Carbon Pricing and Power Sector Decarbonisation: evidence from the UK

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Abstract

The power sector represents a large share of global greenhouse gas (GHG) emissions. Policy-makers have implemented a variety of instruments to decarbonise their power sector. This paper examines the Carbon Price Floor (CPF), a novel carbon pricing instrument implemented in the United Kingdom in 2013. After describing the potential mechanisms behind the recent UK power sector decarbonisation, I apply the synthetic control method on country-level data to estimate the impact of the CPF on per capita emissions. I discuss the importance of potential confounders and the amount of net electricity imports imputable to the policy. Depending on the specification, the abatement associated with the introduction of the CPF range from 104 to 156 millions tons of equivalent CO_2 over the 2013-2017 period. This implies a reduction of between 39% and 48% of total power sector emissions by 2017. Several placebo tests suggest that these estimates capture a causal impact. This paper shows that a carbon levy on high-emitting inputs used for electricity generation can lead to successful decarbonisation.

Keywords: carbon tax, electricity generation, synthetic control method

JEL Codes: D22, H23, Q41, Q48

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1 Introduction

All governments in the world are facing the need to reduce their greenhouse gas emissions in order to tackle climate change. In the past two decades they have implemented a variety of abatement policies to address this challenge, including economic instruments in the form of carbon taxes and markets. The European Union Emission Trading Scheme (hereafter EU ETS) introduced in 2005 is the scheme covering the largest share of global annual GHG emissions to date (World Bank and Ecofys, 2018). It covers all European energy-intensive industrial facilities, and in particular power generators which represent 66% of the emissions covered[1] (Source: EUTL). In spite of this large share, the effectiveness of the EU ETS on abatement in the power sector is relatively scarce. Furthermore, according to a literature review by Martin et al. (2016), the few papers focusing on evaluating the impact of the EU ETS in the power sector find contrasted results depending on the technique used: while the papers based on aggregate data - mostly using ex-ante simulations - point to a rather low effect of the EU ETS, a study based by Ellerman and McGuinness (2008) based on detailed micro data and focused on the UK estimate quite a large total abatement.

Several factors may explain the relative scarcity of such evaluations: first, the difficulty to find a good counterfactual to the plants covered by the EU ETS and have emission information on them. While this difficulty apply to other sectors covered by the EU ETS, it is particularly acute for the power sector, where almost all GHG-emitting installations are covered[2]. A second factor applying to all sectors is the relatively low level of carbon prices on the EU market that prevailed for a long period of time (Koch et al., 2014). These low prices may have provided low incentives for emission reductions for covered plants, and from a policy evaluation evaluation perspective they may make it hard to detect an impact.

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[1] Beyond the emissions covered by the EU ETS, the energy supply sector also represents 30% of total EU emissions in 2016 according to the European Environment Agency(European Environment Agency, 2018)

[2] Only those with a rated capacity of less than 20MW are exempted, which typically represent a very small share of a country's total capacity and production. For example, in the UK in 2015, only 13 of the 95 active fossil-fuel fired power plants have a capacity below 20 MWth. They represent only 0.2% of the installed capacity (Source: Digest of United Kingdom Energy Statistics)

Low prices also triggered political reactions: facing rock-bottom prices at the end of Phase I (2005-2007) and again after the 2009 economic crisis, several EU countries, notably the UK, France and the Netherlands, mentioned the possibility to implement unilateral measures to strengthen the price signal (Newbery et al., 2018).

To date, the UK is the only country to have implemented such measures in the form of a Carbon Price Floor introduced in 2013. With this instrument, all GB power installations[3] subject to the EU ETS have to pay a specific carbon tax in addition to their ETS carbon allowances. The rate of the tax is set annually, and has varied between around £5 and £18 over the 2013-2017 period. Since then, the UK power sector has undergone a remarkable transition: between 2012 and 2017, the coal share in electricity generation fell by 33 percentage points, the renewables share[4] increased by 14 percentage points, gross consumption decreased by 6% (Source: Eurostat), and power sector CO2 emissions decreased by around 57% (Source: EUTL). The transformation of the UK power sector has received significant coverage in the media and policy reports (Evans, 2019; Brown, 2017). However, none of these accounts of the British power sector de-carbonisation tries to isolate and quantify the roles of specific policies in such transformations.

In this paper, I adopt a policy evaluation approach and estimate the impact of the Carbon Price Floor (hereafter CPF) on per capita emissions from the power sector. Using the synthetic control method exposed in Abadie and Gardeazabal (2003) and Abadie et al. (2010, 2015), I build a counterfactual UK power sector with a weighted combination of other European countries' power sector and compare the emission paths of the actual and synthetic UK power sector. I find that the introduction of the CPF is associated with a decrease of between 104 and 156 millions of ton of equivalent CO_2 (hereafter $MtCO_2e$) in the UK over the 2013-2017 period. I then run a set of placebo tests suggesting that the impact is causal. The lower bound corresponds to a setting where the closure or conversion of some power plants is assumed to be independent from the CPF and entirely caused by other policies.

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[3] As explained later, the few generators located in Northern Ireland are not included

[4] excluding biomass

The upper bound assumes that these decisions are either controlled for in the empirical strategy or caused by the Carbon Price Floor. Assuming that installations subject to the tax anticipated its introduction in 2011 and 2012, and imputing the difference between the UK and counterfactual UK 2011 and 2012 emissions decreases the estimated impact to 83 $MtCO_2e$ over the 2011-2017 period. Compared to the synthetic UK emissions, the actual UK emissions were lower by between 39% (with the lower bound specification) and 48% (with the main specification) in 2017.

This paper contributes to several strands in the literature: first, it contributes to the growing empirical literature evaluating the impact of regional and national carbon pricing instruments, notably in Europe. Evidence summarized in Martin et al. (2016) suggest a positive impact of the EU ETS on CO_2 abatement, albeit with a large variation in the magnitude of the impact depending on the period considered, the evaluation technique used (estimates based on aggregate emissions vs. papers employing econometric techniques on micro-data), and the sector considered (energy vs manufacturing sector). As mentionned above, using detailed data from power generators, Ellerman and McGuinness (2008) estimate that the EU ETS caused an abatement of 13 to 21 million tons of CO_2 in the UK power sector in 2005 and 2006. To my knowledge, only one other paper, unpublished to date, looks specifically at the impact of the CPF on CO_2 emission in the UK power sector: using a machine learning approach, (Abrell et al., 2019) find that the UK CPF resulted in fuel switching [5] inducing a total abatement of $24MtCO_2e$. In contrast, the strategy used in this paper to overcome the absence of obvious counterfactual to the 'treated units', the synthetic control method, allows to take into account all the mechanisms via which a carbon tax on high-emitting input fuels may induce a decrease in emissions. This paper also relates to the scarce existing literature examining the rapid decarbonisation of the UK power sector in the recent years. The only published paper to date, by (**?**), describes the evolution

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[5] Fuel switching from gas to coal arises because carbon pricing changes the relative marginal cost of coal- and gas- fired plants. This change affects the merit order (the ranking of power plants by ascending marginal costs), which determines each individual plant's output at every period (hour or half-hour)

of key power sector variables (such as wholesale prices, supply, demand, generation mix) using granular data. In contrast, this paper aims at identifying a causal link between the Carbon Price Floor policy and carbon emissions, and to do so it contrasts the evolution of UK emissions with that of other countries. More broadly, this paper draws from a broader literature examining the drivers of carbon emissions in the power sector. In particular, it uses insights from Van den Bergh and Delarue (2015), who look at the role and interactions of different abatement channels and their contributions to the shape of marginal abatement cost curves in the power sector. Since the UK power sector is embedded in the broader EU carbon market, the paper also draws from Ellerman and McGuinness (2008) and Kirat and Ahamada (2011), who emphasize the role of EU ETS carbon prices and the coal-to-gas price ratio on fuel switching. Third, this paper contributes to a recent literature - mainly unpublished to date - applying the synthetic control method to the analysis of environmental policies : for example, Lee and Melstrom (2018) estimate the impact of a regional carbon pricing initiative on electricity imports, Andersson (2017) evaluate the impact of the Swedish carbon tax, and Isaksen (2018) evaluates the effect of international pollution protocols. A distinctive feature of this work is to rely on plant-level data aggregated at the country-level, allowing to account for specific shocks experienced by individual plants (e.g. plant closure induced by EU air pollution regulation). Finally, while it is not the immediate focus of the paper, a more minor contribution is the discussion of how different levels of regulation may interact and the related risk of a waterbed effect. This risk exists since the policy applies only to one country and one sector embedded in the broader EU ETS carbon market (chapter 15 of the 2014 IPCC report provides a review (IPCC et al., 2014) of this literature).

Beyond the academic contribution, this paper is also relevant from a policy perspective, since it tackles the topical question of how to achieve CO2 emission target by decarbonising electricity. To be in line with the 2015 UN Paris Climate Agreement, OECD countries including most European countries need to be coal-power-free by 2030. While Germany - the country in Europe with the highest power sector emissions - recently announced that coal phase out would only be achieved in 2038, other countries such as France, the Netherlands, Italy, Ireland and Sweden announced earlier dates. However, the means necessary to achieve such transition are still under discussion, and the announced date for phase-out already seems unrealistic for France (Le Hir, 2019). Lessons can probably be drawn from the UK experience exposed in this paper.

The paper is organized as follows: Section 2 presents the Carbon Price Floor policy; Section 3 describes the data used; Section 4 shows the potential mechanisms underlying the de-carbonisation of the UK power sector since 2012; Section 5 presents the empirical strategy used to capture the impact of the CPF on emissions; Section 6 presents the main results and robustness checks; Section 7 concludes.

2 The UK Carbon Price Floor

As explained above, the Carbon Price Floor was introduced in the GB power sector in April 2013. According to a briefing paper by the House of Commons Library[6], the idea of providing a price floor to the low-standing emission allowances on the EU carbon market had actually been discussed as early as 2009, but the Labour Government then at power was opposing it. The policy was put back on the table by the Coalition Government in 2010 and was part of their government agreement (Ares and Delebarre, 2016a). In March 2011, after some expert consultations, the Government announced its decision to introduce a Carbon Price Floor in the 2013/2014 budget year[7]. The Carbon Price Floor would apply only to the generators located in Great Britain and not those located in Northern Ireland, since the latter are part of a single electricity market together with generators from the Republic of Ireland[8]. The official announced goal of the CPF was to tackle price uncertainty on the EU ETS and encourage investment in low carbon technologies in the generation sector; in official

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[6] The House of Commons library is presented as an ”an independent research and information unit providing impartial information for [UK] Members of Parliament of all parties and their staff”

[7] The budget year over which the annual tax rate is set runs form 1st April of year T to to 31 March of year T+1

[8] and Ireland would not impose the same carbon tax on its generators

Table 1: Level of CPS rate for each period in pound per ton of CO2e

Period	CPS rate in £/tCO_2e
April 2013/March 2014	4.96
April 2014/March 2015	9.55
April 2015/March 2016	18.08
April 2016/March 2017	18
April 2017/March 2018	18
April 2018/March 2019	18

Source: Ares and Delebarre (2016a)

communication documents, the Carbon Price floor was labelled "support and certainty for low-carbon investment"(Hirst, 2018).

In practice, the CPF translates into a tax called the Carbon price support (CPS hereafter), which yearly rate depends on projected EU ETS allowance prices and was initially expected to increase over time, with an overall carbon price target of £30 due by 2020. CPS rates in pound per ton of equivalent CO_2 (£/tCO_2e) were announced in March 2011 for the 2013/2014 and 2014/2015 periods, with indicative rates announced for 2015/2016 and 2016/2017. In the 2013 budget, the 2015/2016 rate was finally set at a higher level than the indicative rate, and even higher indicative rates were given for 2016/2017 and 2017/2018. However, in 2014, the Government decided to freeze the CPS rate to £18/tCO_2e (about the 2015/2016 level) until 2019/2020, after business representatives expressed concern over the competitiveness of the UK energy-intensive industries due to generators passing on their CPS costs (Ares and Delebarre, 2016a). Table 1 shows the confirmed level of the CPS rate for each period, taking into account the 2014 freeze.

Because of the freeze and since rates have been determined based on expected future EU ETS allowance prices[9] rather than actual prices, the trajectory of the Carbon Price Floor looks somewhat different from what was first announced. Figure 1 overlays the actual CPS rates converted to euro with the observed European Emission Allowances (EUA) prices since 2009, which sum gives the actual observed carbon price floor. As visible on the figure, the

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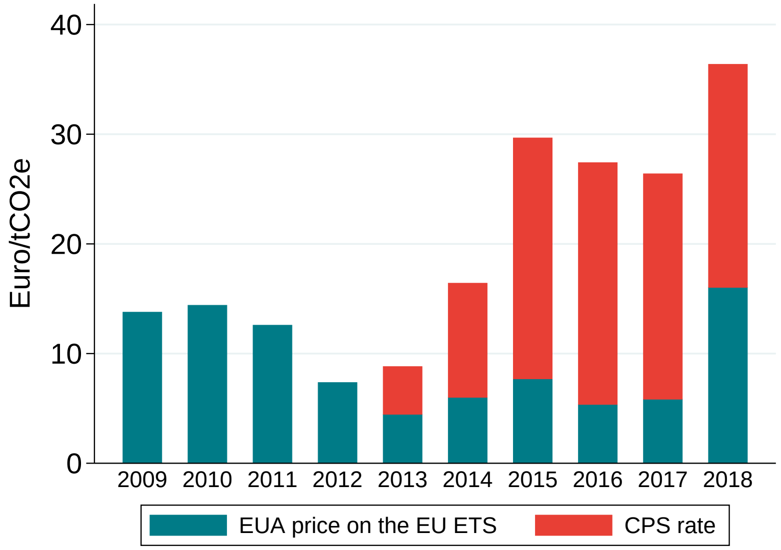
[9] More precisely, rates are determined based on the average annual ICE-ECX benchmark end of day settlement price for carbon for delivery in the target year(Ares and Delebarre, 2016a)

CPS increases substantially the carbon price paid by GB power generators compared to non-GB generators covered by the EU ETS. In 2016, the year where the relative difference is the largest, GB power generators pay a carbon price more than five times higher than non-GB generators.

Figure 1: The Carbon Price Support and EUA price on the EU ETS



Note: EUA price data retrieved from Sandbag website. CPS prices retrieved from House of Commons library (2016), adjusted with appropriate weights to reflect the January to December period rather than April to March, and converted to Euro using yearly averages of monthly market exchange rates.

In terms of coverage, the tax applies to all generators other than stand-by ones[10], with a rated thermal input greater than 2MWth, located in Great Britain, and producing electricity from fossil fuels. This includes conventional power plants as well as Combined Heat and Power (CHP) operators[11] and auto-generators (HM Revenue & Customs, 2017). For power plants using solid fossil fuels (such as coal), natural gas or LPG as an input fuel, the tax is expressed as a specific component of the Climate Change Levy, an environmental tax levied on taxable commodities supplied to businesses and the public sector, of which power

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[10] Stand-by generators are generators used to provide emergency electricity supplies in the event of a failure of a building's usual electricity supply and used only for that purpose purpose. They are typically found in hospitals and other such facilities

[11] CHP plants are only liable to pay the CPS on the so-called ”deemed supply of fuel”, the share of fuel used to produce electricity for the grid . E.g. for a CHP which generation is 80% electricity and 20% heat, the 20% on the heat are exempted from the tax

Table 2: Level of CPS rate by input fuel for each period, in pence per fuel-specific unit

Period	Natural Gas (p[1] per kWh)	Petroleum gas[2] (p per kg)	Coal[3] (p per GJ on GCV[4])	Fuel oil[5] (p per litre)	Gas oil[6] (p per litre)
2013/2014	0.091	1.146	44.264	1.568	1.365
2014/2015	0.175	2.822	81.906	3.011	2.642
2015/2016	0.334	5.307	156.86	5.730	4.990
2016/2017	0.331	5.28	154.79	5.711	4.916
2017/2018	0.331	5.28	154.79	5.711	4.916
2018/2019	0.331	5.28	154.79	5.711	4.916

Notes: [1]p stands for pence. [2]Or other gaseous hydrocarbon in a liquid state.[3]And other solid fossil fuels. [4]GCV stands for Gross Calorific Value and means that the amount of liquid water contained in the coal prior to combustion, that leaves as vapour, is taken into account in the energy calculation. [5]Or other heavy oil or rebated light oil. [6]Or kerosene or rebated bioblend. Source: HM Revenue and Customs 2014, 2016 and 2017 and Envantage website: `https://www.envantage.co.uk/carbon-management/climate-change-levy-agreement/climate-change-levy-rates.html`

generators were exempted thus far. For power plants using oil as an input, which had been benefiting from a relief on tax duty since 2006, the CPS rate is expressed as a reduction to this excise tax relief(HM Revenue & Customs, 2017).

3 The data

Since my empirical strategy (exposed in section 5) relies on a comparison between the UK and other European countries, I need to estimate GHG emissions from each European country's power sector. To do so, I use individual plant-level data from the European Union Transaction Log (hereafter EUTL), the official register of the EU ETS, managed by the EU Commission. The register checks, records and authorises all transactions taking place between participants in the EU ETS. Participants covered by the EU ETS have to monitor and report their CO_2e emissions each year and surrender enough emission allowances to cover their annual emissions. Participants' annual emissions are verified and these verified emissions are available yearly at the installation level for all countries.

For a given period, the EUTL provide data for all covered installations from the countries which are part of the ETS that year. I restrict the analysis and associated database construction to the EU-countries which have been part of the EU ETS since the beginning of the scheme in 2005. It means that I exclude Romania and Bulgaria (who joined in 2007), Croatia (who joined in 2013), Slovenia, (which was part of the scheme from the beginning but only joined the EU in 2015), as well as Norway, Liechtenstein and Iceland, all non-EU countries which joined the scheme in 2008. Finally, I exclude the three countries having less than ten power plants subject to the EU ETS: Luxembourg (only nine power plants), Cyprus (only three) and Malta (only two). Twenty-one countries are left in my main dataset.

Since the CPF applies only to power generators, I had to identify power plants among the installations covered by the EU ETS. The method used to identify power plants is explained in Appendix A.

I obtain an unbalanced plant-level panel of 14,065 plants subject to the EU ETS and located in 21 countries, split into 4,938 power plants (302 for the UK) and 9,127 non-power plants. It is worth noting that the power plants located in the UK and covered by my data do not fully overlap with the power plants subject to the Carbon Price Floor. Two types of power installations are included in my data but not subject to the CPF: first, power installations located in Northern Ireland, which represent a very small share of total UK power sector emissions (2.4% in 2012). Second, standby generators such as those part of hospitals, likely to be only used in case of power shortages. Given that their combined CO2e emissions are also very low, I deem them negligible compared to the rest of UK power plants (in 2012 the six installations belonging to hospitals represent only 0.05% of the UK power sector's emissions). In turn, some power plants subject to the CPF are not in my data: these are the fossil-fuel power plants with a rated thermal input between 2 and 20 MWth. These small plants may represent a substantial share of the total number of power plants, but logically they represent a very small share of total emissions. Overall, most emissions covered by the CPF are in my data. I am also confident that this EUTL emission data accurately reflect other countries' power sector emissions: even if some countries have a larger proportion of small power plants, the bulk of emissions presumably comes from the few large conventional power plants.

I aggregate these data at the country-level separately for power and non-power plants to obtain country-level power sector emissions. I add to this panel country-level variables used in the descriptive and estimation parts. The variables on electricity production by source, consumption and net imports used in section 4 come from Eurostat. The variables used in section 5 are described more specifically in section 5.3 and Appendix B.

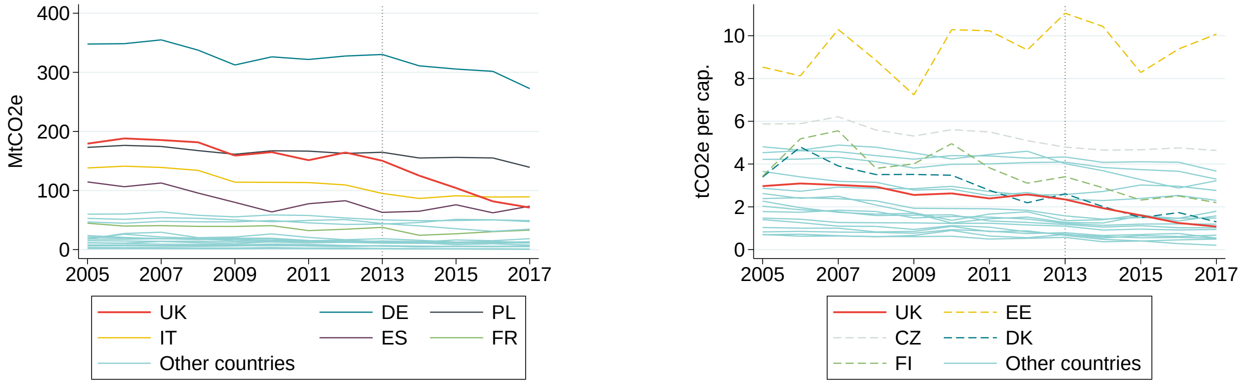
4 The UK power sector decarbonisation and underlying mechanisms

4.1 Descriptive evidence on the UK power sector de-carbonisation

Using the data described above, this section documents the recent changes in UK power sector CO_2 emissions compared to the rest of Europe, and discusses the potential mechanisms behind this change.

As shown on the left-hand side of figure 2, in 2005 the UK power sector had the second largest total CO_2e emissions after Germany. They experienced a large decrease in emissions from 2013 on, year of the introduction of the CPF. The right-hand side of the figure shows that this is also true when emissions are taken per capita: While the UK was among the top emitters in per-capita terms in 2005, by 2017 it had joined the bulk of lower-emitting countries. The potential role of the CPF in explaining such a decrease becomes more plausible when one compares post-2012 emissions to the average for the 2005-2012 period. The left-hand side of figure 3 plots the difference between annual per capita emissions and their 2005-2012 mean. The UK trajectory stands out, especially from 2014 onwards: apart from some outliers exhibiting large deviations from the mean over the whole period, the majority of countries exhibit a mildly decreasing pattern while the UK undergoes a clear fall. The right-hand side of the figure shows the same graph for the non-power installations subject to

Figure 2: Aggregate CO_2e emissions of power installations covered by the EU ETS



(a) Total absolute emissions

(b) Per capita emissions

Note: Emission values were obtained by aggregating, at the country level and every year, the verified emissions of power generators from our EU ETS database. The left-hand side value is a simple sum while the right-hand side is the sum of emissions divided by the average country population that year. The ”Other countries” include all remaining EU countries except Romania, Bulgaria, Slovenia, Croatia, Malta, Cyprus, and Luxembourg.

the EU ETS: there, the UK per capita emissions are extremely stable over time, like most other EU countries. This contrast suggests that there is something specific to the UK power sector around 2013. I now describe the potential underlying channels and the role the CPF may have had in such de-carbonisation.

Figure 3: Aggregate per capita CO_2e emissions of power and non-power installations covered by the EU ETS: Deviation from the 2005-2012 mean

(a) Power installations

(b) Non-power installations

Note: Emission values appearing on these two graphs were obtained in 2 steps: 1)by aggregating, at the country level and every year, the verified emissions of installations from our EU ETS database, and then dividing by the average country population 2)by taking the difference between the obtained yearly per capita emission and the 2005-2012 average. Installations considered for the left-hand side graph are those identified as power generators while the right-hand side shows the same graph for non-power installations. The "Other countries" include all remaining EU countries except Romania, Bulgaria, Slovenia, Croatia, Malta, Cyprus, and Luxembourg.

4.2 The mechanisms underlying decarbonisation

The theoretical channels leading to a decrease in per capita emissions can be illustrated with the following basic equation decomposing per capita emissions:

$$\frac{Q_{CO_2e}}{POP} = \frac{Q_{elec}}{POP}\frac{Q_{CO_2e}}{Q_{elec}} \qquad (1)$$

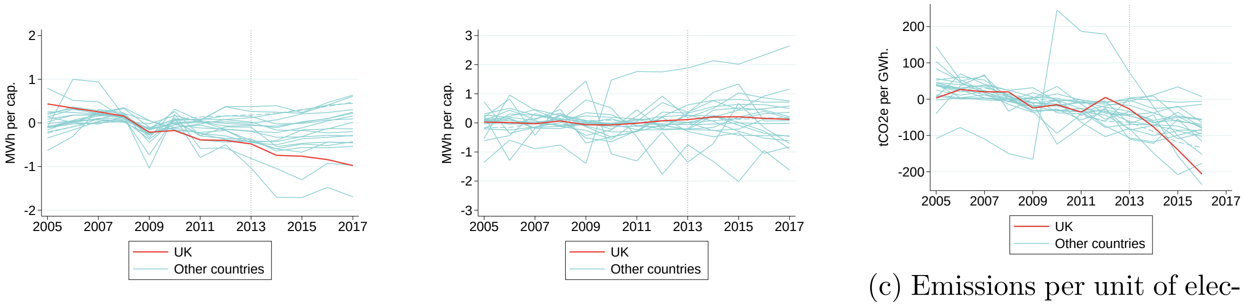
Where POP is total population, Q_{elec} is domestic gross power production (in GWh), and $\frac{Q_{CO_2e}}{Q_{elec}}$ is the emission intensity in the domestic power sector (in tCO2e/GWh).

Noting that Q_{elec} can be rewritten as the difference between domestic gross electricity demand D and net imports $(I - X)$, we can rewrite it:

$$\frac{Q_{CO_2e}}{POP} = (\frac{D}{POP} - \frac{(I-X)}{POP})\frac{Q_{CO_2e}}{Q_{elec}} \qquad (2)$$

This suggests that three different channels may lead to a decrease in per capita emissions:

Figure 4: Channels: evolution of the UK and other countries



(a) Demand per capita

(b) Net imports per capita

(c) Emissions per unit of electricity output

Note: The variables appearing on these two graphs were obtained by taking the difference between the original variable and the 2005-2012 average. The "Other countries" include all remaining EU countries except Romania, Bulgaria, Slovenia, Croatia, Malta, Cyprus, and Luxembourg.

a decrease in demand per capita $\frac{D}{POP}$ (the *demand channel*), an increase in net imports per capita $\frac{(I-X)}{POP}$ (the *trade channel*), and a decrease in the average emission factor of the domestic power sector (the *emission intensity channel*).

Figure 6 shows how the UK compares to the other European countries for each of these channels. Visibly, the emission intensity channel is the channel contributing the most to the break in the UK emission trend after 2013. UK Net imports per capita are on the other hand extremely stable over time compared to other countries. Demand per capita exhibits a decreasing trend over the whole period, making the UK reach among the lowest levels in 2017 compared to the other European countries. However there is no obvious break in trend in 2013.

Disentangling the role of the CPF and other policies While the CPF might have had an impact on each of these channels, graphical evidence suggests that the largest source of decarbonisation after 2013 was a change in the emission intensity of domestic production. Furthermore, other factors might have contributed to the evolution of each of them: demand per capita might have been dampened by the wholesale price effect of the Carbon Price Floor.[12]. Yet other factors such as the continuous improvement of energy efficiency in

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[12] Given past evidence of carbon cost pass-through for the European power sector as a whole in both phases of the EU ETS (Zachmann and Hirschhausen (2008) for the first phase and Hintermann (2016) for

buildings and electric appliances might have played a role too, which would be consistent with the continuous decreasing pattern of Figure 5

Regarding the trade channel, an increase in net imports would be an expected consequence of the CPF increase in the relative cost of domestically produced electricity compared to imported electricity. Considering the UK alone, one note that the UK increased its net imports from 11,800 GWh to 17,500 GWh between 2012 and 2016. However, net imports per capita remain very low compared to other European countries, which can be explained by the relative isolation of the UK and its low interconnection capacity with other countries[13]. It is also worth mentioning that the increase in net imports could come from the increase of 50% in the UK interconnection capacity between 2010 and 2012: In 2010, the UK was only connected to France and Ireland, with a total capacity of 2,500 MW. In 2011, GB became interconnected with the Netherlands, and in 2012 a new undersea interconnector with the Republic of Ireland was completed (OFGEM, 2013). Given the timing of these new interconnections, shortly before the introduction of the CPF, it is difficult to separate out these two factors in triggering an increase in net imports. In any case, as previously discussed the magnitude of this channel is expected to be low. I will however come back to this issue when discussing my identification strategy in section 5.2.

Finally, the average emission intensity of the domestic power sector is likely the most important driver for the decrease in per capita emissions as suggested by Figure 6b. It can be further decomposed as:

$$\frac{Q_{CO_2e}}{Q_{elec}} = \sum_i e_i q_i \tag{3}$$

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the second phase), the CPF may well have led to an increase in electricity prices too, as suggested by Newbery et al. (2018) and Ares and Delebarre (2016b). However, for all customers the effect on demand might have been mitigated by a low price-elasticity of demand ; furthermore, for large buiness customers the price effect was mitigated by a compensation scheme introduced for electro-intensive industries via a specific component of a larger Energy Intensive Industries support (meant to compensate the cost increase induced by climate change policies in general) Ares and Delebarre (2016b)

[13] Being an island, the UK is relatively limited in its ability to trade electricity, which can only occur via undersea inter-connectors for GB, and via undersea connections or ground connections to the Republic of Ireland for Northern Ireland.

Where e_i is the average emission intensity of GHG-emitting process i used for electricity production and q_i is the share of gross electricity production covered with method i (the electric mix). the EUTL Accounting conventions imply that renewables and nuclear energy sources are considered to generate zero emissions[14], so only fossil fuel fired power plants (their share in total production and emission factor) matter in this equation.

My data is not precise enough to compare the average emission factor of each emitting input for all European country. I can however show the evolution of the fuel mix for all countries between 2012 and 2017. To make the UK trajectory visible, figure 5 shows the fuel mix in the UK power sector in 2005, 2012 and 2017. While the shares are quite similar between 2005 and 2012 (apart from the increasing renewables share), between 2012 and 2017 the share of coal falls dramatically (by 33 percentage points). It is compensated by an increase in the share of gas and renewables by 13 percentage points each, an increase in the share of biomass by 5 percentage points and in the share of nuclear by 2 percentage points. The case of the UK looks quite unique when compared with other EU countries like is done on Figure 6, showing the fuel mix for all EU countries in 2012 and 2017 and ranking countries in ascending order of their 2012 coal share. Between the two period, the UK goes from the 6th highest coal share to one of the lowest, while most other countries keep the same ranking.

The Carbon Price Floor can directly impact both the average emission intensity of a given fuel used for generation and the electric mix. Applied as a tax on fuel input, it leads to a higher increase in marginal generation cost for less efficient plants (i.e plants using more coal or more gas by kWh of electricity output). Within a given fuel, it will thus lead to a production reallocation to more efficient plants. The magnitude of such impact depends on the potential for production re-allocation within a given input (there must be room for

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[14] While it is true that power generation itself is emission-free with these sources, manufacturing solar panels, windplants or nuclear plants is not. For biomass, power generation does generate greenhouse gases, but the EUTL does not count them since carbon released when solid biomass is burned is expected to be re-absorbed during tree growth : see `https://ec.europa.eu/clima/sites/clima/files/ets/docs/com_2018_842_final_en.pdf`

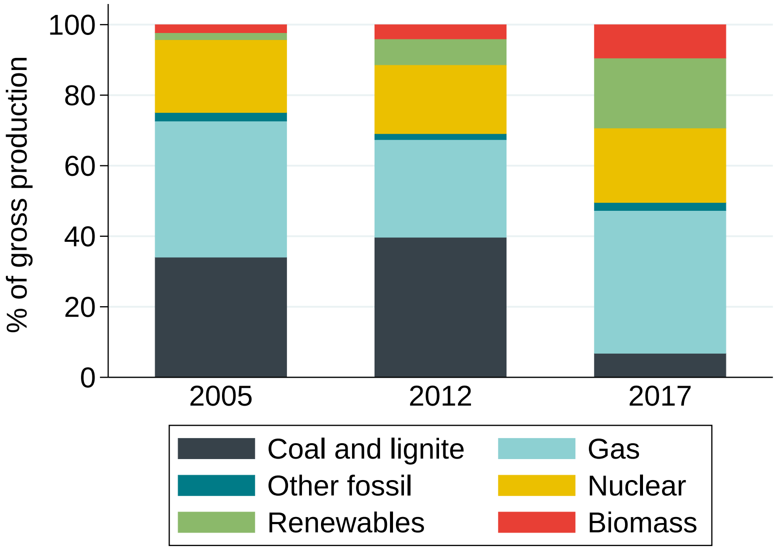
producing more for the most efficient plants), and of the heterogeneity of plants (there must be some plants more efficient than others). The CPF will also induce a change in the electric mix, with two distinct impacts: in the short-run, the CPF increases the marginal cost of coal generation compared to gas generation and induces fuel switching (Van den Bergh and Delarue, 2015). In the long run, this change in the cost of running high-emitting power plants can also affect investments in low-carbon generation. From a plant-level perspective, the CPF can lead to a production re-allocation at the intensive margin, with production re-allocated to either more efficient plants using the same fuel or plants using a lower-emitting fuel; it can also trigger changes at the extensive margin in the form of plant closure.

Two other policies implemented over the period of interest must be accounted for when considering the strong decrease in the emission intensity of gross production visible on Figure6b. First, the EU Large Combustion Plants Directive issued in 2001 induced the closure of several high-emitting power plants. This air pollution regulation imposed air pollutants emission thresholds that large combustion plants had to respect by 2015. Targeted installations could however choose to opt out of the regulation if they committed not to operate the plant for more than 20,000 hours between 1 January 2008 and 31 December 2015 (European Commission, 2001); in practice, it means that the concerned plants had to either retrofit or shut down by 2015. Nine UK plants representing 11% of emissions in 2011 chose this opt-out option and shut down between 2012 and 2015. Three other plants chose to opt-out for part of their sites only (Source: EEA website).

Second, the government started supporting coal-fired power plants converting to biomass in 2012. This support first took the form of dedicated Renewables Obligation Certificates (ROCs). These certificates were embedded in the broader Renewables Obligation scheme designed to support the deployment of large-scale renewable electricity generation; they create an obligation for electricity suppliers to source a proportion of their electricity from plants with ROCs. The scheme was replaced by the Contract for Difference scheme in

2014, which guarantees a government flat payment to generators converting to biomass[15]. Two power plants received government support for the conversion: Drax power station, representing 14% of UK power sector emissions in 2012, benefited from these two schemes and intensified its biomass conversion - started in 2009 at its own initiative - in 2012. Lynemouth power station received support under the CfD scheme and converted to biomass in 2016. The timings of implementation of the CPF and the support policy for biomass conversion are close and make wonder to what extent one led to the other. The decision to grant this subsidy might have been partly motivated by industry lobbying and the government wish to weather the transition for coal-fired power plants facing the Carbon Price Support. On the other hand, even without the Carbon Price Floor it might have made sense to promote coal transition to biomass via subsidies.

Figure 5: UK power sector's input fuel mix in 2005, 2012 and 2017



Note: Data come from Eurostat. Renewables include hydro, solar and wind

Overall, we observe at the same time a large change in the carbon emissions and fuel input mix in the UK after 2012, and almost no change in other European countries that did

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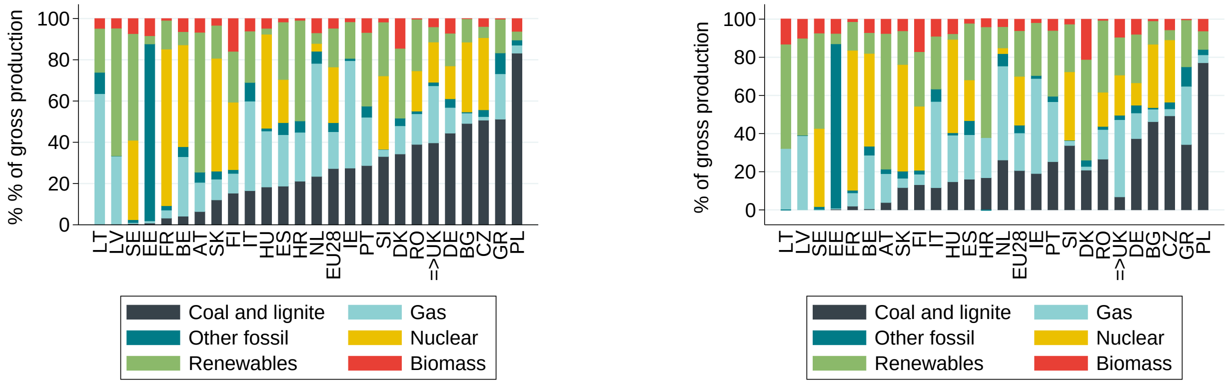
[15] The value of this flat payment is supposed to reflect the difference between the strike price derived from an auctioning process and reflecting generators' true cost (incl. investment in conversion in the case of coal-to-biomass conversion), and the average market price of electricity. See `https://www.emrsettlement.co.uk/about-emr/contracts-for-difference/` for more details

Figure 6: Power sector's input fuel mix in EU countries, 2012 and 2017



(a) 2012

(b) 2017

Note: EU countries are ranked by ascending order of the share of coal in electricity generation in 2012. The three smallest countries (Cyprus, Malta and Luxembourg) are not included, to improve readability. Data come from Eurostat. Renewables include hydro, solar and wind.

not implement a Carbon Price Floor. This suggests a causal link between the introduction of the CPF and the decrease in emissions. I now turn to a more formal empirical setting to estimate the causal impact of the CPF on emissions.

5 Empirical strategy

5.1 The synthetic control method

To estimate the impact of the Carbon Price floor on the power sector in the UK, I use the synthetic control method (or SCM) exposed in Abadie and Gardeazabal (2003) and Abadie et al. (2010, 2015). This method consists in building a counterfactual UK power sector by applying appropriate weights to the set of other European countries' power sectors. It is particularly appropriate in this context since the CPF ”treatment” applies to only one unit and the entire sector with only very few exceptions. Within the UK, there is therefore no obvious group of installations that would perfectly reproduce the counterfactual of how the treated British power plants would have evolved absent the treatment. Using the notation traditionally used in the policy evaluation literature, the challenge is to estimate $\beta_{\text{UK}t}$ when t≥2013, defined as:

$$\beta_{\mathrm{UK}t} = Y_{\mathrm{UK}t} - Y^0_{\mathrm{UK}t} = Y^1_{\mathrm{UK}t} - Y^0_{\mathrm{UK}t} \tag{4}$$

$\beta_{\mathrm{UK}t}$ designates, at each period, the difference between UK power sector emissions in the presence of the CPF policy, $Y^1_{\mathrm{UK}t}$, and UK power sector emissions in the absence of the policy, $Y^0_{\mathrm{UK}t}$. The challenge comes from the fact that the counterfactual outcome $Y^0_{\mathrm{UK}t}$ is not observed when t≥2013.

Let us assume that the observed outcome can be modelled as a linear factor model:

$$Y_{ct} = \beta_{\mathrm{UK}t} T_{ct} + Z_{ct}\alpha + f_t'\lambda_c + \epsilon_{ct} \tag{5}$$

Where T_{ct} is the treatment dummy equal to 1 when $c = UK$ and t≥2013 and 0 otherwise, Z_{ct} is a vector of observed exogenous country characteristics, , f_t is a vector of unobserved time effects or factors, λ_c is a vector of unobserved country-level effects or factor loadings, and ϵ_{ct} is the error term with mean 0 (typically transitory shocks at the country level).

One can easily see that such a model is more flexible than the typical difference-in-difference equation in that time effects and individual effects are allowed to interact. Abadie et al show that with such specification, it is possible to obtain a consistent estimate of $\beta_{\mathrm{UK}t}$ as a function of outcomes observed post-treatment in other countries:

$$\hat{\beta}_{\mathrm{UK}t} = Y_{\mathrm{UK}t} - \sum_{j=1}^{J} w_j^* Y_{jt} \tag{6}$$

Where $\sum_{j=1}^{J} w_j^* Y_{jt}$ is a weighted combination of the outcome for J countries having not implemented the policy, and the vector $W^* = (w_1^* ... w_J^*)'$ should satisfy the three following conditions:

$$\begin{cases} \sum_{j=1}^{J} w_j^* & = 1 \\ \overline{Y}_{\mathrm{UK}}^{K} & = \sum_{j=2}^{J} w^* \overline{Y}_j^{K} \\ Z_{\mathrm{UK}} & = \sum_{j=2}^{J} w^* Z_j \end{cases}$$

With Y_{UK}^{K} a linear combination of pre-intervention power sector emissions in the UK, and $\overline{Y}_j^{K}$ a linear combination of power sector emissions for country j (for example it can be the simple mean of pre-intervention outcomes $\overline{Y}_j^{K} = 1/T_0 \sum_{t=1}^{T_0}(Y_j)$).

In practice, to find the appropriate W vector I rely on an algorithm created by Abadie et al. The algorithm minimizes the distance between a vector of pre-intervention characteristics in the treated region, X_{UK} (with dimensions $K \times 1$) and a weighted matrix of pre-intervention characteristics in the non-treated regions, X_0W (with dimensions $K \times K$). Pre-intervention characteristics are of two types: 1) linear combinations of pre-intervention outcomes, and 2) the Z country characteristics not affected by the intervention. To obtain the W vector, the programme starts with a positive and semi-definite matrix V that defines a dot product. The distance between X_{UK} and X_0W can then be written as

$$X_{\mathrm{UK}} - X_0W = \sqrt{(X_{\mathrm{UK}} - X_0W)'V(X_{\mathrm{UK}} - X_0W)} \tag{7}$$

The goal is to find the vector $W^*(V)$ that minimizes this distance. Such minimization actually comes down to finding the right V matrix, which can be shown to be equivalent to a diagonal matrix assigning weights to linear combination of characteristics in X_{UK} and X_0W (Abadie and Gardeazabal, 2003). Like Abadie and Gardeazabal (2003), I choose the V minimizing the mean squared prediction error of the outcome variable in the pre-treatment periods. Formally, let Y_{UK} be the (8×1) vector of pre-2013 power sector emissions from 2005 to 2012 for the UK and Y_j be the $8 \times J$ matrix of pre-2013 power sector emissions for the J other European countries. Then V^* is chosen such that:

$$V^* = argmin(Y_{\mathrm{UK}} - Y_jW^*(V))'(Y_{UK} - Y_jW^*(V)) \tag{8}$$

where V is the set of all non-negative diagonal $(K \times K)$ matrices.

The ability to build a good synthetic control can be assessed by at least two criteria: first, the closeness of pre-intervention characteristics between treated and synthetic control. This depends on how well these characteristics predict the outcome and can be assessed by comparing pre-intervention characteristics for the treated and synthetic country. The second criterion is the closeness of pre-intervention outcomes between treated and synthetic control, which can be seen graphically or by computing the Mean Squared Prediction Error[16].

Beyond identification, inference can be derived by running a set of placebo studies, which consist in applying the same synthetic control methodology to states that did not implement such a policy (Abadie et al., 2010).

5.2 Potential threats to the identification strategy

An important condition for the synthetic control method to identify the causal impact of the intervention is that candidate units for the synthetic control group (in this case EU countries outside the UK) should not be affected by the intervention. In the case of the CPF, there are two channels via which other European countries' power sectors could be affected by the policy: directly via an increase of their net electricity exports to the UK; and indirectly via the effect of the CPF on demand for carbon allowances on the carbon market and the subsequent effect on EUA prices (the so-called waterbed effect, see Perino (2018)).

Increased electricity imports While I already mentioned increased electricity imports as one of the mechanisms through which the CPF has an impact on UK CO_2e emissions in section 4.2, here I approach electricity imports as a specific challenge to my identification strategy, based on a comparison with other European countries. Indeed, if UK net electricity imports represent a large share of each exporting country's electricity production and if the CPF truly causes an increase in electricity imports, this reallocation of electricity production

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[16] The MSPE gives the square of the difference between the treated unit's and the synthetic control's pre-intervention outcomes.

will artificially increase the UK trading partners' CO_2e emissions linked to this increased electricity production, and the associated gap between the UK and synthetic UK. However, given the specificities of the UK geography and for the same reasons exposed in section 4, I deem the effect of the CPF on other countries' CO_2e emissions via increased exports small. I will nevertheless calculate an upper bound of the amount of CO_2e emissions exported to other European countries due to a CPF-induced reallocation of electricity production.

Waterbed effect The indirect channel refers to the theoretical argument, extensively mentionned in the literature (Böhringer et al., 2008; Goulder and Stavins, 2011; IPCC et al., 2014), that under a common emission cap, any emission reduction in a given country only leads to an emission increase elsewhere. The risk of such a waterbed effect has been mentionned by some authors prior to the introduction of the CPF. (Berghmans and Sartor, 2011; IPCC et al., 2014). However, there are at least three reasons to think that this does not poses a severe threat to my strategy.

First, as far as my identification strategy is concerned, I am only concerned with the effect of a potential waterbed effect on CO_2e emissions *in the power sector*. A waterbed effect materializing as an increase in CO_2e emissions from installations other than power generators would not be an issue for my estimation (although it could be an issue from the point of view of the efficiency of the overall scheme).

Second, one can doubt whether the CPF would empirically result in a substantial increase in EUA prices: a first reason is that UK power installations only represent 8.8% of total verified emissions in 2012 in my data. A second reason is that the determinants of EUA prices are not well understod empirically: according to a study examining price data over 2008-2015, overlapping climate policies (such as support to renewable energies) do play a significant but small impact on EUA prices, but the coal-to gas price ratio, another variable considered important in the theoretical literature, do not have an impact (Koch et al., 2014). All this suggests that the CPF, which affects fuel prices only for a small share of the market, probably had a low impact on prices.

Third, the papers mentioning the risk of a waterbed effect formulate an ex-ante assessment prior to the introduction of the CPF. Their hypothesis depends on theoretical assumptions that are likely not to have hold at the period where the CPF was implemented. Indeed, theoretically the waterbed effect only happens if the emissions cap of the cap-and-trade is binding. In the case of the EU ETS, the annual aggregate demand for allowances has been below the EU-wide cap since 2008, with a surplus of 1.8 bn allowances at the end of phase II (Ellerman et al., 2016). This led to an increase in the banking of allowances[17]. As a consequence, even if the CPF did cause a decrease in EUA prices and induced non-GB power generators to buy more allowances, they probably banked a significant share of them for future use. In that case, the CPF would induce an increase in *future* rather than *current* emissions from non-GB power generators. A final argument going against the waterbed effect and linked to the banking of allowances is the recent set of reforms brought to the EU ETS, and more precisely the Market Stability Reserve. The MSR is a new feature of the ETS implemented in 2019, that withdraws and inject allowances from and to the bank of unused allowances according to a quantitative formula. Crucially, allowances placed in the MSR can also be cancelled when they exceed a certain threshold. As evidenced by Quemin and Trotignon (2018), the MSR can act as a patch to curb some excess supply from past shocks or policies. With its ability to cancel allowances, the MSR can also retroactively and temporarily puncture any waterbed effect created by past overlapping policies as evidenced by Perino (2018): intuitively, the more allowances are banked for future use, the more the MSR is likely to exceed the threshold where it starts cancelling allowances.

In short, while I can not rule out the existence of a waterbed effect inducing non-GB installations and more specifically non-GB power generators to emit more emissions after 2013, the reasons exposed above suggest that this effect is probably very small relative to these installations' total emissions.

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[17] Banking is a mechanism that allows, since phase II, to bank allowances for use in phase III and future years, when the price would be higher

Potential confounders As mentioned in section 4.2, two other UK policies may have contributed to the observed decrease in emissions. These policies could be confounding factors in the estimation of the impact of the CPF policy. Regarding the opting out regime under the LCP Directive which led to some plant closures, the SCM method makes it possible to control for it. Indeed, the LCP directive was imposed to all EU countries, and the UK was not the only country with a significant number of plants deciding to opt out. It should thus be possible to build a synthetic UK where a similar share of emissions belong to plants at risk of closure due to the LCPD. Absent the Carbon Price Floor, UK opted out plants might have decided to make the investments necessary to continue running with coal instead of shutting down. Regarding the biomass conversion policy, I did not find evidence for similar policies in the rest of European countries. The CPF and support for biomass conversion are likely not to be independent from one another. In my main specification I will consider that the decision to subsidise biomass conversion was conditional on the decision to implement the CPF and that plants would not have converted to biomass absent the CPF. I will also present an estimate of my result excluding plants having benefited from government support for biomass conversion.

5.3 Choice of predictors

The set of pre-intervention characteristics X_0 used to build the synthetic UK should be variables predicting aggregate per capita CO_2e emissions in the power sector. To select them, I rely on the literature looking at drivers of emissions (Ellerman and McGuinness, 2008; Van den Bergh and Delarue, 2015; Lee and Melstrom, 2018). For each predictor, the sources and data processing steps are described in Appendix B.

In countries relying both on coal and gas-fired power plants for electricity generation, like the UK, fuel switching has been identified as an important determinant of aggregate emissions. In their article estimating the impact of the EU ETS on coal and gas-fired electricity generation in the UK in 2005-2006, Ellerman and McGuinness (2008) build a linear model of fuel switching. In their specification, fuel switching is measured by the monthly utilization rate of CCGT and coal-fired power plants, and is a function of the coal-to-gas price ratio per MWh of generated electricity, the monthly aggregate demand for electricity, the electricity generated by nuclear plants, plus some flexible interaction terms. The coal to gas price ratio turns out to be an important predictor of fuel switching. While the Carbon price floor directly impacts this ratio since it translates into a differentiated tax on input fuels depending on their carbon content, the pre-2013 ratio can be used as one of the covariates predicting the evolution of CO_2e emissions. Given the non-linear effects of this variable, I also include a quadratic term[18].

While the coal-to-gas price ratio is an important predictor of the amount of high-emitting versus low-emitting fuels used for generation, it does not include polluting solid fuels other than conventional coal, in particular lignite. Lignite is a low-quality type of coal with a very poor calorific value and high emission intensity, that is mostly consumed domestically by the power sector (Berghmans and Alberola, 2013). To account for the large differences in lignite resources and use across European power sectors, I include in my predictors set a dummy variable identifying the countries with large lignite resources: Germany, Poland, Hungary, Greece, Czech Republic, and Bulgaria.

To account for demand from CO_2-emitting power plants, I approximate the demand for electricity generated by fossil fuels with the average of heating degree days each year. This variable approximates the demand for energy needed for heating. In the EU, it is measured as the number of days of the year where the average temperature is below a reference temperature of 15.5°C (under which energy for heating is needed), times the difference in Celsius degrees between this reference temperature and the temperature of the day. Compared to the average annual temperature used in other papers, this variable better accounts for the need for power generation related to low temperatures. Since gas- and coal-fired generation are often used to cover peak power demand, this variable is expected to correlate with the

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[18] In a sensitivity analysis, I also run a specification without this quadratic term. The coal-to-gas ratio weighs less, but the results are virtually unchanged

emission intensity of the power sector.[19]

Finally, to account for the constraint imposed on plants having opted out from the LCP Directive, I add as a predictor the amount of country-level per capita emissions coming from these installations for each country. The decision to opt-out from the Directive was independent from the CPF since it had to be made at the latest by 2007. However, two factors might have been influenced by the CPF: first, how the remaining operation hours of each opted-out plant has been spread over the 2005-2015 period; second, the decision to shut down the plant rather than invest in low-carbon technologies that would bring these plant's emissions in line with the directive requirements. I take the value of this variable in 2009, shortly before the introduction of the CPF. This way, the synthetic UK will be built as a weighted combination of countries having a similar amount of emissions from plants subject to close or retrofit shortly before the announcement of the CPF.

In addition to these 5 predictors, I add lagged per capita emissions for the first and last year of the pre-treatment period, 2005 and 2012. For the optimization described above, the predictors are averaged over the 2005-2012 period, except for the coal-to-gas price ratio and its square, averaged over the 2007-2012 period (see Appendix B for more details).

5.4 Choice of the donor pool

To replicate the evolution of the UK power sector in the absence of the carbon price floor, it is important to discard from the "donor pool" - the set of countries not affected by the CPF that will potentially enter the composition of the synthetic UK - the countries that are likely to fail this exercise (Abadie et al., 2010). This can include three types of countries: First, countries that suffered idiosyncratic shocks to the outcome of interest, ether by directly introducing a policy targeting the power sector or via a more generic exogenous shock likely

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[19] In an alternative specification, I use instead a per capita residual load variable. Residual load measures the amount of electricity demand that needs to be covered by fossil fuels and biomass once generation from so-called "must-run" power generators (nuclear power plants) and those that generate with almost no marginal cost (solar, wind and hydro) is withdrawn. The results (available upon request) are unchanged when I use this residual load variable instead of the number of degree days.

to affect the electricity sector. Second, countries that are likely to be directly affected by the CPF. Third, countries with very different characteristics compared to the UK, which may cause severe interpolation biases.

Regarding the first type of countries, by 2017 no other European countries had adopted such a significant pricing policy as the UK and its carbon price floor. Although France and the Netherlands have recently discussed introducing a carbon price floor as well (Newbery et al., 2018), only the latter have passed a concrete law in August 2018, and the Dutch CPF will only start in 2020. The biggest change in other European countries' power sectors is the case of Germany, which unexpectedly decided to phase out of nuclear energy following the 2011 Fukushima nuclear accident. I therefore exclude Germany from the donor pool. Since the the European debt crisis affected the Greek economic environment very heavily over the period, I also exclude Greece from the donor pool.

Regarding the second type of countries, as mentioned above, one of the consequences of the CPF was an increase in net electricity imports from European countries. The countries exporting electricity to the UK are then likely to themselves experience an increase in their electricity production. If this trade effect is large, not accounting for it would likely over-estimate the net impact of the CPF, since part of the countries from the donor pool would have higher per capita emissions than in the absence of the CPF. I argue that this increase is small and I will try to quantify the amount of such spillovers. Regarding the waterbed effect also mentioned above, I consider the magnitude of the effect too small to be a serious threat to my strategy.

Finally, to avoid having countries too different from the UK, I eliminate the three Baltic countries - Estonia, Latvia and Lithuania - which unlike the UK (and as can be seen on Figure 6), do not use coal for power generation. Since coal-to-gas switching is expected to be one of the important drivers for de-carbonisation, it is most relevant to restrict the analysis to countries who can experience it. In the end, the donor pool includes 15 EU countries.

To ensure that it is possible to build a convex combination of countries that closely reproduce the UK's values for predictors and emissions, I checked that there is common support between the distribution of these predictors in the donor pool and in the UK. This is the case for all variables. The corresponding histograms are in Appendix C

6 Results

6.1 Main result

The main results are visible on figure 7a, which displays the trajectory of per capita emissions for the UK and synthetic UK over the 2005-2017 period. In dotted line, it also shows the simple average of per capita emissions for the 15 countries of the donor pool.

Table 3 below shows the relative weights of each predictor in the V matrix, as well as the average value of each predictor in the UK, synthetic UK, and for the average of the donor pool. The predictor with the highest weight is the number of degree days, followed by the coal-to-gas price ratio and its square. This is not surprising given the aforementioned potential for fuel switching in the UK and the countries forming the synthetic UK. Together, these three variables plus the coal gas price ratio squared make up 94.5% of the total weighting. The pre-treatment predictors' values in the synthetic UK are very close to the values for the actual UK, which is one of the identification assumptions of the SCM. In contrast, compared to the average country in the donor pool, the UK has significantly higher average per capita emissions prior to the introduction of the CPF, a higher amount of emissions from opted out plans, a lower coal-to-gas price ratio, lower number of degree days, and no lignite. These differences justify using the Synthetic Control Method to build a counterfactual accurately replicating the UK power sector.

Reassuringly, on figure 7a the UK and synthetic UK have a similar trajectory before the treatment occurs in 2013, with a Mean Square Prediction Error (MSPE) of 0.008. This suggests that the synthetic UK after 2013 accurately replicates the evolution of per capita emissions in the UK power sector if the CPF had not been introduced. The period where the fit is less good is 2012, year where the UK emissions peak. It is also the year where the share of coal in the UK fuel input mix is the highest and the coal-to-gas price ratio at its lowest point since 2007 (BEIS, 2018). If power could be easily stored, the 2012 peak could also be interpreted as an anticipation effect of the CPF, which was announced in 2011. Coal-fired power plants would then have an interest to use their coal before it becomes highly taxed in 2012, and sell part of the electricity produced with that coal the subsequent years. Given that electricity cannot be stored and production has to match demand at every point in time, such a strategic behaviour is more limited than in other sectors. The only possible case would be if UK coal-fired plants had excess coal stocks from previous coal purchasing contracts, and were ready to use this coal before 2013 to avoid it being taxed and sell the resulting electricity at a price cheaper than their marginal cost. It is reasonable to think that the power plants scheduled to close because of the LCP directive had an even greater interest in adopting such behaviour. Official data on annual coal consumption and stocks by electricity generators indicate that coal stocks as a share of stocks and consumption are indeed lower in 2012 compared to previous periods (20% vs 27% on average over 2005-2012), although the difference is not large. (BEIS (Department for Business, Energy & Industrial Strategy), 2019). This suggests that such an anticipation effect may have taken place. To capture it, I also test a specification where I assume that the treatment started in 2011 rather than 2013 (see section 6.4) .

The gap between the UK and synthetic UK starts in 2014 and widens until 2017, date where per capita UK emissions are 50% lower than in 2012 while they are only slightly lower in the synthetic UK.

The synthetic UK is made of six countries: Ireland (53%), Slovakia (17.5%), Italy (15%) Finland(8.7%), Poland (5.7%), and Denmark (0.1%). The remaining potential control countries have a weight of 0. The large weight of Ireland does not come as a surprise: the two countries have close institutions and energy markets, and like the UK, Ireland has a

Table 3: Predictors' weights and values for UK, synthetic UK and average of the donor pool

Variable	**Weight**	**UK**	**Synth. UK**	**Avg. Donor pool**
Degree days	81.8%	3,020.3	3,019.3	3,076.5
Coal-gas price ratio	0.2%	0.52	0.50	0.71
Coal-gas price ratio squared	12.5%	0.27	0.27	1.26
Per capita opted-out emissions in 2009	5.5%	0.28	0.28	0.22
Lignite dummy	0.01%	0	0.06	0.2
Per cap. emissions 2005	0.008%	3.0	3.1	2.6
Per cap. emissions 2012	0.02%	2.6	2.4	2.1

Note: The weights of the predictors correspond to the diagonal coefficients of the V matrix minimizing the distance between the UK and synthetic UK prior to the introduction of the CPF in 2013. The predictor values are their true value for time-invariant predictors, their average across 2005-2012 for the number of degree days and their average across 2007-2012 for the coal-to-gas price ratio and its squared. See Appendix A for more details.

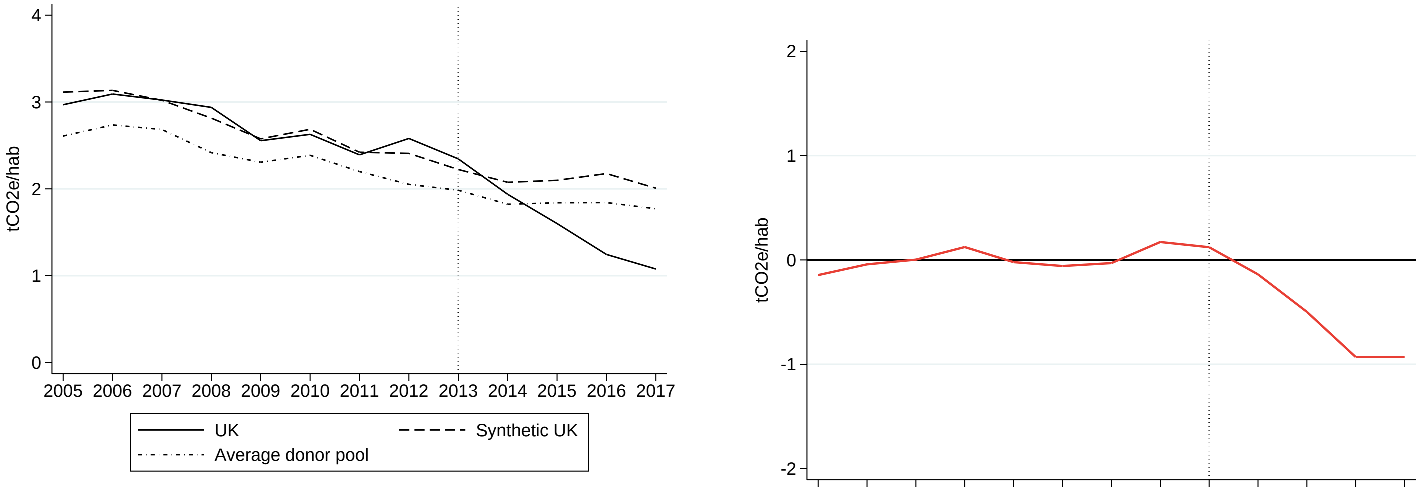
substantial portfolio of coal- and gas-fired power plants.

Figure 7b displays the gap between the synthetic and treated UK, representing the annual decrease in per capita tCO_2e resulting from the introduction of the CPF. As visible on the figure, UK per capita emissions really only started to be significantly lower than the synthetic UK in 2014, with the 2013 UK value even slightly higher than the synthetic UK. From 2014 on they steadily decreased until 2016, and stabilized in 2017. Given the timing of the introduction of the CPF (April rather than January 2013) and the strong increase in its rate between 2013 and 2015, such an emission path makes sense.

I estimate the equivalent annual abatement of tCO_2e by multiplying, at each period starting in 2013, the gap in per capita emissions by the UK total population. I then add up all annual abatements and find a total cumulated abatement of 156 millions of tCO_2e over the 2013-2017 period. By 2017, emissions were lower by 48% (61.4 $MtCO_2e$) in the UK than in the synthetic UK.

In the next section, I look at the role and magnitude of spillovers to other countries in the form of increased UK electricity imports.

Figure 7: UK and Synthetic UK per capita emissions



(a) Absolute per capita emissions for the UK, Synthetic UK and average of the donor pool

(b) Emission gap between treated and synthetic

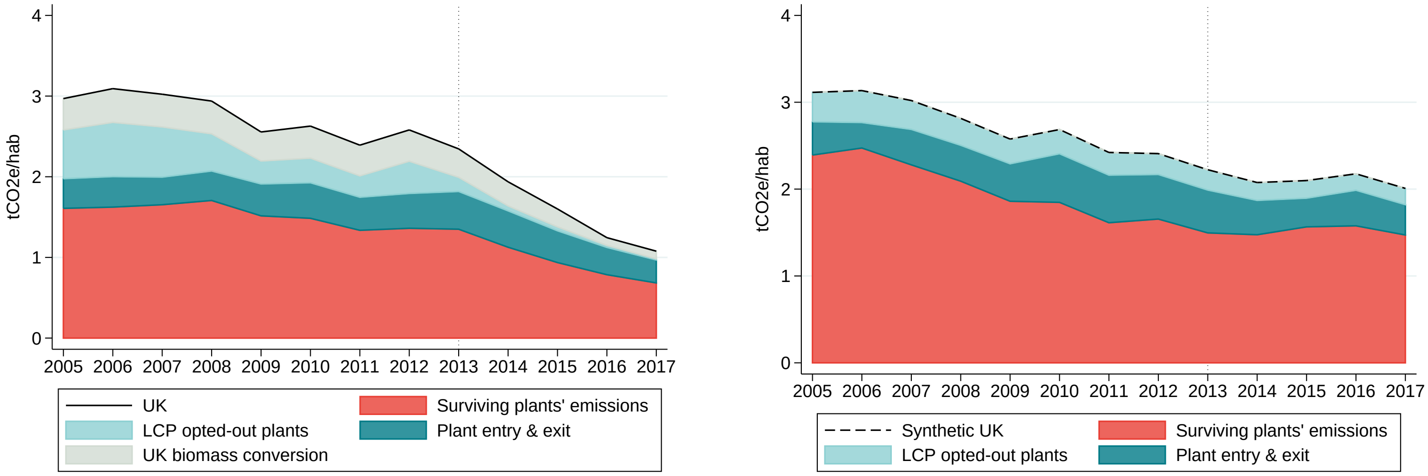
Note: For each period, the variable of per capita emissions corresponds to the sum of CO_2e verified emissions from power installations subject to the EU ETS, divided by the average country population that year. The vertical line is set in 2013, date where the CPF is introduced. The synthetic UK is made of six countries: Ireland (53%), Slovakia (17.5%), Italy (15%) Finland(8.7%), Poland (5.7%), and Denmark (0.1%

6.2 Lower bound removing emissions from potential confounders

In Figure 8 I decompose the UK and synthetic emissions by source, distinguishing between the decrease in emissions which I deem fully imputable to the CPF and the decrease in emissions linked to the two potential confounding factors whose role may have been intensified by the CPF: first, the amount of emissions coming from installations which opted out from the LCP directive in 2005, in light blue on the figure. Second, the amount of emissions coming from plants having converted to biomass, shown in grey (only for the UK). The synthetic UK was built such that a similar amount of emissions falls under the LCP opt out regime in 2009. Therefore heterogeneity in pre-CPF response to the LCP directive is partially controlled for. Over the whole 2005-2012 period, the amount of ”opted out” emissions somewhat differs between UK and synthetic UK. But the most striking difference is the strong decrease of these emissions after 2012 in the UK and their relative stability in the synthetic UK. This difference suggests that the CPF may have intensified UK plants' response to the LCP opting out regime and accelerated their closure. Such an interpretation would confirm a Guardian journalist's statement that "[UK coal-fired] Plants have closed in recent years as EU pollution standards started to bite, but it was increases in the UK's carbon tax that sealed their fate" (Vaughan, 2018). On the other hand, the government support to biomass conversion is unique to the UK and represents a substantial amount of emissions on the left-hand side of figure 8. Once these two potential confounders and the associated emissions have been identified, the remaining emissions can be divided in two: first, emissions from installations present in the data for the whole period (in red on the figure): for these installations, emission reduction can only come from production re-allocation to more efficient and less-emitting plants. This emission decrease at the intensive margin is relatively important after 2013, as visible on the figure. Second, emissions from plants not present in the dataset the whole period, which either entered after 2005 or exited before 2017 (in dark blue). Comparing the red and dark blue areas for the UK and synthetic UK suggests that the emission decrease was driven mostly at the intensive margin by a decrease in plants' emission intensity rather than by plant entry and exit, since only the former shows a marked decrease after 2013.

To obtain a lower bound for the estimate of the impact of the CPF excluding the potential confounding effect of biomass conversion and LCP opting-out regime, I apply the synthetic control method on a modified outcome of per capita emissions: I only keep CO2e emissions coming from non-opted out plants in both the UK and donor pool, and remove emissions coming from power plants having converted to biomass in the UK. The predictor used are the same as in the main specification except for the lag of the outcome in 2005 and 2012, which is taken at its modified value. Since UK per capita emissions before 2013 are significantly lower after these changes, the synthetic UK is also made of different countries, composed at 85% of Belgium, Poland and France. This new synthetic UK accurately replicates the per capita emission path of the UK before 2013. The results visible on Figure 9 are partly

Figure 8: per capita CO2 emissions by source, UK and synthetic UK



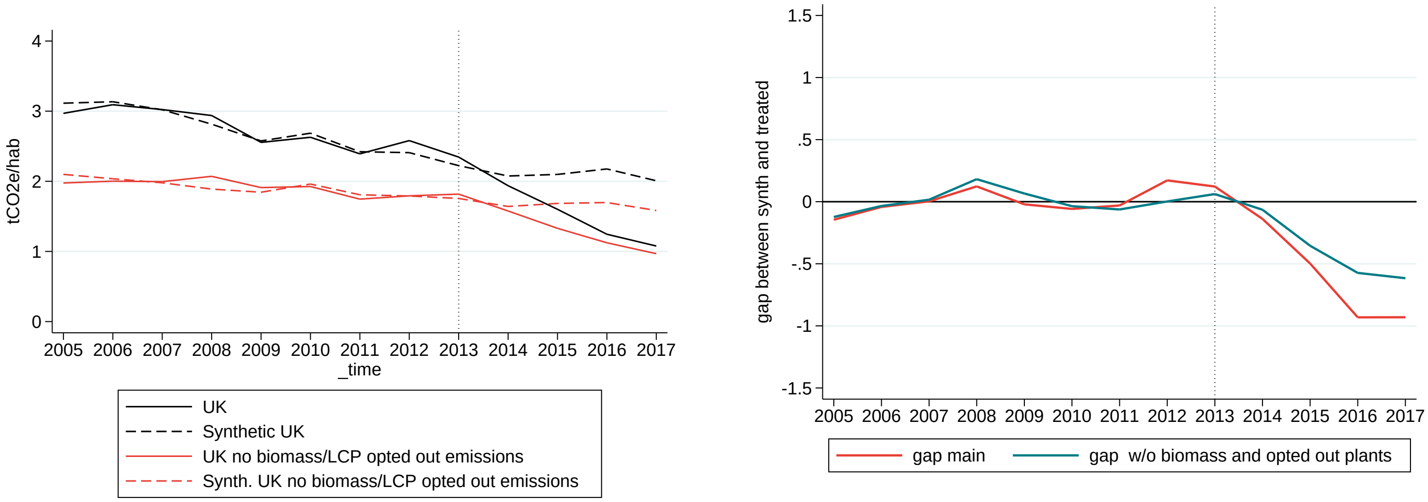
(a) UK

(b) Synthetic UK

Note: For each period, the variable of per capita emissions corresponds to the sum of CO_2e verified emissions from power installations subject to the EU ETS, divided by the average country population that year. The vertical line is set in 2013, date where the CPF is introduced. The synthetic UK is made of six countries: Ireland (53%), Slovakia (17.5%), Italy (15%) Finland(8.7%), Poland (5.7%), and Denmark (0.1%

expected: the level of UK and synthetic UK per capita emissions are lower in this modified version, and the gap between the two is also smaller than in the main specification. This confirms that part of the post-2013 difference in emissions is due to the change in emissions by power plants opted out from the LCP directive or converting to biomass. As already mentioned, the CPF might have reinforced the impact of these two policies by increasing the net cost of keeping these plants running with coal (instead of shutting them down for LCP opted out plants, and converting them to biomass for those converting). Computing the equivalent annual abatement of tCO_2e and adding them up for the 2013-2017 period, I find a total cumulated abatement of 102 millions of tCO_2e, 54 $MtCO_2e$ less than in the main specification. Emissions were lower by 39% in the UK than in the synthetic UK. I consider this as a lower bound of the estimated impact of the Carbon Price Floor over the period.

Figure 9: Synthetic control method excluding emissions from opted out plants and plants having converted to biomass



(a) Absolute per capita emissions

(b) Emission gap between treated and synthetic

Note: Each year, the variable of per capita emissions corresponds to the sum of CO_2e verified emissions from power installations subject to the EU ETS, divided by the average country population that year. The vertical line is set in 2013, the date for the start of the policy. The synthetic UK for the main specification is made of six countries: Ireland (53%), Slovakia (17.5%), Italy (15%) Finland(8.7%), Poland (5.7%), and Denmark (0.1%). The synthetic UK for the new specification is made of nine countries: Belgium (31.9%), Poland (30%), France (22.4%), Ireland (8.9%), Finland (4.6%), Sweden (1.5%), Spain (0.4%), Italy (0.2%) and Portugal (0.1%)

6.3 Inference

In this section, I argue that my results are driven by the causal impact of the Carbon Price Floor by measuring (1) how likely it is to find an effect of the same magnitude as what I find when I apply the method before 2013 (”in time” placebo); (2) how likely it is to find an effect the magnitude from what I find when I apply the method to other countries (permutation test). These tests are run for the main specification[20].

”In-time” placebo One way to check that the results observed are indeed attributable to the reform implemented in 2013 is to assume that a similar reform was implemented

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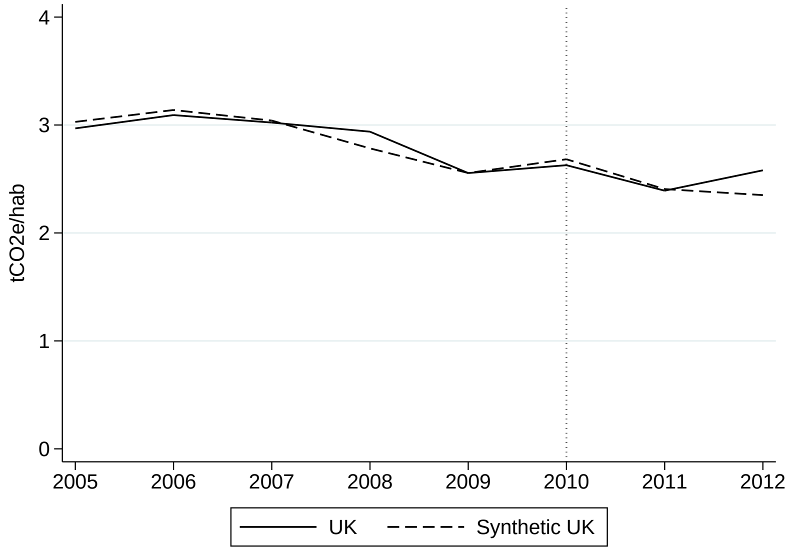
[20] Placebo tests run for the specification without emissions from biomass conversion and LCP opted out plants provide similar results although the magnitude of the difference between the UK and the other countries is smaller. Results available upon request.

at another date prior from 2013, apply the same method to generate a synthetic UK, and check that the UK and synthetic UK have similar per capita emissions before and after this artificial intervention date. Figure 10 shows what happens if I assume that the CPF was implemented in 2010 rather than 2013. Once again the synthetic UK closely resembles the UK emission trajectory before 2010, and as expected there is no significant gap between treated and synthetic UK in 2011 and 2012.

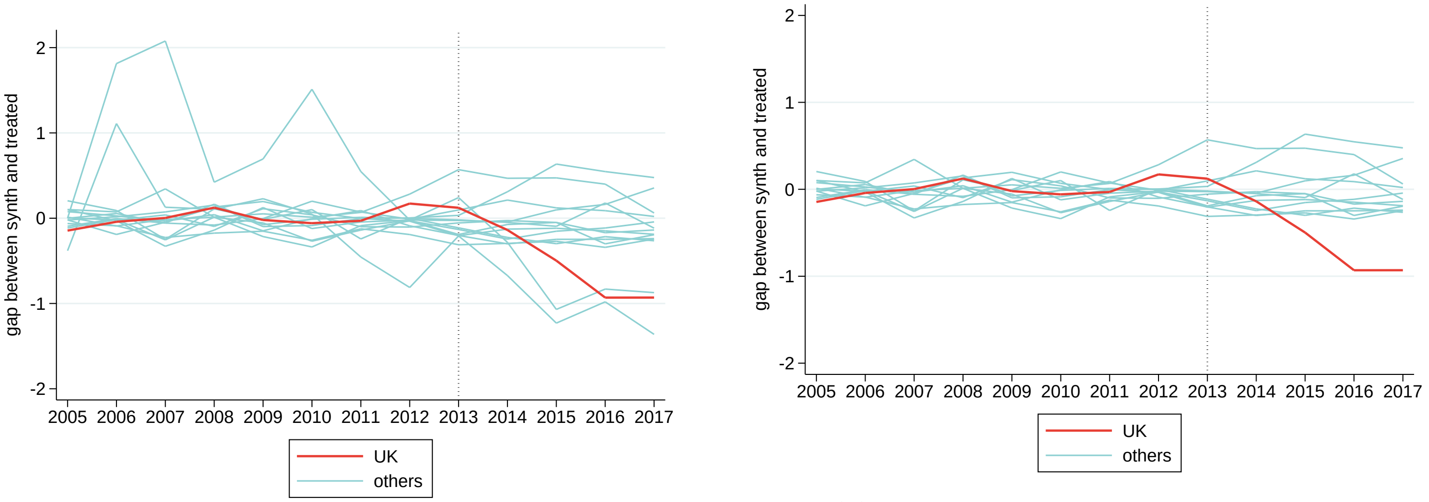
Figure 10: Gap between treated and synthetic UK when the CPF is assumed to be implemented in 2010



Note: Each year, the variable of per capita emissions corresponds to the sum of CO_2e verified emissions from power installations subject to the EU ETS, divided by the average country population that year. Here predictors are averaged over the 2005-2009 period, except for the coal-gas price ratio and its square, averaged over 2007-2010

Permutation test I conduct a series of placebo test where I build a synthetic counterfactual for each country of the donor pool, and test whether any of them experience a drop in per capita emissions (relative to its synthetic counterpart) as large as the UK. If this was the case, it would make it less plausible that the observed path for the UK and synthetic UK is indeed attributable to the CPF. This inferential technique also makes it possible to derive the likelihood one would have to observe an effect as large as the one observed for

Figure 11: Permutation test



(a) All countries

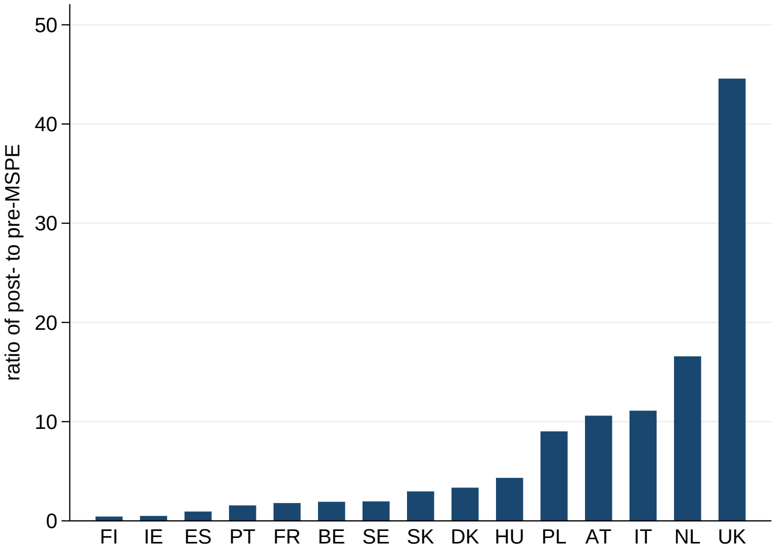
(b) Without the two countries with a large MSPE

Note: In both figures, Czech Republic is not included: for this country it is impossible to find a stable diagonal V matrix. In the right-hand side the countries excluded are those with an MSPE 10 times higher than the UK (Denmark and Finland)

the UK under a random permutation of the intervention on our data (Abadie et al., 2010). Figure 11 shows the gap between the treated and synthetic country for the UK and all the other countries in the donor pool, alternatively assumed to be the treated country. For Czech Republic and France, the countries from the donor pool with respectively the highest and lowest per capita emissions, it is impossible to find a stable V matrix and a convex combination of "control" countries replicating pre-2013 emission path. These countries are not included in the figure. For others, it is possible to find one but the pre-2013 fit is poor, in the sense that the synthetic control fails to replicate the "treated" country emission path and the pre-treatment MSPE is high. Comparing the post-2013 emission gap between the UK and these countries is not very meaningful, since the conditions for the synthetic control to be a good counterfactual are not met. This is why the picture on the right-hand side drops the two countries with a pre-2013 "large" MSPE 10 times greater than the UK (Denmark and Finland). On that figure, the UK clearly stands out as having the largest decrease in per capita emissions after 2013.

Another way to make more plausible the causal relationship between the implementation of the CPF and the emission path of the UK is to compute the ratio of post to pre-MSPE for all countries, where we should observe an unusually high ratio for the UK. Figure 12 shows that the UK ratio is indeed the largest, and is about 5 times higher than the Netherlands, the country with the second highest ratio. To make the parallel between this method and traditional hypothesis testing, we can interpret the result as the estimated probability to observe an effect as large as the one observed for the UK under a random permutation of the intervention on our data by dividing the countries having a higher ratio by the total number of countries. In this case the UK has the highest ratio amongst the 14 countries, so the associated probability is $1/14 = 7.14\%$, the lowest probability one can hope to obtain with a sample of 14 countries. Similar results are found when the permutation tests are run with the specification accounting for imported emissions, with the UK trajectory and post-to-pre MSPE ratio standing out compared to the other countries (results available upon request).

Figure 12: Ratio of post to pre-MSPE



Note: Czech Republic is not included: for this country it is impossible to find a stable diagonal V matrix.

6.4 Sensitivity analysis

Estimate of the impact accounting for exported emissions As discussed in section 4.2 , after 2013 the UK experienced an increase in its net electricity imports, which some researchers suggested was linked to the introduction of the CPF (Newbery et al., 2018). A concern specific to the estimation strategy used here is that these increased imports contaminate the donor pool, which should theoretically not be affected by the policy evaluated. Although descriptive evidence documented in section 4.2 suggest the magnitude of this net imports increase is low related to other countries, the spillover risk might still be substantial given the composition of the synthetic UK: Ireland, one of the three UK trading partners for electricity, has a weight of 53%. In the main specification, I assume that absent the policy, Irish emissions would have been the same as they currently are. Actually, in the absence of the CPF the UK might have exported more electricity to Ireland, and Ireland might have itself produced less electricity and emitted less. If this scenario is true, Ireland's per capita emissions, which weight for half of the synthetic UK, are overestimated. In this section, I address this concern by estimating a lower bound of Ireland's emissions in the absence of the CPF.

To obtain an estimate of the CO_2e emissions associated with UK imports of electricity, I proceed as follows: first, using Eurostat data on electricity trade, I estimate for each year of my period of interest 1) UK net electricity imports from all countries[21], and 2) Ireland's net electricity exports to the UK. Trade data for 2017 are not yet available on Eurostat, so I restrict this analysis to the 2013-2016 post-treatment period.

In a second step, I estimate the increase in UK net imports and Ireland's net exports in the post-treatment period relative to the 2005-2012 mean. Here I assume that all the variation in UK net imports (respectively other countries' net exports) is imputable to the CPF. This is of course oversimplifying, but allows to calculate an upper bound of the spillover.

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[21] They actually only come from France, Ireland and the Netherlands due to the physical constraints exposed above

Third, I calculate the corresponding imported/exported emissions by multiplying each country's net electricity imports/exports with its emission intensity[22]. For simplicity it is assumed that electricity imported from the Netherlands and France was produced respectively in the Netherlands and France. Finally, I apply the synthetic control method again using a modified per capita emission variable instead of the per capita emission variable previously used. This modified outcome variable assumes that all the additional electricity exported to the UK from 2013 onwards is instead produced in the UK. For the UK, it corresponds to the UK observed power sector emissions *plus* its imported emissions. For Ireland it corresponds to each country's observed power sector emissions *minus* their exported emissions. For all other countries, the modified per capita emission variable stays the same.

Figures 13a and 13b overlay the emission path and emission gap for 1) the UK and synthetic UK with the original per capita emission variable, and 2) the UK and synthetic UK with the modified per capita emission variable. As expected, the UK emission paths including its imported emissions are higher than the original UK emission path. However, the difference between the two is very small. Regarding the synthetic UK, its emission path excluding exported emissions is actually higher than the original one in 2013 and 2014. This is explained by the high weight of Ireland in the synthetic control group, and the fact that Ireland's net exports to the UK are lower in 2013 and 2014 compared to the average 2005-2012 period. The synthetic path with modified per capita emissions becomes lower than the original one in 2015 and 2016, reflecting the increase in Ireland's net exports to the UK.

My overall estimate of CO_2e abatement is slightly smaller with this modified synthetic control matching, with a total of 143 $MtCO_2$e abated in the UK relative to the synthetic UK, only 13 $MtCO_2$e less than in the main specification. This result has two implications: first, it confirms that the risk of spillover is low and does not pose a severe threat to the identification strategy. Second, it is informative per se and can be seen as the impact of the CPF on UK CO_2e emissions from a consumption-based rather than a production- based

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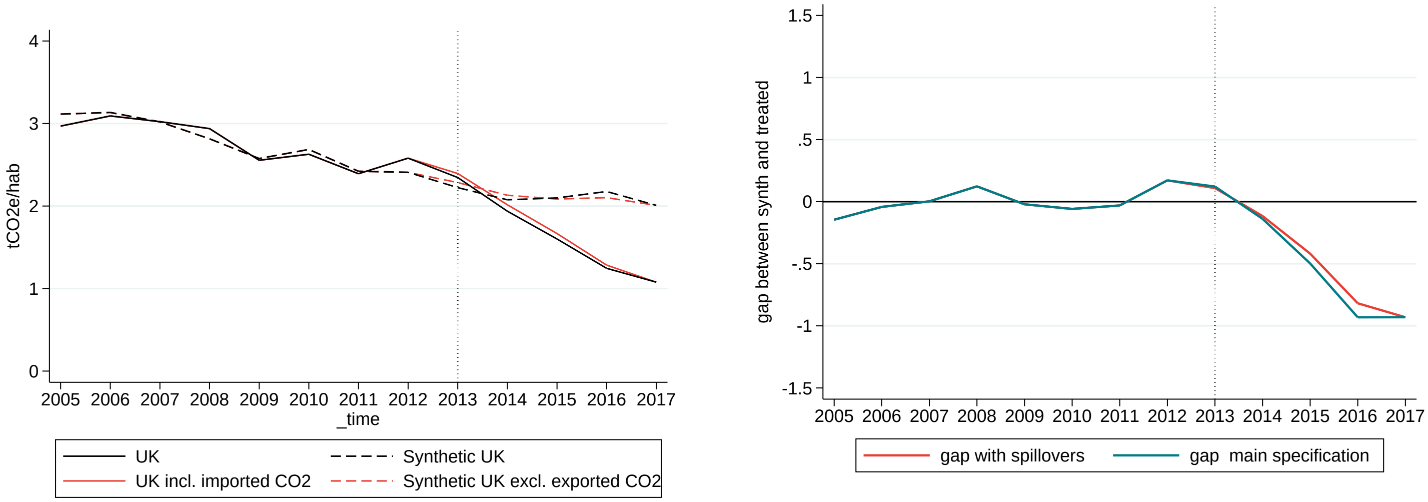
[22] For a given period, a country's emission intensity is defined as its total power sector CO_2e emissions divided by its gross electricity production

Figure 13: Synthetic control method accounting for imports spillovers



(a) Absolute per capita emissions

(b) Emission gap between treated and synthetic

Note: Each year, the variable of per capita emissions corresponds to the sum of CO_2e verified emissions from power installations subject to the EU ETS, divided by the average country population that year. The vertical line is set in 2013, the date for the start of the policy. The synthetic UK for the main specification is made of six countries: Ireland (53%), Slovakia (17.5%), Italy (15%) Finland(8.7%), Poland (5.7%), and Denmark (0.1%). The synthetic UK for the new specification is made of nine countries: Belgium (31.9%), Poland (30%), France (22.4%), Ireland (8.9%), Finland (4.6%), Sweden (1.5%), Spain (0.4%), Italy (0.2%) and Portugal (0.1%)

accounting perspective[23].

Estimate of the impact assuming anticipation effect in 2012 As explained in section 6.1, since the CPF was announced in March 2011, GB installations may have anticipated its introduction in the two years between announcement and actual implementation. This is particularly true for plants subject to the LCP opt-out regime, which had decided to shut down anyway and might have preferred to use their coal stocks when they To account for such potential anticipation effect, I backdate the intervention to 2011 and apply again the SCM - making sure that the predictor values are averaged only until 2010. Figure 14a shows the resulting synthetic UK. The gap between synthetic and treated UK becomes indeed larger

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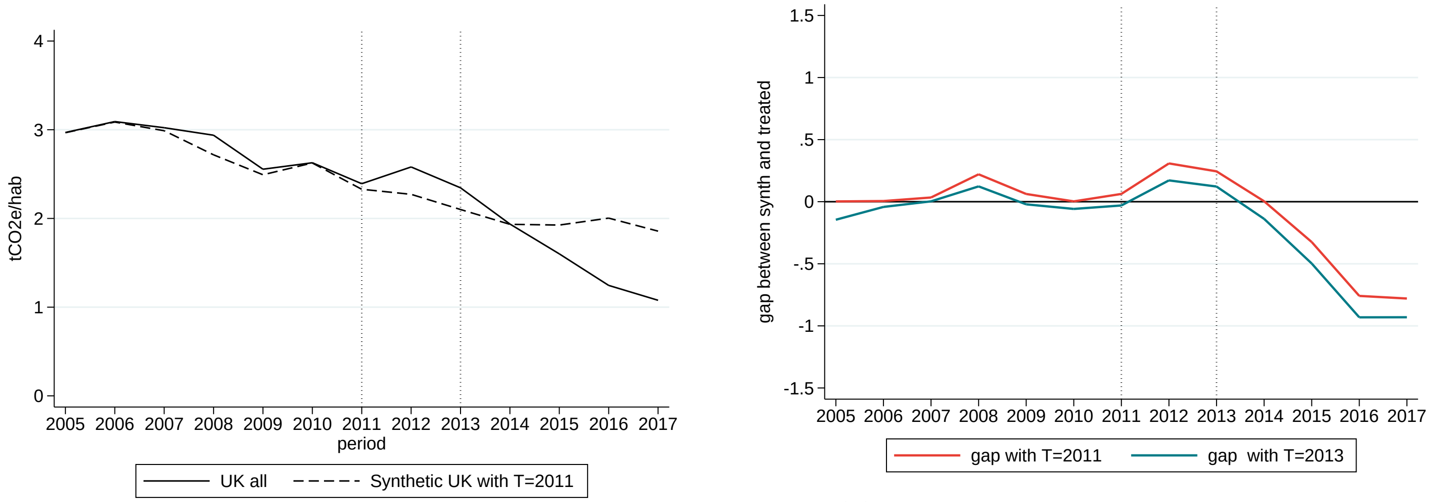
[23] Since all emissions caused by electricity produced in other countries but consumed in the UK are re-allocated to the UK - under the conservative assumption that the variation in electricity imports after 2013 is entirely imputable to the CPF.

Figure 14: Synthetic control method when treatment is assumed to start in 2011, when the CPF was announced



(a) Absolute per capita emissions

(b) Emission gap between treated and synthetic

Note: For each period, the gap is the difference between per capita emissions in the UK and synthetic UK. The vertical lines are set in 2011 and 2013, alternative assumed dates for the treatment start

in 2012 with the UK emitting more than the synthetic UK, suggesting some anticipation effect probably coming from these LCP plants (which are responsible for the 2012 emission peak, as visible on Figure 8a). Figure 14b overlay the two emission gaps with treatment assumed to start in 2013 (main specification) and 2012 (this specification). Given the higher emissions of UK compared to synthetic UK in 2012, the resulting total abatement is lower than in the main specification and amounts to 83 $MtCO_2e$. By 2017, emissions are still lower by 42% compared to the synthetic UK.

6.5 Discussion of the results

Overall, I find that the UK Carbon Price Floor resulted in a total abatement of between 176 $MtCO_2e$ (assuming full spillovers to other countries via increased net imports) and 192 $MtCO_2e$ (assuming no spillovers to other countries via increased net imports) over the 2013-2017 period. These estimates are substantially higher than the results found by Abrell et al.

(2019) who use UK-only data and machine learning techniques to build a counterfactual UK generation sector. Indeed, if I remove the emissions abated in 2017, I find a total abatement of between 61 $MtCO_2e$ (removing emissions from potential confounders) and 94 $MtCO_2e$ (main specification) while they find a total of 26.1 $MtCO_2e$ abated over the same period.

The difference is probably explained by the fact that Abrell et al. only consider the impact on the CPS on fuel switching, while my estimates include all other CPS-induced channels. Notably, the 61 $MtCO_2e$ estimate accounts for production re-allocation from coal-based generation to not only gas-based generation, but also to more efficient coal-fired power plants or to renewable sources of energy. The 94 $MtCO_2e$ estimate also accounts for plant closures and biomass conversion probably caused by a mixture of the Carbon price Floor and other policies.

7 Conclusion

This paper estimates the impact of a carbon tax introduced in the UK power sector in 2013 by comparing the UK power sector's emission path to the power sector's emission path of a weighted combination of non-treated countries. I find that introducing a carbon price support to the EU ETS resulted in a decrease of CO_2e emissions of between 104 and 156 $MtCO_2e$ in the UK over the 2013-2017 period. In 2017, emissions in the UK were halved compared to what would have happened absent the CPF. A set of permutation tests indicate that no such impact is found for any of the 14 countries in the donor pool for which a good synthetic match can be found. These results are robust to small variations in the donor pool and set of predictors used. Importantly, these results include all the different channels through which the CPF may have impacted per capita emissions: demand, trade and the domestic emission intensity of the power sector. While it might be tempting to extrapolate from this promising result the likely impact of a carbon price floor introduced elsewhere, it is important to keep in mind the specificities of the United Kingdom when considering the external validity of these estimates and the feasibility of a similar policy in other contexts: the relative isolation of the UK from other electricity markets have limited the risks of carbon leakage, while countries in continental Europe currently discussing about introducing a carbon price floor (France and the Netherlands) are more interconnected. Furthermore, the political economy context may have been particularly favourable to the introduction of a CPF in 2011, a period where some major coal-fired power plants were already deemed to shut down because of the LCP directive. In this context, companies operating multiple power plants may have been keen on investing in low-carbon generations and shown little resistance to the introduction of the CPF, more so than in the absence of such constraint. An evidence for this is the support shown by UK power companies to the CPF (Hirst, 2018), in strong contrast with the opposition raised by a similar policy proposal in France (Newbery et al., 2018).

While this paper adopts an estimation strategy that allows to take into account all these channels, it also has some limitations: first, it cannot estimate in a causal fashion the relative contributions of the three channels exposed in section. While descriptive evidence suggest that the CPF mostly impacted the emission intensity of domestic production, rather than demand or net imports, the Synthetic Control Method does not make it possible to calculate the impact of the CPF on each channel. Third, having only one treated unit and fifteen units in the donor pool is not sufficient to build confidence intervals as done in Gobillon and Magnac (2016) and Isaksen (2018), and the only way to draw inference is via a permutation test using 14 countries. This limitation is however imposed by the nature of the policy evaluated - the policy applies only to one country, the natural donor pool would have a maximum of 27 countries, the number of EU countries without the UK.

This work opens interesting avenues for future research: first, it would be interesting to go deeper into the different de-carbonisation channels by examining individual plants' behaviours using our rich plant-level dataset. Another promising area for future research concerns the estimation of the health co-benefits associated with the CPF: using coal for power generation not only causes the emission of Greenhouse gases, it also releases in the atmosphere air pollutants such as nitrogen oxide or sulphur dioxide that have long been identified as damaging for human health. The CPF would lend itself well to the estimation of the potential local air quality co-benefits of this mitigation policy.

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Appendix A. Method used to identify power installations in the EUTL plant-level emission data

By default, the EUTL gives the broad sector category of all participants, but there is no specific category for the generation sector. The UK-based think-tank Sandbag kindly provided me with total verified emissions data for 2008-2016 supplemented with a variable identifying all power plants. This identification has been performed internally by Sandbag based on (1) a file circulated by the European Commission in 2014, containing a list of individual participants and their associated NACE rev2 code (including a specific category for Production of electricity), and (2) some additional matching for participants joining the scheme after 2014, based on a top-down approach and desk-based research. For the verified emissions variable, the data provided by Sandbag is the same as the raw data retrieved from the EUTL.

Since Sandbag data is based on the 2008-2016 period, they do not provide information on whether or not an installation covered by the EU ETS is a power plant if the installation closed before 2008 or was opened in 2017. Using information on the date where a given installation first and last appeared in the data, I identified no installations opened in 2017, but 1,624 closed before 2008. I was able to match most of them to a dataset built by a consortium of European universities and hosted by the Florence School of Regulation, listing participating installations until 2013 with their NACE rev2 sectoral classification[24]. The NACE rev2 code allowed to identify 209 additional power plants. For the remaining installations, I flagged as power plants the most obvious ones, which name had "power station" in it or its equivalent in one of the European languages. After this additional matching, the power plant status is missing for only 457 installations, with only 113 of them having non-zero CO_2e emissions for at least one period.

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[24] This dataset is called "Accounts to Firms Matching" and can be downloaded on this website: `http://fsr.eui.eu/climate/ownership-links-enhanced-eutl-dataset-project/`. The dataset was, according to the FSR website, part of a cooperation between several European Universities

Appendix B. Data sources for per capita emissions predictors

This appendix describes how the predictors used for the synthetic control method were built.

Coal-to-gas price ratio

This ratio is not readily available as a harmonized time series for all countries for the electricity generation sector. Sato et al. (2019) produce harmonized sector-specific energy prices and taxes data for 48 countries in the world, but their data stops in 2011 and does not include the power generation sector. I therefore build my own country-specific gas and coal price series for the generation sector by combining Eurostat and IEA sources.

Coal prices For coal, I use annual trade data for imported coal from Comext, the official EU trade statistics publicly available on Eurostat. More precisely, I combine volume and price data for all subcategories of coal that may be used for coal generation (i.e anthracite, codes HS27011110 and HS 27011190 before 2011 and HS 27011100 after 2011 ; bituminous coal, code HS 27011290 ; coal, code HS 27011900) and obtain average nominal unit prices for imported coal. All prices are expressed in Euro. Data for Denmark is only available for 2013 and 2014. I fill the gaps by applying the growth rates from the closest non-missing data source, in this case the IEA nominal price index for industry.

The reason for choosing the Comext trade data over other available sources such as the IEA energy price statistics is its completeness for the time and geographic coverage that interests me. On the other hand, it encompasses coal purchased by all economic agents (rather than only power generators), only includes imported coal (and not coal produced domestically), and does not have taxes. I do not think that this creates a severe bias in the data series, for the reasons set out below.

First, I restrict the type of coal to the subcategories of coal most likely used for electricity generation to come closer to the price paid for coal in the generation sector. Second, even if I do not have price data on coal produced domestically, marginal prices of traded and domestic coal should be about the same if importing coal is efficient from a generator's perspective. Finally, not having taxes should not create too much of a distortion compared to the prices actually paid by generators. Indeed, the generation sector seems to benefit from fuel tax exemptions in most countries: a comparison between the IEA energy prices series in the electricity generation sector excluding and including taxes (for the 10 European countries where the data is available) indicates that no tax applied is applied to gas or coal used in this sector. This seems consistent with the EU Energy Taxation Directive (2003/96/EC) stipulating that member states may apply fuel tax exemptions to energy products and electricity used for combined heat and power generation.

As a consistency check, I compare the obtained coal price series using trade data with IEA price series in the electricity generation sector for the few countries where both data are available. I find that the two series are very close in magnitude and time evolution.

Gas prices For gas, the main source of data is Eurostat. Eurostat provides average wholesale prices in euro paid for gas by industrial customers, for six consumption bands (I1..I6). Gas-fired power plants subject to the ETS are likely to fall amongst the largest bands. Using another database with information on the amount of input fuel used by large combustion plants (the LCP database), I find that electricity generators using gas as an input use on average 2,500,000 GJ, which falls into Eurostat's I5 consumption band. I use the price series in euro excluding VAT and other recoverable taxes and levies but including other taxes, which accounts for country-level differences in fuel taxation.

Where the data is incomplete or missing for this band, the values are imputed from other bands: when it is incomplete, the gaps are filled by imputing values from the consumption band below, I4 (for Ireland and Croatia), or the IEA gas price data (for Greece); when the data is completely missing for I5, the I4 values are used for all the years instead (for Luxembourg).

One drawback of this data source is that the categories (consumption bands) and methodology changed in 2007, which makes it difficult to build a consistent series of coal/gas price ratio before 2007. For this reason, I only use the 2007-2012 period for this variable.

I then combine coal and gas price series to build coal-to-gas price ratio for all European countries over the 2007-2016 period. Since coal Comext data are expressed in kg while Eurostat gas data are in kWh, coal data are converted into kWh in two steps: first, IEA country-specific kg-to-toe conversion factors for steam coal used in industry are applied[25]. For the few missing countries, the same conversion factor as the average for the non-missing countries is applied[26]. A common toe-to-kWh standard conversion factor ($1kWh = 8.6 * 10^{(-5)} toe$) is then applied to give coal price in euro per kWh.

Reassuringly, when comparing my price ratios obtained with my data sources with price ratios from national statistical institutes sources (e.g, in the UK, the Department for Business, Energy and Industrial Strategy publishes such data each quarter), or other sources like IEA, the ratio have about the same magnitude and path over time (with a margin of +/-10%).

Lignite resources

Data on lignite resources in Europe come from the industry association Euracoal (European Association for Coal and Lignite; Source: https://euracoal.eu/info/euracoal-eu-statistics/) I build a lignite dummy variable equal to 1 for countries with lignite resources greater than 0.5 Gt in 2012, and 0 otherwise. The variable is equal to one for Germany, Poland, Hungary, Greece, Czech Republic, and Bulgaria.

Number of degree days

Annual data on Degree days come from Eurostat.

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[25] I prefer to use the conversion factor for industry than for electricity production, since the data used for coal reflects coal imported for both industry and electricity generation

[26] the average does not include the few countries specified to use brown coal for electricity generation - which has a conversion factor half to three times as low as regular coal

Residual load per capita

I define residual load as the difference between electrical energy available for Final consumption taken from Eurostat, and generation from renewables and nuclear power plants. The latter term is calculated as the sum of total net electricity production from six renewable sources (hydro, tide wave and ocean, solar PV, solar thermal and wind) and total net electricity production from nuclear power plants, including conventional plants, auto producers, and co-generation plants[27] This variable is then divided by the average population by country given by Eurostat.

Emissions from opted-out plants in 2009

The amount of CO_2e emissions coming from the installations who opt out from the LCP directive in 2005 comes from manually linking the EUTL dataset with data reported by the installations subject to the LCP directive (data version 3.1). The latter is publicly available on the European Environmental Agency's website. For each installation subject to the LCP directive, a variable indicates whether the installation is included in the opt-out regime. Since there is no common identifier between the EU ETS and LCP data, the 172 installations located in the UK or in a country from the donor pool and reported to have opted out in the LCP data were manually matched. Using information on the plant name and location, available in both datasets, I managed to match all LCP plants to a EU ETS installations except for a Finnish plant and a Polish one. The final variable is obtained by aggregating CO_2e emissions from these opted-out plants in the power sector at the country-level.

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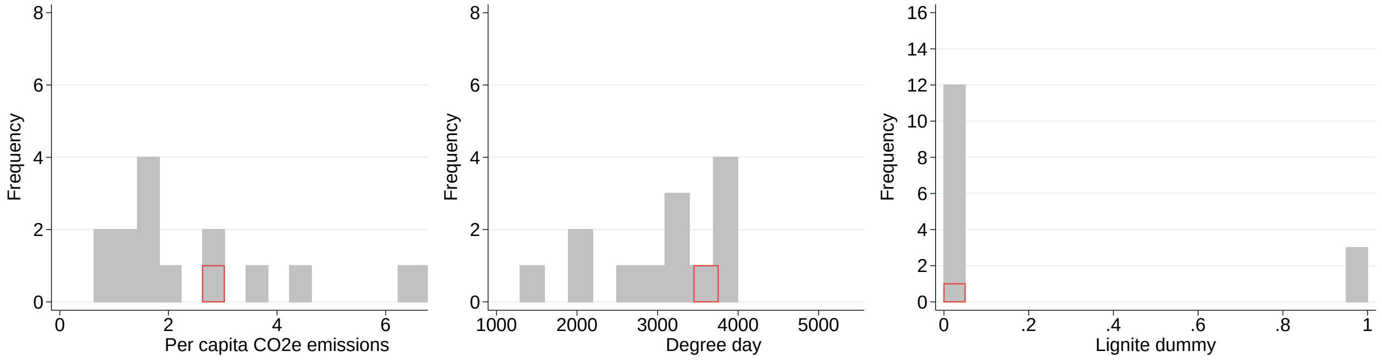
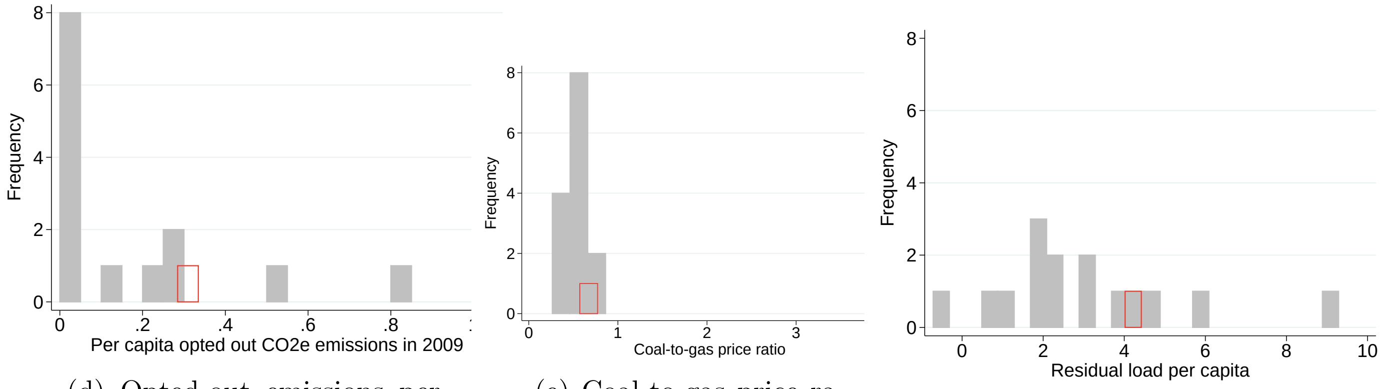
[27] geothermal, biomass and waste are not included since they are available on demand

Appendix C. Common support for the distribution of predictors for the UK and countries from the donor pool

Figure 15: Distribution of characteristics for the UK (in red) and donor pool (in grey)



(a) Per capita CO_2e emissions (b) Number of degree days (c) Lignite dummy



(d) Opted-out emissions per capita (2009) (e) Coal-to-gas price ratio (f) Residual load per capita

Note: for all figures, the reference year is 2010 except for the share of LCP opted-out emissions where the reference year is 2005