Department of Economics
Working Paper No. 293

Effective Climate Policy Doesn't Have to be Expensive

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September 2019

WIRTSCHAFTS UNIVERSITÄT WIEN VIENNA UNIVERSITY OF ECONOMICS AND BUSINESS

Effective Climate Policy Doesn't Have to be Expensive*

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August 19, 2019

Abstract: We compare the effectiveness of different climate policies in terms of emissions abatement and costs in the British and German electricity markets. The two countries follow different climate policies, allowing us to compare the effectiveness of a relatively low EU ETS carbon price in Germany with a significantly higher carbon price due to a unilateral top-up tax (the Carbon Price Support) in the UK. We first estimate the emissions offsetting effects of carbon pricing and of subsidized wind and solar feed-in, and then derive the abatement costs of one tonne of CO_2 for the different policies. We find that a reasonably high price for emissions is the most cost-effective climate policy, while subsidizing wind is preferable to subsidizing solar power. A carbon price of around €35 is enough in the UK to induce vast short-run fuel switching between coal- and gas-fired power plants, leading to significant emissions abatement at low costs.

Keywords: Climate change policy; Carbon price; EU ETS; UK Carbon Price Floor; UK Carbon Price Support; Subsidization of renewables

JEL Classification: L94, L98, Q35, Q38, Q54, Q58

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

*We thank Baran Doda for valuable background information about UK's carbon price floor. Moreover, we thank Florian Szücs for insightful comments.

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1 Introduction

Combating anthropogenic climate change is one of the greatest challenges facing humankind. There are basically two ways of reducing greenhouse-gas (GHG) emissions. On the one hand, policymakers may apply "command-and-control" policies such as subsidies for "green technologies" (wind, solar, electric cars, etc.) and administrative measures (e.g. bans on oil heating, emission performance standards, etc.); on the other hand, market-based policies, such as putting a price on emissions to internalize their negative externalities. Surprisingly, there is no econometric study that compares altogether the (cost) effectiveness of the economic first-best policy, a price on carbon emissions, with the widely applied second-best policies, such as the subsidization of wind or solar power. However, understanding the effectiveness of climate policies in terms of abatement and costs is key for deriving optimal (i.e. least cost) solutions to climate change. This paper fills this gap. We analyze the electricity generation sector – the sector responsible for the lion's share of emissions – in the UK and Germany, because these two countries follow contrasting climate change policies, and show that the market-based instrument of carbon pricing is superior to supply-side policies such as subsidization of wind and solar power.

Many countries have adopted policies to reduce GHG emissions either via international treaties, such as the Paris Accord, or unilaterally. The bulk of measures are of the "command-and-control" type. The European Union (EU) declared its intention to reduce GHG emissions by at least 40% by the year 2030 compared to 1990 and to increase the share of renewable energy sources (RES) in total energy production to at least 32%. Germany, one of the most active countries in the deployment of RES, mostly in the form of wind and solar power, promised in its Climate Action Plan 2050 ("Klimaschutzplan 2050") to reduce GHG emissions by 55% by 2030 and by 80%–95% by the year 2050 relative to 1990 (BMUB, 2017). Germany's share of renewables should climb to 30% by 2030 and to 60% by 2050 (Monopolkommission, 2017). Likewise, the USA – before abandoning the Paris Accord under the Trump administration – followed targets to offset emissions significantly under its "Clean Power Plan" (EPA, 2018). Unfortunately, despite all abatement efforts, global emissions have been increasing steadily.[1] Even Germany, the country that has spent most on renewables per capita worldwide, has seen more or less constant emissions in recent years. However, emissions have declined in the UK (c.f. Figures 2a and 2b). We show in this paper that the introduction of a significant carbon price in the UK is responsible for this development.

We utilize daily electricity generation data at the plant level on all gas and coal power stations in Germany and the UK to compare the effectiveness of two sets of environmental policies. First, we estimate the offsetting effects of RES, in the form of wind and solar power, on carbon emissions from thermal power plants (i.e. coal and gas plants). Because wind and solar

[1] Global emissions rose from 28.13 bn tCO_2 in 2005 to 33.44 bn. tCO_2 in 2017 (BP, 2018).

installations are subsidized by the state, we can calculate the costs of using direct subsidies to abate of one tonne of CO_2. Second, both countries are members of the EU Emission Trading System (ETS) whereby carbon emitting power plants have to buy emission allowances for electricity production. Thus, polluting power plants internalize the costs of emitting CO_2, making their production relatively more expensive compared to clean technologies. Two effects may follow. Coal – emitting more CO_2 than gas per unit of electricity produced and thus becoming relatively more expensive than gas with a rising carbon price – may be replaced by gas, ceteris paribus. Moreover, both gas and coal may be replaced by less carbon-intensive technologies, such as hydro, nuclear, wind, solar, or imports, which do not need to buy emission allowances.

We estimate the effects of the CO_2 price on emissions from gas and coal electricity production, allowing us to calculate the costs of abatement of one tonne of CO_2 using this instrument. Our regression model disentangles the effects of carbon pricing as well as feed-in from wind and solar power from other confounding effects, such as changes in demand, input prices, or seasonality. Moreover, we acknowledge that these effects are interdependent among each other and dependent on the level of demand. Thus, we allow for highly non-linear relationships by introducing a set of interactions and higher order terms (up to the cubic terms). Fortunately, we can evaluate a policy experiment, because the UK introduced a unilateral carbon price support (CPS) *in addition* to the EU ETS price on 1 April 2013. From then on, UK generators had to pay two components, (i) the EU ETS allowance price plus (ii) the CPS, which tops up the allowance price and is both significant and increasing over time (see Section 2 for more details). Thus, we can compare a system solely subject to the EU ETS allowance price (i.e. Germany) with a system subject to a much higher effective CO_2 price (i.e. the UK). This is important since the EU ETS allowance price has been relatively low and is alleged to be ineffective in reducing CO_2 emissions (see, e.g., Elkerbout and Egenhofer, 2017). In contrast, we show that a CO_2 price is indeed effective in reducing emissions, provided that it reaches a sufficiently high level.

For Germany, we estimate that the sample mean EU ETS price of around €8/tCO_2 induces an offset of only 9.6% of total emissions per day, relative to having no carbon price. At such a low carbon price, we thus do not observe a large reduction in emissions. A carbon price this low does not result in fuel switching between dirty coal-based and relatively cleaner gas-based generation. Evaluated at the mean ETS price of €8, we calculate the costs of marginal abatement for an additional tonne of CO_2 emissions to be €52. For the highest observed carbon price of in Germany, €15, we estimate significantly higher abatement – 20% of total daily emissions. The cost effectiveness, in this case, is only €41 per additional tonne of CO_2 emissions abated. We also estimate that wind power is, on average, significantly more effective in abating emissions than solar power. The costs of direct subsidization reveal that, on average, it costs €204 to replace one additional tonne of CO_2 from wind power. For solar power, the costs are very high, at €979 to replace an additional tonne of CO_2, on average.

Given the unilateral top-up CPS in addition to the EU ETS price, our analysis for the UK is based on a wide range of observed carbon prices – between €4 and €37. We find that marginal abatement significantly increases as the carbon price rises to €29, followed by lower (but still positive) marginal abatement at higher carbon prices. Similarly, we find that the cost effectivity of carbon pricing is strongly convex, with a minimum at a carbon price of €36, where marginal abatement of one tonne of CO_2 emissions costs only €30. In contrast, at very low and very high carbon prices (outside the range we observe), abatement costs are vastly higher. Although we find (as in Germany) that putting an adequate price on emissions is more cost effective than subsidizing RES, wind in the UK is more effective than in Germany. Furthermore, over time, falling subsidies for wind result in relatively low costs of replacing an additional tonne of CO_2 by wind. Yet, we argue that with higher levels of wind feed-in as well as with higher carbon prices, wind's abatement effectiveness decreases, leading again to higher marginal costs of abatement.[2]

Another important result is that the policies of carbon pricing and subsidization of wind and solar power can be substitutive or complementary, depending on which technology is replaced by wind or solar at the margin. The marginal effectiveness of wind and solar increases with the carbon price in Germany, but decreases in the UK. This is because the relatively low carbon price in Germany leaves dirty coal to be replaced by wind or solar. In the UK, with its already high carbon price, it is mainly the relatively clean gas that is replaced, reducing the effectiveness of RES.

Our results shed light on the optimum size of an effective carbon price. Newbery et al. (2019) argue that €25–€30/tCO_2 would be adequate – which is somewhat in line with our findings of a high cost-effectiveness of carbon pricing at around €30–€36/tCO2. The UK Government initially set the CPS to increase to £30 (i.e. €35) per tCO_2, on top of the EU ETS price, by 2020 before it froze the CPS at £18.08 (i.e. €20.4) tCO_2 (House of Commons, 2016). CPLC (2017) suggests a *global* carbon price of \$40–\$80 (i.e. €35–€70) per tCO_2 by 2020 and \$50–\$100 per tCO_2 (i.e. 44€–€88) by 2030 to meet the Paris climate target. Our results suggest that a carbon price in the €30s already induces significant fuel switching, so that cleaner gas-fired power plants displace dirty coal. This is evidence that a *modest* carbon price brings about a significant reduction in emissions. In contrast, high carbon prices well beyond €40 are associated with lower marginal abatement effects, 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 substantial.[3]

[2] Given that the UK's solar feed-in was essentially zero until 2014, followed by a negligibly low production share in the subsequent years (see also Appendix Figure B1b), we could not utilize such data in our analysis but can only speculate that subsidizing solar power is even less cost effective than in Germany.

[3] Of course, and as we argue later on, short-term replacement of coal by gas can only happen if enough gas-based electricity generation capacity is already installed. Moreover, here we can only argue for the electricity generation sector and not for other emitting sectors such as transportation or industry.

For other countries planning on introducing unilateral carbon prices, our findings are also relevant, as we show that even relatively modest carbon prices (of around €30/tCO_2) may bring about substantial emissions abatement in the short run - as long as electricity generation from coal can be replaced by gas. The Netherlands will introduce a carbon tax on electricity generation at €18/tCO_2 in 2020, which should rise to €43 by 2030, and France and Germany are currently discussing carbon pricing as a means to finally meet their Paris targets (see, e.g. Gillmann et al., 2018). While a fully cooperative CO_2 price worldwide would be the overall first best, we are far from this optimum (Nordhaus, 2018). In the meantime, this paper is reassuring for those countries that take unilateral measures such as the UK. These measures work at the country level at a manageable cost – and indeed at significantly lower costs than in Germany, where climate policy is based on high subsidies for wind and solar power.[4]

Our paper extends the growing literature, which estimates the emissions offset from 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. (2019a) take both the EU ETS price and wind and solar power into account, yet only derive conclusions 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 first-best policy to other policies, such as direct supply-side subsidization of RES. Fell and Kaffine (2018) compare the effects of wind generation and natural gas prices on emission reduction while Cullen and Mansur (2017) liken the effects of natural gas price changes to changes in the carbon price. Abrell et al. (2019b) also use variation in the price ratio between coal and gas to estimate predicted emission levels and compare them to actual emission levels when evaluating the UK CPS. 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.[5] 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. Moreover, we extend the literature in many other directions. We employ high-frequency data at the power plant level, our empirical model is highly non-linear (i.e. up to the cubic expansion terms and interaction terms), contains a wide range of fixed effects (day of week, month, year), and includes lagged variables, whereas related papers (e.g. Abrell et al., 2019a; Cullen, 2013; Cullen and Mansur, 2017; Fell and Kaffine, 2018; Novan, 2015) are not as rich in

[4]Subsidies for RES may not have the sole purpose of reducing emissions but also of incentivizing their technological maturity. However, a carbon price also sets incentives for R&D or technological change towards clean technologies.

[5]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 imply that the effects of the cost ratio and the carbon price are quantitatively different.

one or more of these dimensions.

2 Background on carbon pricing and renewables

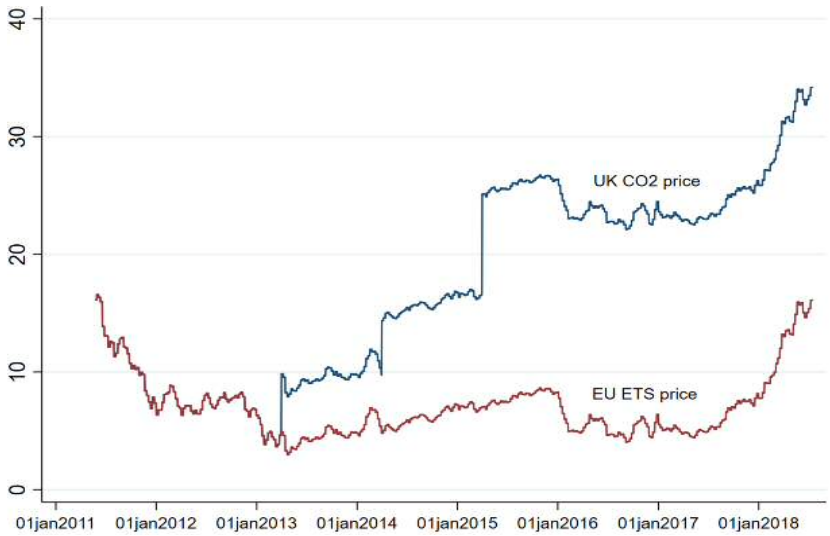
It is important to assess the effectiveness of climate policies in relation to the power sector because this sector represents the major source of global GHG emissions,[6] and at a national level is the main source of emissions in Germany and the UK. The power sectors of both countries are regulated under the EU ETS, which puts a price on emissions.

It is well established that an optimal carbon price (e.g. in the form of a tax) internalizes the externality of emissions (Pigou, 1920). Weitzman (1974) demonstrates that, without uncertainty about the marginal benefit and marginal cost curves, both price-based (e.g. emissions tax) and quantity-based (e.g. cap & trade program) instruments lead to the same level of (optimal) emissions abatement. Thus, carbon pricing represents a first-best solution based on market incentives and leads to cost-efficient emissions abatement (Borenstein, 2012). Economists have long agreed that in practice a direct price on an externality is superior to alternative indirect measures, such as subsidies (see, e.g., Holland et al., 2016). In that respect, Novan (2015, p. 293) argues that "renewable subsidies present a poor option for reducing pollution" and that "emission prices will reduce pollution more efficiently than the current renewable policies (...)."

Against this background, the leading role played by the EU ETS in pricing emissions within the largest cap-and-trade program in the world is a major step in climate policy. The EU ETS regulates around 45% of total EU GHG emissions and represents the biggest emissions trading market in the world (EC, 2016). In the 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 and covers carbon dioxide (CO_2) emissions, as well as CO_2 equivalents of two other greenhouse gases, nitrous oxide (N_2O) and perfluorocarbon (PFC). During the first phase of the EU ETS from 2005–2007, allowances were abundant resulting in an ineffectively low CO_2 price. In the second phase, from 2008–2012, allowances were reduced by 6.5%, but the reduction in economic activity due to the recession resulted again in an abundance of allowances. During the current phase 2013–2020, the cap on EU allowances has been reduced by 1.74% each year and "a progressive shift towards auctioning of allowances in place of cost-free allocation" was introduced (EC, 2016, p. 2). However, for most of the time during its existence, the EU ETS price has been ineffectively low (see Figure 1), 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

[6] According to the International Energy Association, 42% of global emissions in 2006 were from electricity and heat generation (IEA, 2019).

Figure 1: EU ETS price & effective UK CO_2 price (€/tCO_2)



Effective UK CO_2 price = EU ETS 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 EU ETS prices (EUA); House of Commons (2016) for UK CPS rates (converted into Euros according to daily exchange rates from the ECB, 2019).

(see, e.g., Newbery et al., 2019). Moreover, price volatility and expectations of low future carbon prices may work against incentives to invest in long-lived, durable, and sunk electricity generation assets.

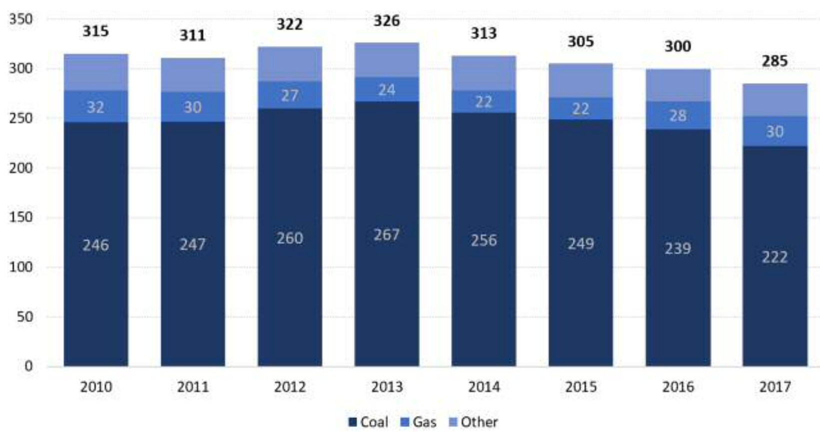
The failure of the EU ETS in inducing a low-carbon transition so far has led EU member states to follow different unilateral (and uncoordinated) climate policies. Germany has been heavily subsidizing RES (with guaranteed feed-in tariffs as well as subsidies for capacity deployment), mostly in the form of wind and solar power, as a means to reduce emissions from the power sector. 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 Online Appendix Figure B1). It plans to provide at least 80% of its gross national electricity supply from RES by 2050, as stated in the German Renewable Energies Act ("Erneuerbare Energien Gesetz", EEG). The costs for the direct subsidization of RES are tremendous, though. The German Federal Court of Auditors ("Bundesrechnungshof", BRH, 2018) estimates the costs directly attributable to the "Energiewende" at (at least) €34 billion in 2017 alone. [7]

Parallel to the subsidization of RES, Germany also decided to phase-out nuclear power as

[7] 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 (Bundesregierung, undated). Similarly, Bernecker (2019) mentions costs of €550–600 Billion.

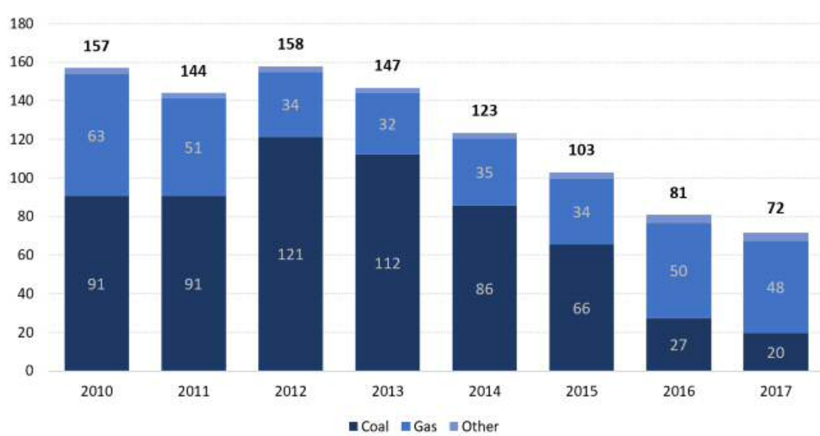
Figure 2: Emissions from power sector ($MtCO_2$)

(a) DE



Source: Umweltbundesamt (2018)

(b) UK



Source: BEIS (2018)

a consequence of the Fukushima-Daiichi nuclear incident in 2011 (Grossi et al., 2017).[8] Thus, a large fraction of RES first has to fill a significant gap in missing electricity production left by the reduction in low-carbon nuclear power (see also Online Appendix Figure B2). However, almost a decade on from Germany's nuclear phaseout, the effectiveness of RES is still in doubt. Emissions from the power sector have been by and large constant (with a minor decrease since 2013), as shown in Figure 2a . 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.

In contrast, the UK follows a different strategy. In April 2013, the British Government introduced a unilateral carbon tax, the CPS, which tops-up the EU ETS allowance price. [9] 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 UK 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 price of emissions, which we can use for policy analysis. Moreover, as the top-up tax preserves the price variation (which would vanish during times of a binding price floor), we can exploit it for econometric regression.

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

The UK strategy seems to pay off in terms of emissions abatement, as can be seen in Figure 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 the UK was high. 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 gas-fired power plants.

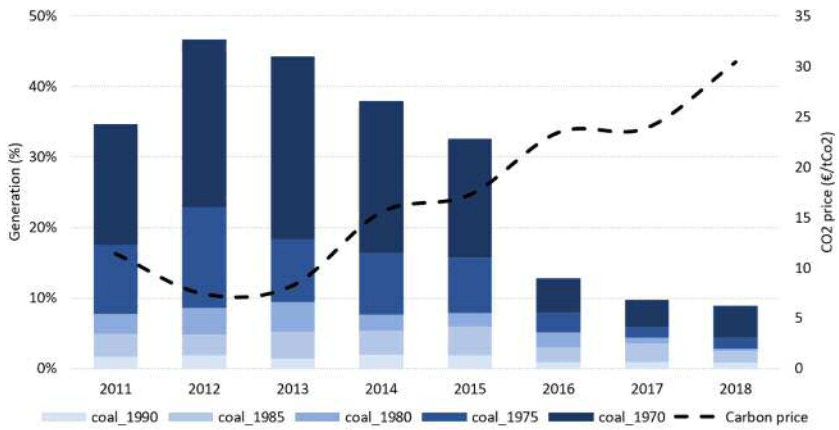
To underline our argument, Figure 3 shows the UK's generation shares of coal and gas by plant vintage. With an increasing carbon price, we see that the most outdated coal plants

[8]Grossi et al. (2017) state that the oldest 6 out of 23 nuclear plants (amounting to 6.3MW capacity, producing around 12% of annual German electricity) were immediately shut off permanently from the system. In subsequent years, additional nuclear capacity was withdrawn.

[9]The British Government calls the program a "Carbon Price Floor", but despite its curious name it does not work in the fashion of a minimum price (e.g. if the EU ETS price falls below a threshold, the floor price becomes effective) but it is essentially a *top-up tax* (CCC, 2014).

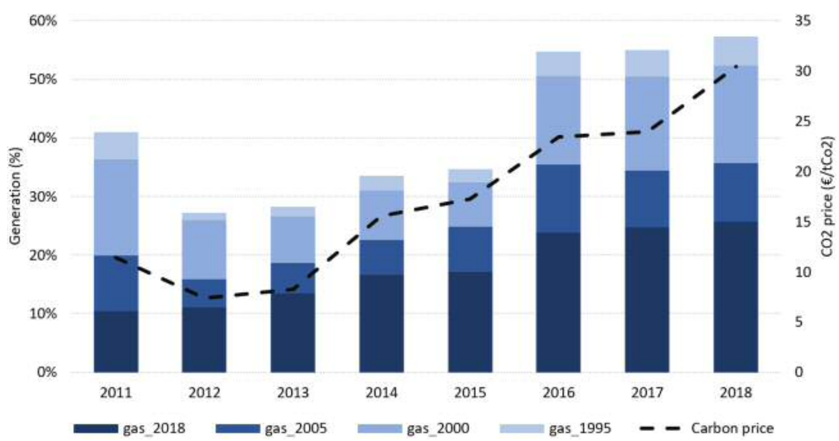
Figure 3: Generation from coal and gas by plant vintage, UK

(a) Coal



Source: own data

(b) Gas



Source: own data

significantly reduce their output (3a), while the most efficient new gas plants significantly increase their production (B1b). Foremost, Figure 3 shows that with an increasing carbon price, a large share of coal-fired generation gets replaced by an increasing share of gas-fired electricity. Given that coal emits more than double the amount of CO_2 per unit of electricity (MWh) than gas, these patterns of gas replacing coal at a higher carbon price may explain why the UK has successfully reduced its emissions from the power sector.

Costs of Climate Policies

We seek to give a first impression (before carrying out our in-depth econometric analysis) about the directly attributable costs of the various climate policies, as pursued by Germany and the UK, based on external data.[10] We utilize data from CEER reports (CEER, 2013, 2015, 2017, 2018) on the expenditures for wind and solar support schemes in Germany and the UK. Data on the annual wind (onshore and offshore) and solar feed-in as well as on CO_2 emissions stem from BMWi (2018a) for Germany and from BEIS (2019) for the UK. Using these data, we can calculate the total expenditures for wind and solar electricity as well as for carbon pricing. Finally, we divide the total expenditures for each climate policy tool (i.e. wind, solar, carbon pricing) by the population of each country (as obtained from Eurostat) to arrive at the expenditures per capita of each policy tool.

Table 1 shows that Germany spends large amounts on RES support schemes per capita, while the expenditures on carbon pricing (within the EU ETS) are much lower. Over the period 2010–2017, Germany spent €1,334 per capita on subsidizing wind and solar power, of which €889 went into solar power and €445 into wind power. Against the relatively modest reduction in emissions (see also Figure 2a) over this period, it seems that the costs relative to the outcome are enormous. Germany's parallel expenditures on carbon pricing were only €246 per capita.

For the UK, we can see that the expenditures per capita for RES are modest, at €196, of which wind received almost the entire sum. The expenditures for carbon pricing, however, are (by coincidence) equal to those of Germany over the period 2010–2017. This is surprising because the UK has had considerably higher carbon prices than Germany since 2013. Evidently, despite the high carbon price in the UK, the drastic reduction in emissions since 2013 (see also Figure 2b) led to quite favorable expenditures on carbon pricing. Overall, this is evidence that Germany's expenditures are huge while its emissions have hardly decreased. On the other hand, the UK spends much less, while drastically reducing its emissions.

[10]Appendix Table A2 provides details about how we calculate the expenditures per capita for RES subsidization.

Table 1: Per capita expenditures for climate policies (€)

Year	Pop. (mio.)	Carb. pr. (€/tCO2)	Emissions (mio. tCO2)	Expend. (mio. €)	Expenditures per capita (€) P	W+S	(W)	(S)
				Germany				
2010	82	14	315	4,521	55	75	(19)	(56)
2011	80	13	311	4,110	51	115	(28)	(86)
2012	80	7	322	2,398	30	146	(41)	(105)
2013	81	4	326	1,450	18	156	(44)	(112)
2014	81	6	313	1,852	23	178	(51)	(126)
2015	81	8	305	2,346	29	209	(77)	(132)
2016	82	5	300	1,605	20	227	(82)	(145)
2017	83	6	285	1,641	20	229	(103)	(126)
Total			*2,477*	*19,923*	***246***	***1334***	***(445)***	***(889)***
				UK				
2010	63	14	157	2,252	36	9	(9)	(0)
2011	63	13	144	1,903	30	15	(15)	(0)
2012	63	7	158	1,174	18	20	(20)	(0)
2013	64	9	147	1,284	20	28	(28)	(0)
2014	64	16	123	2,025	31	25	(25)	(0)
2015	65	30	103	3,062	47	38	(35)	(3)
2016	65	27	81	2,216	34	27	(26)	(2)
2017	66	26	72	1,887	29	35	(32)	(2)
Total			*984*	*15,802*	***246***	***196***	***(189)***	***(7)***

P, W, & S denote carbon pricing, wind, & solar, respectively. Appendix Tables A1 & A2 provide the underlying data and details on how we calculate expenditures.

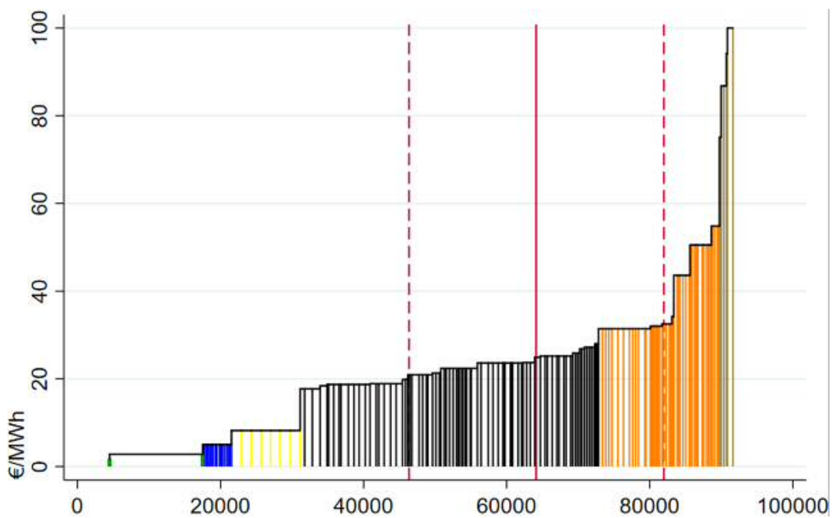
Merit Order effects

We now look at how carbon pricing affects the power supply structure (called the "merit order") in Germany and the UK. In wholesale power markets 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), whereas natural gas plants are located in the rather steep part due to their relatively high marginal costs. At its intersection with demand, under the assumption of perfect competition, the marginal costs of the marginal power plant determine the wholesale price of electricity. 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.[11]

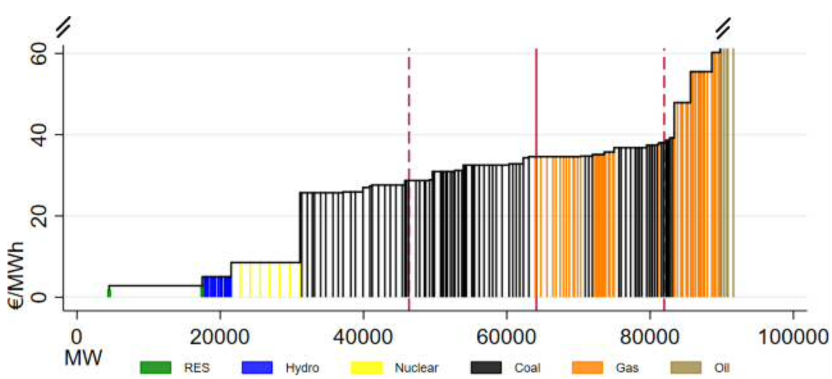
[11] In contrast to our econometric model, which also takes dynamic processes into account, we abstract from the following factors in this static analysis of merit order curves: "must run" power plants needed for supply security; start-up and ramping costs of thermal power plants; heat-coupled power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

Figure 4: Merit order for different carbon prices, DE

(a) Merit order at a carbon price of €5



(b) Merit order at a carbon price of €15



The figure depicts sample averages of available net capacities (i.e. installed gross nameplate capacities 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 (81966 MWh) percentiles. Source: own data

As we can see from Figure 4 for Germany, at a low carbon price (i.e. €5/tCO_2; see Figure 4a) and at average demand (= 64,352 MW per hour) coal represents the marginal technology, while all gas plants are out of the merit order.[12] Hence, gas plants serve as peak-load plants, which only become active during times of higher demand. At subsequently higher carbon prices, fuel switching between the most effective gas plants and the least effective coal plants begins to takes 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 Figure 4b).

For the UK, the picture is even more pronounced, as shown in Figure 5. 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 mean demand (i.e. 35,544 MW per hour), gas represents the marginal technology, which determines the wholesale price. At a higher carbon price of €15, a large proportion of gas plants switch their positions with coal plants in the merit order. For this particular case, 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 mean 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 (and/or during very low wind or solar feed-in).

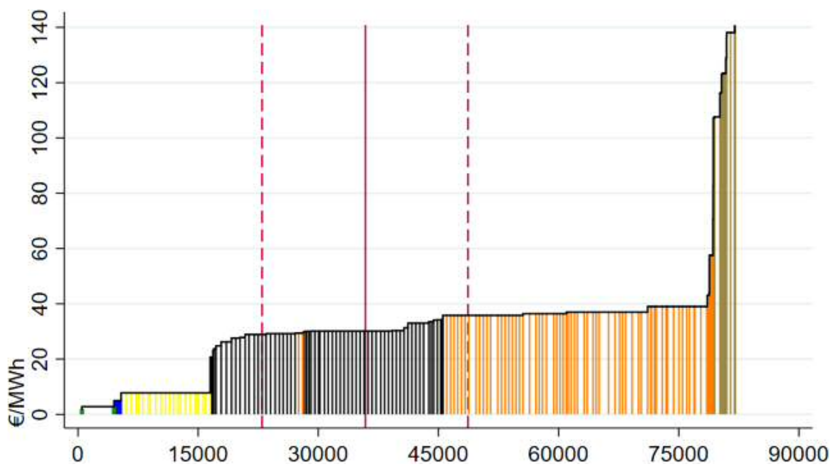
Given long time-to-build lags, it is evident that the scope for emissions reduction through short-term fuel switching crucially depends on the available electricity generation capacity of gas and coal plants. While Germany's gas capacity is only 40% of its coal capacity, in the UK gas may fully replace coal. However, there may be substitution among relatively efficient and inefficient coal plants. That is, a high carbon price may also switch the positions of outdated coal plants and new efficient ones, contributing to emission reduction.

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 substitutive (the policies become less effective) or complementary (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 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. In the UK, on the other hand, gas is more likely to be the marginal technology to start with, and higher carbon prices may reduce the effectiveness of wind (and solar).

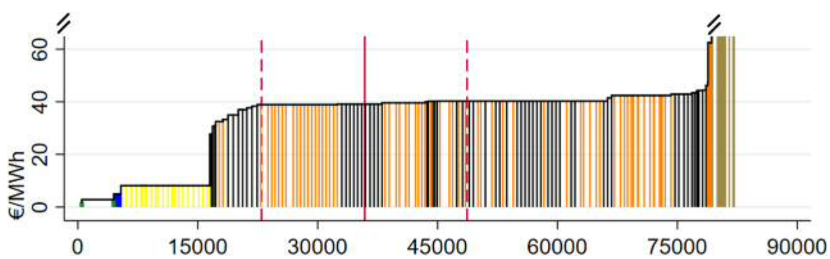
[12]The Merit Orders in Figures 4 and 5 depict the sample averages of available net capacities by generation technology. The installed gross nameplate capacities are corrected for average plant outages (e.g. for maintenance and availability factors adjusted to season). Solar, wind, and hydro electricity are depicted for their sample average feed-in. Demand is given for its sample average.

Figure 5: Merit order for different carbon prices, UK

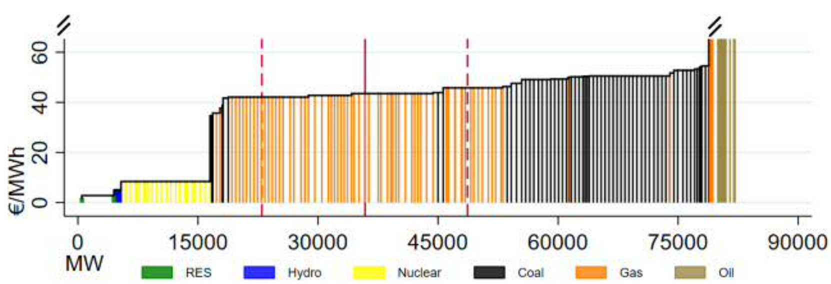
(a) Merit order at a carbon price of €5



(b) Merit order at a carbon price of €15



(c) Merit order at a carbon price of €25



The figure depicts sample averages of available net capacities (i.e. installed gross nameplate capacities 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. Source: own data.

Analogously, Germany and the UK 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 (e.g. nuclear power from France) until the interconnection capacity is exhausted (or until wholesale prices are equal; see the discussion in Gugler et al., 2018). In Figures 4 and 5, higher net imports can be interpreted as a reduction in national demand (i.e. a shift of demand to the left). Thus, with an increasing carbon price, the wholesale price of electricity increases, which may trigger net imports. Our main results for Germany will show that at initially low carbon prices, a marginal increase in the carbon price offsets emissions from coal *and gas*, indicating that both technologies produce less power, but imports balance the missing supply. Then, at higher carbon prices, power from gas becomes profitable leading (in parts) to a fuel switch. For the UK, however, interconnection capacity is limited,such that while at a high carbon price (and especially during high demand) some power may be imported, most of the missing supply from coal is filled by electricity from gas.

3 Methodology

We exploit exogenous variations in wind (W) and solar (S) generation, and in the effective carbon price (P) and load (L; i.e. electricity demand) to explain changes in emissions (y) from thermal electricity plants. Wind and solar electricity feed-in is exogenous, at least in the short run, as these RES are determined by the weather (e.g. wind speed, solar radiation, air density; 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 the overall emissions cap for all participating countries and sectors.[13] Thus, from the perspective of an individual power plant operator, the ETS price can be viewed as exogenous. For the UK, 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 long (years) before any supply or demand realizations of coal or gas power plants. Thus, we also treat the UK carbon price as exogenous. It is also well established that electricity demand is exogenous.[14]

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 plants (actually our data are at the turbine level) in Germany and the UK. Regarding the exogenous variables, we include the level and square of P because the impact of the emissions price on emissions

[13] In a similar analysis, Abrell et al. (2019a) also treat the carbon price as exogenous.

[14] For example, Blázquez et al. (2013) estimate an inelastic electricity demand for Spain both in the short and long run.

may be non-linear. The interactions of P with W, S, and L imply that the effectiveness of the emissions price may also depend upon 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. In 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 variables (see also Cullen, 2013, p.117–118). 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 $\Delta X_{t-i} = X_t - X_{t-i}$.

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. For the UK, 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 hours of remaining operation ('opt-out' option). Since December 2012, nine UK power stations have chosen to cease production (DEFRA, 2012; National Grid, 2007) due to this constraint. We adapt the set of time fixed effects to the different sample periods for Germany (shorter period: 1 January 2017–29 June 2018) and the UK (longer period: 27 May 2011–15 July 2018). For the UK, we apply a set of day-of-week fixed effects as well as quarter-year fixed effects (Fell and Kaffine, 2018). For Germany, we apply day-of-week fixed effects as well as monthly fixed effects.

Thus, our specification isolates from other confounding effects the effects of carbon pricing as well as of wind and solar production on emissions :

$$y_{p,c,n,t} = \sum_{i=1}^{2} \beta_{Pi} P_{t,c}^{i} + \beta_{PW} P_{t,c} W_{t,c} + \beta_{PS} P_{t,c} S_{t,c} + \beta_{PL} P_{t,c} L_{t,c} + \beta_{PCR} P_{t,c} CR_{t,c} +$$
$$\sum_{i=1}^{3} \beta_{Wi} W_{t,c}^{i} + \sum_{i=1}^{3} \beta_{Si} S_{t,c}^{i} + \sum_{i=1}^{3} \beta_{Li} L_{t,c}^{i} + \sum_{i=1}^{3} \beta_{CRi} CR_{t,c}^{i} +$$

$$\sum_{i=1}^{3}\sum_{j=1}^{3}\beta_{WiLj}W_{t,c}^{i}L_{t,c}^{j}+\sum_{i=1}^{3}\sum_{j=1}^{3}\beta_{SiDj}S_{t,c}^{i}L_{t,c}^{j}+\sum_{i=1}^{3}\sum_{j=1}^{3}\beta_{WiSj}W_{t,c}^{i}S_{t,c}^{j}+$$
$$\sum_{i=1}^{5}\beta_{\Delta Wt-i}\Delta W_{t-i,c}+\sum_{i=1}^{5}\beta_{\Delta St-i}\Delta S_{t-i,c}+\delta_{p}D_{p}+\delta_{t}D_{t}+\epsilon_{p,c,n,t}. \tag{1}$$

The subscripts define each power plant turbine p, located in country c (= DE, UK) using electricity generation technology n (= coal, gas) at day t of our sample. For the UK, 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 the UK's total generation (see Figure B1b).[15] Thus, including data on solar electricity production with long periods of zero values would render our highly non-linear econometric estimations impossible.[16]

Since we observe permanent plant exits in the UK, running equation (1) by OLS would not account for this. Outright exits and zero-production periods would only be captured on the extensive margin (on/off decision). 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 response. The two-step model (see, e.g., Greene, 2008, Ch. 24) is as follows. In step one, we estimate 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 ($z_{p,c,n,t} = 1$ if $y_{p,c,n,t} > 0$ and $z_{p,c,n,t} = 0$ if $y_{p,c,n,t} = 0$):

$$z_{p,c,n,t}=\sum_{i=1}^{2}\alpha_{Pi}P_{t,c}^{i}+\alpha_{PW}P_{t,c}W_{t,c}+\alpha_{PS}P_{t,c}S_{t,c}+\alpha_{PL}P_{t,c}L_{t,c}+\alpha_{PCR}P_{t,c}CR_{t,c}+$$
$$\sum_{i=1}^{3}\alpha_{Wi}W_{t,c}^{i}+\sum_{i=1}^{3}\alpha_{Si}S_{t,c}^{i}+\sum_{i=1}^{3}\alpha_{Li}L_{t,c}^{i}+\sum_{i=1}^{3}\alpha_{CRi}CR_{t,c}^{i}+$$
$$\sum_{i=1}^{3}\sum_{j=1}^{3}\alpha_{WiLj}W_{t,c}^{i}L_{t,c}^{j}+\sum_{i=1}^{3}\sum_{j=1}^{3}\alpha_{SiDj}S_{t,c}^{i}L_{t,c}^{j}+\sum_{i=1}^{3}\sum_{j=1}^{3}\alpha_{WiSj}W_{t,c}^{i}S_{t,c}^{j}+$$
$$\sum_{i=1}^{5}\alpha_{\Delta Wt-i}\Delta W_{t-i,c}+\sum_{i=1}^{5}\alpha_{\Delta St-i}\Delta S_{t-i,c}+\delta_{p}D_{p}+\delta_{t}D_{t}+$$
$$\sum_{i=1}^{5}\alpha_{Lt-i}\Delta L_{t-i,c}+u_{p,c,n,t}. \tag{2}$$

The exclusion restriction rests on the inclusion of the five day lags of load ($\sum_{i=1}^{5}\Delta L_{t-i,c}$; 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

[15] 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).

[16] For this reason, the empirical model for UK plants reduces to: $y_{p,c,n,t} = \sum_{i=1}^{2}\beta_{Pi}P_{t,c}^{i} + \beta_{PW}P_{t,c}W_{t,c} + \beta_{PL}P_{t,c}L_{t,c} + \beta_{PCR}P_{t,c}CR_{t,c} + \sum_{i=1}^{3}\beta_{Wi}W_{t,c}^{i} + \sum_{i=1}^{3}\beta_{Li}L_{t,c}^{i} + \sum_{i=1}^{3}\beta_{CRi}CR_{t,c}^{i} + \sum_{i=1}^{3}\sum_{j=1}^{3}\beta_{WiLj}W_{t,c}^{i}L_{t,c}^{j} + \sum_{i=1}^{5}\beta_{\Delta Wt-i}\Delta W_{t-i,c} + \delta_{p}D_{p} + \delta_{t}D_{t} + \epsilon_{p,c,n,t}$.

(IMR), as $\hat{\lambda}_{p,c,n,t} = \phi(.)/\Phi(.)$, where ϕ is the normal pdf and Φ is the cdf.

In step two, we run the outcome equation (1), corrected for selection by adding $\hat{\lambda}$, via OLS: $y_{p,c,n,t} = \mathbf{X}_{p,c,n,t}\beta + \rho\hat{\lambda}_{p,c,n,t} + \epsilon_{p,c,n,t}$. From this, we can predict the *full effect* of carbon pricing, which is composed of the *intensive* and *extensive* margin impacts (see also Fell and Kaffine, 2018):

$$\mathbb{E}[y_{p,c,n,t}|\mathbf{X}_{p,c,n,t},\mathbf{V}_{p,c,n,t}] = \phi(\mathbf{V}_{p,c,n,t}\alpha)[\mathbf{X}_{p,c,n,t}\beta + \rho\lambda_{p,c,n,t}]. \quad (3)$$

The estimated probability of having positive emissions ($\phi(\mathbf{V}_{p,c,n,t}\alpha)$) represents the extensive margin impact, whereas the intensive margin impact is given by $[\mathbf{X}_{p,c,n,t}\beta + \rho\lambda_{p,c,n,t}]$.

4 Data

We utilize data on daily electricity production from coal and gas power-plant turbines in Germany and the UK to calculate CO_2 emissions at the power-plant turbine level. In our sample, we observe 85 coal and 53 gas power plants in Germany and 63 coal and 78 gas power plants in the UK. The electricity generation data stem from the EEX (2018) Transparency Platform for Germany and from PLATTS PowerVision (2018) (i.e. coal- and gas-fired generation) and Gridwatch (2018) (i.e. wind and solar generation) for the UK.[17] We merge these data by 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 factors and efficiency factors by plant vintage as provided by the Austrian Transmission System Operator, Austrian Power Grid (APG).[19] In aggregate, our calculated emissions properly fit official statistics on CO_2 emissions, which is evidence that our modeling approach is sophisticated.[20]

Data on the EU ETS carbon price come from the EEX (2018).[21] Data on the unilateral carbon tax in the UK, which tops up the ETS price, stem from House of Commons (2016). Moreover, we obtain data of hourly wind and solar feed-in as well as demand in Germany, available for the hourly period 1 January 2017–29 June 2018, from ENTSO-E (2018). For the UK, we

[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 the UK electricity market in cooperation with Sheffield University. The reason for choosing Gridwatch as the main data source for the UK is that the data are available for a much longer time period (i.e. since 27 May 2011) than the EEX data.

[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] Umweltbundesamt (2018) publishes emissions and efficiency factors for Germany's thermal power plants.

[20] A comparison of our sample data of yearly aggregated UK emissions (as derived from the electricity generation data) with official statistics from BEIS (2018) give an average consistency of 99% for the years 2012–2017 (for which we observe the full yearly period in our data). Our sample data of German emissions accord with official statistics from Umweltbundesamt (2018) to 85% for the year 2017 (for which we observe the full yearly period in our data). The difference occurs because the EEX data in our sample only cover power plants equal or greater than 100 MW (so small plants are not covered).

[21] The EEX Transparency Platform provides information about Central European wholesale energy markets.

Table 2: Summary statistics

(a) Germany							
Variable	Mean	StD.	Min	p25	p50	p75	Max
Coal-based emissions (tCO2)	6,334	5,765	0	1,265	4,952	10,313	21,187
Gas-based emissions (tCO2)	661	1,015	0	0	8	1,154	6,594
Carbon price (€)	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)	1,544	182	666	1,429	1,573	1,682	1,881
Cost ratio (P_{coal}/P_{gas})	0.51	0.06	0.18	0.46	0.52	0.55	0.62

(b) United Kingdom							
Variable	Mean	StD.	Min	p25	p50	p75	Max
Coal-based emissions (tCO2)	3,355	4,979	0	0	0	8,011	15,343
Gas-based emissions (tCO2)	1,143	1,514	0	0	0	2,181	9,168
Carbon price (€)	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	1,195
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. UK: sample period is May 27, 2011–July 15, 2018.

obtain data on wind feed-in and demand from Gridwatch (2018) for the much longer hourly period 27 May 2011–15 July 2018. This is important, because we observe low carbon prices in the UK before the introduction of the top-up tax on 1 April 2013, and the subsequent increases of the unilateral tax in 2014 and 2015. We aggregate the hourly data to the daily frequency to match the other data. 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, as in Cullen and Mansur (2017) and Fell and Kaffine (2018).

Table 2 provides summary statistics for Germany and the UK. We can see that the German electricity market, with an average daily load of 1,544 GWh, is about twice the size of the British market, which has an average load of 814 GWh. On average, a German power plant emits 6,995 tCO_2 each day, which can be almost entirely attributed to coal-based emissions (6,334 tCO_2) with a minor fraction to gas (661 tCO_2). In the UK, average emissions per coal plant (3,355 tCO_2) and per gas plant (1,143 tCO_2) are not as unbalanced as in Germany. Moreover, the share of wind in Germany (19.8% = $306/1,544$) is much more pronounced than in the UK (7% = $59/814$). The carbon price in Germany is determined by the EU ETS, with a daily mean of €7.82, whereas the effective UK carbon price, composed of the EU ETS price plus the CPS, lies at a much higher mean of €19.71. The standard deviations of all variables are high relative to their means, pointing to sufficient variation for econometric regression.

5 Results

This section presents our empirical results on the effectiveness of emissions abatement from carbon pricing and from wind and solar power. We first discuss our results for Germany. In contrast to the UK, Germany has not intervened unilaterally against the low EU ETS carbon price, but rather relies on vast subsidies for wind and solar power. Next, we provide evidence for the UK, which has less wind and solar power in place but a significantly higher effective carbon price due to its unilateral top-up tax on the EU ETS price. Finally, we put our results into perspective and evaluate the climate policies in Germany and the UK in terms of directly attributable costs.

5.1 CO_2 abatement: Germany

Carbon pricing

In Table 3, we predict the *daily* emissions of *all* German coal and gas power plants for various carbon price levels (evaluated at mean values for other control variables).[22] Moreover, Table 3 gives the marginal abatement effect at each carbon price, which is calculated as the additional CO_2 abatement if the price increased by one Euro. All estimates are based on the Heckman regression estimates of equations (1) and (2), as provided in Table B3 in the Online Appendix. To do this, we use the estimates from the Heckman two-step estimator (eq. 3) incorporating both the intensive (i.e. generation conditional on operating) and extensive (on/off decision) margin responses.[23] We present the estimates for Germany within a relatively narrow range of *observed* carbon prices between €4 and €16 (as well as out-of-sample predictions for low carbon prices between €0 and €4) during the sample period January 1, 2017–June 29, 2018.

At a low carbon price of €1/tCO_2, we predict 586,621 tCO_2. Predicted emissions drop by 21% once we reach a carbon price of €16 (i.e. 461,289 tCO_2). The total marginal abatement increases modestly from 8,162 tCO_2 at a carbon price of €4/tCO_2 to 8,766 tCO_2 at €9/tCO_2 and then modestly declines again to 8,258 at €15/tCO_2. However, the marginal abatement effects on coal differ from those on gas-based emissions. At successively higher carbon prices, *coal*-fired emissions decline significantly, resulting in higher marginal abatement effects. At a low price of €4, a marginal increase in the carbon price by €1 (to €5) abates 6,525 tCO_2 per day from coal-fired electricity generation (of all German coal-fired power plants). At a price

[22] That is, we predict the average daily emissions per power plant (eq. 3) and then multiply this value by the number of power plants.

[23] Tables A3 and A4 in the Appendix present the estimated probabilities of producing electricity with coal or gas-fired power plants for various levels of the carbon price as well as for different wind, and solar feed-in levels.

Table 3: Effects of carbon pricing, DE

Carbon price (€/tCO_2)	Predicted emissions (tCO_2)			Marginal abatement (tCO_2)		
	Coal	Gas	Total	Coal	Gas	Total
			Out of sample			
1	552,701	33,920	586,621	5,033	2,208	7,241
2	547,668	31,712	579,380	5,581	2,018	7,599
3	542,087	29,694	571,782	6,078	1,827	7,905
			In sample			
4	536,009	27,868	563,876	6,525	1,636	8,162
5	529,484	26,231	555,715	6,921	1,449	8,370
6	522,563	24,782	547,345	7,266	1,267	8,533
7	515,297	23,514	538,811	7,561	1,091	8,652
8	507,736	22,424	530,159	7,809	920	8,729
9	499,927	21,503	521,430	8,010	756	8,766
10	491,917	20,748	512,664	8,168	597	8,764
11	483,749	20,151	503,900	8,285	442	8,727
12	475,465	19,708	495,173	8,364	292	8,655
13	467,101	19,417	486,518	8,408	144	8,552
14	458,693	19,273	477,966	8,421	-3	8,419
15	450,271	19,276	469,547	8,407	-149	8,258
16	441,864	19,425	461,289			

All estimates are evaluated at means for other control variables. Predicted emissions and marginal abatement effects are calculated as a composite of *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.

of €15, a marginal increase (to €16) brings about a reduction of 8,407 tCO_2 per day due to reduced coal-fired electricity generation.

Naturally, the marginal abatement effects of the carbon price on emissions from *gas*-fired electricity generation are much smaller, since gas plants produce less electricity than coal plants, and each MWh of electricity produced from gas plants contains less CO_2 (less than half compared to old coal plants) than from coal. Moreover, marginal abatement declines with rising carbon prices. At a low carbon price of €4, 1,636 tCO_2 per day are abated at the margin. But at a carbon price of €14 marginal abatement turns negative, meaning that predicted emissions from gas increase. This is the turning point for *fuel switching* in Germany. For carbon prices of €14 or higher, the most ineffective coal plants are replaced by the most effective gas plants, which thus produce more emissions at the margin.

Taking the results of coal and gas together, we observe fairly constant marginal abatement (see Table 3) over the observed range of carbon prices in Germany. During our sample period, the mean ETS price is only around €8, which marginally offsets on average 8,729 tCO_2 per day (evaluated for the average carbon price of €8 and for means of other control variables). That is, the installation of the EU ETS reduces, on average, merely 9.6% of the daily emissions relative to having no carbon price in place (i.e. relative to predicted emissions of 586,621 tCO_2 at a carbon price of €1/tCO_2) in Germany, implying that the carbon offset has been modest so far. In contrast, an ETS price as high as €15 replaces already 21% of average predicted emissions in Germany relative to no CO_2 price in place. In practice, it seems that the relatively modest carbon prices observed in Germany have only had limited effectiveness in terms of abating CO_2 emissions.

The limited effectiveness of the carbon price in Germany can be explained by the logic of electricity markets. At a low ETS 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 Figure 4a. Only at higher carbon prices (from €14 on), would more and more electricity generation from coal be replaced by gas, which significantly increases the effectiveness of the CO_2 price.

One may wonder which sources of electricity would re-establish demand-supply parity at each instant in Germany, if both coal- and gas-fired generation were eventually reduced by an increase in the carbon price (as observed for carbon prices up to €14; see Table 3). 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. Only for carbon prices above €14 does fuel switching unfold, i.e. more and more gas replaces coal, which would be the most effective short-term climate policy available.[24] This implies that Germany's effectiveness in terms of replacing emissions through carbon pricing depends heavily on imports (whereas the UK is relatively shut off from electricity imports; see also Online Appendix Tables B5 and B6). These imports, however, may also contain emissions, which are not taken into account, thus putting the effectiveness of carbon pricing in Germany (i.e. 21% emissions reduction at a price of €16) into perspective.

Wind and solar

Table 4 shows the marginal abatement effects of wind and solar power in Germany (evaluated at means for other control variables). Both marginal abatement curves imply 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. Indeed, Figure 4a shows that for a low carbon price (as we observe most of the time in Germany) and for average demand, wind essentially offsets coal emissions, making it highly effective. By taking the integral over the marginal abatement

[24] Short-term fuel switching is, of course, only possible in countries with enough installed capacity of gas-fired power plants.

Table 4: Marginal abatement effects of wind & solar, DE

Wind (GWh)	Mrg. abatement (tCO2)			Solar (GWh)	Mrg. abatement (tCO2)		
	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 5: Marginal abatement effects of wind & solar for different carbon prices, DE

Carbon price (€)	Wind: mrg. abatem. (tCO2)			Carbon price (€)	Solar: mrg. abatement (tCO2)		
	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).

function up to the sample mean value of wind,[25] we estimate that, on average, wind in Germany abates 126,340 tCO_2 per day. Evaluated against predicted emissions of 689,607 tCO_2 during zero wind feed-in (and evaluated at means for other control variables), wind in Germany replaces an average of 18% of daily emissions.

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. That is, evaluated at the relatively low sample mean of the ETS price (i.e. €7.82/tCO_2) and average demand, solar can increasingly replace mainly coal, so that it can unfold its full abatement potential. Taking the integral over the marginal abatement function up to the sample mean of solar production of 110 GWh, 29,607 tCO_2 are offset each day, on average. Again, evaluated against predicted emissions of 589,707 tCO_2 during zero solar feed-in (and evaluated at means for other control variables), solar in Germany only replaces an average of 6% of daily emissions.

Moreover, we can show that for relatively low carbon prices as observed in Germany (i.e. €4–€16/tCO_2), wind and solar power complement the EU ETS. Table 5 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. However, once the carbon price is high enough to induce extensive fuel switching, such that most coal-based emissions get replaced, wind and solar may only be able to further offset emissions from gas. This would severely limit their effectiveness (as it already seems to be the case in the UK; see Section 5.2).[26]

So far, we have shown that the effectiveness of the limited range of carbon prices observed in Germany has only been modestly successful in abating CO_2 emissions because the price was not high enough to induce vast fuel switching. For the German supply structure, having relatively modern coal plants and rather inefficient gas plants, fuel switching starts at around €14/tCO_2. Hence, we would need carbon prices well above €14 to benefit from a significant short-term reduction in emissions due to large-scale replacement of coal with gas.[27] Moreover, we show that as long as vast amounts of coal and gas have not switched positions in the merit order, wind and solar as policy tools are complementary to the EU ETS. Finally, evaluated for average conditions, wind outperforms solar power, making it the more effective tool for climate policy in Germany. However, our results are not yet indicative about the *cost* effectiveness of each individual climate policy, which we will investigate in Section 5.3. Before we do so, we present our main results for the UK, which follows a climate strategy of high carbon

[25] We approximate the integral over the marginal abatement function up to an average feed-in of 300 GWh wind as $50 \cdot (482 + 447 + 420 + 401 + 390 + 386) = 126,340$ tCO_2.

[26] In the Online Appendix, we also evaluate the effectiveness of wind and solar against load and find that while wind's effectiveness stays nearly constant, solar's effectiveness strongly vanishes with higher load.

[27] As predicted by our model, this seems to be happening at the time of writing (July, 2019), when the EU ETS price reached around €25. In the first half of 2019, German CO_2 emissions from electricity production decreased by 15%, because of coal-gas switching (see FAZ, 4 July 2019, "Stromerzeugung verursacht deutlich weniger CO2", www.faz.net/aktuell/wirtschaft/stromerzeugung-verursacht-deutlich-weniger-co2-16268214.html, access 10 July 2019).

prices instead of a vast subsidization of wind and solar power.

5.2 CO_2 abatement: UK

Carbon pricing

As mentioned above, the UK has experienced a much larger effective carbon price from 1 April 2013 onward, since it introduced the unilateral top-up tax (the CPS) in addition to the EU ETS price. This policy measure allows us to estimate the effects of the carbon price over a much wider price range than for Germany. During the sample period 27 May 2011–15 July 2018, we observe carbon prices between €4 and €37.

Again, we use our Heckman estimates of equations (1) and (2) (see Appendix Table B4 for the regression output) and derive the full effect (eq. 3) of the carbon price, including the intensive and extensive margin responses. While we found fairly constant marginal abatement within the range of observed carbon prices of €4–€16 in Germany, Table 6 shows that in the UK marginal abatement is a concave function, which significantly increases from low to medium carbon prices until it reaches a maximum at €29/tCO_2. The daily predicted emissions from *all* UK coal and gas power plants fall from 273,197tCO_2 at a price of €1 to 189,703 tCO_2 at a carbon price the hight of €38 during the very recent sample period (i.e. a difference of 83,494 tCO_2 per day) – a reduction by 31% attributable to the carbon price. From Table 6 we also observe that vast amounts of coal-based emissions are replaced at medium to high carbon prices. That is, 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 the UK.

Our estimates also show that at a carbon price of €14/tCO_2, fuel switching sets in. This is indicated by negative marginal abatement from gas, meaning that more and more electricity is produced from gas power plants, substituting for the loss of coal-fired electricity. Thus, in line with Germany, the replacement of the most ineffective coal plants by the most efficient gas plants starts at a carbon price of around €14. With even higher carbon prices well beyond €38/tCO_2, the marginal offset of coal-based emissions would start declining, as fewer and fewer coal plants stay in the merit order to be pushed out. This is why total marginal abatement (as the sum of marginal abatements of coal- and gas-based emissions) finally tapers off for high carbon prices.

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 the UK electricity market. [28] During our sample period (27 May 2011–15 July 2018), 33 power plant units with a total capacity of 14,250

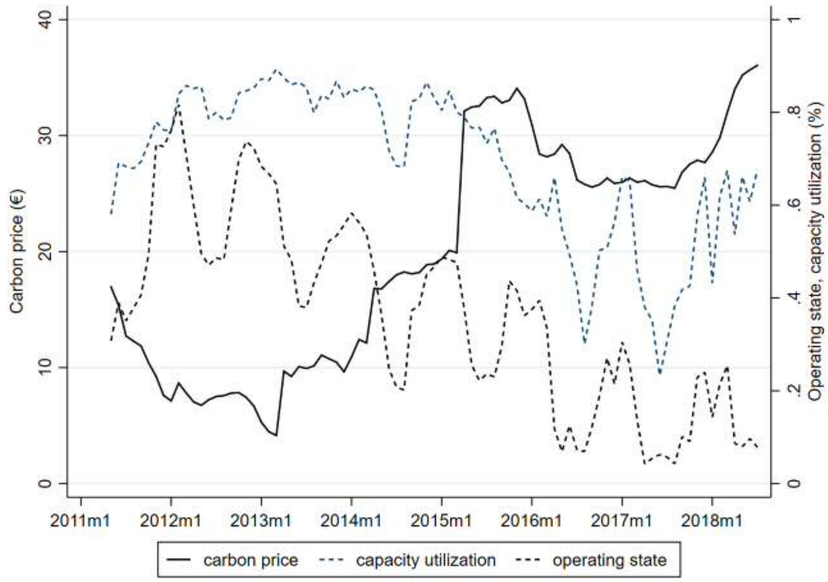
[28] For Germany, although we do observe periods of inaction for some power plants, we do not observe the permanent exit of any coal plants during our observation period.

Table 6: Effects of carbon pricing, UK

Carbon price (€/tCO_2)	Predicted emissions (tCO_2)			Marginal abatement (tCO_2)		
	Coal	Gas	Total	Coal	Gas	Total
Out of sample						
1	213,400	59,797	273,197	-1,116	1,197	81
2	214,516	58,600	273,116	-854	1,091	237
3	215,369	57,509	272,879	-591	986	395
In sample						
4	215,960	56,523	272,483	-329	884	555
5	216,289	55,639	271,928	-68	783	715
6	216,357	54,856	271,213	192	684	876
7	216,166	54,172	270,337	449	587	1,036
8	215,716	53,585	269,301	705	490	1,195
9	215,011	53,095	268,106	958	395	1,353
10	214,053	52,700	266,753	1,208	301	1,509
11	212,846	52,399	265,244	1,454	207	1,661
12	211,392	52,191	263,583	1,697	114	1,811
13	209,695	52,077	261,772	1,935	21	1,956
14	207,760	52,056	259,816	2,168	-71	2,097
15	205,592	52,127	257,719	2,396	-164	2,232
16	203,196	52,291	255,487	2,618	-256	2,362
17	200,578	52,547	253,125	2,835	-349	2,485
18	197,743	52,897	250,640	3,044	-443	2,601
19	194,699	53,340	248,039	3,246	-537	2,709
20	191,453	53,877	245,329	3,441	-632	2,810
21	188,011	54,508	242,520	3,628	-727	2,901
22	184,383	55,236	239,619	3,807	-824	2,983
23	180,576	56,059	236,636	3,976	-921	3,055
24	176,600	56,981	233,581	4,136	-1,019	3,117
25	172,464	58,000	230,464	4,287	-1,119	3,168
26	168,177	59,119	227,296	4,427	-1,219	3,208
27	163,751	60,338	224,088	4,556	-1,321	3,236
28	159,194	61,658	220,853	4,675	-1,423	3,252
29	154,520	63,081	217,601	4,782	-1,526	3,256
30	149,738	64,607	214,345	4,877	-1,630	3,247
31	144,861	66,238	211,098	4,960	-1,735	3,225
32	139,900	67,973	207,873	5,031	-1,841	3,191
33	134,869	69,813	204,682	5,090	-1,946	3,143
34	129,779	71,760	201,539	5,135	-2,053	3,083
35	124,644	73,812	198,456	5,167	-2,159	3,009
36	119,477	75,971	195,448	5,187	-2,265	2,922
37	114,290	78,236	192,526	5,193	-2,370	2,823
38	109,097	80,606	189,703			

All estimates are evaluated at means for other control variables. Predicted emissions and marginal abatement effects are calculated as a composite of *all* UK 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.

Figure 6: UK 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.

MW left the market permanently, while only 30 coal plants with a total capacity of 13,885 MW remained active (c.f. Online Appendix Tables B1 and B2). Moreover, spells of inactive periods of coal plants increased significantly during times of high CO_2 prices following the introduction of the unilateral top-up tax. Figure 6 shows 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 diminishes 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.[29] In addition, Figure 6 indicates that with a high carbon price since the last price jump on 1 April 2015, active coal plants' production (dashed blue line) becomes more volatile, most likely because coal and gas plants have switched their positions, such that coal has taken the peak-load function and gas serves as base-load (i.e. less volatile production).

Appendix Table A5 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 declines significantly from 39% at a carbon price

[29] 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.

of €5 to 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 to 56% at a price of €37, indicating that gas substitutes for electricity production from coal both on the intensive as well as extensive margin.

To sum up, the supply structure in the UK, with relatively efficient gas plants and relatively inefficient coal plants, allows for vast fuel switching at medium to high carbon prices. We find that 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 price of €29, although it remains substantial over the whole range of observed prices. Both coal and gas respond in both dimensions, the intensive and extensive margins, although in opposite directions. Thus, the carbon price itself helped encourage a large number of coal power plants to exit the market for good in the UK.

Wind

The UK has significantly less feed-in of wind power than Germany (both in relative and absolute terms). Table 7 gives the marginal abatement effects of wind for different feed-in levels in the UK, evaluated at means for other control variables. Importantly, we evaluate the marginal effectiveness of wind conditional on the sample average carbon price of €19.71, at which many coal and gas plants have already switched their positions. Thus, we can see that wind replaces not only emissions from coal but also from gas. The marginal abatement curve is concave with a maximum effectiveness of 992 tCO_2 at wind feed-in level of 100 GWh. This is in stark contrast to Germany, where wind feed-in of 100 GWh brings about a marginal replacement of only 447 tCO_2. The higher effectiveness of UK'S wind in terms of emissions reduction than in Germany is most likely because for a higher average carbon price, wind can (at least partly) push coal out of the merit order, whereas in Germany it is mainly gas that is replaced for a relatively low average carbon price. At the sample mean of around 60 GWh (actually 59.32 GWh) of wind feed-in, wind marginally replaces 962 tCO_2 (i.e. 655 tCO_2 from coal and 307 tCO_2 from gas) per day. Wind's total abatement in the UK, calculated as the integral up to 60 GWh of wind,[30] is about 54,000 tCO_2. This means that the sample average wind feed-in in the UK replaces 17% of total predicted emissions without wind (i.e. 313,494 tCO_2 per day evaluated for zero wind feed-in and at the means of other control variables).

Table 8 shows the marginal performance of wind power, evaluated at its sample average feed-in, abating emissions for the range of observed carbon prices. The higher the carbon

[30] We approximate the integral over the marginal abatement function of wind as $10 \cdot (823 + 860 + 892 + 920 + 943 + 962) = 54,001$ tCO_2.

Table 7: Marginal abatement effects of wind, UK

Wind (GWh)	Marginal abatement (tCO_2)		
	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.

price, the lower the marginal reduction of coal-powered emissions and the larger the marginal reduction of gas-powered emissions. A higher carbon price moves coal more and more out of the merit order leaving less to be replaced by wind, and at the same time moves more and more gas into the merit order to be replaced by wind. Thus, with fewer coal-based emissions to be offset by wind with higher carbon prices, wind offsets progressively more gas at higher carbon prices. In total, 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 (e.g. €36), the effectiveness of wind reduces by around half compared to its effectiveness at low carbon prices (e.g. €4) because the potential for replacing coal-based emissions vanishes. Moreover, Figure C2 in the online appendix indicates that the effectiveness of wind in the UK tapers off at high electricity demand, because during peak load wind offsets gas rather than coal at the margin.

Table 8: Marginal abatement effects of wind for different carbon prices, UK

Carbon price (€)	Wind: marginal abatement (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.

5.3 Cost effectiveness of climate policies

As laid out above, the empirical results so far have only addressed the effectiveness of carbon pricing and feed-in of wind and solar power in terms of abating CO_2 emissions. Cullen (2013) points out when valuing offset emissions one needs to consider the regulatory status of the pollutant and its marginal damage costs. Offset emissions do not imply a reduction in total emissions if emissions are regulated under a binding cap-and-trade program such as the EU ETS (i.e. the "water-bed effect"). That is, if one country introduces a unilateral abatement policy (e.g. a top-up-tax to the EU ETS price as in the UK or vast subsidies for RES as in Germany), abated emissions lead to an abundance of emissions permits, which will be used for emissions somewhere else. Moreover, marginal damage costs would have to be estimated, which is beyond the scope of this paper (see, e.g. Tol, 2005, for a review of this literature). For these reasons, we confine our analysis to the question of the directly attributable costs of the various policies.[31]

[31] We only account for the direct payments of generators (DE: payments for EU ETS allowances; UK: payments for EU ETS allowances plus tax payments due to the CPS). We do not account for increased total production costs due to fuel switching (i.e. a rising carbon price leading to an increase in more expensive natural gas and a decrease in cheaper coal generation) or other electricity substitution (such as imports).

That is, we try to answer the question: what have been the costs of each tonne of CO_2 abatement using a carbon price or subsidies for wind or solar power? Moreover, it should be kept in mind that we estimate the costs of CO_2 abatement policies only in the respective areas of the policy, Germany and the UK. We do not account for the externalities of these policies, such as pollution permits being freed up for use elsewhere in the EU ETS system, nor for possible leakage or import/export effects.[32]

Germany

We measure the costs of marginal abatement from carbon pricing in Germany based on our estimates, as presented in Table 3, as follows.[33] We utilize the total predicted emissions attributable to each carbon price to calculate the associated costs simply as the carbon price multiplied by the respective emissions. This further allows for calculating the marginal costs related to each carbon price as the change in costs by an incremental increase in the carbon price (e.g. from €4 to €5). We finally divide the marginal costs by the marginal abatement for each carbon price to arrive at the *costs of marginal abatement* of one tCO_2.

Table 9 presents the costs of marginally abating one tonne of CO_2 for each carbon price observed in Germany. The results presented above suggest that within the limited range of ETS prices, predicted emissions from our model decrease only moderately (from 586,621 tCO_2 at €1 to 461,289 tCO_2 at €16) and the respective marginal abatement effects are fairly constant within this range of prices. This yields slightly declining costs of marginal abatement with higher carbon prices. At the sample mean carbon price of around €8, the associated costs of marginal abatement are €52, and for a price as high as €15, it costs €41 to abate an additional tonne of CO_2.

Let us compare the cost effectiveness of carbon pricing with subsidies for wind and solar power in Germany. We estimated that an average GWh of wind production offsets 386 tCO_2 per day (see Table 4; this accords to 0.386 tCO_2 per *MWh*). In 2017, subsidies per MWh feed-in of onshore and offshore wind are €64.71 and €159.07, respectively (CEER, 2018). The feed-in ratio of onshore to offshore wind is 84.4% to 15.6%. We thus calculate the average costs of abating one tCO2 from wind at €204 (= (€64.71 · 0.844+€159.07 · 0.156)/0.386 tCO_2). From Table 4 we can see that marginal abatement tends to increase with higher levels of wind (evaluated for

[32] The possible externalities are varied and complex. E.g., an increased carbon price leads to a reduction of permits used in the UK electricity sector but relieves permits in other industries in the UK and/or in other countries of the ETS, offsetting the initial effect via reduced carbon prices. More wind and solar generation also reduces demand for permits reducing the carbon price leading to less CO_2 abatement elsewhere. Carbon leakage (i.e. the relocation of production sites to countries not covered by the ETS) may not be a big problem in the electricity sector, whereas trade may partially offset the initial effects. For example, the UK carbon tax may lead to a higher wholesale electricity price, attracting electricity imports to the UK (although interconnector capacity limits the scope for trade). The effects on CO_2 emissions depend on the CO_2 content of these imports. Likewise, more wind in Germany may lead to more exports leading to CO_2 offsets also in other countries.

[33] Since it may be difficult to follow the description of how we measure the marginal costs of abatement, Appendix Table 9 provides more details.

Table 9: Cost effectiveness of carbon pricing, DE

(1)	(2)	(3)	(4)	(5)	(6)
Carbon price (€)	Predicted emissions (tCO2)	Marg. abatement (tCO2)	Emissions costs (€)	Marginal costs (€)	Costs of marg. abatem. (€/tCO_2)
	[see Table 3]	[see Table 3]	[(1)·(2)]	[change in (4)]	[(5)/(3)]
Out of sample					
1	586,621	7,241	586,621	572,140	79.02
2	579,380	7,599	1,158,761	556,584	73.25
3	571,782	7,905	1,715,345	540,161	68.33
In sample					
4	563,876	8,162	2,255,506	523,069	64.09
5	555,715	8,370	2,778,575	505,493	60.39
6	547,345	8,533	3,284,068	487,612	57.14
7	538,811	8,652	3,771,680	469,594	54.27
8	530,159	8,729	4,241,275	451,597	51.73
9	521,430	8,766	4,692,872	433,771	49.48
10	512,664	8,764	5,126,643	416,255	47.49
11	503,900	8,727	5,542,899	399,177	45.74
12	495,173	8,655	5,942,076	382,655	44.21
13	486,518	8,552	6,324,731	366,794	42.89
14	477,966	8,419	6,691,524	351,687	41.78
15	469,547	8,258	7,043,211	337,415	40.86
16	461,289		7,380,626		

the mean carbon price of €7.82/tCO_2 and other control variables). This leads to the conclusion that the cost effectiveness of wind also tends to increase with higher shares of wind. At a high level of wind feed-in of 700 GWh (again, evaluated for the mean carbon price), marginal abatement is around 626 tCO_2, which yields an average cost of €126/tCO_2. We thus conclude that while with higher levels of wind in Germany, the average cost effectiveness of wind improves, the cost effectiveness of wind remains well below the cost effectiveness of the carbon price.

The average marginal offset of one GWh of solar is estimated at 270 tCO_2 (see Table 4; this accords to 0.270 tCO_2 per *MWh*). Given average subsidies for solar power of €264.41 per MWh, we calculate the average costs of abating one tCO2 from solar power at €979 (=€264.41/0.270). Again, the marginal effectiveness of solar power tends to increase between the sample average of 110 GWh (270 tCO_2 per day) up to high solar feed-in levels of 250 GWh of 681 tCO_2 per day. At this high level of solar feed-in, the associated costs of marginal abatement significantly fall to €388/tCO_2. However, 250 GWh of solar feed-in reflects the maximum observed in Germany during our sample period, and its associated costs are still significantly higher than those of wind and even more so than those of the carbon price. We can thus conclude that carbon pricing in Germany is significantly more cost effective than the subsidization of wind power and extremely cost effective compared to solar power.

Our cost analysis seems plausible given the findings by Abrell et al. (2019a), who estimate that the costs for abating one tCO_2 through solar power range between €500 and €1,200 in Germany. Regarding wind, the authors estimate costs of €110–€340/tCO_2. Our estimates on the average cost effectiveness of both wind (i.e. 204 €/tCO_2) and solar power (i.e. 979 €/tCO_2) are within these intervals. Also, in line with other scholars (Abrell et al., 2019a; Novan, 2015), we find that the higher subsidies for solar power do not seem to be justified, as wind abates more CO_2 per MWh than solar, evaluated at the sample mean. Novan (2015) estimates that wind outperforms solar in terms of abatement and also concludes that higher subsidies for solar are not justified. Also, although not part of his empirical analysis, he argues that climate policies should be targeted at emissions offset, proposing emissions taxes or tight cap-and-trade programs. We are the first to deliver a comprehensive empirical analysis of carbon pricing as well as RES subsidization to draw a direct comparison of the cost effectiveness of these policies and find corroborative evidence for Novan (2015)'s recommendation.

UK

For the UK, we observe a wider range of carbon prices compared to Germany, up to a price of €37. The predicted emissions from our model, which can be attributed to the respective carbon prices, are given in Table 10.[34] The emissions fall as the carbon price increases, and the resulting marginal abatement function is concave with a maximum at a carbon price of €29. Moreover, from the total costs of emissions, measured as the carbon price times emissions, we get a resulting marginal costs function, which decreases over the range of UK sample prices (as already provided in Table 6) until a carbon price of €36 is reached. Eventually, this gives us a strongly falling function of marginal abatement costs with costs of abatement reaching a minimum of €29.9/tCO_2 at a relatively high carbon price of €36. For carbon prices beyond €36 the costs of marginal abatement increase again (which holds true for the out-of-sample prediction of the costs of marginal abatement).

The relatively low costs of marginal abatement at medium to high carbon prices are good news for effective climate policy-making. With higher carbon prices, more coal gets pushed out of the market, an the gas that generally fills the production gap contains less CO_2 emissions per unit of electricity produced. Eventually, for very high carbon prices beyond €36/tCO_2, there seems to be little scope left for replacing further coal-based emissions, which results in increasing costs of marginally offsetting emissions. At the sample mean of the carbon price of

[34] Due to the highly non-linear model, its corners may be imprecisely estimated. Thus, the costs of marginal abatement of very low carbon prices may be overstated, and should thus be viewed with caution.

Table 10: Cost effectiveness of carbon pricing, UK

(1) Carbon price (€)	(2) Predicted emissions (tCO2) [see Table 6]	(3) Marg. abatement (tCO2) [see Table 6]	(4) Emissions costs (€) [(1)·(2)]	(5) Marginal costs (€) [change in (4)]	(6) Costs of marg. abatem. (€/tCO_2) [(5)/(3)]
Out of sample					
1	273,197	81	273,197	273,035	3,369.50
2	273,116	237	546,232	272,404	1,148.41
3	272,879	395	818,636	271,297	686.24
In Sample					
4	272,483	555	1,089,933	269,709	486.09
5	271,928	715	1,359,642	267,637	374.21
6	271,213	876	1,627,280	265,083	302.67
7	270,337	1,036	1,892,362	262,049	252.93
8	269,301	1,195	2,154,411	258,543	216.30
9	268,106	1,353	2,412,955	254,575	188.15
10	266,753	1,509	2,667,530	250,158	165.82
11	265,244	1,661	2,917,688	245,308	147.65
12	263,583	1,811	3,162,996	240,043	132.56
13	261,772	1,956	3,403,039	234,386	119.82
14	259,816	2,097	3,637,425	228,363	108.91
15	257,719	2,232	3,865,789	222,002	99.45
16	255,487	2,362	4,087,791	215,334	91.17
17	253,125	2,485	4,303,125	208,395	83.86
18	250,640	2,601	4,511,520	201,220	77.36
19	248,039	2,709	4,712,739	193,850	71.55
20	245,329	2,810	4,906,589	186,328	66.32
21	242,520	2,901	5,092,917	178,699	61.60
22	239,619	2,983	5,271,616	171,011	57.33
23	236,636	3,055	5,442,627	163,313	53.46
24	233,581	3,117	5,605,940	155,658	49.94
25	230,464	3,168	5,761,598	148,098	46.75
26	227,296	3,208	5,909,696	140,690	43.86
27	224,088	3,236	6,050,386	133,487	41.25
28	220,853	3,252	6,183,873	126,549	38.92
29	217,601	3,256	6,310,421	119,931	36.84
30	214,345	3,247	6,430,353	113,692	35.02
31	211,098	3,225	6,544,045	107,889	33.45
32	207,873	3,191	6,651,934	102,578	32.15
33	204,682	3,143	6,754,512	97,814	31.12
34	201,539	3,083	6,852,326	93,651	30.38
35	198,456	3,009	6,945,977	90,140	29.96
36	195,448	2,922	7,036,117	87,331	29.89
37	192,526	2,823	7,123,448	85,269	30.21
38	189,703		7,208,717		

around €20, the costs of marginal abatement are estimated at €66/tCO_2. For 2018, the mean carbon price lies at €35, for which the costs of marginal abatement are 30€/tCO_2.

Again, we can compare these findings with the cost effectiveness of wind power. An average GWh of wind power in the UK replaces 962 tCO_2 per day (see Table 7; this accords to 0.962 tCO_2 per *MWh*). In 2017, the average subsidies per MWh of onshore and offshore wind were equal, at €51.76 (CEER, 2018). Thus, the average costs of abating one tCO_2 through wind power are €53.81 (=€51.76/0.962 tCO_2). This is in stark contrast to Germany, were the average effectiveness of wind is much lower (i.e. 386 tCO_2 per GWh of wind) and subsidies are on average higher.

In the UK, the effectiveness of wind – given the overall low wind feed-in – increases with higher feed-in levels (as discussed in Section 5.2), whereas the average UK subsidies for wind decreased significantly over the years leading up to 2017.[35] However, given the already high carbon price, wind and carbon pricing are substitutive policies in the UK (as discussed in Section 5.2). Thus, a further deployment of wind in the future and the high carbon price (leaving only gas to be replaced) will reduce its effectiveness. Thus, for example, in 2018 at an average carbon price of €35, the cost effectiveness of wind was €72.3/tCO_2. We conclude therefore that while wind is more effective in the UK than in Germany, the effectiveness of the carbon price remains unmatched.

6 Conclusion

We compare the (cost) 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, by analyzing the electricity generation sectors in Germany and the UK. We explain why Germany has failed and the UK has succeeded in reducing GHG emissions. These two countries follow significantly different carbon abatement policies. While Germany relies excessively on direct subsidization of wind and solar energy, the UK introduced a unilateral carbon price support (CPS) in addition to the EU ETS price on 1 April 2013, gradually increasing the carbon price to more than €30/tCO_2 for UK generators.

We utilize daily electricity generation data at the plant level on all gas and coal power stations in Germany and the UK 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 RES, in the form of wind and solar power, on carbon emissions. Finally, we calculate under reasonable assumptions the marginal abatement costs of these sets of policies.

[35] In 2016, subsidies per MWh of onshore and offshore wind were €54,50 each (CEER, 2018). In 2015, subsidies per MWh were €72.26 for onshore and €61.53 for offshore wind (CEER, 2017). Weighted by their capacity shares of 62.2% and 37.8%, respectively, the average subsidy per MWh of wind feed-in was €61.95.

Our main finding is that putting a carbon price on emissions is the most cost effective way of reducing emissions. In Germany, at a carbon price of €15, the marginal abatement costs of one tonne of CO_2 are €41. This policy already offsets 21% of daily emissions; a higher carbon price (e.g. as witnessed in the UK) would be even more effective. This compares favorably with the marginal abatement costs of wind of around €204, and even more so with those of solar of around €979. This is due to the fact that, on average, solar power in Germany is less efficient (i.e. it reduces less CO2 per unit of electricity output) but receives much higher subsidies compared to wind power. The high carbon price in the UK (brought about by the CPF) results in substantial abatement of more than 30% of total emissions, and approximately half of emissions from coal. Costs of marginal abatement fall over the range of UK sample prices, which gives a minimum of €29.9/tCO_2 at a carbon price of €36. While wind is more effective than in Germany (at a cost of €72.3/tCO_2 in 2018), the cost effectiveness of carbon pricing remains unmatched. Secondly, we find that policies can be substitutive or complementary, depending on which technology is replaced by wind or solar at the margin. The marginal effectiveness of wind and solar increases with the carbon price in Germany, but decreases in the UK. 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 the UK – 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 effectiveness.

What does our study add to the climate change discussion? First, as expected from an economics standpoint, putting a price on emissions is shown to be the least costly way to reduce emissions. Economists have always favored 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 doesn't have to be expensive. 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 depend on pre-existing capacities. If countries are endowed with an abundance of relatively efficient gas fired power plants, such as the UK, putting a high price on carbon is a very effective policy, since coal can be replaced in a relatively short-term manner at reasonable costs. This dramatically reduces GHG emissions. If countries partly lack this endowment, as Germany, short-run replacements are more difficult to attain. Finally, let us mention one caveat: this study analyses 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.

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Appendix

A Additional Tables and Figures

Table A1: Expenditures for carbon pricing

Country	Year	Population[a] (mio.)	Carbon price[b] (€/tCO2)	Emissions[c] (mio. tCO2)	Expend. (mio. €)	Expend. per capita (€) Carbon price
DE	2010	82	14	315	4,521	55
DE	2011	80	13	311	4,110	51
DE	2012	80	7	322	2,398	30
DE	2013	81	4	326	1,450	18
DE	2014	81	6	313	1,852	23
DE	2015	81	8	305	2,346	29
DE	2016	82	5	300	1,605	20
DE	2017	83	6	285	1,641	20
UK	2010	63	14	157	2,252	36
UK	2011	63	13	144	1,903	30
UK	2012	63	7	158	1,174	18
UK	2013	64	9	147	1,284	20
UK	2014	64	16	123	2,025	31
UK	2015	65	30	103	3,062	47
UK	2016	65	27	81	2,216	34
UK	2017	66	26	72	1,887	29

[a] Source: Eurostat
[b] Sources: EEX (2018) for the EU ETS price; House of Commons (2016) for the UK CPS
[c] Sources: Umweltbundesamt (2018) for DE; BEIS (2018) for UK

Table A2: Expenditures for RES

Country	Year	Population[a] (mio.)	Avg. support (€/MWh)[b] Wind[d]	Solar	Generation (TWh)[c] Wind	Solar	Expend. (mio. €) Wind	Solar	Expend. per capita (€) Wind	Solar	Wind & Solar
DE	2010	82	41	388	39	12	1,584	4,550	19	56	75
DE	2011	80	45	354	50	20	2,266	6,935	28	86	115
DE	2012	80	63	320	52	26	3,259	8,440	41	105	146
DE	2013	81	67	292	53	31	3,526	9,038	44	112	156
DE	2014	81	71	283	58	36	4,152	10,212	51	126	178
DE	2015	81	78	277	80	39	6,237	10,712	77	132	209
DE	2016	82	84	314	80	38	6,718	11,949	82	145	227
DE	2017	83	81	264	106	39	8,513	10,418	103	126	229
UK	2010	63	70	200	7.97	0	555	0	9	0	9
UK	2011	63	73	290	12.91	0	939	0	15	0	15
UK	2012	63	73	292	17.16	0	1,249	0	20	0	20
UK	2013	64	74	257	23.96	0	1,782	0	28	0	28
UK	2014	64	60	232	26.76	0	1,597	0	25	0	25
UK	2015	65	68	155	33.26	1	2,247	218	35	3	38
UK	2016	65	55	55	30.71	2	1,674	111	26	2	27
UK	2017	66	52	52	40.95	3	2,120	154	32	2	35

[a] Source: Eurostat
[b] Source: CEER (2013, 2015, 2017, 2018)
[c] Source: BMWi (2018a) for DE, BEIS (2019) for UK
[d] Average support for wind weighted by feed-in of onshore and offshore wind (not shown for sake of brevity).

Table A3: Predicted probabilities of producing conditional on the carbon price, DE

Carbon price (€)	Coal plants	Gas plants
5	91.1%	49.9%
6	90.2%	46.8%
7	89.2%	44.2%
8	88.3%	41.9%
9	87.3%	39.9%
10	86.3%	38.4%
11	85.3%	37.2%
12	84.3%	36.3%
13	83.3%	35.8%
14	82.4%	35.7%
15	81.5%	35.8%
16	80.6%	36.3%

This Table gives the the probability of producing electricity from coal- or gas-fired power plants based on probit estimates of eq. 2 for Germany.

Table A4: Probability of producing conditional on wind & solar feed-in, DE

Wind (GWh)	Coal	Gas	Solar (GWh)	Coal	Gas
50	93.8%	59.6%	10	89.3%	44.9%
100	93.2%	54.8%	30	89.9%	45.4%
150	92.3%	50.8%	50	90.0%	45.3%
200	91.3%	47.4%	70	89.7%	44.7%
250	90.1%	44.6%	90	89.2%	43.6%
300	88.5%	42.3%	110	88.3%	42.0%
350	86.8%	40.4%	130	87.3%	40.0%
400	84.7%	38.9%	150	86.3%	37.7%
450	82.5%	37.5%	170	85.2%	35.0%
500	80.1%	36.3%	190	84.2%	32.0%
550	77.5%	35.0%	210	83.5%	28.8%
600	74.9%	33.7%	230	83.1%	25.5%
650	72.2%	32.2%	250	83.4%	22.1%
700	69.8%	30.5%			

This Table gives the the probability of producing electricity from coal- or gas-fired power plants based on probit estimates of eq. 2 for the UK.

Table A5: Probability of producing conditional on the carbon price, UK

Carbon price (€)	Coal plants	Gas plants
5	38.5%	34.8%
7	37.5%	34.7%
9	36.5%	34.7%
11	35.3%	34.9%
13	34.1%	35.3%
15	32.8%	35.9%
17	31.4%	36.7%
19	29.9%	37.7%
21	28.4%	38.9%
23	26.8%	40.3%
25	25.2%	41.9%
27	23.6%	43.7%
29	21.9%	45.7%
31	20.3%	47.9%
33	18.6%	50.4%
35	17.0%	53.0%
37	15.3%	55.9%

This Table gives the the probability of producing electricity from coal- or gas-fired power plants based on probit estimates of eq. 2 for the UK.

Table A6: Probability of producing conditional on wind feed-in, UK

Wind (GWh)	Coal plants	Gas plants
5	29.8%	42.8%
15	29.6%	42.5%
25	29.5%	41.9%
35	29.4%	41.0%
45	29.3%	40.0%
55	29.3%	38.7%
65	29.4%	37.3%
75	29.5%	35.7%
85	29.7%	34.0%
95	29.9%	32.2%
105	30.1%	30.4%
115	30.4%	28.6%
125	30.8%	26.8%
135	31.1%	25.0%
145	31.5%	23.3%

This Table gives the the probability of producing electricity from coal- or gas-fired power plants based on probit estimates of eq. 2 for the UK.

ONLINE APPENDIX

Effective Climate Policy Doesn't Have to be Expensive

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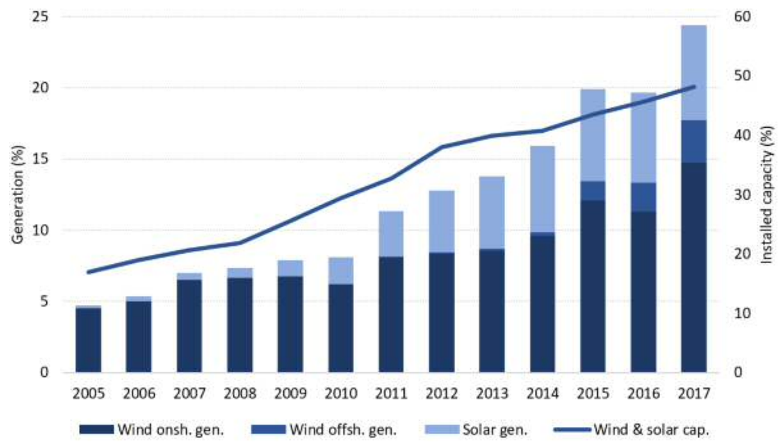
B Additional Tables and Figures

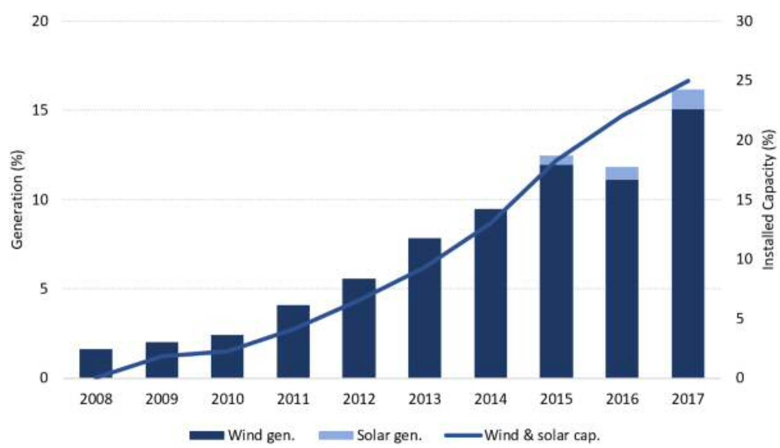
Figure B1: generation and capacity shares of wind and solar power (%)

(a) DE



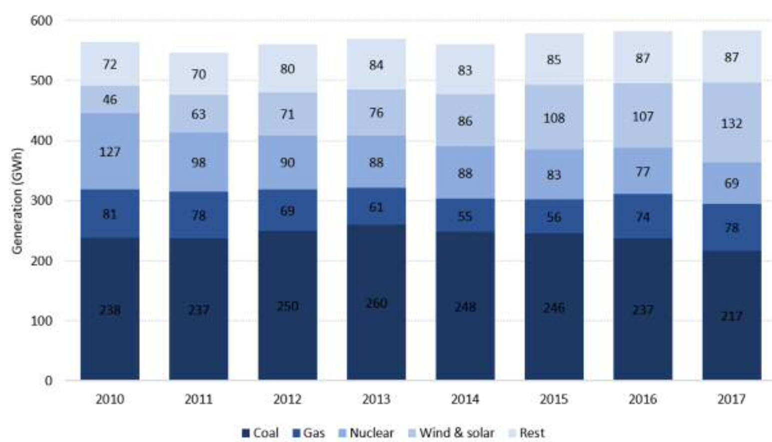
Source: BMWi (2018a,b)

(b) UK



Source: BEIS (2019)

Figure B2: Generation by technology, DE



Sources: Umweltbundesamt (2018)

Table B1: Inactive coal power plant units, UK

Plant name	Unit #	Capacity (MW)	Inactive since
Kingsnorth	ST 4	485	2017 Jun *
Drax	ST 1R	645	2017 Apr *
Ferrybridge C	ST 1	490	2017 Mar *
Ferrybridge C	ST 2	490	2017 Mar *
Ferrybridge C	ST 3	490	2017 Mar *
Ferrybridge C	ST 4	490	2017 Mar *
Rugeley B	ST 6R	488	2017 Mar
Rugeley B	ST 7R	496	2017 Mar
Kingsnorth	ST 3	485	2016 Jun *
Didcot A	4	485	2016 Apr *
Longannet	ST 1	574	2016 Apr
Longannet	ST 2	485	2016 Apr
Longannet	ST 3	574	2016 Apr
Longannet	ST 4	574	2016 Apr
Kingsnorth	ST 2	574	2015 Jun *
Cockenzie	1	260	2015 Jun *
Didcot A	3	500	2015 Apr *
Cockenzie	2	265	2015 Mar *
Cockenzie	3	270	2015 Mar *
Cockenzie	4	265	2015 Mar *
Kingsnorth	ST 1	485	2014 Jun *
Didcot A	2	485	2014 Apr *
Drax	ST 3R	645	2014 May *
Uskmouth 1 Fifoots Point	13	115	2014 Mar
Uskmouth 1 Fifoots Point	14	115	2014 Mar
Uskmouth 1 Fifoots Point	15	115	2014 Mar
Didcot A	1	485	2013 Apr *
Drax	ST 2R	645	2013 Mar *
Ironbridge	1 R	470	2013 Mar *
Ironbridge	2 R	420	2013 Feb *
Tilbury Rwe Npower	ST 8R	320	2012 Dec *
Tilbury Rwe Npower	ST 9R	285	2012 Dec *
Tilbury Rwe Npower	ST 10R	280	2012 Dec *
Total	33 units	14,250	

* Unit officially exited (either decommissioned or continues its operations as a biomass unit).

Table B2: Active coal power plant units, UK

Plant name	Unit #	Capacity (MW)
Aberthaw B	8	524
Aberthaw B	7	524
Aberthaw B	9	535
Cottam	3	500
Cottam	2	500
Cottam	4	497
Cottam	1	497
Drax	ST 5	645
Drax	ST 4R	645
Drax	ST 6	645
Eggborough	2 R	480
Eggborough	1 R	490
Eggborough	3 R	495
Eggborough	4 R	495
Fiddlers Ferry	1	485
Fiddlers Ferry	2	485
Fiddlers Ferry	4	506
Fiddlers Ferry	3	485
Lynemouth	1R	133
Lynemouth	2R	132
Lynemouth	3R	132
Ratcliffe-On-Soar	4	505
Ratcliffe-On-Soar	3	500
Ratcliffe-On-Soar	1	500
Ratcliffe-On-Soar	2	502
West Burton A	3	492
West Burton A	2	492
West Burton A	4	484
West Burton A	1	480
Wilton Power	ST1-3	100
Total	30 units	13,885

Table B3: Regression Output, DE

	Coal						Gas				
P	-333.5093	**	$W*D^3$	0.0000		P	-14.7979		$W*D^3$	-0.0000	
	(150.4788)			(0.0000)			(66.6543)			(0.0000)	
P^2	-2.7181		W^2*D^3	0.0000		P^2	0.6406		W^2*D^3	0.0000	
	(2.7902)			(0.0000)			(1.2814)			(0.0000)	
CR	28,866.8418	**	W^3*D^3	-0.0000	*	CR	-7,789.1016		W^3*D^3	-0.0000	
	(12,820.8633)			(0.0000)			(5,609.7422)			(0.0000)	
CR^2	-83,927.9219	***	S*D	-0.0000		CR^2	17,314.0293		S*D	-0.0000	**
	(32,548.7656)			(0.0000)			(13,969.6953)			(0.0000)	
CR^3	67,101.0547	***	S^2*D	0.0000		CR^3	-13,512.4619		S^2*D	0.0000	**
	(26,039.0625)			(0.0000)			(11,108.8906)			(0.0000)	
W	0.1228		S3*D	-0.0000		W	0.1258		S^3*D	-0.0000	*
	(0.3477)			(0.0000)			(0.1681)			(0.0000)	
W^2	-0.0000		$S*D^2$	0.0000		W^2	-0.0000		$S*D^2$	0.0000	**
	(0.0000)			(0.0000)			(0.0000)			(0.0000)	
W^3	0.0000	**	S^2*D^2	-0.0000		W3	0.0000		S^2*D^2	-0.0000	**
	(0.0000)			(0.0000)			(0.0000)			(0.0000)	
S	0.8574		S^3*D^2	0.0000		S	1.5516	**	S^3*D^2	0.0000	*
	(1.1417)			(0.0000)			(0.6517)			(0.0000)	
S^2	-0.0000		$S*D^3$	-0.0000		S^2	-0.0000	**	$S*D^3$	-0.0000	**
	(0.0000)			(0.0000)			(0.0000)			(0.0000)	
S^3	0.0000		S^2*D^3	0.0000		S^3	0.0000	*	S^2*D^3	0.0000	**
	(0.0000)			(0.0000)			(0.0000)			(0.0000)	
D	-0.0082		S^3*D^3	-0.0000		D	0.1157	**	S^3*D^3	-0.0000	*
	(0.0948)			(0.0000)			(0.0553)			(0.0000)	
D^2	0.0000		ΔW_{t-1}	0.0001		D^2	-0.0000	**	ΔW_{t-1}	0.0000	
	(0.0000)			(0.0001)			(0.0000)			(0.0000)	
D^3	-0.0000		ΔW_{t-2}	-0.0000		D^3	0.0000	**	ΔW_{t-2}	-0.0000	
	(0.0000)			(0.0001)			(0.0000)			(0.0000)	
P*CR	502.8192	**	ΔW_{t-3}	0.0001		P*CR	99.6816		ΔW_{t-3}	0.0000	
	(245.2283)			(0.0001)			(107.7481)			(0.0000)	
P*W	-0.0001	***	ΔW_{t-4}	0.0001		P*W	0.0000	**	ΔW_{t-4}	-0.0001	
	(0.0000)			(0.0001)			(0.0000)			(0.0000)	
P*S	-0.0002		ΔW_{t-5}	-0.0001		P*S	0.0001	*	ΔW_{t-5}	-0.0000	
	(0.0001)			(0.0001)			(0.0000)			(0.0000)	
P*D	0.0001	***	ΔS_{t-1}	-0.0012	**	P*D	-0.0000	***	ΔS_{t-1}	-0.0001	
	(0.0000)			(0.0005)			(0.0000)			(0.0002)	
W*D	-0.0000		ΔS_{t-1}	0.0020	***	W*D	-0.0000		ΔS_{t-1}	-0.0001	
	(0.0000)			(0.0005)			(0.0000)			(0.0002)	
W^2*D	0.0000		ΔS_{t-3}	-0.0004		W^2*D	0.0000		ΔS_{t-3}	0.0000	
	(0.0000)			(0.0005)			(0.0000)			(0.0002)	
W^3*D	-0.0000	**	ΔS_{t-4}	0.0006		W^3*D	-0.0000		ΔS_{t-4}	0.0002	
	(0.0000)			(0.0005)			(0.0000)			(0.0002)	
$W*D^2$	-0.0000		ΔS_{t-5}	-0.0006		$W*D^2$	0.0000		ΔS_{t-1}	-0.0006	***
	(0.0000)			(0.0005)			(0.0000)			(0.0002)	
W^2*D^2	-0.0000		$\hat{\lambda}$	-1,805.4100	***	W^2*D^2	-0.0000		$\hat{\lambda}$	-776.5982	***
	(0.0000)			(138.5527)			(0.0000)			(37.2059)	
W^3*D^2	0.0000	*				W^3*D^2	0.0000				
	(0.0000)						(0.0000)				
Obs.			36,563			Obs.			14,068		
R^2			0.825			R^2			0.675		

The regressions include day-of-week and monthly fixed effects. Sample period: 1 January 2017–29 June 2018. Standard errors in parentheses. ***, **, * signify statistical significance at the 99%, 95%, and 90% level, respectively.

Table B4: Regression Output UK

Coal						Gas					
P	187.6537	***	W^2*D	-0.0000		P	-41.4135	***	W^2*D	-0.0000	
	(42.1971)			(0.0000)			(13.8410)			(0.0000)	
P^2	-2.8082	***	W^3*D	0.0000		P^2	0.3474		W^3*D	0.0000	
	(0.9222)			(0.0000)			(0.2401)			(0.0000)	
CR	31,421.1699	***	W*D^2	-0.0000		CR	2,281.5691	*	W*D^2	-0.0000	**
	(4,240.0029)			(0.0000)			(1,186.7061)			(0.0000)	
CR^2	-80,818.4688	***	W^2*D^2	0.0000		CR^2	1,271.9083		W^2*D^2	0.0000	
	(8,586.7959)			(0.0000)			(2,215.5269)			(0.0000)	
CR^3	56,498.6719	***	W^3*D^2	-0.0000		CR3	-1,947.9681		W^3*D^2	-0.0000	
	(5,604.3262)			(0.0000)			(1,331.4818)			(0.0000)	
W	-0.1160		W*D^3	0.0000		W	-0.1003	*	W*D^3	0.0000	**
	(0.1713)			(0.0000)			(0.0572)			(0.0000)	
W^2	0.0000		W^2*D^3	-0.0000		W^2	0.0000		W^2*D^3	-0.0000	
	(0.0000)			(0.0000)			(0.0000)			(0.0000)	
W^3	-0.0000		W^3*D^3	0.0000		W^3	-0.0000		W^3*D^3	0.0000	
	(0.0000)			(0.0000)			(0.0000)			(0.0000)	
D	0.0218	***	ΔW_{t-1}	-0.0014	***	D	0.0052	***	ΔW_{t-1}	-0.0009	***
	(0.0052)			(0.0005)			(0.0020)			(0.0001)	
D^2	-0.0000		ΔW_{t-2}	0.0008	*	D^2	-0.0000	**	ΔW_{t-2}	-0.0000	
	(0.0000)			(0.0005)			(0.0000)			(0.0001)	
D^3	0.0000		ΔW_{t-3}	-0.0006		D^3	0.0000	**	ΔW_{t-3}	-0.0000	
	(0.0000)			(0.0005)			(0.0000)			(0.0001)	
P*CR	-179.9605	***	ΔW_{t-4}	-0.0002		P*CR	-48.3920	***	ΔW_{t-4}	-0.0001	
	(44.7036)			(0.0005)			(12.6871)			(0.0001)	
P*W	0.0003	***	ΔW_{t-5}	-0.0009	**	P*W	-0.0001	***	ΔW_{t-5}	0.0001	
	(0.0000)			(0.0004)			(0.0000)			(0.0001)	
P*D	-0.0001	***	$\hat{\lambda}$	-270.7316	**	P*D	0.0001	***	$\hat{\lambda}$	-789.2795	***
	(0.0000)			(108.5102)			(0.0000)			(47.7451)	
W*D	0.0000					W*D	0.0000	*			
	(0.0000)						(0.0000)				
Obs.		59,980				Obs.		97,208			
R2		0.633				R2		0.595			

The regressions include day-of-week and quarter-year fixed effects. Sample period: 27 May 2011–15 July 2018. Standard errors in parentheses. ***, **, * signify statistical significance at the 99%, 95%, and 90% level, respectively.

Table B5: Marginal effects of trade flows for different carbon prices, DE

Carbon price (€/tCO2)	Import (MWh)	Export (MWh)	Net imports (MWh)
5	6,227	2,582	3,645
6	5,625	575	5,049
7	5,022	-1,431	6,453
8	4,420	-3,437	7,857
9	3,818	-5,444	9,262
10	3,215	-7,450	10,666
11	2,613	-9,457	12,070
12	2,011	-11,463	13,474
13	1,409	-13,470	14,878
14	806	-15,476	16,282
15	204	-17,483	17,686
16	-398	-19,489	19,091

Table B6: Marginal effects of trade flows for different carbon prices, UK

Carbon price (€/tCO2)	Import (MWh)	Export (MWh)	Net imports (MWh)
5	-0.4312	0.1793	-0.6117
7	-0.3695	0.1590	-0.5286
9	-0.3079	0.1387	-0.4454
11	-0.2462	0.1184	-0.3623
13	-0.1846	0.0981	-0.2792
15	-0.1229	0.0778	-0.1961
17	-0.0613	0.0575	-0.1130
19	0.0004	0.0372	-0.0299
21	0.0621	0.0169	0.0532
23	0.1237	-0.0034	0.1364
25	0.1854	-0.0237	0.2195
27	0.2470	-0.0441	0.3026
29	0.3087	-0.0644	0.3857
31	0.3703	-0.0847	0.4688
33	0.4320	-0.1050	0.5519
35	0.4936	-0.1253	0.6350

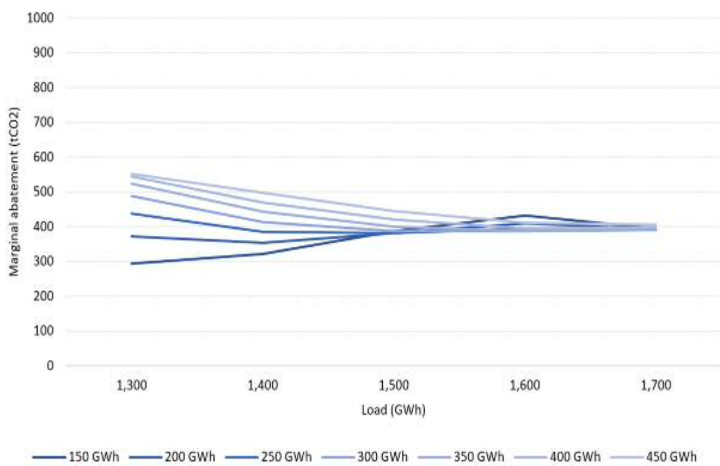
C Effectiveness of wind and solar for different load profiles

The abatement effectiveness of wind and solar generation depends also on the level of demand as well as on the actual amount of wind and solar generation already in the market. Thus, Figure C1 presents marginal abatement effects of wind and solar at various production levels in Germany, for load values ranging between 1,300 GWh and 1,700 GWh (evluated at means for other control variables). Notably, wind and solar feed in at different hours of the day so that median electricity demand fundamentally differs (see Appendix Figure D1a). While the median load during wind production is 64.1 GWh, median load during solar production is significantly higher at 71.3 GWh. We can see that for low demand, wind is more effective at higher feed-in levels. However, with increasing load, marginal abatement of the various wind feed-in levels converges to about 400 tCO_2 (per GWh of wind). In contrast, solar seems to be highly effective only for little solar feed-in during times of low demand. With higher demand, solar's effectiveness diminishes significantly. An explanation is that for high levels of load, more and more gas is in the merit order, so that the relatively limited feed-in of solar cannot replace substantial amounts of coal-based emissions.

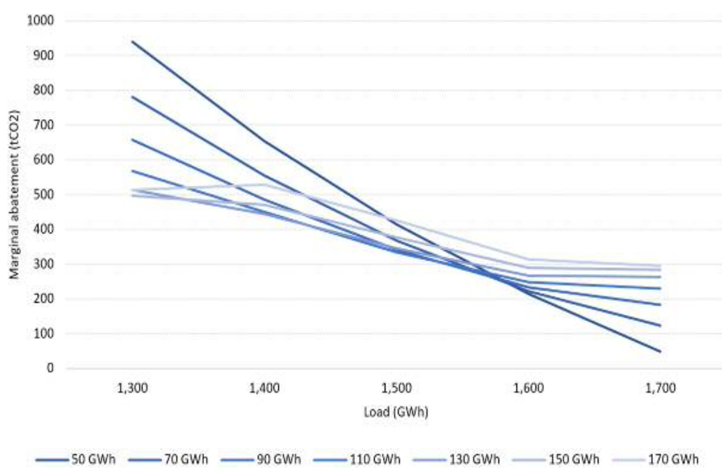
Figure C2 shows marginal effects of offsetting emissions for various feed-in levels of wind in the UK, evaluated for different demand levels. Although it is difficult to find common patterns for low, medium and high wind feed-in evaluated at low-to-medium electricity demand, it seems that the effectiveness of all wind profiles tapers off at high electricity demand. The main reason is that at high load, wind offsets rather gas than coal at the margin, leading to a limited effectiveness.

Figure C1: Marginal abatement of wind & solar for different levels of load, DE

(a) Wind, DE

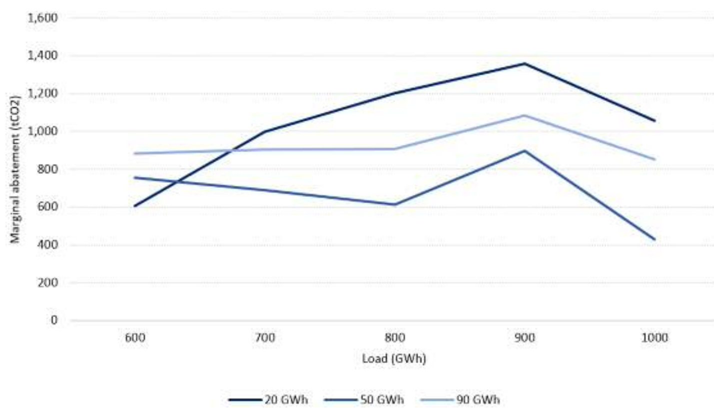


(b) Solar, DE



The Figures show marginal abatement effects of wind and solar evaluated at different feed-in levels and for varying demand. Other control variables are evaluated at their means.

Figure C2: Marginal effects of wind on abatement, UK



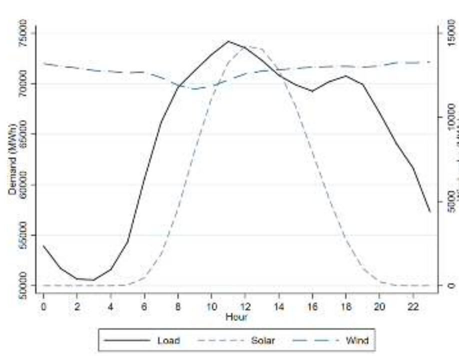
The Figure shows marginal abatement effects of wind evaluated at different feed-in levels (for means of the other variables).

D Patterns of wind, solar, and demand

Figures D1a and D1b depict the averages of demand as well as wind and solar (only for Germany) feed-in by hour of the day. For both countries we observe typical electricity demand patterns, with two peaks around noon and in the evening hours, whereas the absolute peak for Germany is during noon and for the UK at around 7 pm. In Germany, solar feed-in peaks also at noon, which correlates pretty well with demand. For both countries, we observe that wind feed-in is, on average, rather stable during the day (despite tremendous intermittency, which the Figures cannot depict as they provide mean values), implying that wind produces not only during hours of high demand but also during low demand (e.g. at night).

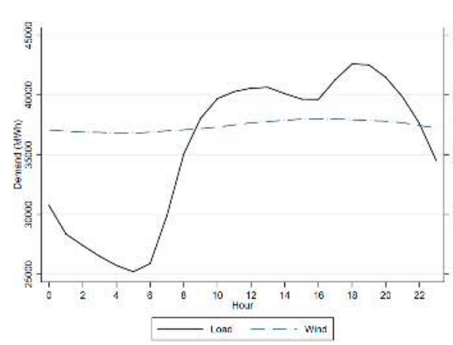
Figure D1: Patterns of wind, solar, and demand in the course of a day

(a) DE



Sample averages over 1 January 2017 – 29 June 2018.
Source: own data

(b) UK



Sample averages over 27 May 2011 – 15 July 2018.
Source: own data