 standard deviation results in a decline of the (average) production of gas-fired plants by 0.29 MWh and increase in the production of coal-fired plants by 0.21 MWh, while a similar change in the price of coal results in an increase of the production of gas-fired plants by only 0.04 MWh and a decrease in the production of coal-fired plants of 0.17 MWh.

23. Although the coefficient for CO₂ price on coal-fired production is not significant on 10%, the best estimate for this coefficient appears to be a negative number. After all, statistical insignificance means that the true value of the coefficient is uncertain, but given the data and model specification, the estimated value is the best estimate one can get.

24. EZ. 2015. "Kamerbrief over Het Uitfaseren van de Kolencentrales in Nederland." <https://www.rijksoverheid.nl/documenten/kamerstukken/2015/12/18/kamerbrief-over-het-uitfaseren-van-de-kolencentrales-in-nederland>.

TABLE 2

Results of the panel regression analysis on the hourly production of gas and coal-fired power plants in the Dutch power market, 2006–2014

Production per hour	Gas-fired plants	Coal-fired plants
constant	−9.005*** (0.119)	−20.46*** (0.344)
Gt−1	0.973*** (0.000145)	0.988*** (0.000197)
P _{gas}	−0.0511*** (0.00274)	0.0364*** (0.00779)
P _{coal}	0.0139** (0.00621)	−0.0646*** (0.0176)
P _{CO₂}	0.0461*** (0.00205)	−0.00919 (0.00577)
L	0.000679*** (1.22e−05)	0.000514*** (3.52e−05)
T _{NL}	−0.0151*** (0.00327)	−0.0275*** (0.00940)
1st diff. RES _{NL}	0.00771 (0.0111)	−0.0574* (0.0320)
W _{GER}	0.00724** (0.00319)	0.0398*** (0.00928)
R ²	0.96	0.98
Observations	2,472,274	617,827
Number of plants	32	8

Note: Standard errors in parentheses

*, **, *** refer to 10%, 5% and 1% significance levels, respectively.

See Table A.7 for the full overview of the results.

costs (Figure 10). At a demand level of 9,000 MWh, the average system-marginal costs in 2014 increase from 45 euros to about 65 euros if coal-fired power plants were taken out of power supply. As a consequence of an increase in domestic system-marginal costs, import flows will also increase, since it will become relatively cheaper to import rather than generating electricity at home. Yet, as shown in table 1, the import capacity is constrained, namely 5.2 GW in 2014, which means that import will only be partly able to reduce the price effect of a forced closure of all power plants.

The final indicator regarding the role of coal-fired power plants is the short-term break-even price of CO₂, which is the price at which electricity producers are indifferent between dispatching coal or gas-fired power plants. The break-even price appears to be volatile from year to year, which is caused by the fluctuating gas and coal prices (Figure 11). The maximum value of the break-even price since 2006 is approximately 40 euros/ton, whereas its minimum value was approximately 5 euros/ton. A positive relationship exists between this break-even price and the spread between the gas price and the coal price. After all, the more expensive gas

Source: ACM database, own calculations

FIGURE 10

Merit order in Dutch power market, with and without coal-fired power plants, 2014 (average per year).

FIGURE 11

Actual CO₂ price and break-even CO₂ price between dispatching coal and gas-fired power plants, 2006–2014 (average per year).

is compared to coal, the higher the price of CO₂ which is needed to make both types of plant break even. This relationship is, however, weakened, because of the increase in the technical efficiency of gas-fired power plants from 2006 to 2014 (Figure 12). Gas-fired power plants have,

FIGURE 12

Relationship between break-even price of CO₂ and the spread between the gas price and the coal price, 2006 and 2014 (daily data).

on average, become more efficient, which means that a lower CO₂ price is needed to arrive at the break-even level of marginal generation costs.

4. CONCLUSION AND POLICY IMPLICATIONS

The fundamental challenge for governments aiming to reduce carbon emissions is how to align this target with decentralized decision making in power markets characterized by competition between power firms. Using a unique dataset of hourly plant-level data, we find that the decentralized decisions regarding the dispatch of power plants by electricity producers is strongly influenced by relative fuel prices of coal and gas, despite the existence of climate policies. We also find that, despite its low levels in the past, the price of CO₂ in the ETS had a negative effect on the dispatch of coal-fired power plants and a positive effect on the dispatch of gas-fired power plants. Hence, the price of CO₂ triggers the substitution of coal-fired plants by gas-fired plants. These results are in line with what was found by McGuinness and Ellerman (2008) for the UK power market during the earlier years of the ETS.

We also find a small negative impact of the presence of renewable-electricity production in the Netherlands on the production by coal-fired plants. Contrary to what might be expected, we find that an increase in German renewable-electricity production raises production by the Dutch conventional power plants, which was also shown by the scatter plots in Figure 8. This phenomenon is related to the impact of renewable energy on congestions within the German

grid and the resulting cross-border loop flows which reduces the size of the available cross-border capacity between Germany and the Netherlands. Hence, we have the paradox that more renewable-electricity production in one country stimulates fossil-fuel production in a neighboring country, although both countries are closely connected. Apparently, investments within the German grid will reduce the impact of renewable electricity production within Germany on cross-border loop flows and the available transport capacity for international trade.

In spite of the implementation of a number of climate-policy measures meant to foster the transition of the energy system, coal-fired power plants have become more important in the Dutch market since 2006. The increase in their contribution to total production could be expected given the changes in relative fuel prices, but coal-fired power plants also became more important for providing flexibility. Although gas-fired plants are technically better equipped to offer flexibility, it is important to acknowledge that coal-fired plants increasingly appear to be able to supply this service to the market.

A measure to reduce the share of coal-fired generation which is currently considered in a number of countries is to force power firms to close these plants. Such a policy measure is at odds with the idea to have decentralized decision making characterized by competition between independently operating power firms. Given the current constraints on cross-border capacity, such an intervention in the power market likely results in considerably higher prices for consumers as well as costs for societies compared to a market-based intervention directed at changing the incentives for power producers. After all, in case of a forced closure, the shareholders have to be compensated, while in the case of a market based policy measure such as higher carbon tax or higher carbon price, such a compensation is not needed. Moreover, such a policy measure is not effective to reduce the overall level of CO₂ emissions because of the existence of the ETS, as any reduction in emissions will reduce the carbon price and, hence, raise emissions in other industries. This is the so-called waterbed effect of the ETS.²⁵

Having examined the Dutch power market, we learn that an increase in CO₂ price levels gives an incentive to electricity producers to use gas-fired power plants instead of coal-fired plants. Looking at the short-term dispatch decisions as well as the realized volatility in relative fuel prices since 2006, we conclude that in all years a CO₂ price of 43 euro/ton would have been sufficient to provide incentives for power producers to dispatch a gas plant instead of a coal plant. This price is the top of the range of realized break-even values of the CO₂ price, which is between 7–43 euro/ton over the period since 2006. Hence, internalizing the external (CO₂) costs by raising the CO₂ price is the appropriate measure to align the principles of a market-based power industry and the wish to implement effective climate-policy measures at relatively low costs.

Another issue is how to realize such an increase in the price of CO₂. Reducing the cap in the ETS on top of the already implemented annual reduction would be the most straightforward measure, although this depends on a delicate political process in the European Union. A national price floor in the scheme does have an effect on the domestic level of emissions, but unfortunately not on the European level emissions because of the waterbed effect. Hence, looking for European answers to the need to further reduce the cap within the Emissions Trading Scheme remains required.

25. The measure to implement a Market Stability Reserve within the ETS, which is meant to reduce the impact of the oversupply on the permit price, may have a cancelling effect on this waterbed effect, but this will only happen if the permits which will be withdrawn from the market will actually be cancelled. So far it is not certain whether this will really happen.

APPENDIX

TABLE A.1

Table of descriptive statistics, 2006–2014 (per hour)

Variables	Mean	Standard deviation	Minimum	Maximum
G (in MW)	139.5	178.4	0.0	1598.1
P _{gas} (in Euro/Kwh)	20.6	5.8	2.5	50.0
P _{coal} (in Euro/Kwh)	9.8	2.6	5.4	20.0
P _{CO2} (in Euro/Kwh)	11.0	7.1	.01	30.0
L (in MW)	6993.4	1942.3	1068.31	13237.5
T _{NL} (in degrees Celsius)	10.7	6.6	−17.8	33.4
RES _{NL} (in MW)	1211.5	207.3	835844.7	1427.6
W _{GER} (in GW)	4.7	4.3	.02875	29.5

TABLE A.2

Correlation matrix of variables in panel regression analysis excluding dummies, 2006–2014 (per hour)

Variables	G	P _{gas}	P _{coal}	P _{CO2}	L	T _{NL}	RES _{NL}
P _{gas}	−0.0478						
P _{coal}	−0.0122	0.4988					
P _{CO2}	0.0567	0.1166	0.3859				
L	0.1973	−0.0630	−0.0134	0.0386			
T _{NL}	−0.0554	−0.1895	0.0266	−0.0117	−0.2211		
RES _{NL}	−0.0854	0.3197	0.1084	−0.1039	−0.0347	−0.0500	
W _{GER}	−0.0138	0.0622	0.0168	−0.1144	−0.0337	−0.1330	0.1010

TABLE A.3

Unit root test results—Fisher type test, augmented Dickey-Fuller

Variables	P-value
P _{gas}	0.0000
P _{coal}	0.0000
P _{CO2}	0.0000
L	0.0000
T _{NL}	0.0000
RES _{NL}	0.9998
1 st diff. RES _{NL}	0.0000
W _{GER}	0.0000

TABLE A.4

Multicollinearity test results, R-squared of regression estimates with explanatory variables taken as the dependent variable

Variables	Gas-fired plants	Coal-fired plants
P _{gas}	0.36	0.35
P _{coal}	0.39	0.38
P _{CO2}	0.21	0.19
L	0.70	0.71
T _{NL}	0.65	0.65
RES _{NL}	0.14	0.14
W _{GER}	0.14	0.14

Note: a lag of 1 has been applied.
H0: All panels contain unit roots.
Ha: At least one panel is stationary.

Note: multicollinearity if R-squared > 0,80.

TABLE A.5
Autocorrelation test results,
Wooldridge test

Variables	P-value
G	0.00

H0: no first-order autocorrelation
Ha: first-order autocorrelation exists
Note: a lagged term of production has been included to account for first-order autocorrelation.

TABLE A.6
Test for fixed versus random
effects, Hausman test

Variables	P-value
All power plants	0.00

H0: difference in coefficients not systematic.
Ha: difference in coefficients is systematic.

TABLE A.7
Results of the panel regression analysis on the hourly production of
gas and coal-fired power plants, 2006–2014

Production per hour	Gas-fired plants	Coal-fired plants
constant	−9.005*** (0.119)	−20.46*** (0.344)
G _{t−1}	0.973*** (0.000145)	0.988*** (0.000197)
P _{gas}	−0.0511*** (0.00274)	0.0364*** (0.00779)
P _{coal}	0.0139** (0.00621)	−0.0646*** (0.0176)
P _{CO2}	0.0461*** (0.00205)	−0.00919 (0.00577)
L	0.000679*** (1.22e−05)	0.000514*** (3.52e−05)
T _{NL}	−0.0151*** (0.00327)	−0.0275*** (0.00940)
1 st diff. RES _{NL}	0.00771 (0.0111)	−0.0574* (0.0320)
W _{GER}	0.00724** (0.00319)	0.0398*** (0.00928)
h_dum2	2.576*** (0.0889)	3.321*** (0.256)
h_dum3	4.704*** (0.0892)	8.384*** (0.257)
h_dum4	6.519*** (0.0893)	13.61*** (0.257)
h_dum5	8.642*** (0.0892)	21.64*** (0.257)
h_dum6	11.22*** (0.0888)	31.55*** (0.256)
h_dum7	15.79*** (0.0886)	42.29*** (0.256)
h_dum8	19.62*** (0.0896)	44.94*** (0.259)
h_dum9	16.33*** (0.0913)	39.40*** (0.263)
h_dum10	11.24*** (0.0926)	31.48*** (0.267)

(continued)

TABLE A.7
Results of the panel regression analysis on the hourly production of
gas and coal-fired power plants, 2006–2014 (*continued*)

Production per hour	Gas-fired plants	Coal-fired plants
h_dum11	8.582*** (0.0934)	26.11*** (0.269)
h_dum12	7.679*** (0.0939)	23.63*** (0.271)
h_dum13	6.245*** (0.0939)	20.59*** (0.271)
h_dum14	6.650*** (0.0938)	20.07*** (0.270)
h_dum15	6.003*** (0.0934)	19.37*** (0.269)
h_dum16	6.084*** (0.0928)	18.76*** (0.268)
h_dum17	6.506*** (0.0924)	20.62*** (0.266)
h_dum18	8.256*** (0.0924)	25.57*** (0.267)
h_dum19	6.808*** (0.0922)	23.39*** (0.266)
h_dum20	6.633*** (0.0920)	22.48*** (0.265)
h_dum21	3.325*** (0.0912)	18.90*** (0.263)
h_dum22	2.444*** (0.0904)	17.21*** (0.261)
h_dum23	1.921*** (0.0897)	15.67*** (0.258)
h_dum24	−1.062*** (0.0887)	7.216*** (0.256)
d_dum2	0.644*** (0.0539)	0.471*** (0.155)
d_dum3	−0.382*** (0.0560)	−0.242 (0.161)
d_dum4	−0.412*** (0.0561)	−0.580*** (0.162)
d_dum5	−0.425*** (0.0560)	−0.720*** (0.161)
d_dum6	−0.529*** (0.0544)	−0.705*** (0.157)
d_dum7	−0.637*** (0.0486)	−0.538*** (0.140)
q_dum2	0.515*** (0.0472)	0.0500 (0.137)
q_dum3	0.432*** (0.0546)	0.359** (0.158)
q_dum4	0.0127 (0.0384)	−0.0780 (0.111)
R2	0.96	0.98
Observations	2,472,274	617,827
Number of plants	32	8

Note: standard errors in parentheses.

*, **, *** refer to 10%, 5% and 1% significance levels, respectively.

✎ ACKNOWLEDGMENTS ✎

The authors acknowledge the Netherlands Authority for Consumers & Markets (ACM) for its valuable support and two anonymous reviewers as well as the editor for their useful comments. The authors, however, are fully responsible for the contents of this article and, consequently, for any remaining shortcomings.

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