Journal of Environmental Economics and Management 106 (2021) 102405

Contents lists available at ScienceDirect

Journal of Environmental Economics and Management

journal homepage: www.elsevier.com/locate/jeem

Effectiveness of climate policies: Carbon pricing vs. subsidizing renewables

Klaus Gugler [a,*], Adhurim Haxhimusa [b], Mario Liebensteiner [c]

[a] Vienna University of Economics and Business (WU), Institute for Quantitative Economics, Welthandelsplatz 1, 1020, Vienna, Austria
[b] University of Applied Sciences of the Grisons, Centre for Economic Policy Research, Comercialstrasse 20, 7000, Chur, Switzerland
[c] Friedrich-Alexander University (FAU) Erlangen-Nuremberg, Institute of Economic Research, Germany

ARTICLE INFO

Article history:
Received 30 June 2020
Revised 11 December 2020
Accepted 12 December 2020
Available online 24 December 2020

JEL classification:
L94
L98
Q35
Q38
Q54
Q58

Keywords:
Climate change policy
Carbon price
EU ETS
Carbon price support
Subsidization of renewables

ABSTRACT

Most but not all economists view carbon pricing as most effective to combat carbon emissions, whereas other policies are widely applied and highly debated. We quantify the effectiveness of climate policies in the form of pricing carbon and subsidizing renewable energies for Germany's and Britain's power sectors. While Germany relies on heavy subsidies for renewables but on a weak price for carbon certificates (EUA) from the EU Emission Trading System (ETS), its emissions hardly declined. To underpin the low EUA price, Britain introduced a unilateral tax on power sector emissions, the Carbon Price Support (CPS). Within only five years, carbon emissions declined by 55%. Our results demonstrate that in the power sector, even a modest carbon price (~€30/tCO_2) can induce significant abatement at low costs within a short period as long as "cleaner" gas plants exist to replace "dirty" coal plants. We also find that carbon pricing is superior to subsidizing wind or solar power in these two countries.

© 2021 The Authors. Published by Elsevier Inc. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

1. Introduction

Enormous efforts have been undertaken to combat anthropogenic climate change, whereas global emissions have been increasing steadily (BP, 2018), which may threaten future economic activity, agriculture, and health (Burke et al., 2015). Economic theory clearly emphasizes that putting a price equal to the social damages on greenhouse-gas (GHG) emissions internalizes their negative externality via market-based incentives (e.g. Pigou, 1920). Many economists thus argue that pricing emissions may represent a first-best policy, leading to effective emissions abatement at lowest possible costs (e.g. Borenstein, 2012). Other policies, such as subsidies for "green technologies" (e.g. wind, solar, electric cars, etc.) and administrative measures (e.g. bans on oil heating, emission performance standards, etc.), which are popular among policy-makers and widely applied in the climate change agendas of many countries, represent only second-best options. However, there are alternative opinions, arguing that a mix of policies may best lead to a deep decarbonization at accelerated pace (Hepburn et al., 2020; Rosenbloom et al., 2020),

* Corresponding author.
E-mail addresses: klaus.gugler@wu.ac.at (K. Gugler), adhurim.haxhimusa@fhgr.ch (A. Haxhimusa), mario.liebensteiner@fau.de (M. Liebensteiner).

https://doi.org/10.1016/j.jeem.2020.102405
0095-0696/© 2021 The Authors. Published by Elsevier Inc. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

or even argue against carbon pricing (Patt and Lilliestam, 2018). Given that many policy-makers and even some scholars and experts do not view carbon pricing as the single most important tool to tackle climate change, and that administrative measures and subsidies are widely applied, it is relevant to understand not only if carbon pricing turns out as the most efficient policy in an empirical evaluation, but also to know the order of magnitude of abatement and costs associated with different climate policies, as well as their mutual interaction effects (e.g. if policies can be mutually supportive or are contrasting each other). Such knowledge may determine future political action.

Our research goal is thus to compare and quantify the effectiveness of carbon pricing and subsidizing renewable energies (RE). Relevant for the policy debate, we seek to evaluate these policies with a particular focus on their short-term effectiveness, as time is pressing to mitigate the worst impacts of climate change. Our focus is on Germany's and Britain's power sectors – the sector responsible for the lion's share of emissions – because, as we argue, their power sectors follow the same qualitative principles, whereas the two countries pursue different climate policies. The power sectors are comparable since prices are determined in wholesale day-ahead markets by "merit order curves", i.e. bid schedules determined by marginal costs. Moreover, electricity generation sources (e.g. renewables, nuclear, gas, and coal) and patterns – while quantitatively different – are qualitatively comparable. This comparability allows us to estimate an econometric model of carbon emissions using the same set of determinants for the two countries. The two countries differ, however, in their policies. Germany's power sector emissions are subject to a price for emission certificates (EUA) as determined by the EU Emission Trading System (ETS), which was low for a long period, whereas Germany heavily subsidizes RE. In contrast, Britain's support for RE is less pronounced (and falling), whereas the country placed a significant unilateral tax, the "Carbon Price Support" (CPS), on its power-sector emissions in parallel to the EUA price. Notably, despite its heavy RE subsidies, Germany's power sector emissions only declined modestly in recent years, while Britain's emissions fell by an astonishing 55% in only five years since the introduction of the CPS.

In a first step, we analyze emissions abatement associated with carbon pricing and RE subsidies using a rich dataset of daily electricity generation data at the plant unit level of all gas and coal power stations in Germany and Britain together with important plant characteristics to calculate CO_2 emissions. Our econometric model identifies abatement effects by drawing on the exogenous variation in the feed-in from wind and solar power as well as carbon pricing. We can isolate these effects by controlling for other potentially confounding effects, such as changes in demand, input prices, and seasonality. Moreover, we acknowledge that these effects are interdependent among each other by estimating a highly flexible, non-linear regression specification with interactions and higher order terms. We account for the problem of temporary production shutdowns in both countries as well as permanent exits of coal power plants in Britain by applying a Heckman two-step selection model. This way we can estimate "full" abatement effects, which not only incorporate the *intensive* margin (i.e. how plants' emissions respond to variations in our variables of interest) but also the *extensive* margin (i.e. on-off decisions of plants). Thus, the Heckman procedure also allows for isolating the effects of variations in the carbon price and RE feed-in on power plants' production adjustments (including shutdowns) from other regulations, such as air quality directives (e.g. the Large Combustion Plant Directive; LCPD).

In a second step, we seek to estimate the directly attributable costs of marginal abatement in terms of carbon pricing and subsidies for RE. We acknowledge that it may be problematic to compare the costs of a carbon price, which represent payments from power plant operators to the state, with subsidies for renewables, which are payments from the state to plant operators. However, we argue that the two instruments are comparable, because electricity consumers will eventually pay in the form of higher electricity tariffs. In the first case, plant operators will pass on the costs of the carbon price to end-consumers (Dagoumas and Polemis, 2020; Fabra and Reguant, 2014; Fell et al., 2015; Guo and Gissey, 2019; Hintermann, 2016), whereas in the second case, the costs of subsidizing RE will be financed through taxes paid by electricity consumers (Abrell et al., 2019). Hence, we calculate the costs for RE support as the average subsidies for one MWh of wind or solar power relative to their marginal abatement. To calculate the costs of carbon pricing, we measure the additional expenditures for carbon pricing relative to the change in emissions, as induced by a marginal increment in the carbon price (i.e. marginal expenditures relative to marginal abatement).

This way, we can also account for the non-linearity in the abatement function. For example, at a low carbon price level (e.g. €6/tCO_2), a marginal price increase may lead to significantly higher expenditures for certificates (i.e. the emissions base may be large and stay almost unchanged, so that the higher carbon price causes significantly more expenditures) while abatement may be small (e.g. since gas remains too expensive to replace coal). In contrast, at a moderate carbon price (e.g. €14/tCO_2), an incremental increase may make some gas-fired plants more economical than some coal-fired plants, leading to significant marginal abatement relative to moderate marginal expenditures. At a high carbon price (e.g. $\geq$ €40/tCO_2), the costs of marginal abatement may increase again, because most coal plants may have already been replaced by gas plants, so that a further increasing carbon price may only offset relatively efficient gas plants (e.g. through imports).

It is important to emphasize the strengths and limitations of our cost analysis. Intuitively, we ask how much abatement can the state/consumers/taxpayers "buy" with, for example, one billion euro when pricing carbon, or subsidizing wind and solar. We do not account for any induced inefficiencies (e.g. increased costs of production by switching from (cheap) coal to more expensive gas; increased network costs due to RES intermittency), nor for the effects following from changes in the wholesale electricity price induced by the policies, nor for other general equilibrium effects (e.g. redistribution of tax revenues, etc.). We thus acknowledge that our approach of measuring costs is far from perfect, yet informative for policy making.[1]

One of our main findings is that the weak EUA price in Germany only led to a moderate reduction of emissions (by 10% on average), whereas for higher carbon prices, abatement tends to increase significantly. On the other hand, Britain's much higher effective carbon price (due to the CPS) resulted in significant carbon abatement (up to 31%). We explain this vast effect by the fact that Britain's carbon price was high enough to push significant amounts of "dirty" coal out of the market, while "cleaner" gas became relatively more economical and thus filled a large proportion of the gap in electricity production. Another important finding is that wind and solar power have also contributed to emissions abatement in both countries (wind and solar in Germany by 18% and 6%, respectively, on average; wind in Britain by 17%).[2] Moreover, we find that the effectiveness of RE depends crucially on the level of the carbon price. Thus, whether carbon pricing and RE subsidies reinforce or weaken each other's abatement effectiveness depends on which technology ("dirty" coal or "cleaner" gas) is replaced at the margin. During our sample period, marginal abatement of wind and solar increases with the carbon price in Germany, but decreases in Britain.[3]

Our cost estimates for the different policies provide a clear picture. In both countries, carbon pricing is superior to subsidizing RE as long as the price is high enough to induce significant emissions abatement. For Germany, we calculate that it costs €52 to abate an additional tonne of CO_2 for the relatively low sample mean carbon price (€7.82/tCO_2) and that these costs decrease for higher carbon prices, while the costs of marginal abatement of mean wind and solar feed-in are €206 and €978, respectively. This owes to the fact that solar power abates on average less CO_2 than wind but enjoys higher subsidy payments. Britain's costs of marginal abatement of carbon pricing is strongly convex, with a minimum at a carbon price of €36, where it costs only €30 to offset an additional tonne of CO_2. Wind in Britain is more effective in abating emissions than in Germany and receives significantly less subsidies, resulting in relatively low costs of €54 to replace an additional tonne of CO_2. Yet, we show that with higher levels of wind feed-in as well as with higher carbon prices, wind's abatement effectiveness decreases, limiting its cost effectiveness. Once we adjust our findings to trade-related emissions, our main findings and conclusions remain robust.

Our results shed light on the workings of a carbon price in the power sector, suggesting that even relatively modest carbon prices of around €30/tCO_2 may bring about substantial emissions abatement in the short run – as long as relatively "clean" gas-fired power plants are available to displace "dirty" coal. In contrast, high carbon prices well beyond €35 are associated with lower marginal abatement, because most of the coal-fired electricity generation will already have been replaced, leaving only emissions from gas to be offset, and the associated costs are thus substantial.

Even though a unilateral climate policy (e.g. a national carbon tax or subsidies for RE) will lead to higher emissions elsewhere under an emissions cap-and-trade program (i.e. the "waterbed effect"; this applies only as long as no carbon border adjustments are in place), knowing the abatement and costs associated with unilateral climate policies may well allow for conclusions about internationally coordinated climate strategies. Firstly, if many countries enacted effective unilateral policies and withdrew the associated emissions allowances, total emissions would be reduced, and the waterbed effect would be avoided. Secondly, our study is reassuring for those countries that take unilateral measures (so called "nationally determined contributions", NDCs) to reach their national emission reduction targets at a manageable cost, such as in Britain. Such NDCs are at the heart of the Paris Agreement to achieve long-term goals of climate policy (UNFCCC, 2020).

We see our contribution to the literature threefold. First, we are the first to compare and quantify the effectiveness of a carbon price with other politically more popular interventions, such as financial support for wind and solar power. The literature has not yet achieved such a comparison in a well defined setting. Key results of this study are that carbon pricing is more effective than other supply-side instruments despite its lack of popularity, and that even a relatively moderate carbon price can already induce significant abatement in the power sector within a short period of time. At the same time, we argue that pre-existing capital stocks and easily available substitutes are essential for this conclusion. Second, we extend the scope of analysis beyond one country. We compare a country emphasizing carbon pricing (Britain) with a country putting more relative weight on command-and-control measures (Germany). While this appears to be a trivial contribution at first sight, a careful analysis and comparison of the potential different options available to politicians across different countries is central to combat climate change. The ensuing international benchmarking against relevant peers is a powerful force to nudge politicians to take the "right" measures. Finally, we contribute methodologically. Climate change policy is "active" in that many measures are set ranging from carbon pricing over supply-side measures, such as subsidizing various forms of renewables, to other more interventionist measures, such as setting emission standards or (essentially) prohibiting some types of plants altogether (e.g. the LCPD). We disentangle the effects of the carbon price and of wind and solar electricity from the effects of these other measures by emphasizing their covariance with emissions. The Heckman procedure in combination with our detailed data allows us, for example, to separate plant exit due to the heightened carbon price in Britain from exits due to other measures, such as the LCPD. Knowing the effects of the different policies is a prerequisite for efficient policy making.

Our study extends the growing literature, which estimates the emissions offset from different climate policies. One strand analyzes only second-best climate policies with respect to their abatement effects via wind and/or solar power (Cullen, 2013; Novan, 2015). Abrell et al. (2019) take both the EU ETS price and wind and solar power into account, yet only derive conclusions

[1] The costs of climate policies, (e.g. expenditures for certificates or state subsidies) feature prominently in policy debates (e.g. Handelsblatt, 2013) and decision making (e.g. German Federal Government, 2020), and are of course most relevant for carbon-intensive companies (see, e.g., a statement by Voestalpine, a steel company and the largest emitter of carbon emissions in Austria; voestalpine, 2020).

[2] Britain's *solar* feed-in was essentially zero until 2014 and negligibly low thereafter (see Fig. B1b), so we could not utilize solar data for the UK in our analysis.

[3] Intuitively speaking, this is because the relatively low carbon price in Germany leaves "dirty" coal to be replaced by wind or solar, while in Britain, with its already high carbon price, it is mainly the relatively "clean" gas that is replaced.

for renewables, leaving the carbon price to serve merely as a control variable. There is no study that empirically investigates pricing of CO_2 and compares this policy to other policies, such as direct supply-side subsidization of RE. Fell and Kaffine (2018) compare the effects of wind generation and natural gas prices on emission reduction while Cullen and Mansur (2017) and Linn and Muehlenbachs (2018) liken the effects of natural gas price changes to changes in the carbon price. Although it may be intuitive to expect similar (but opposite) effects from natural gas price changes and carbon price changes, the quantitative effects may differ.[4] We thus prefer to directly include a carbon price compared to indirect methods (e.g. by assuming that the price of gas mimics the effect of a CO_2 price) in order to infer the effectiveness of the respective policies.

2. Background on carbon pricing and renewables

The power sectors in Germany and Britain follow similar principles, whereas there are differences on the one hand in the structure of electricity supply (capacities and sources of electricity generation) and on the other hand in the composition of climate policies. In both countries day-ahead wholesale markets determine the electricity price according to demand and supply bids (i.e. the "merit order curve"), where the latter is essentially determined by the marginal costs of available power plants. Therefore, carbon pricing, and wind or solar feed-in affect market outcomes in a qualitatively similar manner. Increases in the carbon price lift the marginal costs of fossil-fuel powered plants, shifting them to the right of the merit order. Wind and solar feed in reduce the residual demand for fossil fuel powered plants.

Both countries use similar sources for electricity production, however these sources differ quantitatively. Online Appendix Table B1 portrays the two electricity sectors as of 2017. Britain relied heavily on gas (46%), nuclear (21%), and hard coal (8%), but burned no lignite. Germany's most important sources of energy are lignite (21%), hard coal (14%), gas (14%), and nuclear (12%). Both countries, particularly Germany, have measurable infeed of RE, particularly wind and to a lesser extent solar. Germany is a net exporter with a sizable trade share (11%), while Britain is a net importer with a lower reliance on trade (4%). We can also see that Britain has relatively new and thus more efficient gas power plants (efficiency factor of 0.591) compared to Germany (0.447), while Germany's hard-coal fired plants are more efficient (0.412) relative to Britain's (0.348). From the emission factor (i.e. CO_2 emissions per unit of electricity), it becomes evident that gas (0.191) is associated with significantly less CO_2 emissions than hard coal (0.337) and lignite (0.385), whereas the latter two do not differy by much. In a nutshell, while there are quantitative differences in the supply structures of the two countries's electricity sectors, it seems valid to assess both markets analogously in an econometric model as they rely on quantitatively similar principles.

The power sectors of both countries are regulated under the EU ETS, which puts a price on emission permits. In the EU ETS, power plants (but also factories and other emitting firms that are covered) receive or purchase emission allowances, which can be traded. The emissions cap is set at the EU level. However, the achieved price for emission certificates (EUA) was low (well below estimates about the social costs of carbon, see e.g. Ellerman et al., 2015) most of the time, which may be explained by problems associated with political-economy and behavioral-economy considerations, such as a lack of regulatory commitment (an abundance of allowances may lead to an insufficiently low CO_2 price) or missing social acceptance of high CO_2 prices in the population (Newbery et al., 2019).

The power sector is responsible for the major source of global GHG emissions (42% in 2016; IEA, 2019), and also at a national level it is the main source of emissions in both countries. The failure of the EU ETS in inducing a low-carbon transition so far has led EU member states to follow different unilateral (and uncoordinated) climate policies. Germany has been heavily subsidizing RE (with guaranteed feed-in tariffs as well as subsidies for capacity deployment), mostly in the form of wind and solar power, as a means to reduce emissions from the power sector. Other goals have been to induce the technological maturity of RE and to foster energy independence (Calel and Dechezleprêtre, 2016). Over the period 2005–2017, Germany's share of installed wind and solar *capacity* rose from 17% to 48%; wind and solar *feed-in* climbed from 5% to 24% (see also Fig. B1). Germany plans to provide at least 80% of its gross national electricity supply from RE by 2050, as stated in the German Renewable Energies Act ("Erneuerbare Energien Gesetz", EEG). The costs for the direct subsidization of RE are tremendous, though. The German Federal Court of Auditors ("Bundesrechnungshof", BRH, 2018) estimates the costs directly attributable to the decarbonization of the electricity system ("Energiewende") at (at least) €34 billion in 2017 alone.[5]

Parallel to the subsidization of RE, Germany also decided to phase-out nuclear power as a consequence of the Fukushima-Daiichi nuclear incident in 2011 (Grossi et al., 2017). Thus, a large fraction of RE first has to fill a significant gap in missing electricity production left by the reduction in low-carbon nuclear power (see also Fig. B2). However, almost a decade on from Germany's nuclear phaseout, the effectiveness of RE is still in doubt, because emissions from the power sector have been by and

[4] First, natural gas price changes may have different determinants than carbon price changes. Natural gas prices may respond to general macroeconomic conditions or supply-side technological changes (e.g. "fracking"), while carbon prices are (also) determined by political economy factors, e.g. how many allowances are issued. Second, long-term contracts and/or vertical integration of gas suppliers make it likely that pass-through to marginal costs differ between natural gas and carbon price changes. Thus, firms may treat a shock to marginal costs that is due to fuel price changes differently than a comparable shock due to changing carbon prices. Our empirical estimates indeed imply that the effects of the cost ratio and the carbon price are quantitatively different.

[5] DICE Consult (2016) estimates the direct costs of the German transition towards decarbonization of the electricity system ("Energiewende") at €133 billion between 2000 and 2015 and at €283 billion for 2000–2025. The German Government estimates investment costs related to the Energiewende of around €550 billion between 2017 and 2050 (German Federal Government, 2020). Similarly, Bernecker (2019) mentions costs of €550–600 billion.

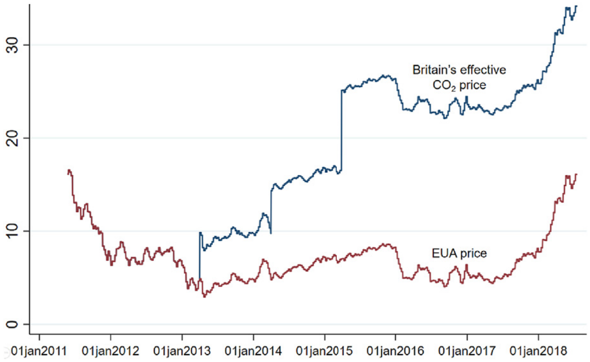

Fig. 1. EUA price & Britain's effective CO_2 price (€/tCO_2). Britain's effective CO_2 price = EUA price + CPS. 1 April 2013–31 March 2014: CPS = £4.94 (= €5.84); 1 April 2014–31 March 2015: CPS = £9.55 (= €11.46); 1 April 2015–31 March 2021: CPS = £18.08 (= €24.63).
Sources: EEX (2018) for EUA prices; House of Commons (2016) for Britain's CPS rates (converted into Euros according to daily exchange rates from the ECB, 2019).

large constant, with a moderate decrease since 2013, as shown in Fig. 2a.[6]

In contrast, Britain follows a different strategy. In April 2013, the British Government introduced a unilateral carbon tax, the CPS, which tops-up the EUA price (see Fig. 1).[7] When the CPS was introduced, it was due to rise every year from £4.94/tCO_2 in 2013 to a price of £30/tCO_2 in 2020. At Budget 2014, the British Government announced that the CPS would be capped at £18/tCO_2 from 2016 to 2020 to limit the competitive disadvantage faced by businesses and to reduce energy bills for consumers. This price freeze was extended to 2021 in Budget 2016 (House of Commons, 2016). Given its magnitude, the CPS represents a significant increase in the effective carbon price, which we can use for policy analysis.

Britain also subsidizes electricity from RE, but the relative magnitude of wind and solar is less than in Germany. The share of wind and solar capacity made up 25% in 2017 compared to a 48% share in Germany (see Fig. B1). However, Britain's and Germany's RE production in 2017 was 16% and 24%, respectively, indicating that the gap between actual RE feed-in and installed capacity is less pronounced in Britain than in Germany, since Britain has a more favorable environment for wind (its solar feed-in is negligibly low).

Britain's strategy seems to pay off in terms of emissions abatement, as indicated by Fig. 2b. Since the introduction of the CPS in 2013, emissions from the power sector have fallen significantly, especially during recent years when the effective carbon price in Britain was high. Indeed, Fig. 2b shows that the share of coal has diminished as gas-fired production has taken the lead. The figure thus suggests that putting a significantly high price on carbon emissions induces a fuel switch between coal- and idle gas-fired power plants.[8]

Merit order effects. — We now look at how carbon pricing affects the power supply structure (called the "merit order") in Germany and Britain.[9] Wind, solar, hydro, and nuclear plants are located in the beginning of the merit order due to their low marginal costs, followed by various forms of coal (e.g. lignite, hard coal). Due to their high marginal costs but flexible production, gas plants generally serve as a backup for times of peak load or low feed-in from RE. A carbon price essentially increases the marginal costs of CO_2-emitting thermal plants, and the marginal costs of coal plants face a relatively stronger increase than gas plants because of their higher emission factors. Feed-in from wind and solar essentially shifts the merit order curve to the right.[10]

As we can see from Fig. 3 for Germany, at a low carbon price (i.e. €5/tCO_2; see Fig. 3a) and at median demand (= 64,352 MW per hour) coal represents the marginal technology, while all gas plants are out of the merit order. At subsequently higher carbon

[6] In September 2018, the German Federal Court of Auditors (BRH, 2018) was highly critical, noting that Germany will clearly fail its goal of significantly reducing emissions despite enormous financial burdens on its citizens and the economy.

[7] The British Government calls the program a "Carbon Price Floor", but despite its name, it does not work in the fashion of a minimum price (e.g. if the EUA price falls below a threshold, the floor price becomes effective) but it is essentially a *top-up tax* (CCC, 2014) (so that even for an EUA price of zero, the carbon price cannot fall below the CPS rate). Thus, Britain's carbon price follows the variance of the EUA price, which we can exploit for econometric regression (see also Fig. 1).

[8] To underline our argument, Fig. B3 shows Britain's generation shares of coal and gas by plant vintage. With an increasing carbon price, we see that the most outdated coal plants significantly reduce their output, while the most efficient new gas plants significantly increase their output to fill the production gap.

[9] The Merit Orders in Figs. 3 and 4 depict the sample averages of available net capacities by generation technology ranked according to their marginal costs. The installed gross nameplate capacities are corrected for average plant outages (e.g. for maintenance and availability factors adjusted to season). Solar, wind, and hydro electricity are depicted for their sample average feed-in. Demand is given for its sample median. Using the approach as is applied in this study, we refer to Gugler et al. (2020) (Appendix A) for details on how we construct the marginal costs.

[10] In contrast to our econometric model, which also takes dynamic processes into account, this static, graphical analysis abstract from the following factors: "must run" power plants needed for supply security; start-up and ramping costs of thermal power plants; heat-coupled power plants.

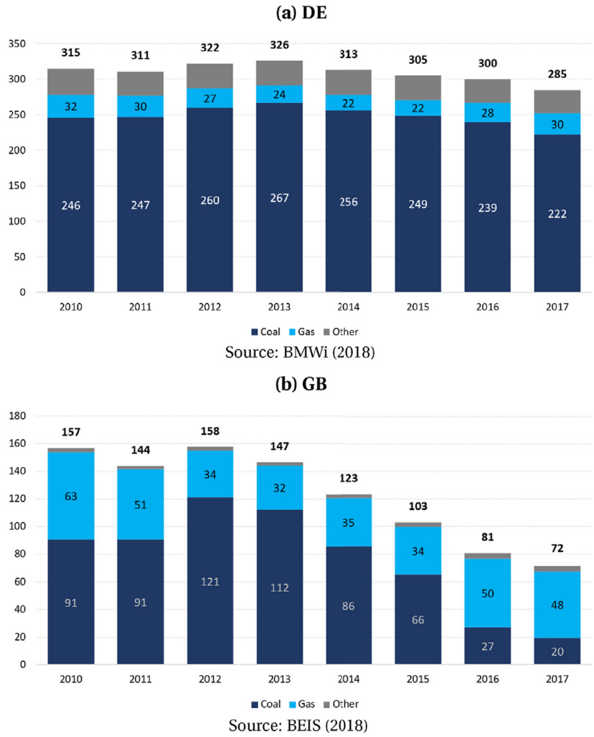

Fig. 2. Emissions from power sector ($MtCO_2$).

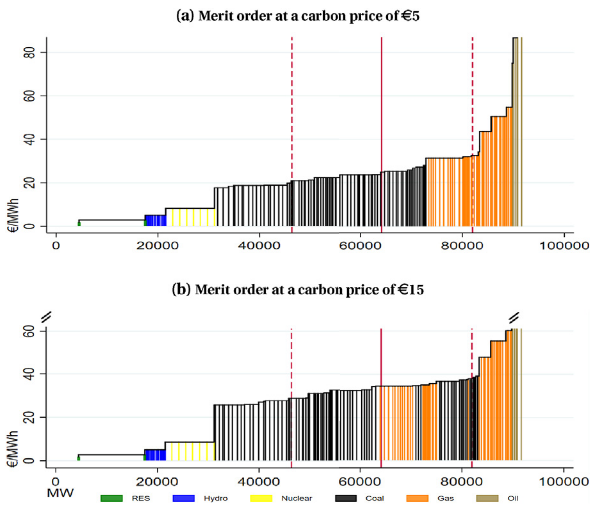

Fig. 3. Merit order for different carbon prices, DE. The figure depicts sample averages of available net capacities (i.e. installed gross nameplate capacities, adjusted for an efficiency factor, and corrected for availability factors adjusted to season and average plant outages, e.g. due to maintenance) in MW by generation technology. Vertical lines indicate demand at the 5th (46,353 MWh), 50th (64,119 MWh), and 95th (81,966 MWh) percentiles. See Gugler et al. (2020, App. A) for details on how we construct the marginal costs.

prices, fuel switching between the most (carbon) effective gas plants and the least (carbon) effective coal plants begins to take place. At a carbon price of €15, some gas plants have replaced the most ineffective coal plants, so that for some demand levels, now gas represents the marginal technology (see Fig. 3b).

Fig. 4 shows for Britain that for a low carbon price of €5, which we could observe during the period before the introduction of the CPS on 1 April 2013, essentially all coal plants are located before the gas plants. At a higher carbon price of €15, a large

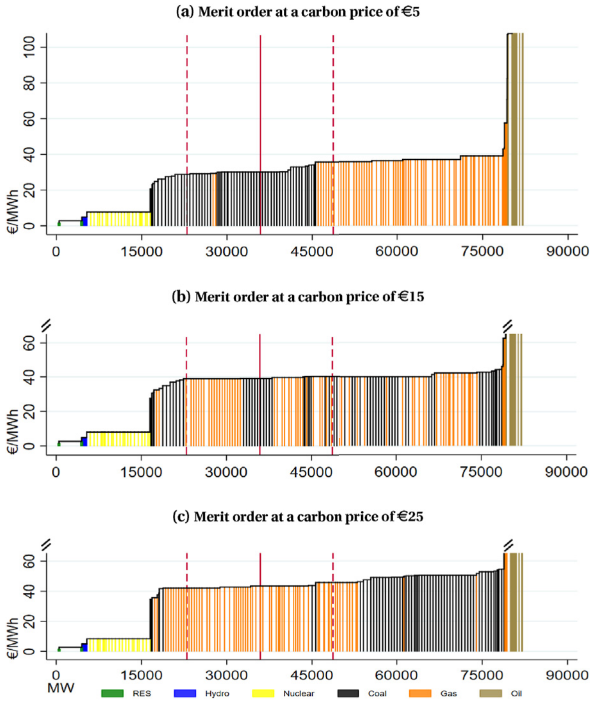

Fig. 4. Merit order for different carbon prices, GB. The figure depicts sample averages of available net capacities (i.e. installed gross nameplate capacities, adjusted for an efficiency factor, and corrected for availability factors adjusted to season and average plant outages, e.g. due to maintenance) in MW by generation technology. Vertical lines indicate demand at the 5th (22,980 MWh), 50th (35,887 MWh), and 95th (48,679 MWh) percentiles. See Gugler et al. (2020, App. A) for details on how we construct the marginal costs.

proportion of gas plants switch their positions with coal plants in the merit order. A significant amount of coal is replaced by gas, implying that CO_2 emissions decrease significantly. At an even higher price of €25, gas replaces essentially the entire coal-fired power generation at median demand. Hence, a higher carbon price may only be able to bring about additional marginal abatement by replacing coal-fired generation in very high demand states.

It is also worth discussing the interaction effects of the carbon price and the influence of wind and solar power on abatement. In principle, both opposing (the policies become less effective) or mutually supportive (the policies become more effective) relations are possible. The effectiveness of wind and solar depends on which technology (gas or coal) is the marginal technology to be replaced in the market in a given hour. In Germany, at a low carbon price (e.g. €5/tCO_2), wind and solar have little effect on abatement because predominantly gas plants get pushed out of the merit order. At higher carbon prices, the effectiveness of wind and solar may become more pronounced, as coal also gets replaced. Britain, on the other hand, has a higher carbon price to start with so that gas is the marginal technology. Then, higher carbon prices may reduce the effectiveness of wind (and solar).

Moreover, Germany and Britain may import electricity up to their available interconnection capacities from neighboring countries. Power imports happen as long as the supply structure of a neighbor allows production of cheaper electricity until the interconnection capacity is exhausted (or until wholesale prices are equal; Gugler et al., 2018). In Figs. 3 and 4, higher net imports can be interpreted as a reduction in national demand (i.e. a shift of residual demand to the left). Thus, with an increasing carbon price, the wholesale price of electricity increases, which may trigger net imports. We will take up the issue of trade again in section 5.3.

3. Methodology

We exploit exogenous variations in wind (W) and solar (S) generation, the effective carbon price (P), and load (L; i.e. electricity demand) to explain changes in emissions (y) from thermal power plant units.[11] Wind and solar electricity feed-in is exogenous, at least in the short run, as these RE are determined by the weather (see also Novan, 2015). The carbon price may be considered exogenous in the short run as the EU ETS price is determined on the exchange for emission permits, which are restricted by

[11] The related literature on carbon abatement of various climate policies also treat wind and solar feed-in (Cullen, 2013; Fell and Kaffine, 2018; Novan, 2015) as well as the carbon price (Abrell et al., 2019) as exogenous.

the overall emissions cap for all participating countries and sectors. Thus, from the perspective of an individual power plant operator, the ETS price can be viewed as exogenous. For Britain, the effective carbon price consists of the EU ETS price plus the CPS, which is determined by policy. The schedule for introducing and then increasing the CPS was determined years before any supply or demand realizations of coal or gas power plants. Thus, we also treat Britain's carbon price as exogenous.

Our model represents a flexible functional form as it allows for highly non-linear relationships through higher-order terms and interactions. We run regressions for four different dependent variables, namely *daily* CO_2 emissions either from coal- or gas-fired power plant turbines in Germany and Britain. Regarding the exogenous variables, we include the level and square of P because the impact of the carbon price on emissions may be non-linear. The interactions of P with W, S, and L imply that the effectiveness of the carbon price may also depend on the levels of wind, solar, and demand. Thus, we include W, S, and L in levels, squared, and cubic terms and all of their interactions.

In line with Cullen and Mansur (2017) and Fell and Kaffine (2018), we control for the "cost ratio", defined as the coal-to-gas input price ratio ($CR = P_{coal}/P_{gas}$), to account for the effects of changes in relative coal-to-natural gas prices. Again, CR is introduced in level, squared, and cubic terms as well as being interacted with the emissions price. This way, we are able to isolate the effects of the carbon price from effects of movements in the coal-to-gas input price ratio. To control for dynamic adjustments of power plants, such as accommodating output to start-up, ramping and shut-down costs, and also firms' expectations, we include lagged values of wind and solar feed-in (see also Cullen, 2013, p.117–118).[12]

We include a vector of cross-sectional fixed effects for each plant turbine (D_p), to capture unobserved heterogeneity between power plants, which is constant over time (e.g. location, vintage). D_t is a set of time fixed effects to capture day-of-week patterns as well as seasonality.[13] Due to data constraints, the sample periods for Germany spans one and a half years of daily observations (i.e. 1 January 2017–29 June 2018), while we observe several years for Britain (27 May 2011–15 July 2018). For this reason, we adapt the set of time fixed effects to the different sample periods. We apply day-of-week as well as monthly fixed effects for Germany and day-of-week as well as quarter-year fixed effects for Britain.

Our specification is:

$$y_{p,t} = \sum_{i=1}^{2} \beta_{Pi} P_t^i + \beta_{PW} P_t W_t + \beta_{PS} P_t S_t + \beta_{PL} P_t L_t + \beta_{PCR} P_t CR_t + \sum_{i=1}^{3} \beta_{Wi} W_t^i + \sum_{i=1}^{3} \beta_{Si} S_t^i +$$
$$\sum_{i=1}^{3} \beta_{Li} L_t^i + \sum_{i=1}^{3} \beta_{CRi} CR_t^i + \sum_{i=1}^{3} \sum_{j=1}^{3} \beta_{WiLj} W_t^i L_t^j + \sum_{i=1}^{3} \sum_{j=1}^{3} \beta_{SiLj} S_t^i L_t^j + \sum_{i=1}^{3} \sum_{j=1}^{3} \beta_{WiSj} W_t^i S_t^j +$$
$$\sum_{k=1}^{5} \beta_{\Delta Wt-k} \Delta W_{t-k} + \sum_{k=1}^{5} \beta_{\Delta St-k} \Delta S_{t-k} + \delta_p D_p + \delta_t D_t + \epsilon_{p,t}. \tag{1}$$

The subscripts define each power plant turbine p at day t of our sample. We run equation (1) for four subsamples of coal or gas plants located in Germany or Britain.[14]

Since we observe periods of temporary inaction in both countries as well as permanent plant exits (i.e. periods of zero production until the end of the sample) in Britain, running equation (1) by OLS would not account for this. Outright exits and zero-production periods would only be captured on the extensive margin. The extensive margin refers to plants which shut their production temporarily or even permanently because of variations in the carbon price and RE infeed (and other control variables), whereas the intensive margin refers to variations in plants' emissions (thus variations in electricity production) conditional on being operational. For this purpose, we follow Fell and Kaffine (2018) and apply a Heckman two-step model to estimate the full effect of P on emissions, which is composed of the intensive (generation conditional on operating) and extensive margin (on/off decision) response. The two-step model (see Greene, 2008, Ch. 24) estimates in step one the selection equation via a probit regression, which estimates a plant's probability of operating (i.e. producing electricity and thus having positive emissions) or not ($z_{p,t} = 1 \text{if} y_{p,t} > 0 \text{and} z_{p,t} = 0 \text{if} y_{p,t} = 0$):

[12] In particular, Cullen (2013) suggests a transformation by subtracting the current value of a variable from its lagged values to obtain the impact of current and lagged information in the coefficient of the contemporaneous variable. This is to avoid dealing with numerous coefficients of lagged variables. Hence, we include a set of lag-transformed variables ΔX, where $\Delta X_{t-i} = X_t - X_{t-i}$.

[13] For Britain, the time fixed effects are particularly relevant as they may absorb, for example, the effect of the EU 'Large Combustion Plant Directive' (LCPD, 2001/80/EC), which requires thermal power plants above 50 MW to limit emissions of sulphur dioxide, nitrogen oxides, and dust. Plants could either comply with the policy or close after 20,000 h of remaining operation ('opt-out' option). Since December 2012, nine British power stations have chosen to cease production (National Grid, 2007; DEFRA, 2012) due to this constraint.

[14] For Britain, we cannot apply the data on solar electricity, since feed-in of solar power was essentially zero before the year 2015, and since then has only made up a negligible share of Britain's total generation (see Fig. B1b). Although rising in the more recent years of the sample, the share of solar feed-in is negligible, with a mean of 0.31% during 2011–2017 (BEIS, 2019). Thus, including data on solar electricity production with long periods of zero values would render our highly non-linear econometric estimations impossible. For this reason, the empirical model for British plants reduces to: $y_{p,t} = \sum_{i=1}^{2} \beta_{Pi} P_t^i + \beta_{PW} P_t W_t + \beta_{PL} P_t L_t + \beta_{PCR} P_t CR_t + \sum_{i=1}^{3} \beta_{Wi} W_t^i + \sum_{i=1}^{3} \beta_{Li} L_t^i + \sum_{i=1}^{3} \beta_{CRi} CR_t^i + \sum_{i=1}^{3} \sum_{j=1}^{3} \beta_{WiLj} W_t^i L_t^j + \sum_{k=1}^{5} \beta_{\Delta Wt-k} \Delta W_{t-k} + \delta_p D_p + \delta_t D_t + \epsilon_{p,t}$.

$$z_{p,t} = \sum_{i=1}^{2} \beta_{Pi} P_t^i + \beta_{PW} P_t W_t + \beta_{PS} P_t S_t + \beta_{PL} P_t L_t + \beta_{PCR} P_t CR_t + \sum_{i=1}^{3} \beta_{Wi} W_t^i + \sum_{i=1}^{3} \beta_{Si} S_t^i +$$
$$\sum_{i=1}^{3} \beta_{Li} L_t^i + \sum_{i=1}^{3} \beta_{CRi} CR_t^i + \sum_{i=1}^{3}\sum_{j=1}^{3} \beta_{WiLj} W_t^i L_t^j + \sum_{i=1}^{3}\sum_{j=1}^{3} \beta_{SiLj} S_t^i L_t^j + \sum_{i=1}^{3}\sum_{j=1}^{3} \beta_{WiSj} W_t^i S_t^j +$$
$$\sum_{k=1}^{5} \beta_{\Delta Wt-k} \Delta W_{t-k} + \sum_{k=1}^{5} \beta_{\Delta St-k} \Delta S_{t-k} + \delta_p D_p + \delta_t D_t + \sum_{k=1}^{5} \alpha_{Lt-k} L_{t-k,c} + u_{p,c,n,t}. \tag{2}$$

The exclusion restriction rests on the inclusion of the five day lags of load ($\sum_{i=1}^{5} L_{t-i,c}$; see also Fell and Kaffine, 2018) as well as on the different moments of the variables included in the selection and outcome regressions. From equation (2), we obtain the inverse Mill's ratio (IMR, also called the "non-selection hazard"), as $\widehat{\lambda}_{p,t} = \phi(.)/\Phi(.)$, where ϕ is the normal pdf and Φ is the cdf, which corrects for the selection bias (i.e. bias from many zero-production values).

In step two, we run the outcome equation (1), corrected for selection by adding $\widehat{\lambda}$, via OLS: $y_{p,t} = \mathbf{X}_{p,t}\beta + \rho\widehat{\lambda}_{p,t} + \epsilon_{p,t}$, where $\mathbf{X}$ and $\mathbf{V}$ represent the right-hand-side variables from the outcome and the selection equation, respectively. From this, we can predict the *full effect* of carbon pricing, which is composed of the *intensive* and *extensive* margin impacts:

$$\mathrm{E}[y_{p,t}|\mathbf{X}_{p,t}, \mathbf{V}_{p,t}] = \Phi(\mathbf{V}_{p,t}\alpha)[\mathbf{X}_{p,t}\beta + \rho\lambda_{p,t}], \tag{3}$$

The estimated probability of having positive emissions ($\Phi(\mathbf{V}_{p,t}\alpha)$) represents the extensive margin impact (i.e. on/off decision), whereas the intensive margin impact (i.e. generation conditional on operating) is given by $[\mathbf{X}_{p,t}\beta + \rho\lambda_{p,t}]$.

The Heckman two-step procedure is particularly important to rule out concerns about other confounding policies, such as the LCPD. In the first step, we determine the decision whether to operate or exit the market. Any exits not explained by variations in the carbon price, wind, or solar may be explained be other policies, such as the LCPD. While we cannot quantify the effects of these other policies, we can quantify the effects of the carbon price, wind and solar on plant exits.[15]

Eventually, we calculate *marginal abatement* with respect to carbon pricing, wind, and solar feed-in, where we evaluate all other variables at their means, as:

$$MA(x) = -\frac{\partial \mathrm{E}[y_{p,t}|\mathbf{X}_{p,t}, \mathbf{V}_{p,t}]}{\partial x}, \quad x = \{P, W, S\}. \tag{4}$$

For the credibility of our results, we follow Abrell et al. (2019); Cullen (2013); Novan (2015) and assess how a marginal change in wind or solar infeed or a marginal change in the carbon price offsets electricity generation of other technologies. If load was inelastic, then the market clearing condition requires in the case of carbon pricing that generation responses need to add up to zero, and that an additional MWh of RE should offset one MWh of other technologies. For this purpose, we use hourly aggregated time series data on electricity generation by technology (hard coal, lignite, gas, hydro, etc.) and apply a flexible specification (i.e. generation as a function of wind, solar, carbon price, load, cost ratio, and their interactions, plus 24 hourly lags of wind and solar, and day-of-week, hourly, and monthly fixed effects; see notes to Table B2).[16] Table B2 shows that the market clearing condition holds for wind and solar (the coefficients of the individual technologies add up to about minus one) as well as for carbon pricing (the induced marginal changes of other technologies add up almost to zero).

4. Data

We utilize data on daily electricity production from coal and gas power-plant turbines in Germany and Britain to calculate CO_2 emissions at the turbine level. In our sample, we observe 85 coal and 53 gas turbines in Germany and 63 coal and 78 gas turbines in Britain. The German electricity generation data stem from the EEX (2018) Transparency Platform and are available for 1 January 2017–29 June 2018 for the daily frequency. However, for Britain we need to observe a longer period in order to investigate the full range of carbon prices before and after the introduction of the CPS as well as its two elevations. Hence, we collected data from PLATTS PowerVision (2018) (i.e. coal- and gas-fired generation) and Gridwatch (2018) (i.e. wind and solar generation) to arrive at our sample for Britain spanning the daily period 27 May 2011–15 July 2018.[17] We merge these data by

[15] Moreover, to mitigate concerns about the influence of the LCPD in a qualitative manner, we bring up further reasons why the LCPD may not be responsible for the significant drop in emissions: The LCPD applies to all EU thermal power plants. However, we do not see significant emissions reductions (neither exits of coal-fired power plants) in other EU countries, which heavily rely on coal electricity, such as Germany. Moreover, an analysis of the abatement effects of individual climate policies, based on a simulation model by the British regulatory authority for energy markets Ofgem (2018, 2019), attributes only a negligible part of the entire emissions reduction since 2012 to air quality directives, such as the LCPD. Reassuring for our study, Ofgem finds that carbon pricing, foremost since the introduction of the CPS, was the most important factor reducing emissions.

[16] Using Abrell et al. (2019)'s model (which is precisely for Germany but less flexible concerning the carbon price) yields nearly identical results.

[17] EEX is the European Energy Exchange for Germany, Austria, and France (trading spot electricity, natural gas, CO_2 emission allowances, and coal). Gridwatch is a platform that provides data about Britain's electricity market in cooperation with Sheffield University. The reason for choosing Gridwatch as the main data source for Britain is that the data are available for a much longer time period (i.e. since 27 May 2011) than the EEX data.

Table 1
Summary statistics.

(a) Germany							
Variable	Mean	StD.	Min	p25	p50	p75	Max
Coal-based emissions (tCO2)	6334	5765	0	1265	4952	10,313	21,187
Gas-based emissions (tCO2)	661	1015	0	0	8	1154	6594
Carbon price (€/tCO_2)	7.82	3.44	4.26	5.07	6.96	9.53	16.35
Wind (GWh)	306	201	33	139	256	418	967
Solar(GWh)	108	69	5	43	105	166	248
Load (GWh)	1544	182	666	1429	1573	1682	1881
Cost ratio (P_{coal}/P_{gas})	0.51	0.06	0.18	0.46	0.52	0.55	0.62
(b) Britain							
Variable	Mean	StD.	Min	p25	p50	p75	Max
Coal-based emissions (tCO2)	3355	4979	0	0	0	8011	15,343
Gas-based emissions (tCO2)	1143	1514	0	0	0	2181	9168
Carbon price (€/tCO_2)	19.71	9.75	3.15	10.18	19.07	27.78	37.04
Wind (GWh)	59	43	1	26	49	84	244
Load (GWh)	814	121	69	726	813	895	1195
Cost ratio (P_{coal}/P_{gas})	0.41	0.12	0.12	0.31	0.38	0.50	0.94

Notes: All values are for the daily frequency. Coal- and gas-based emissions are per power plant; other variables are for the power sector. DE: sample period is January 1, 2017–June 29, 2018. Britain: sample period is May 27, 2011–July 15, 2018.

plant name and turbine number with PLATTS PowerVision (2018)[18] to obtain plant characteristics, such as construction date, turbine type, fuel type, and nameplate capacity. We then calculate CO_2 emissions by applying emission and efficiency factors by plant vintage as provided by the Austrian Transmission System Operator, Austrian Power Grid (APG). That is, we basically follow Gugler et al. (2020)'s approach, who also use the PLATTS data and explain in Appendix A how to construct the marginal costs (*mc*) of each power plant. Then we simply apply a plant-specific emission factor (from APG) to each MWh of electricity produced. Our calculated emissions match well with official statistics on CO_2 emissions at the power plant level for the year 2017 (Carbon Market Data, 2020) (i.e. correlation of 99%).

Data on the EU ETS carbon price come from the European Energy Exchange (EEX, 2018). Data on the unilateral carbon tax in Britain, which tops up the EUA price, stem from House of Commons (2016). We also collected data on the daily spot prices of coal and gas, as provided by PLATTS PowerVision (2018), allowing us to create a measure of the relative fuel costs. Table 1 provides summary statistics for Germany and Britain. The standard deviations of all variables are high relative to their means, pointing to sufficient variation for econometric regression.

5. Results

We first discuss our results for Germany, then for Britain, taking solely a national perspective. Then, we also adjust our results for trade-related emissions to provide robustness. Finally, we put our results into perspective and evaluate the climate policies in Germany and Britain in terms of directly attributable costs.

5.1. CO_2 abatement: Germany (national perspective)

Carbon pricing. — Table 2 provides the level of emissions (by fuel source) attributable to the various carbon prices as predicted by our model, as well as marginal abatement, which is simply the change in emissions for an incremental change in the carbon price.[19] We report all estimates aggregated over *all* German coal and gas power plant turbines. Moreover, Fig. 5 visualizes the marginal abatement effects across the sample range of carbon prices in Germany.

Table 2 reveals that total emissions fall with higher carbon prices. The highest observed carbon price of €16/tCO_2 already replaces 21% of daily carbon emissions relative to having no carbon price in place, whereas the significantly lower sample mean carbon price of €8 is responsible for a reduction by around 10%. We can also see that coal-based emissions fall constantly, while gas-based emissions fall up to a carbon price of €14/tCO_2 and then increase again. To investigate this further, we now look into the marginal abatement effects of carbon pricing across fuel types.

Fig. 5 shows that the marginal abatement function is non-linear, with a modest increase up to a carbon price of €9/tCO_2, followed by a modest decline up to a price of €16/tCO_2. The marginal abatement effects of coal and gas differ significantly. At successively higher carbon prices, *coal*-fired emissions decline significantly, resulting in higher marginal abatement. For example, a marginal increase of the carbon price from €15 to €16 brings about a reduction of 8400 tCO_2 of coal-based emissions per

[18] PLATTS is a major independent data and information provider for energy and commodity markets. The 'PowerVision' database provides information about characteristics of European power plants.

[19] For completeness, Table B3 presents the full regression output of estimating the outcome equation (1), whereas Tables B5 and B6 present the probit estimates of the selection equation (2) with respect to carbon pricing as well as wind and solar power, respectively.

Table 2
Emissions and marginal abatement associated with carbon pricing, DE.

Price (€/tCO_2)	Predicted emissions (tCO_2)						Mrg. abtm. (tCO_2)		
	Coal		Gas		Total		Coal	Gas	Total
Out of sample									
1	552,701	(0.0%)	33,920	(0.0%)	586,621	(0.0%)	5033	2208	7241
2	547,668	(−0.9%)	31,712	(−6.5%)	579,380	(−1.2%)	5581	2018	7599
3	542,087	(−1.9%)	29,694	(−12.5%)	571,782	(−2.5%)	6078	1827	7905
In sample									
4	536,009	(−3.0%)	27,868	(−17.8%)	563,876	(−3.9%)	6525	1636	8162
5	529,484	(−4.2%)	26,231	(−22.7%)	555,715	(−5.3%)	6921	1449	8370
6	522,563	(−5.5%)	24,782	(−26.9%)	547,345	(−6.7%)	7266	1267	8533
7	515,297	(−6.8%)	23,514	(−30.7%)	538,811	(−8.1%)	7561	1091	8652
8	507,736	(−8.1%)	22,424	(−33.9%)	530,159	(−9.6%)	7809	920	8729
9	499,927	(−9.5%)	21,503	(−36.6%)	521,430	(−11.1%)	8010	756	8766
10	491,917	(−11.0%)	20,748	(−38.8%)	512,664	(−12.6%)	8168	597	8764
11	483,749	(−12.5%)	20,151	(−40.6%)	503,900	(−14.1%)	8285	442	8727
12	475,465	(−14.0%)	19,708	(−41.9%)	495,173	(−15.6%)	8364	292	8655
13	467,101	(−15.5%)	19,417	(−42.8%)	486,518	(−17.1%)	8408	144	8552
14	458,693	(−17.0%)	19,273	(−43.2%)	477,966	(−18.5%)	8421	−3	8419
15	450,271	(−18.5%)	19,276	(−43.2%)	469,547	(−20.0%)	8407	−149	8258
16	441,864	(−20.1%)	19,425	(−42.7%)	461,289	(−21.4%)			

All estimates are evaluated at means for other control variables. Predicted emissions and marginal abatement effects are aggregated over *all* German coal or gas power plants per day. Values in parentheses represent cumulative relative changes. The mean (median) carbon price is €7.82 (€6.96). All estimates are significant at the 5% level.

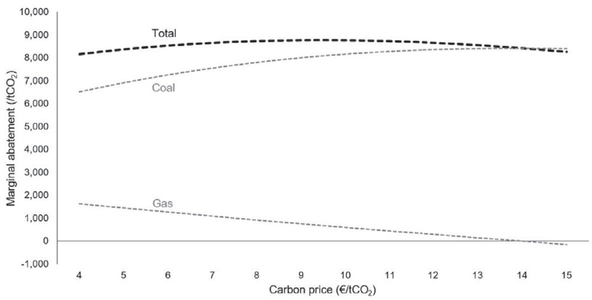

Fig. 5. Marginal abatement of carbon pricing, DE. All estimates are evaluated at means for other control variables. Predicted emissions and marginal abatement effects are aggregated over *all* German coal or gas power plants per day. The mean (median) carbon price is €7.82 (€6.96). All estimates are significant at the 5% level.

day. Marginal abatement is much less pronounced for gas-based emissions. We can see that marginal abatement declines with rising carbon prices and turns negative at a carbon price of €14. This is the starting point for *fuel switching* in Germany, meaning that gas-based electricity production and thus emissions increase as a reaction to the carbon price. We should emphasize that this result is estimated for the sample means of other variables (i.e. ceteris paribus), whereas it depends crucially on the relative magnitude of the input prices of coal and gas.

The limited effectiveness of the carbon price in Germany can be explained by the insufficient carbon price and by the logic of electricity markets. At a low carbon price, the additional costs of emitting CO_2 are not large enough to displace large amounts of coal in the merit order (as witnessed by Fig. 3a). That is, up to a carbon price of €14, *imports* become more and more economical and push gas *and* coal plants out of the merit order.[20] At higher carbon prices (from €14 on) electricity generation from coal begins to be replaced by gas (i.e. fuel switching), which offsets significant amounts of CO_2 and therefore increases the effectiveness of the carbon price. Another important issue limiting the effectiveness of carbon pricing is that nearly all abatement due to the carbon price is shouldered by hard coal plants, whereas lignite can largely remain in the market (see Appendix Fig. B4). This is because the emission factors of lignite plants are not much larger (only by 10%, on average) than those of hard coal plants, while the marginal costs of lignite are significantly lower (Gräbner et al., 2010), so that increasing carbon prices hardly change the relative marginal costs of the two technologies. Consistent with our results that hard coal takes the main burden of

[20] A regression of German net imports (i.e. imports minus exports) reveals that net imports (e.g. from France, which has a high share of nuclear electricity; or Austria, which has a high share of run-of-river generation) increase by approximately the same amount as coal- and gas-fired generation decrease with a higher carbon price, thereby substituting for the missing load in Germany.

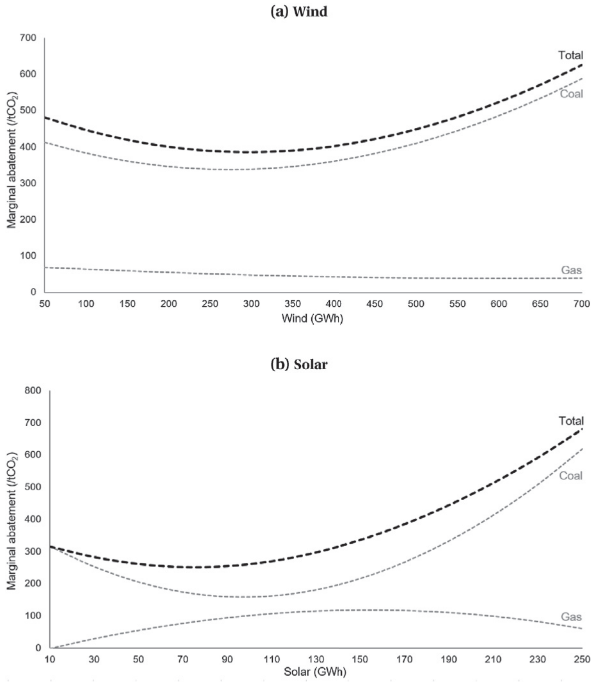

Fig. 6. Marginal abatement of wind & solar, DE. Marginal effects are evaluated at means for other control variables. All estimates are significant at the 5% level. The mean (median) values of wind and solar are 305.78 GWh (255.74 GWh) and 108.18 GWh (104.68 GWh), respectively. All point estimates underlying this graph are provided in Appendix Table A1.

adjustment to rising carbon prices, Germeshausen and Wölfing (2020) find that lignite is the marginal technology in the German/Austrian wholesale market in only 3–7% of hours, because the input price advantage of lignite outweighs any carbon price disadvantage vis-a-vis hard coal (which is the marginal technology far more often).

Wind and solar. — Table A1 presents the marginal abatement effects of wind and solar power in Germany across a range of observed feed-in levels (evaluated at means for other control variables; c.f. eq. (4), and Fig. 6a and b visualize the effects. We can see that for higher levels of wind and solar feed-in, marginal abatement tends to modestly decline followed by an increase. Evaluated for the mean level of wind feed-in of around 300 GWh, a marginal increase of wind by one GWh replaces 386 tCO_2 per day, which can be almost entirely attributed to abatement of emissions from coal. By taking the integral over the marginal abatement function up to the sample mean value of wind, we estimate that wind in Germany replaces 18% of daily emissions relative to no wind in place.

Solar marginally replaces 270 tCO_2 per day at its sample mean of around 110 GWh, which is significantly less than wind. However, its marginal abatement tends to increase with higher feed-in. At the relatively low mean carbon price (€8) and average demand, solar can increasingly replace coal, so that it can unfold its full abatement potential. Taking the integral over the marginal abatement function up to its sample mean, solar in Germany replaces an average of 6% of daily emissions relative to no solar in place.

Moreover, we can show that for relatively low carbon prices as observed in Germany (i.e. €4–€16/tCO_2), wind and solar power reinforce the effectiveness of the EU ETS. Appendix Table A2 shows that wind and solar become more effective with higher carbon prices. This is the case because rising carbon prices imply that wind and solar replace more and more coal (and less gas).

We can conclude that Germany has only been modestly successful in abating CO_2 emissions because for a long period the carbon price was not high enough to induce large scale fuel switching. Our estimates are that we would need carbon prices well above €14/tCO_2 (evaluated at mean input prices and other confounders) to benefit from a significant short-term emissions reduction due to large-scale replacement of coal by gas.[21] Moreover, as long as wind and solar replace coal, RE and carbon prices reinforce each other in reducing emissions. Finally, evaluated for average conditions, wind outperforms solar power, making it the more effective tool for climate policy in Germany.

[21] This appears to be happening in 2019 and 2020 when the EUA price reached around €25 and emissions dropped significantly due to coal-gas switching (see, e.g., FAZ, 2019).

Table 3
Emissions and marginal abatement associated with carbon pricing, GB.

Price (€/tCO_2)	Predicted emissions (tCO_2)						Mrg. abtm. (tCO_2)		
	Coal		Gas		Total		Coal	Gas	Total
Out of sample									
1	213,400	0.0%	59,797	(0.0%)	273,197	(0.0%)	−1116	1197	81
2	214,516	(0.5%)	58,600	(−2.0%)	273,116	(−0.0%)	−854	1091	237
3	215,369	(0.9%)	57,509	(−3.8%)	272,879	(−0.1%)	−591	986	395
In sample									
4	215,960	(1.2%)	56,523	(−5.5%)	272,483	(−0.3%)	−329	884	555
5	216,289	(1.4%)	55,639	(−7.0%)	271,928	(−0.5%)	−68	783	715
6	216,357	(1.4%)	54,856	(−8.3%)	271,213	(−0.7%)	192	684	876
7	216,166	(1.3%)	54,172	(−9.4%)	270,337	(−1.0%)	449	587	1036
8	215,716	(1.1%)	53,585	(−10.4%)	269,301	(−1.4%)	705	490	1195
9	215,011	(0.8%)	53,095	(−11.2%)	268,106	(−1.9%)	958	395	1353
10	214,053	(0.3%)	52,700	(−11.9%)	266,753	(−2.4%)	1208	301	1509
11	212,846	(−0.3%)	52,399	(−12.4%)	265,244	(−2.9%)	1454	207	1661
12	211,392	(−0.9%)	52,191	(−12.7%)	263,583	(−3.5%)	1697	114	1811
13	209,695	(−1.7%)	52,077	(−12.9%)	261,772	(−4.2%)	1935	21	1956
14	207,760	(−2.6%)	52,056	(−12.9%)	259,816	(−4.9%)	2168	−71	2097
15	205,592	(−3.7%)	52,127	(−12.8%)	257,719	(−5.7%)	2396	−164	2232
16	203,196	(−4.8%)	52,291	(−12.6%)	255,487	(−6.5%)	2618	−256	2362
17	200,578	(−6.0%)	52,547	(−12.1%)	253,125	(−7.3%)	2835	−349	2485
18	197,743	(−7.3%)	52,897	(−11.5%)	250,640	(−8.3%)	3044	−443	2601
19	194,699	(−8.8%)	53,340	(−10.8%)	248,039	(−9.2%)	3246	−537	2709
20	191,453	(−10.3%)	53,877	(−9.9%)	245,329	(−10.2%)	3441	−632	2810
21	188,011	(−11.9%)	54,508	(−8.8%)	242,520	(−11.2%)	3628	−727	2901
22	184,383	(−13.6%)	55,236	(−7.6%)	239,619	(−12.3%)	3807	−824	2983
23	180,576	(−15.4%)	56,059	(−6.3%)	236,636	(−13.4%)	3976	−921	3055
24	176,600	(−17.2%)	56,981	(−4.7%)	233,581	(−14.5%)	4136	−1019	3117
25	172,464	(−19.2%)	58,000	(−3.0%)	230,464	(−15.6%)	4287	−1119	3168
26	168,177	(−21.2%)	59,119	(−1.1%)	227,296	(−16.8%)	4427	−1219	3208
27	163,751	(−23.3%)	60,338	(0.9%)	224,088	(−18.0%)	4556	−1321	3236
28	159,194	(−25.4%)	61,658	(3.1%)	220,853	(−19.2%)	4675	−1423	3252
29	154,520	(−27.6%)	63,081	(5.5%)	217,601	(−20.4%)	4782	−1526	3256
30	149,738	(−29.8%)	64,607	(8.0%)	214,345	(−21.5%)	4877	−1630	3247
31	144,861	(−32.1%)	66,238	(10.8%)	211,098	(−22.7%)	4960	−1735	3225
32	139,900	(−34.4%)	67,973	(13.7%)	207,873	(−23.9%)	5031	−1841	3191
33	134,869	(−36.8%)	69,813	(16.8%)	204,682	(−25.1%)	5090	−1946	3143
34	129,779	(−39.2%)	71,760	(20.0%)	201,539	(−26.2%)	5135	−2053	3083
35	124,644	(−41.6%)	73,812	(23.4%)	198,456	(−27.4%)	5167	−2159	3009
36	119,477	(−44.0%)	75,971	(27.0%)	195,448	(−28.5%)	5187	−2265	2922
37	114,290	(−46.4%)	78,236	(30.8%)	192,526	(−29.5%)	5193	−2370	2823
38	109,097	(−48.9%)	80,606	(34.8%)	189,703	(−30.6%)			

All estimates are evaluated at means for other control variables. Predicted emissions and marginal abatement effects are calculated as a composite of *all* British coal or gas power plants per day. Values in parentheses represent cumulative relative changes. The mean (median) carbon price is €19.71 (€19.07). All estimates are significant at the 5% level.

5.2. CO_2 abatement: Britain (national perspective)

Carbon pricing. — Table 3 presents emissions and the respective marginal abatement by fuel source for various carbon prices according to our model predictions.[22] All estimates are aggregated over all British coal and gas turbines. Fig. 7 visualizes the marginal abatement effects.

While we found rather constant marginal abatement within the narrow range of observed carbon prices of €4–€16 in Germany, Fig. 7 shows that in Britain marginal abatement is a concave function, which significantly increases from low to medium carbon prices until it reaches a maximum at €29/tCO_2. Predicted emissions from coal are cut approximately in half due to the observed high carbon price of nearly €38/tCO_2. From this perspective, the emissions price instrument has contributed significantly to reducing coal-based emissions in Britain. Moreover, as in Germany, at a carbon price of €14/tCO_2, fuel switching sets in. This is indicated by negative marginal abatement from gas. At high carbon prices well beyond €38/tCO_2, the marginal offset of coal-based emissions starts declining, as fewer and fewer coal plants stay in the merit order to be pushed out. This is why total marginal abatement finally tapers off for high carbon prices. Looking at the predicted emissions reported in Table 3, our results are that a carbon price at the height of €38, as observed during the very recent sample period, reduces 31% of daily emissions relative to no carbon price in place.

[22] For completeness, Table B4 presents the full regression output of estimating the outcome equation (3), whereas Tables B7 and B8 present the probit estimates of the selection equation (2) with respect to carbon pricing as well as wind and solar power, respectively.

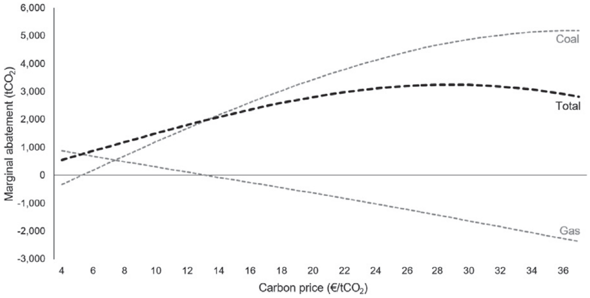

Fig. 7. Marginal abatement of carbon pricing, GB. All estimates are evaluated at means for other control variables. Marginal abatement effects are calculated as a composite of *all* British coal or gas power plants per day. The mean (median) carbon price is €19.71 (€19.07). All estimates are significant at the 5% level. All point estimates (including predicted emissions) underlying this graph are provided in Appendix Table 3.

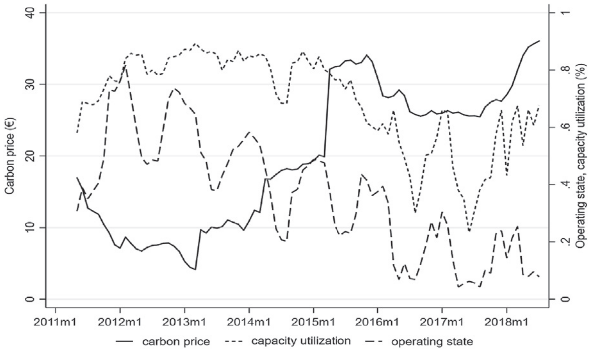

Fig. 8. British coal plants: operating state and capacity utilization. Operating state refers to the percentage of coal plants being active (i.e. producing electricity 1/0). Capacity utilization gives the share of electricity produced relative to total available capacity for those coal plants that are active. Both rates are observed (not estimated) sample values.

Our estimates include both the intensive and the extensive margin responses. A few words are in order about the relative magnitudes of these two kinds of effects, because a substantial fraction of coal-powered plants permanently exited Britain's electricity market.[23] During our sample period (27 May 2011–15 July 2018), 33 power plant units with a total capacity of 14,250 MW left the market permanently, while 30 coal plants with a total capacity of 13,885 MW remained active (c.f. Tables B9 and B10). Moreover, spells of inactive periods of coal plants increased significantly during times of high carbon prices following the introduction of the CPS. Fig. 8 suggests that the percentage of coal plants producing electricity on a given day (dashed black line) decreases with an increasing carbon price (solid black line) over time. What is more, the capacity utilization rate of those coal plants, which are active (i.e. producing electricity; dashed blue line), also appears to diminish with an increasing carbon price over time. This implies that not only do fewer coal plants stay online in the market but that those which stay produce significantly less electricity.[24]

To quantify the extensive margin, Table B7 presents the probit estimates of the selection equation (eq. (2); i.e. the first stage of the Heckman procedure) indicating the probability of coal and gas plants producing electricity (and thus emitting CO_2) for each observed carbon price. We see that the probability of producing electricity from coal on a given day declines significantly from 39% at a carbon price of €5–15% at a price of €37. Hence, the full abatement effect of the carbon price related to coal-fired electricity generation is driven to a substantial degree by the extensive margin response. Conversely, for gas plants, the probability of being active increases substantially from 35% at a low carbon price of €5–56% at a price of €37, indicating that gas

[23] For Germany, although we do observe periods of inaction for some power plants, we do not observe the permanent exit of any coal plants during our observation period.

[24] Since this implies a sub-optimal utilization rate, given start-up and ramping costs, additional costs are incurred. We do not try to quantify these.

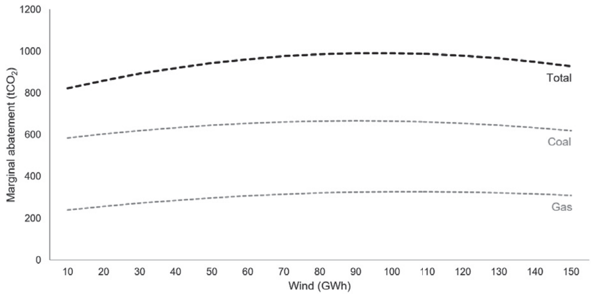

Fig. 9. Marginal abatement of wind, GB. Marginal effects are evaluated at means for other control variables. All estimates are significant at the 5% level. The mean (median) value of wind is 59.32 GWh (49.25 GWh). All point estimates (including predicted emissions) underlying this graph are provided in Appendix Table A3.

substitutes for electricity production from coal both on the intensive as well as the extensive margins.[25]

To sum up, in Britain large-scale displacement of coal by gas in the merit order results in a drastic decrease of emissions starting at a carbon price of around €14. At successively higher CO_2 price levels, coal-fired generation is increasingly pushed out of the merit order while more gas comes in. The effectiveness of the carbon price at reducing emissions begins to taper off at a carbon price of €29, although it remains substantial over the whole range of observed carbon prices. Both coal and gas respond in both dimensions, the intensive and extensive margins, although in opposite directions.

Wind. — Fig. 9 gives the marginal abatement effects of wind, evaluated at means for other control variables. Importantly, we evaluate the marginal effectiveness of wind conditional on the sample average carbon price of approximately €20, at which many coal and gas plants have already switched their positions. Thus, we can see that wind replaces not only emissions from gas but to a large extent from coal. The marginal abatement curve is concave with a maximum effectiveness of 992 tCO_2 at a wind feed-in level of 100 GWh. The higher effectiveness of Britain's wind in terms of emissions reduction than in Germany most likely results from a higher carbon price so that wind can mostly push out coal. By taking the integral over the marginal abatement function up to the sample mean infeed of wind, we estimate that wind in Britain replaces 17% of daily emissions.

Moreover, we can assess wind's performance for various carbon prices. Appendix Table A4 shows that with higher carbon prices, wind can offset less and less coal-based emissions but progressively more gas. The lower potential for offsetting coal reduces the total marginal abatement of wind with increasing carbon prices. We can conclude that for high carbon prices, wind's effectiveness diminishes substantially, because the potential for replacing coal-based emissions vanishes.

5.3. *Climate policy in the context of international trade*

The national perspective is relevant if countries seek to meet their emission targets via unilateral measures. However, climate policies may bring about changes in electricity trade and thus we are also interested in how trade-related emissions alter our estimates. We will show that Germany's imports, which create CO_2 emissions abroad, increase significantly at low carbon prices with the carbon price, whereas for higher prices, additional imports become negligible if the carbon price rises. Moreover, Germany exports considerable shares of its renewable energy, offsetting emissions in neighboring countries. Thus, even though German taxpayers pay for the RE subsidies, wind and solar partly unfold their abatement effectiveness outside Germany. In contrast, Britain's inter-connection capacity (with France, the Netherlands, and Ireland) is frequently congested. Consequently, Britain's imports and exports hardly change with successively higher carbon prices or more wind electricity.

We use daily electricity generation data from ENTSO-E (2018b) on Germany's and Britain's neighboring countries (for which interconnectors are available) to assess their shares of coal and gas relative to national electricity production (c.f. Table B11). Then, we calculate the weighted emission factors of these countries' coal and gas power plants.[26] Finally, we use data of German and British imports and exports to construct trade shares for each trading partner, allowing us to calculate the *weighted average CO_2 content of imported and exported electricity* for Germany and Britain. We acknowledge that the weighted average is only an approximation for the marginally abated emissions, yet such data are not available. On average, one GWh of Germany's imports induce emissions of 237 tCO_2 abroad, while one GWh of exports offsets 175 tCO_2 abroad. For Britain, we calculate that one GWh of imported electricity is associated with 118 tCO_2, whereas one GWh of exported electricity replaces 241 tCO_2 abroad.

Next, we regress the German and British imports and exports on the same set of variables used in equation (3) and additionally control for neighboring countries' demand, wind, and solar electricity in levels, squared, and cubic terms, as well as their

[25] Note that these extensive margin responses are not due to other policies than the carbon price (e.g. the LCPD), since the estimates utilize the covariance of the carbon price with emissions to arrive at these conclusions.

[26] We follow the same approach as described in section 4, using information about nameplate capacity, plant vintage (construction year), and turbine type, to infer about plants' efficiency factors, and to eventually arrive at CO_2 emission factors of neighboring countries.

interactions with the carbon price. From the regressions, we can assess how the carbon price as well as wind and solar power influence the two countries' imports and exports. Eventually, we multiply the estimated marginal effects by the weighted average CO_2 content of imports and exports to estimate the average emissions abated in neighboring markets.

Table B12 presents our estimates of the marginal effects of import-related emissions with respect to carbon pricing (also in relation to our estimates for the national perspective). For Germany, we find that a successively increasing carbon price from €4 to €16 increases imports significantly, by around 60% (i.e. from 64 to 102 GWh),[27] but that the marginal effects are strongly declining (i.e. decreasing additional imports with higher prices, as interconnectors become frequently congested). Hence, import-related emissions are non-negligible relative to the national estimates of national marginal abatement for low carbon prices (e.g. 21% relative to the national estimates at a carbon price of €4), but converge towards 0% for successively higher carbon prices. In Britain, the additional imports associated with higher carbon prices are more or less zero, thus hardly alter our national estimates.

Regarding RE, we find for Germany that wind and solar electricity reduce imports and increase exports (except for very large solar feed-in above 230 GWh), adding to their marginal abatement. Table B15 shows that low-to-medium feed-in of German wind power significantly offsets emissions abroad (i.e. 13–18% relative to national marginal abatement for wind feed-in up to 300 GWh) but shrinks successively (to only 5%) at higher levels of wind. We also find that solar power induces net exports, mainly for low-to-medium feed-in levels, adding significantly to their abatement (i.e. 13–34% relative to national marginal abatement up to solar feed-in of 170 GWh). In contrast, higher solar feed-in hardly alters our estimates of national marginal abatement. For Britain, the effects of wind on net imports are negligible (c.f. Table B16).

We conclude that trade-related emissions are only relevant under certain circumstances. For Germany, increasing the carbon price starting from low carbon prices induce imports, and thus put our estimates of national marginal abatement into perspective. Increasing the carbon price at higher carbon prices, however, does not induce more emissions via additional imports, as interconnectors become frequently congested. Moreover, low-to-medium German wind and solar power partly unfold their effectiveness abroad via exports. For Britain, variations in the carbon price or wind power hardly impact trade, as interconnectors are frequently congested. In what follows, we will report both national as well as trade-adjusted estimates of costs of marginal abatement, as long as the difference is economically relevant.

5.4. Costs

So far, we looked into the abatement effects associated with carbon pricing and feed-in of subsidized wind and solar power. We now assess the *directly attributable costs* of marginally abating one tonne of Co_2 under each climate policy. This is indeed challenging, because a carbon price represents a payment of a carbon-emitting producer to the state, whereas a RE subsidy is essentially a payment by the state to producers of wind and solar electricity. We thus rest our cost-effectiveness analysis on the assumption that electricity consumers will eventually pay for either program in the form of higher electricity tariffs, so that the burden of the policies falls to the consumer side. Several studies (Dagoumas and Polemis, 2020; Fabra and Reguant, 2014; Fell et al., 2015; Hintermann, 2016; Guo and Gissey, 2019) demonstrate that power plant owners fully pass on their additional costs for a carbon price to end-consumers, while the subsidies for RE are financed via a consumption surcharge, which is added to the final electricity tariff (Abrell et al., 2019). In other words, we measure how much abatement the state/consumers/taxpayers can "buy" using carbon pricing (which is paid by energy firms running fossil-fueled power plants, but eventually passed-on to final consumers) or RE subsidies (as paid by electricity consumers to owners of wind and solar power plants). We do not account for any induced inefficiencies (e.g. increased costs of production by switching from (cheap) coal to more expensive gas; increased network costs due to RE intermittency) nor for the effects following from changes in the wholesale electricity price induced by the policies nor for other, general equilibrium effects (e.g. redistribution of tax revenues, etc.). We thus acknowledge that our approach of measuring costs is far from perfect, yet informative for policy making.

We measure the costs of marginal abatement (*CMA*) for each climate policy as the directly associable marginal expenditures (*ME*; i.e. eventually the additional costs for electricity consumers) relative to attributable marginal abatement (*MA*; as estimated by our econometric model; c.f. equation (4)) for an incremental change in the policy. Regarding RE, the costs of marginal abatement are:

$$CMA(x) = \frac{ME(x)}{MA(x)}, \quad x = \{W, S\}, \tag{5}$$

where $W$and S denote the level of wind and solar infeed in MWh. We equate the marginal expenditures for an additional unit of RE output simply by average subsidies per MWh of wind or solar power.

We now turn to carbon pricing. We first calculate the total expenditures for a given carbon price ($TE(P)$) as the payments of thermal power plant owners to the state (which are then passed on to end-consumers in the form of a higher electricity tariff), which depend on the level of emissions attributable to a given carbon price ($\mathrm{E}[y_{p,t}|\mathbf{X}_{p,t}, \mathbf{V}_{p,t}]$; c.f. equation (3)) multiplied by the carbon price (P): $TE(P) = \mathrm{E}[y_{p,t}|\mathbf{X}_{p,t}, \mathbf{V}_{p,t}] \cdot P$.[28] This further allows for calculating the marginal expenditures related to

[27] One reason for the increase in imports would be that neighboring countries may be less affected by a higher EU ETS carbon price, because of their more carbon-neutral production.

[28] This is simply the carbon price times the respective (total) emissions, as reported in column 4 of Tables 2 and 3).

each carbon price as the change in expenditures by an incremental increase in the carbon price: $ME(P) = \partial TE(P)/\partial P$. We then calculate the costs of marginal abatement for a given carbon price as the marginal expenditures for a marginal increase in the carbon price relative to the associated marginal abatement:

$$CMA(P) = \frac{ME(P)}{MA(P)}. \tag{6}$$

Hence, our analysis accounts for the non-linearity in the abatement function. Intuitively speaking, for a low carbon price and thus a large emissions base, which is associated with high expenditures, a marginal increment in the price may only induce low abatement while the increase in expenditures may be significant (i.e. a higher carbon price for a hardly changed emissions base). In this case, the marginal costs of abatement may be high. However, for a moderate carbon price level, a marginal increment in the price may induce a switch between some coal and gas plants, resulting in significant marginal abatement while the marginal expenditures may be moderate. This may result in quite favorable costs of marginal abatement. Finally, for a high carbon price, which may have already pushed most coal plants out of production, we may estimate high costs of marginal abatement again; yet this time because we only get little abatement for moderate additional expenditures. In what follows, we compare the costs of marginal abatement evaluated at mean values of wind and solar feed-in and carbon prices.

Germany. — We estimate moderately declining costs of marginal abatement with higher carbon prices. Evaluated at the relatively low sample mean carbon price of around €8/tCO_2, we estimate costs of marginal abatement of €52 for the national perspective (or €59 adjusted for trade). For a price as high as €15/tCO_2 the costs of marginal abatement decrease to €41/tCO_2.

Regarding RE, Germany granted €79,430[29] and €264,410 per GWh of wind and solar electricity fed into the grid, respectively. At the average wind feed-in of around 300 GWh an additional GWh of wind marginally abates 386 tCO_2, resulting in costs of marginal abatement of €206 for the national perspective (or €182 adjusted for trade). Hence, the costs to abate one tonne of tCO_2 associated with average subsidized wind are significantly higher than with the average carbon price in Germany. At the average solar feed-in of around 110 GWh an additional GWh of solar abates 270 tCO_2, resulting in costs of marginal abatement of €978 for the national perspective (or €744 adjusted for trade). Using these estimates, we can ask how much one can "buy" using carbon pricing or RE subsidies. In Germany one billion euro spent on a carbon price of €8/tCO_2 (or €15/tCO_2) would additionally abate around 20 million tCO_2 (or 25 million tCO_2), around five million tCO_2 if spent on wind subsidies, and only one million tCO_2 if spent on solar subsidies. We can thus conclude that carbon pricing in Germany is significantly more cost effective than the subsidization of wind or solar power.[30]

Britain. — We estimate that the costs of marginal abatement decrease almost over the entire sample range of Britain's carbon prices. We estimate that the curve reaches its minimum at a carbon price of around €36/tCO_2, for which the costs of marginal abatement fall to €30, and (slightly) increase again for higher carbon prices.

Again, we can compare these findings with the costs of marginal abatement of wind power. In 2017, Britain's feed-in tariff per GWh of wind power (equally for onshore and offshore wind) was €51,760 (CEER, 2018). At the average wind feed-in of around 50 GWh one additional GWh of wind abates 934 tCO_2 (which is much more than in Germany), resulting in costs of marginal abatement of €55. In Britain, spending one billion euro on a carbon price of €36/tCO_2 would abate 33 million tCO_2, while wind would abate 18.5 million tCO_2. We therefore conclude that while British wind's costs of marginal abatement come close to those of carbon pricing, carbon pricing gains the upper hand.

6. Conclusion

We compare the effectiveness of the economic first-best policy, a price on carbon emissions, with widely applied second-best policies, such as the subsidization of wind or solar, in terms of emissions abatement and costs. We do this by analyzing the electricity generation sectors in Germany and Britain, as these two countries' electricity sectors are comparable but follow significantly different carbon abatement policies. While Germany relies excessively on direct subsidization of wind and solar energy, Britain introduced a unilateral carbon price support (CPS) in addition to the EU ETS allowances price on 1 April 2013, gradually increasing the carbon price to more than €30/tCO_2 for British electricity generators.

We utilize daily electricity generation data at the plant-turbine level on all gas and coal power stations in Germany and Britain to compare the effectiveness of these two sets of environmental policies. First, we estimate the effects of the carbon price on emissions from thermal power plants (i.e. coal and gas plants). Second, we estimate the offsetting effects of RE, in the form of wind and solar power, on carbon emissions. Third, we also take a perspective on international electricity trade and account for emissions related to imports and exports. Finally, we calculate under reasonable assumptions the costs of abating an additional tonne of CO_2 of these sets of policies.

We find that pricing emissions is superior to financially supporting RE as long as the carbon price is high enough to unfold its abatement potential. For the power sector, we can show that even moderate carbon prices can already bring about substantial abatement once ineffective coal plants get replaced by cleaner gas plants. The abatement potential of such a fuel-switch, however, depends on the pre-existing capital stock. Moreover, we find pronounced differences in the estimated costs of abating

[29] The subsidies for onshore and offshore wind are €64,710 and €159,070, respectively (CEER, 2018). We use the feed-in ratio of onshore to offshore wind of 84.4%–15.6% to calculate the weighted average.

[30] Our cost analysis for RE is in line with the literature. For Germany, Abrell et al. (2019) estimate costs for abating one tCO_2 via solar power in the range of €500–€1,200, and via wind in the range of €110–€340. Similarly, Novan (2015) estimates that wind outperforms solar in terms of abatement in Texas.

one tonne of CO_2 associated with carbon pricing and subsidized wind and solar power. In Germany, at a carbon price of €15, the costs of marginal abatement of one tonne of CO_2 are €41. This policy already offsets 21% of daily emissions compared to having no carbon price in place; a higher carbon price would be even more effective. This compares favorably with the costs of marginal abatement of mean wind of €206, and even more so with those of mean solar of €978. This is due to the fact that, on average, solar power in Germany is less efficient (i.e. it reduces less CO_2 per unit of electricity output) but receives much higher subsidies per GWh compared to wind power. Our findings persist once we adjust our estimates for electricity trade induced by the carbon price or RE feed-in. We also show that Germany's heavy support payments for wind and solar power partly unfold their abatement in neighboring countries via exports.

The high carbon price in Britain (brought about by the CPS) results in substantial abatement of more than 30% of total emissions compared to no carbon price, and approximately half of the emissions from coal. Costs of marginal abatement fall to a minimum of €30/tCO_2 at a carbon price of €36/tCO_2. While wind in Britain is more effective than in Germany, the costs of marginal abatement of carbon pricing remain unmatched. As Britain's interconnectors are frequently congested, electricity trade hardly changes with variations in the carbon price or wind feed-in, so that taking trade-related emissions into account does not change our results.

Secondly, we find that RE subsidization and carbon pricing can be mutually enforcing or opposing policies, depending on which technology is replaced at the margin. Marginal abatement of wind and solar increases with the carbon price in Germany, but decreases in Britain. This is because – starting from a low carbon price – increasing carbon prices in Germany puts more and more coal at the margin to be replaced by wind or solar. In Britain – having a high carbon price – coal is already largely replaced by gas and given further increases in the carbon prices, wind pushes more and more gas out of the merit order, reducing its marginal abatement.

What does our study add to the climate change discussion? First, putting a price on emissions is shown to be the least costly way to reduce emissions and that the order of magnitude is pronounced. Even a relatively modest carbon price (of around €30) can already abate significant amounts of CO_2 as long as gas capacity is available to replace coal. Most economists favor market-based instruments on theoretical grounds – it is good to know that they are also right empirically. Thus, the reassuring message from our study is that national policies – in view of the difficulties of full multilateral cooperation – can work. Effective climate policy does not have to be expensive.[31] Second, however, the (short run) effectiveness of environmental policies in general depends on easily available substitutes. In the electricity sector, with long time-to-build lags, the effectiveness of policies depends on pre-existing capacities. If countries are endowed with an abundance of relatively efficient gas-fired power plants, such as Britain, putting a high price on carbon emissions is a very effective policy, since coal can be replaced in a relatively short-term manner at reasonable costs. This bears policy relevance as, indeed, most European countries and U.S. states have substantial idle gas capacity to potentially replace coal-based electricity output. Thus, a high-enough carbon price would dramatically reduce emissions from the electricity sector.

Finally, let us mention some caveats. In an emissions cap-and-trade program, such as the EU ETS, unilateral policies to reduce emissions, will lead to higher emissions in other sectors and countries not covered (i.e. the "waterbed effect"). Thus, while unilateral measures may help reaching national emissions targets, an effective carbon price would have to be internationally coordinated across countries and cover all sectors of the economy. Also, this study analyses only short-run fuel switching. It does not analyze longer-run effects of the policies, such as investment-incentive effects in low carbon generation capacity, nor effects on R&D to induce technological change. Ultimately, these effects will be the decisive ones for whether or not humankind succeeds in curbing global warming. However, just as it does in the short term, we have no reason to doubt that a proper carbon price also provides better longer term incentives than other climate policies do.

Declaration of competing interest

None. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Acknowledgments

We thank Baran Doda for valuable background information about Britain's carbon price floor. Moreover, we thank Jan Abrell, Mirjam Kosch, Florian Szücs and participants at the EARIE 2019 in Barcelona, Disentis Energy Research Talk, and the Conference on Auctions, Competition, Regulation, and Public Policy 2019 in Lancaster for helpful comments.

[31] Tol et al. (2019) corroborate this postulation by stating that "climate policy need not cost a lot, but imperfect implementation could cause hundreds of billions of euros' worth of unnecessary welfare losses."

Appendix

A. Additional Tables and Figures

Table A1
Marginal abatement of wind & solar, DE

Wind (GWh)	Mrg. abtm. (tCO_2/GWh)			Solar (GWh)	Mrg. abtm. (tCO_2/GWh)		
	Coal	Gas	Total		Coal	Gas	Total
50	413	69	482	10	317	−1	316
100	383	64	447	30	254	30	283
150	361	59	420	50	206	56	262
200	346	55	401	70	175	78	252
250	339	51	390	90	160	95	255
300	339	47	386	110	163	108	270
350	346	45	391	130	182	116	298
400	360	42	403	150	217	119	336
450	382	40	422	170	268	118	385
500	410	39	449	190	334	111	445
550	445	38	483	210	414	100	514
600	486	38	524	230	509	83	592
650	534	38	572	250	620	61	681
700	587	39	626				

Marginal effects are evaluated at means for other control variables. All estimates are significant at the 5% level. The mean (median) values of wind and solar are 305.78 GWh (255.74 GWh) and 108.18 GWh (104.68 GWh), respectively. Predicted emissions for zero wind and solar feed-in are 689,607 tCO_2 and 589,707 per day, respectively.

Table A2
Marginal abatement effects of mean wind & solar for different carbon prices, DE

Price (€/tCO_2)	Wind: mrg. abtm. (tCO_2/€)			Price (€/tCO_2)	Solar: mrg. abtm. (tCO_2/€)		
	Coal	Gas	Total		Coal	Gas	Total
4	318	53	370	4	124	115	239
5	325	51	376	5	137	111	248
6	333	49	382	6	151	106	257
7	340	47	387	7	164	101	265
8	348	45	393	8	177	97	274
9	356	43	398	9	190	92	282
10	363	41	404	10	203	87	290
11	370	39	409	11	215	83	298
12	378	37	415	12	228	78	306
13	385	35	420	13	240	73	313
14	393	33	425	14	252	69	321
15	400	31	431	15	264	64	329

Marginal effects are evaluated at means for other control variables. All estimates are significant at the 5% level. The mean (median) value of the carbon price is 7.82 €/tCO_2 (6.96 €/tCO_2).

Table A3
Marginal abatement effects of wind, GB

Wind (GWh)	Mrg. abtm. (tCO_2/GWh)		
	Coal	Gas	Total
10	584	239	823
20	603	257	860
30	620	272	892
40	634	286	920
50	646	297	943
60	655	307	962
70	661	315	976
80	665	321	986
90	666	325	991
100	665	327	992
110	661	327	988
120	654	325	979
130	645	321	966
140	633	316	949
150	619	309	928

Marginal effects are evaluated at means for other control variables. The mean (median) value of wind is 59.32 GWh (49.25 GWh). All estimates are significant at the 5% level. Predicted emissions for zero wind feed-in are 313,494 tCO_2 per day.

Table A4
Marginal abatement effects of mean wind for different carbon prices, GB

Price (€/tCO_2)	Wind: mrg. abtm. (tCO_2/€)		
	Coal	Gas	Total
4	898	255	1153
6	855	261	1116
8	812	267	1079
10	769	274	1042
12	726	280	1006
14	683	287	969
16	640	293	933
18	597	300	896
20	554	306	860
22	511	313	823
24	467	319	787
26	424	326	750
28	381	332	713
30	338	338	676
32	295	344	639
34	251	350	601
36	208	356	564

Marginal effects are evaluated at means for other control variables. The mean (median) carbon price is €19.71 (€19.07). All estimates are significant at the 5% level.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jeem.2020.102405.

References

Abrell, J., Kosch, M., Rausch, S., 2019. Carbon abatement with renewables: evaluating wind and solar subsidies in Germany and Spain. J. Publ. Econ. 169, 172–202.

BEIS, 2019. National statistics, energy trends: "electricity production and availability from the public supply system (et 5.4. Department for Business, Energy and Industrial Strategy (BEIS), www.gov.uk/government/statistics/electricity-section-5-energy-trends.

Bernecker, 2019. Was kostet die Energiewende? FinanzNachrichten.de. May 14 https://www.finanznachrichten.de/nachrichten-2019-05/46703532-was-kostet-die-energiewende-118.htm.

Borenstein, S., 2012. The private and public economics of renewable electricity generation. J. Econ. Perspect. 26 (1), 67–92.

BP, 2018. Statistical Review of World Energy – All Data 1975–2017.

BRH, 2018. Special Purpose Report Pursuant to Article 99 Federal Budget Code on the Coordination and Governance of Energy Transition by the Federal Ministry for Economic Affairs and Energy. Bundesrechnungshof (Federal Court of Auditors).

Burke, M., Dykema, J., Lobell, D.B., Miguel, E., Satyanath, S., 2015. Incorporating climate uncertainty into estimates of climate change impacts. Rev. Econ. Stat. 97 (2), 461–471.

Calel, R., Dechezleprêtre, A., 2016. Environmental policy and directed technological change: evidence from the european carbon market. Rev. Econ. Stat. 98 (1), 173–191.

Carbon Market Data, 2020. EU ETS Database.

CCC, 2014. The Budget Freeze in Carbon Price Support. Committee on Climate Change (CCC), 31 March. www.theccc.org.uk/2014/03/31/the-budget-freeze-in-carbon-price-support/.

CEER, 2018. Status Review of Renewable Support Schemes in Europe for 2016 and 2017. Council of European Energy Regulators (CEER). Public Report C18-SD-63-03.

Cullen, J., 2013. Measuring the environmental benefits of wind-generated electricity. Am. Econ. J. Econ. Pol. 5 (4), 107–133.

Cullen, J.A., Mansur, E.T., 2017. Inferring carbon abatement costs in electricity markets: a revealed preference approach using the shale revolution. Am. Econ. J. Econ. Pol. 9 (3), 106–133.

Dagoumas, A.S., Polemis, M.L., 2020. Carbon pass-through in the electricity sector: an econometric analysis. Energy Econ. 86, 104621.

DEFRA, 2012. United Kingdom National Emission Reduction Plan for Implementation of the Revised Large Combustion Plants Directive (2001/80/ec). Department for Environment, Food & Rural Affairs (DEFRA).

DICE Consult, 2016. Kosten der Energiewende: Untersuchung der Energiewendekosten im Bereich der Stromerzeugung in den Jahren 2000 bis 2015 in Deutschland. Gutachten im Auftrag der Initiative Neue Soziale Marktwirtschaft (INSM).

ECB, 2019. European Central Bank: Daily Exchange Rates. http://sdw.ecb.europa.eu/browse.do?node=9691296.

EEX, 2018. Transparency in Energy Markets. www.eex-transparency.com/.

Ellerman, A.D., Marcantonini, C., Zaklan, A., 2015. The European Union emissions trading system: ten years and counting. Rev. Environ. Econ. Pol. 10 (1), 89–107.

ENTSO-E, 2018b. Transparency Platform. https://transparency.entsoe.eu/.

Fabra, N., Reguant, M., 2014. Pass-through of emissions costs in electricity markets. Am. Econ. Rev. 104 (9), 2872–2899.

FAZ, 2019. Stromerzeugung Verursacht Deutlich Weniger CO2. Frankfurter Allgemeine Zeitung. 4 July.

Fell, H., Hintermann, B., Vollebergh, H., 2015. Carbon content of electricity futures in phase II of the EU ETS. Energy J. 36 (4).

Fell, H., Kaffine, D.T., 2018. The fall of coal: joint impacts of fuel prices and renewables on generation and emissions. Am. Econ. J. Econ. Pol. 10 (2), 90–116.

German Federal Government, 2020. Was bringt, was kostet die Energiewende. https://www.bundesregierung.de/breg-de/themen/energiewende/was-bringt-was-kostet-die-energiewende-394146.

Germeshausen, R., Wölfing, N., 2020. How marginal is lignite? two simple approaches to determine price-setting technologies in power markets. Energy Pol. 142, 111482.

Gräbner, M., von Morstein, O., Rappold, D., Günster, W., Beysel, G., Meyer, B., 2010. Constructability study on a German reference IGCC power plant with and without CO2-capture for hard coal and lignite. Energy Convers. Manag. 51 (11), 2179–2187.

Greene, W.H., 2008. Econometric Analysis, sixth ed. Prentice Hall, Upper Saddle River, N.J..

Gridwatch, 2018. G.B. National Grid Status. www.gridwatch.templar.co.uk/.

Grossi, L., Heim, S., Waterson, M., 2017. The impact of the German response to the Fukushima earthquake. Energy Econ. 66, 450–465.

Gugler, K., Haxhimusa, A., Liebensteiner, M., 2018. Integration of European electricity markets: evidence from spot prices. Energy J. 39, 1–26.

Gugler, K., Haxhimusa, A., Liebensteiner, M., Schindler, N., 2020. Investment opportunities, uncertainty, and renewables in European electricity markets. Energy Econ. 85, 1–16.

Guo, B., Gissey, G.C., 2019. Cost Pass-Through in the British Wholesale Electricity Market: Implications of Brexit and the ETS Reform.

Handelsblatt, 2013. Hohe Kosten: FDP will "Neustart" für Energiewende.

Hepburn, C., Stern, N., Stiglitz, J.E., 2020. "Carbon pricing" special issue in the European Economic Review. Eur. Econ. Rev. 127, 103440.

Hintermann, B., 2016. Pass-through of CO2 emission costs to hourly electricity prices in Germany. Journal of the Association of Environmental and Resource Economists 3 (4), 857–891.

House of Commons, 2016. Carbon Price Floor (CPF) and the Price Support Mechanism. Briefing Paper, Nr. 05927, 8 January 2018.

IEA, 2019. CO2 Emissions Statistics: an Essential Tool for Analysts and Policy Makers.

Linn, J., Muehlenbachs, L., 2018. The heterogeneous impacts of low natural gas prices on consumers and the environment. J. Environ. Econ. Manag. 89, 1–28.

National Grid, 2007. Large Combustion Plant Directive. GCRP 07/32, September https://www.nationalgrideso.com/document/24356/download.

Newbery, D.M., Reiner, D.M., Ritz, R.A., 2019. The political economy of a carbon price floor for power generation. Energy J. 34 (1).

Novan, K., 2015. Valuing the wind: renewable energy policies and air pollution avoided. Am. Econ. J. Econ. Pol. 7 (3), 291–326.

Ofgem, 2018. State of the Energy Market. https://www.ofgem.gov.uk/publications-and-updates/state-energy-market-2018.

Ofgem, 2019. State of the Energy Market. https://www.ofgem.gov.uk/publications-and-updates/state-energy-market-2019.

Patt, A., Lilliestam, J., 2018. The case against carbon prices. Joule 2 (12), 2494–2498.

Pigou, A.C., 1920. The Economics of Welfare. Macmillan, London.

PLATTS PowerVision, 2018. S&P Global Platts PowerVision.

Rosenbloom, D., Markard, J., Geels, F.W., Fuenfschilling, L., 2020. Opinion: why carbon pricing is not sufficient to mitigate climate change – and how "sustainability transition policy" can help. Proc. Natl. Acad. Sci. Unit. States Am. 117 (16), 8664–8668.

Tol, R.S.J., Rutherford, T., Böhringer, C., 2019. The EU 20/20/2020 Targets. VOX EU, https://voxeu.org/article/large-welfare-costs-second-best-eu-climate-policies. (Accessed 16 August 2019).

UNFCCC, 2020. Nationally Determined Contributions (NDCs). United Nations Framework Convention on Climate Change. https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement/nationally-determined-contributions-ndcs#:
:text=Nationally%20determined%20contributions%20(NDCs)%20are,the%20impacts%20of%20climate%20change.

voestalpine, 2020. EU Emissions Trading: Voestalpine's Position on the "Market Stability Reserve". https://www.voestalpine.com/group/en/group/environment/eu-emissions-trading-voestalpine-position-on-the-market-stability-reserve.html.

Further reading

BEIS, 2018. National Statistics: Provisional UK Greenhouse Gas Emissions National Statistics 2017. Department for Business, Energy and Industrial Strategy (BEIS), https://www.gov.uk/government/statistics/provisional-uk-greenhouse-gas-emissions-national-statistics-2017.

BMWi, 2018. Climate change 11/2018: Entwicklung der spezifischen Kohlendioxid-Emissionen des deutschen Strommix in den Jahren 1990–2017. German Federal Ministry for Economic Affairs and Energy (BMWi).

BMWi, 2018a. Erneuerbare Energien in Zahlen: Nationale und internationale Entwicklung im Jahr 2017. German Federal Ministry for Economic Affairs and Energy (BMWi).

BMWi, 2018b. Zeitreihen zur Entwicklung der erneuerbaren Energien in Deutschland 1990–2017. German Federal Ministry for Economic Affairs and Energy (BMWi).

ENTSO-E, 2018a. Statistical Factsheet 2017. https://eepublicdownloads.azureedge.net/clean-documents/Publications/Statistics/Factsheet/entsoe_sfs_2017.pdf.