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How Marginal is Lignite? Two Simple Approaches to Determine Price-Setting Technologies in Power Markets

How marginal is lignite? Two simple approaches to determine price-setting technologies in power markets

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Abstract

The parameterisation of energy and climate policies often depends on the technology, which is price-setting in electricity markets. We propose two simple approaches to determine marginal technologies in electricity wholesale from available data. Both approaches are complementary, computationally lightweight, and do not require specific software. Identification is based upon assumptions which are commonly used in more complex energy system models and which vary according to the approach. We illustrate the relevance of our approach for consistent policy parameterization with an example from the compensation scheme for indirect emission costs from the EU Emissions Trading Scheme (EU ETS). We find that the current policy design severely overweighs CO₂ emissions from lignite power plants in the CWE power market.

JEL codes: Q41, Q48, Q58

Keywords: Marginal technology, price formation, power market, indirect cost compensation

1 Introduction

The impact of market-based energy and climate policies often depends on how they affect energy prices. In the case of wholesale electricity prices, “marginal plants” of electricity production are crucial for these price changes. Marginality describes - for a specific plant and point in time - the situation in which all cheaper technologies are already fully employed, and the plant in question is the least costly available option needed to satisfy total demand. So, the price to get this plant running is also the price that clears the market. Thus, marginal plants are usually said to be price-setting. An assessment of energy policies that affect electricity prices therefore crucially relies on information about marginality.

This article illustrates two simple approaches that allow to infer marginal technologies from observed market data in a transparent manner and with high timely resolution. Such an approach can be particularly helpful whenever the parameters for specific policies depend on assumptions of marginality and the determination of these parameters requires a high level of transparency and reproducibility. Executing and comparing two separate procedures can help to check the robustness of the results and the conclusions drawn.

The motivating example for this study is the compensation mechanism for indirect CO₂ costs from emissions trading in the European Union (EU) through the EU Emissions Trading Scheme (EU ETS). Indirect CO₂ cost arise from emission allowance cost that are passed-through onto the price for electricity. Implementing a compensation scheme of these cost for electricity consuming industries is optional for EU Member States but the European Commission has issued binding guidelines for Member States on a maximum level of firm’s compensation amount (EU Commission 2012). This level depends among other things on region-specific emission factors of power production, which are specified in the guidelines. Thus, the parameterization of these emission factors is crucial for the compensation level to be as intended by the regulator. According to the European Commission, the current emission factors are based on the weighted average CO₂ intensities of electricity generation from fossil fuels in the respective regions. From an economic point of view, the deficiency of such a policy specification is evident: In light of the marginality argument, the average emission intensity of fossil fuel fired power production does not inform about the actual CO₂ cost contained in the power market clearing price - even under complete cost-pass through of CO₂ cost, which is likely the case in electricity wholesale markets (Fabra and Reguant 2014; Hintermann 2016). When the emission allowances cost for the production of electric power is passed on to consumers, the electricity price change will depend on the emission intensity of the marginal plant. The marginal plant in today’s electricity system will supposedly be a fossil fuel fired plant but even this is not necessarily the case. Moreover, for different hours and load levels different technologies with varying emission intensities will be marginal. And the proportion in which these technologies will be marginal is most likely not the same as the technology’s share in total generation of fossil fuel based technologies. Consequently, a compensation scheme that is based on emission factors ignoring these aspects will almost certainly over- or undercompensate relative to the intended level of compensation for indirect CO₂ costs. One prominent case might be the inclusion of emissions from technologies that are not marginal in a relevant number of hours. Lignite is typically the most emission intensive fuel with specific CO₂ emissions, i.e. emissions per electricity generated, clearly

exceeding those of hard coal and natural gas. But lignite plants in Western Europe also typically have lower specific fuel costs than natural gas or hard coal plants. While it appears reasonable to assume hard coal and natural gas power plants to be marginal technologies for most of the time, it is an open question whether lignite is price-setting in a relevant number of hours. If lignite is not marginal for a significant share of hours each year, including CO₂ emissions from lignite in the calculation of emission factors may overstate the actual impacts and consequently, the level of indirect cost compensation.

This question is of particular importance for regions, in which lignite plants constitute a significant share in fossil fuel fired electricity generation. Central Western Europe (CWE), covering France, Germany, Austria and the Benelux countries, comprises countries with heterogeneous power systems. Power production in France and Belgium is dominated by nuclear power; for Austria hydro power is the dominating source. The bulk of all fossil fuel power plants in the CWE region are located in Germany. And among all CWE countries, only Germany possesses active lignite power stations. Still, CO₂ emissions from lignite account for about 42 percent of all CO₂ emissions in electricity generation in the CWE region (period from 2005 to 2015, own calculation based on data from Eurostat and IPCC default emission factors for fossil fuels. Note that lignite in Germany typically exhibits a higher emission intensity than the IPCC factors, see Juhrich (2016)). Thus, the impact of CO₂ emissions from lignite on the average emission factor is non-negligible. But in Germany, lignite plants are usually considered to be base load capacities, which - by definition - are hardly price-setting.

All these arguments do not bite without a proper quantification. The most common and widely accepted approach to study the power system and its interdependencies are energy system models. These are typically numerically solvable optimisation models which use various input data and technological information to represent the system-wide provision of electric power in detail. Kallabis, Pape, and Weber (2016), Hirth (2018), as well as Weigt and von Hirschhausen (2008) can serve as examples for such an approach, comparing realised prices in the past with model results for marginal cost. Admittedly, a strength of numerical energy system models is their capability to produce forecasts and scenario analyses, see e.g. Weron (2014) for an overview. A common point of critique brought forward is usually that such optimisation models are heavily driven by the underlying assumptions and that their validity is hard to assess. For example, Knopf (2016) investigates the sensitivity with respect to the selection of representative days. However, the majority of quantitative research output depends on assumptions, no matter what specific methodology is chosen. More important than dependence on assumptions is the transparency of assumptions and their potential impact. An important stream of research is working on opening energy system models and their underlying data sources for public scrutiny and collaborative work. Pfenninger et al. (2018) and Pfenninger et al. (2017) provide an authoritative account of these efforts. Open energy system modelling is a great leap forward for transparency in policy consulting and policy design. However, as powerful and transparent as these models are, their usage and scrutiny will always be restricted to a group of experts with corresponding training. The aim of our work is therefore not to rival with fully fledged energy system models, but rather to provide an accessible alternative for the ex-post determination of marginal technologies, which could be used to inform policy makers in their assessment of a policy and its parameterisation. Our approach is computationally lightweight and

does not depend on specific software. Given that the regulator decides on some general assumptions, our approach could even serve for a dynamic and purely data driven updating of policy parameters.

In this paper, we show how the fundamental idea of energy system models can be used for a much simpler but not less plausible method to determine the marginal technologies from observed data. We do so by taking a view from two different angles: (1) looking on realised load and its relation to available capacity, (2) looking on realised prices and how they compare to approximated marginal costs. The presented approaches evidently require a number of assumption, but not substantially more or more critical ones than those required for more complex energy system models. Moreover, these assumptions vary between our two approaches. Thus, comparing results across approaches will help to check their plausibility. Finally, the approaches do not require any optimisation algorithm. Indeed, all we do is to summarise and interpret a number of descriptive statistics against the backdrop of a set of transparently stated assumptions. Thus, our approach is easily reproducible without the need of specific modelling software. The contribution of this paper is to exemplify how such a simple calculation can be used to check the parameterisation of a policy for consistency with the declared aim and against the backdrop of the assumptions made. We do so for just a subcase of a specific technology - lignite based power generation - in a specific market - the German and Austrian wholesale electricity market - but comparable approaches are straightforward to implement for similar questions in different circumstances.

Overall, we find that the share of hours, in which lignite was likely price-setting in the German and Austrian wholesale market for electricity, was clearly below 10 percent for the period covered in our sample. This finding is in stark contrast to the weight of 39 percent that CO₂ emissions of lignite currently have in the average emission factor. Therefore, including total CO₂ emissions from lignite in the calculation for the current emission factors for indirect CO₂ cost compensation clearly overstates its actual impacts on the indirect CO₂ costs in Central Western Europe.

The remainder of the paper is structured as follows. Section 2 explains the concept of marginality, outlines the empirical approaches to identify marginal plants, and discusses their challenges. Section 3 and 4 present the analyses of both approaches to identify marginal technologies in detail. Section 5 concludes.

2 Concept of marginality and empirical approaches

2.1 Motivation to study marginality of lignite power plants

Emissions from lignite fired power plants have a high weight in the emission factor that is used to compensate industries for indirect CO₂ costs. However, for the German market, lignite plants are generally considered to serve base load, running most of the time due to their low marginal costs. This means that the electricity price level is no crucial determinant of the decision to produce power from lignite once the investment costs are sunk. In return, one can assume that the marginal costs of lignite plants, including marginal emission costs, are no crucial driver of the electricity price level. Such reasoning would obviously fail (a.) due to enormous

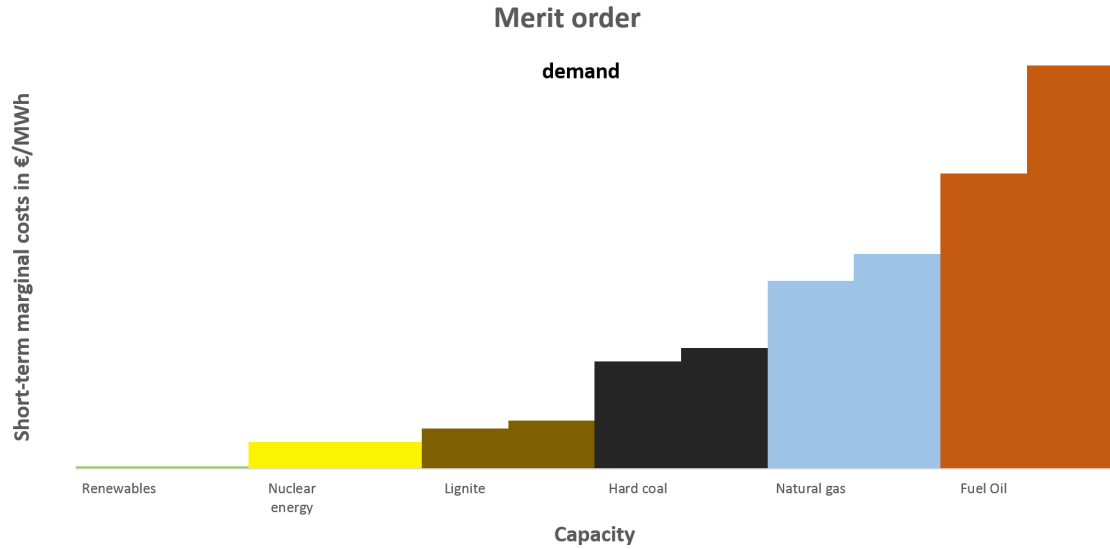


Figure 1: The merit-order (stylised) as a concept for price formation in electricity markets

increases in their marginal costs, e.g. when greenhouse gas emissions are priced heavily, or (b.) when lignite plants are priced out of the market due to cheaper rival technologies. The former scenario (a.) does not prevail in any jurisdiction around the world yet. The latter scenario (b.), however, could be relevant in energy systems with large renewable or nuclear capacities in the market or in connected neighbouring markets. Both of the latter conditions apply for Germany.

2.2 The concept of marginality and the merit-order

‘Merit-order-pricing’ is a stylised model of price formation in electricity markets: when power plants are ordered according to their marginal costs, the last plant that is necessary to satisfy demand sets the price. But what price does the plant set? One possible assumption would be that all plants are pricing at their own marginal costs. An economically more plausible assumption is that the plant owner is pricing just a tiny amount below the marginal cost of the closest competitor to keep the next plant out of the market but still raising the own margin. Without more detailed plant level information, but knowing that no generation technology is completely monopolised within the German-Austrian market, we can assume that all plants of the same technology compete with each other, and thus, it is the marginal cost of the marginal technology which is setting the price. Indeed, most of the well-established energy system models used in industry and for policy consulting are based on some variant of such a merit order model. Figure 1 illustrates the concept.

2.3 Approaches to evaluate if a technology is price setting

Based on a simplified merit-order model and without detailed plant level data, we consider two different approaches, one based on quantities, the other one on prices, to identify time periods in which lignite plants can be expected to be price setting:

1.) **Marginality according to residual load:** We identify hours in which total electricity demand is such that it fulfils the following two criteria: a.) Load is so high that it cannot be covered alone by production from technologies that rank before lignite in the merit-order; b.) load is so low that no technology which is more expensive than lignite is needed to satisfy total demand. In this approach, we identify residual load for lignite after production from cheaper technologies is subtracted and evaluate whether it falls within the range of available capacity for lignite rather than exceeding it. Due to the varying nature of electricity demand, this approach is most reasonably executed at the highest available frequency.

2.) **Marginality according to marginal costs:** We identify time periods, in which electricity prices are above the marginal costs of the most efficient lignite power plants, such that lignite plants are in the market, but below the marginal costs of the closest more expensive competitor which in our case is the most efficient hard coal fired power plants. Both technologies are subject to start-up and ramping costs which render them inflexible to a certain degree with respect to high frequency price changes. We therefore compare marginal costs to daily average prices, assuming that plants are sufficiently flexible to react to price drops that extend over at least 24 hours. Moreover, note that the day-ahead auction takes place at noon the day before delivery. A plant that would have to shut down or to start-up for the period of 24 hours would still have 12 hours to adjust before the beginning of the delivery period. Taking daily average prices may thus help to overcome the potential bias introduced by those inflexibilities.

Taking the two approaches in parallel and comparing the results helps us to control for the drawbacks of either one. Our residual demand based approach requires technology specific production data which is not available before July 2015. We therefore restrict our analysis to the time period where a full data set is available.

2.4 Challenges of identification of the marginal technology

The following paragraphs address potential issues concerning the concept of marginality and pricing behaviour of power plants, specifically deviations from the merit-order due to inflexibilities, forward contracting and - capacities. These aspects can be dealt with on one hand, by using additional market specific information. On the other hand, and this approach applies more generally, we believe that taking two different perspectives - one on prices, one on quantities) - with possibly different frequencies of observation allows to account for deviations in plant scheduling.

2.4.1 Deviations from the strict merit-order model

The merit-order model is economically and technologically intuitive, but a bit too simplistic to fully capture the reality of production and pricing decisions in the markets. Plants might stay on the grid during hours where the price appears to be below their (short run) marginal costs, or plants that could possibly produce profitably for certain hours might stay out of the market for some unobserved reasons. The former plants are often referred to as “must-run capacities” while the exact reason for why they “must-run” is not evident. Possibilities are e.g. combined heat-power plants that base their production decisions on the need for heat and dump the co-produced

electricity on the market. Start-up and ramping costs are another possibility which could convince a plant owner to stay online for certain hours at a loss to be able to produce during other subsequent hours with a profit. A different possibility is the fact that power can be traded in blocks of several hours, days or weeks. A producer who is completely hedged against short time price changes might thus not react to hourly prices when the effort for short term trading exceeds the expected benefit. This latter form of inflexibility is sometimes referred to as ‘economic must-run’. Evidently, all of these kinds of frictions or other market effects are blurring the picture that one can obtain based on simple merit-order reasoning.

Aside of these hard to quantify technological and economic aspects, the merit-order model relies on the assumption that firms base their decisions on marginal costs alone, disregarding possibilities to exert market power and total cost recovery. That said, merit-order pricing still is the dominating assumption underlying most energy system models. Moreover, in the competitive market setting that we currently observe on the Central-European power markets, marginal cost based pricing appears to be a reasonable assumption.

2.4.2 Start-up costs, block bids and economic must-run

An exact separation of ‘economic’ or ‘technological’ must-run is not possible. In the end, every production decision is based on an economic decision subject to technologically determined constraints and costs. While the number and capacities of combined-heat-power plants are known, there is no data on which of these plants base their production decision on heat and which on power market related information. The German Transmission System Operators (TSOs) commissioned a study on the dimension of the capacity which can be expected to “must run” (Consentec 2016). The results give a first impression on the scale of the phenomenon.

Besides combined-heat-power, inflexibilities in adjusting electricity generation are another highly relevant technological aspect of production which translates into economic terms in form of start-up and ramping costs. The high costs to heat especially large power plants, such as lignite or nuclear plants, render a fast adjustment of production to short lived price changes unattractive. The day-ahead market for electric power at EPEXSpot accounts for such kind of frictions by allowing so-called “block-bids”. While the standard traded unit in the day-ahead market is the delivery of electric power during a specific hour of the following day, block-bids allow tying together several hour-contracts to larger blocks of hours. Common blocks are “base load” or “peak load blocks” which capture all 24 hours, or all hours from 8 a.m. to 8 p.m. respectively. A selling bid for example is executed when the average price for all covered hours is above the price limit of the seller. The seller has then sold power for all hours of the block, although the price for power in some of these hours might be below the variable production cost of the producing plant. For an outsider, observing a plant producing at prices below its marginal costs therefore apparently “must-run”, although it might go offline when such low prices prevail for a longer period.

3 Analysis of marginality according to residual load

3.1 The approach based on residual load calculation

In the first approach, we evaluate the relevance of lignite as a price setting technology through the analysis of market data on load, generation, and available capacity. The approach builds on market quantities rather than prices. The identification is based on the merit-order model: Assuming a set of technologies with typically lower marginal cost than lignite (e.g. hydro, nuclear, also called ‘inframarginal technologies’ in the following), we conclude that lignite is not price setting whenever the observed output from these technologies alone suffices to serve overall demand. Lignite would then be ‘out-of-the-market’. On the contrary, when total demand exceeds the production from cheaper technologies, we know that the ‘residual load’ for lignite power plants is just the difference of total demand and the production from these cheaper technologies. We can then compare this residual demand to the available capacity of lignite. If lignite capacities do not suffice to meet residual demand, we know that more expensive technologies must kick-in and lignite will thus again not be price setting. Classifying all observed time periods according to these possibilities allows us to deduce those periods in which lignite is neither out-of-the-market, nor insufficient to meet its residual demand. For these periods, lignite power plants qualify to be at the margin, and thus price-setting.

3.2 Data sources on production, consumption, and capacities

3.2.1 Data on generation

We obtain hourly day-ahead planned generation for the German-Austrian bidding zone from the EEX transparency platform for all available technologies, comprising the following: *biomass, coal, gas, pumped-storage, run-of-the-river, seasonal-store, coal-derived-gas, garbage, lignite, oil, other, uranium, wind-offshore, wind-onshore*. Technology specific data for generation is available from 29 July 2015 onwards. The last day in our sample is 28 July 2017, giving us exactly two years for the analysis. So all seasons enter with equal frequency.

The implausibly low reported quantities on generation from wind and biomass in this data set, and the missing information on solar requires us to use further data. For wind and solar power, we use the hourly data on day-ahead predicted inflows from the EEX transparency platform.

As there is no corresponding data on power production from biomass, we follow Agora Energiewende in their approach to impute values as documented online <http://www.agora-energiewende.de/agorameter>. Biomass is hereby assumed to enter uniformly and at a stable rate. The production levels are imputed such that they conform to the yearly reported overall production as well as to the intra-yearly increases in installed capacity.

3.2.2 Data on cross-border flows

We obtain scheduled cross-border flows for all interconnectors to/from the German-Austrian bidding zone in hourly frequency from the ENTSO-E transparency platform. We aggregate flows into net-flows such that negative flows indicate net imports. Several interconnectors, especially smaller ones, lack data for significant time windows. Corresponding flows are counted as “zero” when calculating total net exports from the German-Austrian bidding zone to neighbouring countries. The corresponding interconnectors are minor in terms of capacity and excluding all observations due to missing data on some interconnectors would mean to throw away a lot of available information from the other interconnectors and the data sources.

Following this definition, we observe net cross-border flows from 29 July 2015 to 28 July 2017.

3.2.3 Data on demand

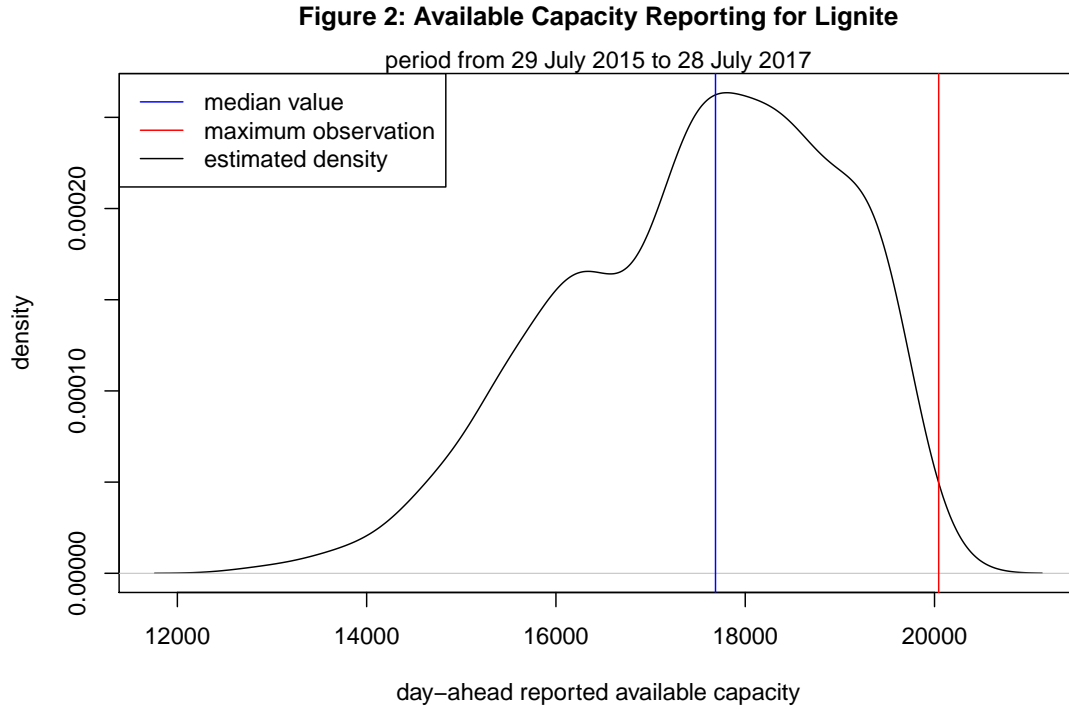
We obtain data on the total system load for the German-Austrian bidding zone from the ENTSO-E transparency platform at hourly frequency. It is known from Hirth and Schumacher (2015) that these load levels do not represent actual total electricity consumption in precise quality due to several reporting problems, especially with respect to self-consumption. However, these data are the only available in sufficiently high frequency. Moreover, the ENTSO-E data is consistent with the other data we use. We therefore rely on the ENTSO-E data, which also represents the industry standard.

A total of 96 hours in our sample has missing values for predicted load. We replace the corresponding missing entries with the realised load levels whenever the latter are available.

3.2.4 Data on available capacity

We obtain information on available capacity from the EEX transparency platform and screen all documented capacity reports for the last available date before actual production. Thus, we typically capture the day-ahead reported availabilities.

Due to shortcomings of the EEX transparency platform when updating their server in 2016, available capacity reports from the first semester of 2016 are completely missing. Discarding the whole semester for the analysis would significantly reduce our sample. As a means of interpolation, we alternatively use the median reported available capacity within the time frame from 29 July 2015 and 28 July 2017 which amounts to 17.686 GW. In other words, half of the daily reported values are above this number, while the other half is below. Note that the distribution of records of available capacity for lignite is left-skewed such that our median capacity is much closer to the maximum observed available capacity of 20.044 GW rather than to the minimum observed capacity (see Figure 2 below). Details and validity checks are reported later in conjunction with the empirical analysis.



3.2.5 Data on ‘must-run’ capacities

As explained before, the definition of must-run capacities is vague, and a clear cut quantification is missing. The crucial characteristic of must-run capacities for this analysis is that they are by definition not responding to electricity price level. Technologies that are more expensive could thus alter the residual load for lignite. Moreover, some parts of the lignite plants might also be ‘must-run’ capacities and therefore would not bid according to marginal costs. We use the results of Consentec (2016) as a measure of must-run capacities which are considered to be generating independently of the price level. Averaging over the three different scenarios in Consentec (2016) yields the following quantities for must-run capacities:

Table 1: Must-Run Capacities based on Consentec, 2016

Fuel Type	Capacity in MW
lignite	8526.3
uranium	6981.7
coal	2587.3
gas	1901.3
oil	62.0
garbage	148.3
run-of-the-river	118.3
pumped-storage	70.3
seasonal store	18.3
other	869.0

3.3 Results on marginality according to residual load

3.3.1 Marginality based on simple residual load

Taking all information together, we obtain the following data set with the corresponding variables for our residual load calculation.

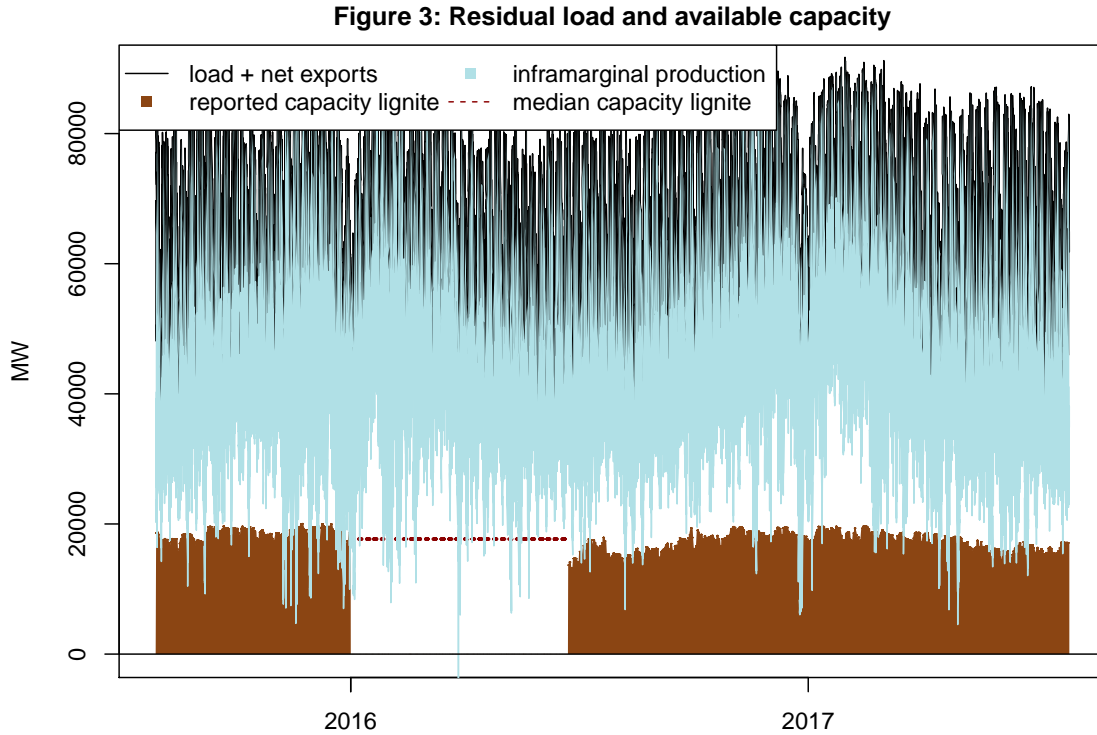
Table 2: Descriptive statistics for data on quantities

Variable	Min	Median	Max	Observations	Missing
predicted load	38131	62359	85600	17540	4
planned generation nuclear	2852	8174	9926	17542	2
planned generation garbage	8	136	222	17542	2
planned generation run-of-the-river	221	1690	4302	17542	2
predicted wind and solar	5891	17969	58090	17533	11
net exports	-7065	4675	13744	17542	2
available lignite capacity	12852	17686	20044	13369	4175
inframarg	13284	27968	69423	17533	11

In total, we have 17,532 complete hourly observations, except for the available capacity of lignite. Residual load for lignite power plants is calculated as system load minus the generation from technologies that are considered to run at lower marginal costs (thus being inframarginal compared to lignite). We consider the following technologies to fulfil this condition: uranium, run-of-the-river, garbage, wind, solar, biomass.

To illustrate our approach consider Figure 3. It shows (from top to bottom) day-ahead predicted load plus net export (black line), planned production from technologies that are considered to be inframarginal (shaded area in light blue), and the reported available capacity of lignite (dark brown shaded area) over the course of our sample period. Residual demand for lignite is therefore given by the lower border of the light blue shaded area. The occurrences where residual demand dips into the range of available capacity of lignite are those which can be considered to be hours where lignite would be marginal (not yet accounting for must-run technologies). The

first half of 2016 shows the large gap in the time series of available capacities. For not completely discarding this period, one has to assume some form of interpolation for the available capacity of lignite. In our case, we chose the median value of those values that we do observe, depicted by the dashed, red line below.



Evaluating our sample for the marginality of lignite, using the median available capacity of lignite for interpolation, we obtain 541 hours out of 17,532 fulfilling the marginality condition. This corresponds to 3.1 of all hours.

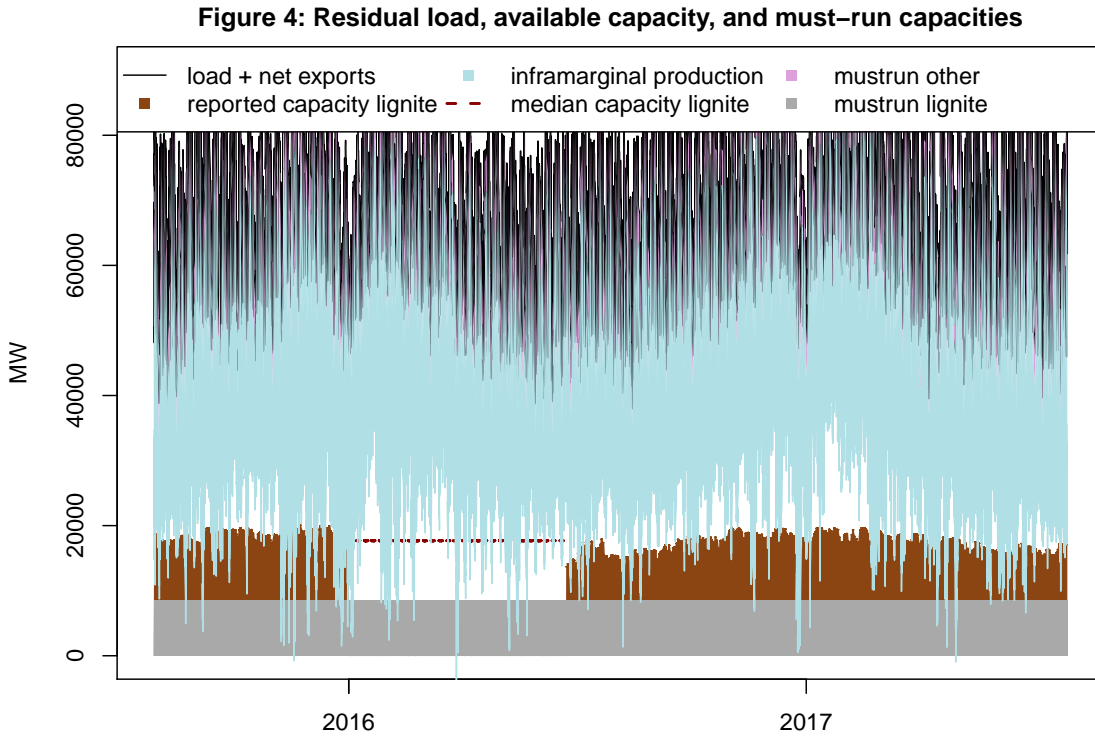
3.3.2 Sensitivity with respect to interpolation

The graphical presentation in Figure 3 indicates that the actual reported available capacities do not vary much around the median and drop more prominently below, rather than above. This suggests that the median could serve as a good proxy for the missing data. To get a better understanding of how well the median proxies actual available capacities in relation to residual load, we compare both methods on the same reduced sample. Precisely, we calculate the ratio of marginal hours for lignite solely based on the sample where we have actual reports and compare this ratio with the ratio that one obtains, using only the median capacity on the same sample. We find 2.8 percent of hours in which lignite is likely marginal using the actual reports, compared to 3.2 when using the median of the available capacity as a proxy. This suggests that our approach using the median rather overestimates the number of hours where lignite is marginal compared to the actual reports. This is not surprising in light of the skewed distribution of available capacity, showing that the median is closer to the maximum rather than the minimum. Overall, both numbers are still very close which makes us confident that the interpolation we used before is a good approximation.

3.3.3 Accounting for must-run capacities

The previous numbers do not take into account that several capacities might must run. This applies both to e.g. hard coal or gas fired plants which would then be placed in the merit-order before lignite plants, but it would also apply to parts of the lignite plants. Plants that must run are by definition not reacting to price signals and are therefore not price setting in the sense of marginal-cost-based pricing. As discussed above, information on capacities that ‘must run’ and to what degree this ‘must’ applies is sparse. As an approximation, we are using the information from Consentec (2016) to account for must-run capacities by technology. In the following, we add must-run capacities for technologies which had not yet been declared to be inframarginal (e.g. hard coal, gas, oil...) to the block of inframarginal production. On the other hand, we consider only those available capacities of lignite power plants to be potentially price setting which exceed the capacities that are declared to ‘must run’.

Figure 4 below depicts again predicted load plus net exports in black. But now, we subtract the must-run capacities of more expensive technologies (coal, gas, etc. in pink). Again, we moreover subtract the production from cheaper, inframarginal technologies (nuclear, renewables in light blue) to obtain residual demand for lignite (lower border of the light blue shaded area). Reported available capacities of lignite are depicted in dark brown as before. We moreover account for the must-run capacities of lignite which cannot be price setting. They are marked below in light gray.



For this modified setting, we find 1,344 hours fulfilling the marginality criterion based on the interpolation of missing availability data with the median. This corresponds to 7.7 percent of hours in our sample. When using only those hours for which we have full capacity reports, we find 7 percent of hours fulfilling the marginality criterion, while when we use the median as a proxy for available capacity over the full sample, we find 8.3 percent. Again this points to our interpolation using the

median is overstating rather than understating the importance of lignite as a price setting technology.

3.3.4 Robustness check: maximum available capacity

This analysis takes different approaches to determine residual demand for lignite plants and compares it to reported available capacities where possible. It moreover uses an interpolation for periods where available capacity reports are missing, and checks the sensitivity of this approximation. The chosen method (taking the median) is found to exaggerate rather than underestimate the relevance of lignite as a marginal technology. As another robustness check for this interpolation, we repeat the analysis using the clearly exaggerating assumption that available capacity in the time where reports are missing had been at the maximum value we observe in our sample. Under this maximum assumption, we find 3.7 percent of our sample to fulfil the marginality condition, not taking potential must-run capacities into account, and 9 percent when accounting for must-run capacities as detailed above. Note that these values are still clearly below 10 percent, even though these values are exaggerated due to the maximum assumption on available capacity.

4 Analysis of marginality according to marginal costs

4.1 The approach based on marginal cost calculation

In the first approach, we have drawn conclusions on the relevance of lignite as a price setting technology from data on demand, production, and capacity. Such a quantity-based analysis evidently depends on a number of assumptions concerning the merit-order and the price responsiveness of power plants. The second approach takes a different perspective on the same question, drawing conclusions from realised prices and production costs. Lignite power plants are considered to be price setting when market conditions are such that lignite plants can recover their marginal costs (meaning they are “in the money”) but more expensive competitors cannot (putting the latter “out of the money”). We are thus interested in the price range that spans between the marginal costs of lignite power plants and the closest marginal competitor, usually hard coal fired plants. We then identify how often the observed prices fall within this price range, suggesting that lignite plants have been price-setting during the corresponding periods.

This approach does not depend on observed quantities or assumptions about must-run capacities. Moreover, by looking at daily average prices it is possible to overcome some of the previous assumptions. Consider for example block bids which have been discussed in the introduction as a possibility to rationalise production of conventional power plants in hours when prices are clearly below their marginal costs. In the following, we consider day-ahead prices for the full block of 24 hours of the following day. These blocks are traded one day ahead at noon, leaving 12 hours before delivery begins. Thus, a conventional coal or lignite plant with limited flexibility can sell such a block and still has half a day to ramp up, and no need to adjust production during the day. The plant thus could be marginal for the whole day on average, although in

the shorter run, we see price variations between different hours. Thus, we consider this approach to be more robust with respect to the ramping and the specification of must-run technologies. On the other hand, we have to rely on estimates for the marginal costs of lignite and hard coal plants, based on the data we describe in the following.

4.2 Data on prices and cost

4.2.1 Data on prices for electricity and emission allowances

We obtain hourly day ahead auction prices for the German-Austrian bidding zone from EEX. The hourly prices are averaged on a daily basis which is equivalent to the *Physical Electricity Index* Phelix. EU emission allowances prices are obtained from the EUA spot market at EEX.

4.2.2 Data on the cost of power production from lignite

Lignite is hardly traded and usually produced close to the actual plant it fires. The most recent study on the production cost of lignite is from Öko-Institut (2017). They distinguish production costs of older and newer plants. As a lower bound for our relevant price range, we are interested in the lowest marginal costs of lignite, which are with the newer and more efficient plants. For newer lignite plants, Öko-Institut (2017) estimates marginal fuel costs of 3.6 Euro per Megawatt hour (MWh) electric output and additional variable costs of 2 Euro per MWh electric output. The study moreover reports specific CO₂ emissions of 963 kilogram (kg) per MWh electric output. Together with the EUA prices, we can approximate daily marginal costs for the production of electric power from lignite by summing up fuel cost and emission cost per MWh electric output.

4.2.3 Data on the cost of power production from hard coal

For the price of hard coal, we refer to the weekly McCloskey MCIS Marker coal price index for North-West Europe. It is normalised to the price of hard coal with a calorific value of 6000 kilocalories (kcal) per kg for delivery in the Amsterdam-Rotterdam-Antwerp (ARA) region harbours. We translate the price into Euro values, using the European Central Banks (ECB) official USD/EUR daily exchange rate. We moreover adjust the price per ton to represent the inner German 2015 average heat rate for hard coal of 6448 kcal/kg (Arbeitsgemeinschaft Energiebilanzen 2017). To account for shipping costs from ARA to Germany, we add costs of 1.53 Euro per ton as suggested by BAFA (2016). Finally, we attribute the weekly published price index to each following day after its publication until a new price observation is available.

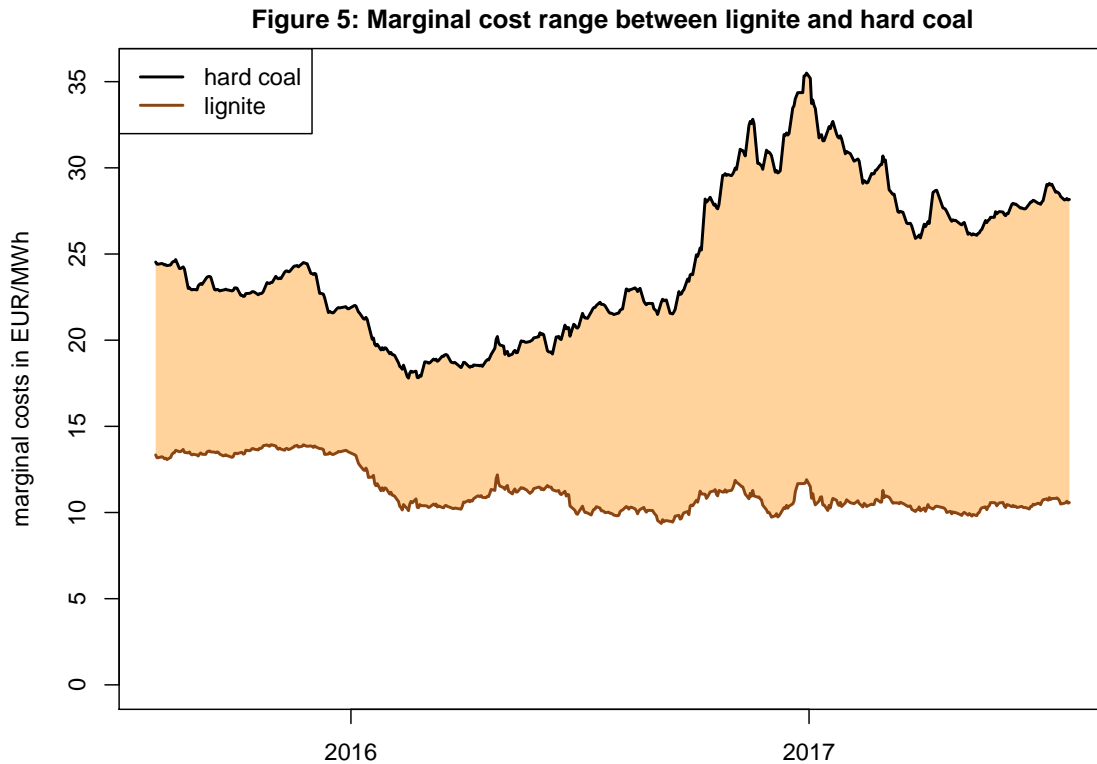
As we are interested in the closest competitor to lignite, we look for the lowest marginal costs of a hard coal plant. We observe efficiency rates of 0.465 for the most efficient German hard coal plant based on the data gathered by *Open-Power-System-Data.org*. With respect to the CO₂ content of the fuel, we refer to Juhrich (2016), reporting 93.6 ton CO₂ per Terajoule (TJ) thermal input for hard coal. From these numbers, we can calculate fuel cost per MWh electric output for the most efficient

hard coal plant. Together with the CO₂ price data, we can moreover calculate the emissions cost per MWh electric output. Finally, we are lacking precise estimates on further marginal cost components such as wear-and-tear. As a proxy, we use the same amount of 2 Euro per MWh electric output as for the lignite plants.

4.3 Results on marginality according to marginal costs

4.3.1 Marginality according to marginal costs

Figure 5 depicts the evolution of marginal costs for hard coal and lignite plants that we calculate based on the efficiency levels, CO₂ contents, input prices, and further variable costs as detailed above.

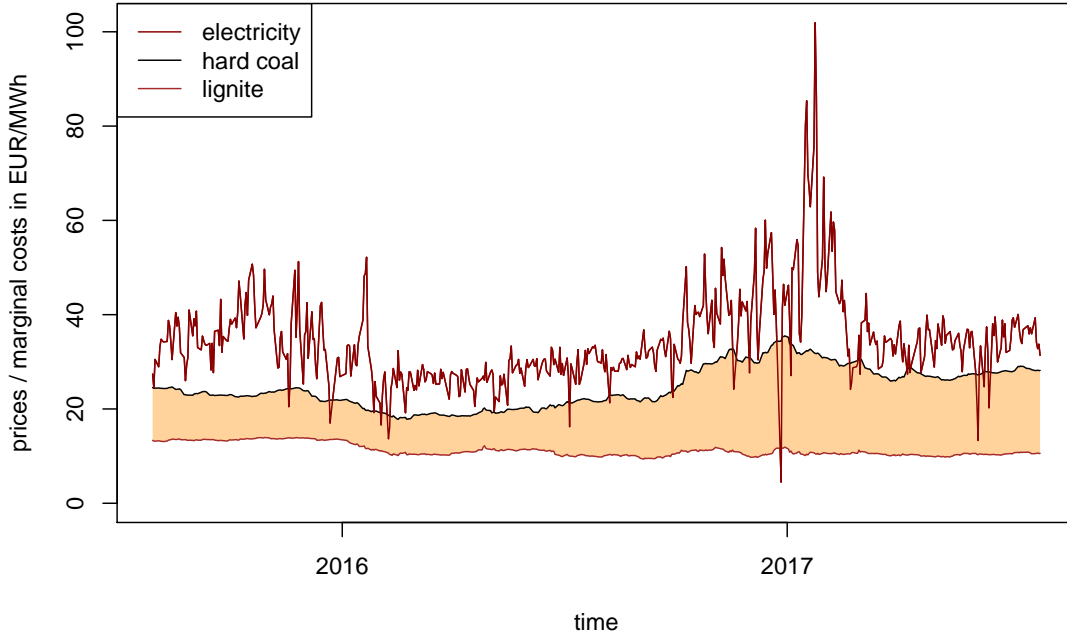


The range between the marginal costs of these two types of fuels (here shaded in light brown) can be expected to be the price range in which lignite power plants are price setting. The following graph (Figure 6) puts on a larger scale the daily average power prices (physical electricity index, “Phelix”) in comparison to the marginal costs.

It is evident that over the course of this period, power prices rarely fall into the range which spans between the marginal costs of lignite and hard coal fired power plants. This suggests that typically more expensive technologies than lignite are price setting in the day ahead market.

However, in late 2016, we also observe power prices dipping below the marginal costs of lignite, thus implying that coal and lignite plants would have been out of the market altogether. Precisely, we find that power prices are in between the marginal costs of lignite and hard coal for 38 days of our sample which covers 646 days in total. In relative terms, the days where lignite would be potentially marginal correspond to 5.9 percent of the total number of days within our observed time period.

Figure 6: Power prices and marginal cost range between lignite and hard coal



4.3.2 Robustness checks: fuel switch

Throughout this study, we have largely considered the merit-order to be stable across generation technologies. In other words: while we did allow costs to fluctuate for different fuels, we did not consider the case where marginal costs of different technologies switch their order.

For the case of hard coal and lignite, we can see from the Figure 5 and 6 that such a switch is clearly out of reach. Lignite fuel is produced at very low cost onsite. All the dynamics we see in marginal costs for electricity production from lignite are due to varying CO₂ prices. Hard coal on the other hand is imported at world market prices. Freight costs and emission costs apply on top. While lignite is slightly more emission intensive than hard coal, higher CO₂ prices still drive marginal costs for both technologies. The relative difference in emission intensity is not as large as it is between hard coal and gas. Thus, the leverage for CO₂ prices is much smaller when comparing hard coal with lignite. For a fuel switch to occur, one would need to see drastically dropping prices for hard coal and/or drastically increasing prices for emission allowances to compensate for the fuel price advantage that lignite currently enjoys. Both does not seem likely yet. Let us consider what the implications would be if any other fuels switched order:

Let us first consider the case of a fuel switch between lignite and cheaper technologies. Possible candidates are wind, solar, biomass, hydro, and nuclear. The marginal costs of renewables can reasonably be considered to be zero. While this is not entirely true for biomass, biomass capacities in Germany are remunerated through a specific feed-in tariff, which puts them for the merit-order into the same category as wind or solar. As lignite has evidently non-zero marginal costs, a fuel switch of lignite and one of the renewable technology appears to be out of reach.

Nuclear, in contrast, has positive but small and rather stable fuel costs. A switch

with lignite appears to be unlikely. But even if such a switch occurred, what would be the consequence? Consider the Figures 5 and 6 depicting the range of costs between lignite and hard coal: In case some cheaper technology took the position of lignite, this new fuel would become the new closest competitor. Thus, the cost range in which lignite can be considered to be marginal would shrink.

Consider now the case of a fuel switch at the other end of the merit-order, e.g. between hard coal and natural gas. Such a change of relative position is not impossible and has been witnessed in several markets before (e.g. in the USA in conjunction with decreasing natural gas prices). Again, in Figures 5 and 6, if we had a fuel switch at the upper end, there would be a new closest competitor upwards, e.g. natural gas instead of hard coal, and the relevant cost range would become smaller. Thus, considering fuel switching would drive our results even further down, pointing to less importance of lignite as a price setting technology.

In summary, the possibility of a fuel switch would rather decrease the likelihood of lignite being marginal.

4.3.3 Robustness check: peak and off peak prices

The analysis of costs and prices has yet focused on daily average prices. This allows overcoming the implausible assumption that lignite plants can adjust quickly to hourly changes in the markets. In contrast, by bidding for complete days, the marginal cost of lignite plants might have an important effect on the equilibrium price for electricity. These daily averages obviously wash down price variation, e.g. between night and day hours. One might thus wonder if evaluating complete days could mask the marginality of lignite plants specifically during the off-peak hours. Therefore, we split our hourly prices into blocks between 8 a.m. and 8 p.m., capturing prices during the day and between 8 p.m. and 8 a.m. for the night. For not splitting two consecutive nights in half, we have shifted the last four hours of each day to the next day. Thus, we calculate an average price per night, capturing 12 consecutive hours. Doing so, and comparing the corresponding prices with our marginal cost range gives us 22 day-time averages as well as 73 nights where prices are in that range. In total, this amounts to 7.4 percent of hours.

5 Conclusion and policy implications

We have presented two different approaches to evaluate the relevance of specific power production technologies to be price setting. One approach solely focuses on quantity data and takes a merit order of technologies as given. Comparing the derived residual demand with available capacity provides an indicator for the technology in question to be price-setting. No price or cost data is needed. The other approach is independent of any quantity data by simply calculating minimal marginal costs for competing technologies. Comparing the range between minimal marginal costs of competing technologies with realised prices provides an alternative measure for the technology in question to be price-setting. Both approaches are computationally simple and lightweight and use data which is usually available for most power markets. Moreover, both approaches are based on a number of assumptions that are frequently made in the study of power markets. But as both

approaches vary in the assumptions they require and in the data they use, comparing the obtained indicators from either approach can be informative.

We illustrate the implementation and the possibility to calculate variants and robustness checks at hand of lignite power in the German market. None of the variants that we applied throughout this study suggests that lignite plants are price setting for much more than 3 to 7 percent, and evidently less than 10 percent of all observed periods in our sample, spanning from 29 July 2015 to 28 July 2017. This result contrasts with the average contribution of lignite power in the German-Austrian bidding zone in which lignite plants had an average share of 39 percent in fossil fuel power production over the years 2005 to 2015. Evidently, the share in production and the relevance as a price setting technology of lignite clearly diverge. While this insight might be trivial for experts, it is of a certain relevance for policies that are implemented in a couple of EU member states. The European commission allows to compensate electricity intensive sectors for incurred indirect CO₂ costs that are passed-on by power producers through electricity price. For the calculation of these compensation, the commission uses emission intensities of power production that are based on the average contribution of specific fuels to the mix of fossil fuel fired power production. Here, lignite is found to be the most emission intensive technology but to be inframarginal for most of the time.

Consequently, our analysis illustrates the potential fallacies that occur if policies ignore the relevance of marginality in power generation. In the example of the EU compensation scheme for indirect CO₂ costs, our results suggest that the weight of lignite in the specified regional emission factor is likely too high. On a broader scale, our study suggests that alternative procedures for the parameterization of such policies are available and that these approaches can be implemented in a transparent and computationally non-demanding manner. Based on a predefined set of assumptions and data sources, these approaches could even be used for a dynamically updating of policy parameters that depend on power prices and their constituents.

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