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# Carbon Pricing: A Comparison between Germany and the United Kingdom

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**Abstract**

Climate change is a global problem that almost every country – 191 parties had signed the Paris Agreement - has committed to undertake. The European Union (EU) has been one of the pioneers in implementing policies that tackle greenhouse gas emissions (GHG). In 2005, the European Emissions Trading Scheme (EU ETS) was launched as the first carbon market. Despite the EU ETS evolving throughout the years, the United Kingdom (UK) implemented an additional policy. In 2013, the UK introduced a Carbon Price Floor (CPF). This paper examines the impact of carbon pricing on GHG emissions during phase III of the EU ETS (2017-2020) in Germany and the UK. Electricity generated by nuclear and renewable sources are considered in the analysis. There are two research questions. First, is the impact of carbon pricing in these two countries, measured by using an Ordinary Least Squares (OLS) model for panel data. The results show that the UK has been more successful in reducing GHG emissions because of the CPF implementation. Second, whether the Market Stability Reserve (MSR) – a policy within the EU ETS – acted as a Carbon Price Floor (CPF) for Germany. Using a model of Differences in Differences (DD), this paper showed that the MSR significantly reduced the CO2 emissions of Germany.

*Keywords:* Carbon price; EU ETS; CO2 emissions; carbon price floor; market stability reserve; differences in differences.

## 1. Introduction

The European Union (EU) recognizes climate change as one of the most significant economic, social, and environmental challenges that the world faces (Bruggeman & Gonenc, 2013). The climate goals to reduce greenhouse gases (GHG) emissions are led by international commitments such as the 1997 Kyoto Protocol and the 2015 Paris Agreement, the last was ratified by 191 parties (including the EU) (The United Nations, 2021). Before the 2015 Paris Agreement, the EU implemented policies in various areas to tackle climate change and fulfill its GHG emissions reduction targets of 20% by 2020, 40% by 2030, and climate neutrality by 2050 (European Environment Agency, 2020). One of the tools to combat climate change is the European Emissions Trading System (EU ETS) which is the largest and the world's first carbon market since 2005 (European Commission, 2021a). At the time of its creation and until 2020, the scheme included the United Kingdom (UK) as a participant. The EU ETS operates in phases, whose align progressively to the EU climate policy objectives. Phase 1 (2005 - 2007) was a pilot phase, phase 2 (2008 - 2012) comprised the first commitment period of the Kyoto Protocol, and phase 3 (2013 - 2020) comprised the second commitment period of the Kyoto Protocol (European Commission, 2021a).

In April 2013, at the beginning of the third phase of the EU ETS, the UK Government introduced a Carbon Price Floor (CPF) as a complementary measure to the EU ETS (Hirst, 2018). The British Government launched the UK CPF on top of the EU ETS to promote long-term investments in clean technologies. According to the UK Government, the price of the European Allowances (EUAs) was not high enough to support these risky investments, which are necessary to accomplish British environmental goals (Hirst, 2018). Since its implementation, the rate of this tax has oscillated between £5 - £18. At the same time, the EU Commission introduced some reforms to strengthen the EUA price. Considering that taxes are paid per ton of $CO_2$, the marginal cost of high polluter fossil-fuel power plants has increased considerably more compared to the less polluting ones. As a consequence, most countries in Europe have a cleaner electricity. However, the mixes of electricity have changed differently.

By 2020, Germany and the UK generated 44.9% and 42.3% of their electricity from renewable sources (i.e. hydro, solar, wind, and other renewables) (Our World in Data,

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2021). When nuclear energy is included, 56.2% and 59.3% of German and British electricity, respectively, is generated by clean sources (Our World in Data, 2021). Nevertheless, electricity generated by fossil-fuel sources differs significantly. In Germany, 23.7% of electricity was generated by coal (hard coal plus lignite), in the UK only 1.7% (Our World in Data, 2021). Studies carried by Gugler, Haxhimusa, and Liebensteiner (2021) and Wilson and Staffell (2018) have compared the impact of carbon pricing between these two countries. Both authors agreed that the UK CPF has been more effective in reducing $CO_2$ emissions. However, both authors have missed the consideration of two facts: 1) the nuclear policy, and 2) the Market Stability Reserve (MSR).

In 2011, Germany officially announced that the country will shut down all its nuclear power plants by 2022 (World Nuclear Association, 2021a). Conversely, the UK supports nuclear energy and recognizes it as fundamental to fulfill its environmental goals (World Nuclear Association, 2021b). Between these two countries, only Germany is closing nuclear power plants. Could this factor influence the success of the CPF in the UK when compared to Germany? Considering that only one of them has to replace a reliable electricity source that represents more than 10% of its electricity mix, nuclear phase-out may be a factor. Especially because fossil fuels are the other reliable source available, the only capable to substitute nuclear. This document will include electricity generated by nuclear energy as an explanatory variable for the $CO_2$ emissions. If the variable is found significant, the model will produce a robust estimator of the relationship between the carbon price and $CO_2$ emissions, as well. The latter is the first goal of this document.

On the other hand, the implementation of the MSR in 2019 stabilized the price of the EUA. For instance, during the Covid-19 crisis, the price of the EUA fell to 16 € /ton, but it recovered its previous value after four months. On top of that, since the MSR was implemented, the EUA had experienced an uptrend. Edenhofer et al. (2017) and Schmidt (2020) concluded that the MSR reform was less effective than a CPF to promote decarbonization. Nevertheless, these authors did not compare its effectiveness with the UK CPF. Could the MSR act as a CPF? This paper will test the behavior of the $CO_2$ emissions in Germany after its implementation in 2019.

The Ordinary Least Squares (OLS) model for panel data will be used to test the influence of carbon pricing in tackling the $CO_2$ emissions of the UK and Germany. To see specifically how the carbon price has impacted $CO_2$ emissions per fossil fuel, a distinction between coal, gas, and lignite will be done. This goes in line with the methodology followed by Gugler et al. (2021). To test whether the MSR has operated similar to the UK CPF, a model of Differences in Differences (DD) will be carried out using the same variables. This method was employed by Abrell, Kosch, and Rausch (2021).

Discussions about the introduction of a CPF to the EU ETS are on the table (Flachsland et al., 2020). Therefore, to determine whether its introduction makes sense on top of the MSR is the contribution of this research to the debate. The repercussions of an additional reform are enormous. Especially because the EU ETS is being followed by other countries. South Korea and the People's Republic of China (China) are two of them. South Korea released the South Korea Emissions Trading Scheme (KETS) in January 2019 to reduce its GHG emissions by 2030 (Winchester & Reilly, 2019). In China, the operations of its ETS started officially in 2021, after concluding a test phase (IEA, 2021). Both countries have followed the recommendations of the EU Commission such as the implementation of market stabilization policies. Still, only South Korea has stated its desire to implement a carbon price floor or ceiling in case of oversupply (International Carbon Action Partnership, 2021). The fact that South Korea may introduce a carbon price floor only in case of market oversupply, instead of introducing it as a permanent measure (like in the UK), validates the lack of consensus of its effectiveness. Since almost all countries aim to combat climate change, it is important to contribute to reply this open question.

The paper proceeds as follows: In the next section, the existing literature is presented. In the third section, the background about the EU ETS and the UK CPF as well as the electricity generation of each country are described. Then, the two hypotheses are presented. After that, the paper presents the data and the methodology in section five and six, respectively. In section seven, the empirical findings are discussed, and section eight concludes the study with the main findings and future research directions.

## 2. Literature review

Since the introduction of the EU ETS and the UK CPF, a rich body of literature reviewing the effectiveness of these policies to undertake GHG emissions has emerged. Specifically, mixed results about these two policies can be found in the literature. The results differ depending on the industries (Abrell, Faye, & Zachmann, 2011) and countries studied (Koch, Fuss, Grosjean, & Edenhofer, 2014), the time frame analyzed (Muûls, Colmer, Martin, & Wagner, 2016) and (Ellerman, Convery, & de Perthuis, 2010), and the methodologies used to determine the effectiveness (Declercq, Delarue, & D'haeseleer, 2011) and (Bel & Joseph, 2015). This document will present literature from the introduction of the EU ETS, in 2005, to the present year, 2021. However, studies from 2017 will be presented extensively because in that year starts the scope of this investigation.

In the following section, relevant studies about the EU ETS and the UK CPF will be presented. The literature is divided as follows: first, studies about the EU ETS in phases I (2005 - 2007) and II (2008 - 2012) are presented. Then, literature about the EU ETS in phase III (2013 - 2020) are introduced. Third, research that investigated the impact of the UK CPF in the British $CO_2$ emissions are discussed. Fourth, studies that compare the effectiveness of carbon pricing in the UK and Germany are presented. Finally, the research gap is explained.

### 2.1. EU ETS in phases I (2005 - 2007) and II (2008 - 2012)

During phases 1 and 2, events such as the over-allocation of EUAs and the economic recession have undermined the efficacy of the EU ETS (Oestreich & Tsiakas, 2015), (Laing, Sato, Grubb, & Comberti, 2013), (Abrell et al., 2011), and (Anderson & Di Maria, 2011). Accordingly, Declercq et al. (2011) and Bel and Joseph (2015) found that the reduction of GHG emissions during the recession (2008 - 2009) was caused by the economic crisis. It should be noted that both studies used different econometric methods. Declercq et al. (2011) used a counterfactual scenario that estimates how the fuel prices, electricity demand, and $CO_2$ price would have been affected if the economic recession had not happened. Then, the authors compared both scenarios. On the other hand, Bel and Joseph (2015) used historical emissions data as a baseline for their dynamic panel model. The indicators used in this analysis are a variable representing policies, the $CO_2$ emissions under the EU ETS, the electricity industry index, the price of electricity and gas, a dummy variable for the economic crisis, and the consumption of coal, natural gas, and electric energy. However, Abrell et al. (2011) agrees partially, concluding that the EU ETS impacted the reduction of GHG emissions. The authors analyzed the change in firms' emissions from the first to the second phase. The authors found that both changes in the economic activity and the changes in the EU ETS from the first to the second phase explained the reduction of GHG emissions. This suggests that the stricter rules imposed in phase 2 (2008 - 2012) as a lower cap, less free allocation, and higher penalties improved the effectiveness of the EU ETS. Hintermann, Peterson, and Rickels (2016) agree with this finding. Moreover, the authors add that the reduction of EUAs during the recession (2008 - 2009) shows that the instrument is flexible to adapt to market conditions while maintaining its value above zero. The authors reached these conclusions after analyzing the existent literature about the EU ETS, excluding studies about a carbon price floor. Nevertheless, the authors concluded that a CPF in the EU ETS would be less environmentally beneficial than reforms such as limited banking [1].

The studies discussed so far show that there is not a consensus about the effectiveness of the EU ETS to tackle GHG emissions during phases 1 and 2. On top of GHG emissions reductions, another key objective of the EU ETS is to promote clean investments. This was studied by Hoffmann (2007) and Rogge, Schneider, and Hoffmann (2011). After surveying agents of the power sector in Germany, both authors resolved that the EUAs were driving small - but insufficient investments in low-carbon technologies. In line with this objective, but opposed to what Hoffmann (2007) and Rogge et al. (2011) found out, the UK government determined in 2010 that the EU ETS alone was ineffective in reducing GHG emissions. Therefore, in December, the UK surveyed companies and individuals involved in the power sector to know their opinion on a carbon reform proposal (UK Government, 2010). This document addressed the need for a carbon price on top of the existing EUAs to promote long-term investments in low-carbon technologies. It noted that these technologies are essential to achieve the transition towards a greener future but are risky investments due to their higher risk and volatility compared with fossil fuels. After the consultation, the CPF was announced as an environmental tax in the Budget 2011 to become effective from April 2013 (UK Government, 2011).

[1]The banking policy allowed ETS participants to transfer their unused allowances from phase 2 to phase 3 (European Commission, 2015a).

### 2.2. EU ETS in phase III (2013 - 2020)

The policies of the EU ETS in phase 3 changed substantially. This phase introduced new sectors and aimed to increase the control of the new allowances (a detailed explanation will be found in section 3.1.3). At the same time, the UK CPF became effective in April 2013.

Discussions about the advantages that a price floor would represent for the EU were introduced by several authors. Koch et al. (2014) were among the first. The authors analyzed the period from January 2008 to October 2013 with an Ordinary Least Squares (OLS) model. The variables included were the price change of gas and coal, a theoretical switching price between gas and coal, the price change of the European stock exchange, and the electricity production growth from wind, solar, and water sources. They determined that the reformed EU ETS would be ineffective in promoting decarbonization because the EUA price was not significantly affected by demand shocks (e.g., economic recession). This finding challenged the results discussed before and undermined the effectiveness of phase 3 because its changes were focused on reducing these effects. Hence, the authors suggested setting a price floor, which will promote decarbonization by reducing the uncertainty of the dynamics of the EUA price. Accordingly, Edenhofer et al. (2017) supported this view and added that a price floor would reduce the regulation uncertainty, market myopia[2], and the waterbed effect[3].

Conversely, Gerlagh, Heijmans, and Rosendahl (2021) suggested that a further modification of the MSR could be good enough to improve its effectiveness. They analyzed the impacts of the MSR with a dynamic model of two periods. The variables included in the model were the supply of allowances, the interest rate, the elasticity of the emissions' demand, and parameters that estimate the banking effect,

[2]It is referred to the lack of long-term view by market participants. In the EU ETS, there is an absence of a minimum price that secures return over investments. Therefore, its design does not reduce market myopia, undermining investments in low-carbon technologies (Edenhofer et al., 2017) and (Schmidt, 2020). On the other hand, a CPF directly tackles this problem by securing a minimum price.

[3]It is when an opposite result is derived from an economic policy. In the EU ETS is caused mainly by two factors. First, because of its fixed cap. When companies reduce GHG emissions, the demand for EUAs decreases while the value of the cap is kept. Second, due to the MSR. The EUAs store in the MSR are expected to be bid later, instead of being eliminated. In both cases, the price of EUAs is negatively affected, undermining the effectiveness of the policy (Gugler et al., 2021), (Edenhofer et al., 2017), and (Schmidt, 2020).

and the cancellation policy. The authors proposed two revisions. On the one hand, that the MSR develops a hybrid price-quantity cancellation policy that cancels EUAs when the demand drops. At the same time, that the EUAs hold by MSR should be based on continuous rules rather than the discrete ones that are published yearly.

Another part of the literature focused on the impacts that the reformed phase 3 had on the endorsement of technologies that reduce GHG emissions. Eichhammer, Friedrichsen, Healy, and Schumacher (2018) studied these effects in the industries of cement clinker, pig iron, ammonia, and nitric acid, representing 40% of industrial emissions under the EU ETS. They had two interesting findings. On the one hand, they found that phase 3 had increased the incentives to adopt clean technologies. On the other hand, they found that by 2017, there was no evidence that the companies adopted these technologies, with nitric acid as the only exception. Finally, the authors stated that rising carbon prices - at that moment € 16 - will drive investments in low-carbon production processes. Perino and Willner (2016) looked into the impact of the MSR. The authors carried a dynamic optimization equilibrium model to study the MSR when it was proposed in 2015. Their approach took into consideration parameters such as banking, cost of abatement, allowances that declined at a constant rate, and an infinite time horizon. The authors concluded that the MSR is effective only when the markets perceive temporary scarcity - which is not always the case. About the low-carbon investments, they determined that its impact is ambiguous the EUA price is still uncertain. Both reasonings are compatible with the arguments exposed in the previous paragraph that support the establishment of a CPF - because it would promote long-term investments by securing a minimum carbon price.

Likewise, the Global Financial Crisis in phase 2, the Covid-19 crisis affects the EUA during phase 3. Gerlagh, Heijmans, and Rosendahl (2020) carried a study about the impact of this crisis on the MSR. After using a deterministic model to simulate an ETS market with and without the MSR, the authors concluded that the MSR is a good stabilizer. Nevertheless, the extent of it depends on the duration of demand shocks. The MSR works well for short-lived demand shocks, but not at all for long-lived demand shocks. By the end of their research, the type of shock that the Covid-19 crisis was, was not clear. The authors coincided that the dynamics that the MSR follows, are uncertain and that the introduction of a price floor would be a policy improvement.

### 2.3. UK Carbon Price Floor (2013 - 2020)

Another part of the literature focused on the effects of the CPF in the UK. Abrell et al. (2021) analyzed the impact of the UK CPF on the fossil-fired power plants from 2009 to 2016. The variables used by the authors were the hourly output by fossil fuel plants, fuel and carbon prices, the available hourly capacity, the residual demand, and the efficiency, emissions, and emission factor per power plant. They analyzed 35 plants of natural gas and 15 coal-fired plants. The authors used machine learning to predict the behavior of the power plants without the UK CPF. After creating the control group, they compared the GHG emissions with a Difference in Differences (DD) method. They found that, from 2013 to 2016, the UK CPF lowered the emissions by 6.2% at an average cost of € 18 per ton. One of the limitations of this paper is that it focuses only on short-term variables, excluding effects such as the investment in renewables and energy efficiency.

Likewise, Marion (2019) examines the same effect but considers the growth in wind and solar capacity, opted-out plants, and net imports of electricity. The author used the DD method to compare a synthetic UK power sector production per capita (created by weighting different European countries' production) with the real one. She tests the robustness of her estimation by running an "in-time" placebo and a permutation test. The author concluded that the UK CPF was a successful policy that reduced the GHG emissions of the power sector by a range from 41% to 49% over the 2013 - 2017 period. Also, she found that there was no increase in net imports. Both documents agreed that the UK CPF was significantly effective in reducing GHG emissions from the UK. Also, both papers recognized that the carbon tax was high enough that left many fossil-fired plants out of business. On the other hand, both papers lack of analyzing the impact of the UK CPF in driving low-carbon investments, which are fundamental to reach the zero target in GHG emissions of the UK. This paper will incorporate that analysis by measuring the impact of the carbon price in electricity generated by renewable sources.

### 2.4. Carbon Pricing in Germany compared to the UK

It is hard to compare the reduction of GHG emissions among different countries. Among the various reasons that emerged are the differences in energy sources, market interconnection, climate policies, and electricity price determination. Nevertheless, the UK and Germany have similar energy sources as well as the same electricity price determination (both will be discussed in section 3.4). Still, the countries have taken different climate policies in the last decade.

Gugler et al. (2021) compares the success of these countries' policies in encouraging the production of renewables. The authors examined the effects of the carbon price on $CO_2$ emissions from gas and coal, as well as on the production of wind and solar energy in the UK and Germany. The effects depend on the different climate policies that both countries exercised. The UK used a carbon pricing scheme, while Germany offered subsidies for renewables. First, the authors estimated daily $CO_2$ emissions from gas and coal plants after conducting two models: a Heckman two-step and an OLS. Then, they used the same model to derive its marginal effects on carbon pricing, and energy production from wind and solar. They got mixed results. On the one hand, they concluded that a carbon pricing scheme is more effective than renewable subsidies when its carbon price is high enough. For both countries, that means a carbon price above € 14/t$CO_2$. On the other hand, they concluded that these two policies together can be mutually enforcing in Germany but mutually opposing in the UK. The reason behind this is that the carbon costs in Germany are low compared with the UK.

Similarly, Wilson and Staffell (2018) agrees that the carbon price encouraged fuel switching in the UK faster than in Germany. However, the method they followed is different. The authors analyzed the fuel-switching through data comparison. Nevertheless, both documents agreed that most of the British switch was towards gas and not renewables, which is the main objective. Still, they also recognized that a higher carbon price could replace gas for renewables. These findings support that the UK CPF has been more effective in reducing GHG emissions than the EU ETS alone because its price was higher.

### 2.5. Research gap

As explained in the previous paragraphs, several studies have examined the influence of the EU ETS and the UK CPF at different periods, industries, and among different countries. Also, most of the research has focused on one of these two policies, being scarce the studies that compared them. However, two factors are missing: 1) the consideration of the nuclear policy, and 2) the implementation of the MSR. The addition of the electricity generated by nuclear sources as an explanatory variable of the $CO_2$ emissions makes sense. This is sustained by the fact that only Germany had closed nuclear power plants since 2011. Also, because it is the only reliable carbon-free energy source that can generate electricity 24 hours a day, 7 days a week in a reliable way, as fossil fuels (Gates, 2021). If this factor is relevant, it will add value to the debate on the effectiveness of the UK CPF. Also, to test whether the introduction of the MSR could have acted as a CPF for the EU ETS is missing. The MSR operated as a good stabilizer during the Covid-19 crisis, where the EUA price maintained its value above € 16 and then quickly recovered despite the economic recession. To determine whether the EU ETS is as effective as the UK CPF due to the MSR is the second goal of this research. To do so, two models will be performed: an OLS panel data, and a Differences in Differences model.

Another difference is that this research compares the effectiveness of the EU ETS in Germany with the UK in the period from January 2017 to December 2020. A period when the EU Commission had implemented market stabilizer reforms, the UK CPF was in operation, Germany's nuclear phase-out was a reality, the MSR was announced (in 2017), and then implemented (in 2019).

The paper will continue as follows: In the next section, the background about the EU ETS and the UK CPF as well as the electricity generation of each country is described. Then, the two hypotheses are presented. After that, the paper presents the data and the methodology in section five and six, respectively. In section seven, the empirical findings are discussed, and section eight concludes the study with the main findings and future research directions.

## 3. Background on the EU ETS and UK CPF

### 3.1. Development of the EU ETS

Climate change is a problem that needs global cooperation to be effectively solved. For that purpose, the United Nations (UN) created the United Nations Framework Convention on Climate Change (UNFCCC) in 1994 (European Environment Agency, 2014). The UNFCCC organized and helped to monitor the 1997 Kyoto Protocol, the first globally legally binding agreement on GHG reduction that the EU ratified (European Commission, 2021a). The EU ETS was launched in 2005 to help the EU to meet its Kyoto targets, and later on, their 2015 Paris targets. The scheme is based on a cap-and-trade system, where the cap represents the GHG emissions that can be emitted by installations covered by the system. The trading principle allows the companies to trade EUAs within the cap. For emissions to decline, the cap is expected to decrease over time. At the end of each year, an installation must pay a penalty if it does not have enough EUAs to cover its emissions (Hirst, 2018). That means that if a company increases its production without decreasing its emissions, it must buy EUAs in the trading market. The participating countries and industries, the rate at which the cap decreases, and the penalty that participating companies must pay have changed throughout the different phases. All phases will be described in the incoming paragraphs. Nevertheless, an extended analysis will be carried out for phase 3. This is because the scope of this study is focused on the period January 2017 to December 2020 - which belongs to that phase.

#### 3.1.1. Phase 1 (2005 - 2007)

The first phase of the EU ETS was a pilot phase where 27 countries participated. The penalty for non-compliance was set at € 40 p/ton. It covered the $CO_2$ emissions of power stations and other combustion plants ($\geq$ 20MW), oil refineries, coke ovens, iron and steel plants, cement clinker, glass, lime, bricks, ceramics, pulp, and paper and board (European Commission, 2015a). To avoid the risk that companies move their production abroad (carbon leakage), the EU issued almost 100% of the EUAs for free. This phase helped the EU to set a carbon price, to create infrastructure to monitor, report and verify the emissions, and allowed the free trade of EUAs (European Commission, 2021a).

The European Environment Commissioner Stavros Dimas concluded that the EU ETS was being successful because compliance rates were high and $CO_2$ emissions in 2006 increased by 0.3% below the economic growth, which grew by 3% (European Commission, 2007). By the end of the first phase of the EU ETS, it was not possible to clearly measure the impact on $CO_2$ emissions because of the lack of verified data (European Commission, 2007).

Nevertheless, this phase suffered from some difficulties. First, the EUAs were delivered based on wrong estimates - which later caused an oversupply. Second, the (almost) totally free allocation of the EUAs happened in an uneven way - which favored some firms over others. Abrell et al. (2011)

determined that non-metallic minerals were negatively affected in comparison to the other sectors. Third, many companies profited from the system without reducing $CO_2$ emissions. Sijm, Neuhoff, and Chen (2006) and Smale, Hartley, Hepburn, Ward, and Grubb (2006) demonstrated that power companies made windfall profits due to the EU ETS. At the end of the phase, the price of the EUAs was zero. Also, the EUAs not used could not be stored because banking was not allowed.

### 3.1.2. Phase 2 (2008 - 2012)

The second phase of the EU ETS was binding. It considered the targets of the first commitment of the Kyoto Protocol. Alternative ways of reducing emissions abroad were allowed through the Certified Emission Reductions (CERs)[4] and Emission Reduction Units (ERUs)[5] (European Commission, 2015a). Also, the phase added new features. First, three new countries participated: Norway, Iceland, and Liechtenstein. Second, the penalty for non-compliance was increased to € 100 p/ton. Third, the cap was reduced by 6.5%, the free allocation of EUAs fell to 90%, and their banking was allowed. Fourth, the aviation sector was included in 2012 - applying only to flights between airports located in the European Economic Area (EEA) (European Commission, 2021a). Finally, some countries took voluntary measures such as the inclusion of nitrous oxide (N2O) on top of $CO_2$ and auctioning.

As a result of the measures took to strengthen the EU ETS, the price of the EUAs increased during the firsts six months of 2008 until the Global Financial Crisis (GFC) hit. The recession (2008 - 2009) caused a contraction in global production that subsequently reduced the demand for EUAs. Figure 1 shows the falling of the EU ETS price from almost 30€ /$tCO_2$ in mid-2008 to less than 7€ /$tCO_2$ at the end of 2012. Despite the collapse of the price, the EU reduced its GHG emissions by 8% below 1990 levels. Thus, the EU exceeded the target of 5% (European Commission, 2021b). During this period, Germany and the UK reduced their emissions by 21% and 12.5%, respectively.

By the end of phase 2, there was an excess of two billion unused EUAs that could be banked to be used in phase 3. The EU considered the EU ETS as a good policy instrument that needed further reforms. Connie Hedegaard, European Commissioner for Climate Action stated that the EU ETS was reducing GHG emissions, but that the market oversupply was undermining its impacts on energy efficiency and green technologies (European Commission, 2012). In that same meeting, the EU Commission approved the delay of 900 million allowances that were supposed to be held in 2013. Conversely, the UK believed that the EU ETS reforms were not strong enough. After approving the CPF in 2011, they introduced it in April 2013 as an additional cost on top of the EU ETS to meet its goals towards decarbonisation (UK Government, 2011).

### 3.1.3. Phase 3 (2013 - 2020)

The third phase was also binding and summed up 31 countries after Croatia joined in 2013. It considered the targets of the 2nd commitment period of the Kyoto Protocol. The targets for 2020 were a 20% cut in GHG emissions from 1990 levels, a share of 20% in renewables, and an improvement of 20% in energy efficiency (European Commission, 2021c). This phase introduced many changes. First, the consignment of EUAs. The power industry was required to buy them via auctioning, while the industry and heating sectors received them for free (European Commission, 2015a). This occurred after the EU ETS Directive determined that companies of the power sector passed the cost of allowances to the consumers (European Commission, 2015a). Second, the cap started to decrease by 1.74% yearly. Third, the abatement solutions through the CERs and ERUs were reduced - meaning that domestic solutions were preferred (European Commission, 2015a). Fourth, the sectors of aluminum, petrochemicals, ammonia, nitric, adipic, and glyoxylic acid production, $CO_2$ capture, transport in pipelines, and geological storage of $CO_2$ were added (European Commission, 2015a). Finally, the inclusion of nitrous oxide (N2O) from all nitric, adipic, and glyoxylic acid production and PFC from aluminum production became mandatory (European Commission, 2015a).

Moreover, the EU ETS Directive made two relevant adjustments in this phase. The first was 'back-loading', a measure that postponed until 2019, the auction of 900 million of EUAs that were scheduled to be sold during the period 2014 - 2016 (European Commission, 2021a). This mandate allowed the reduction of the surplus of allowances generated after the GFC. The second was the Market Stability Reserve (MSR), drafted firstly in 2015, but confirmed in 2017, that operates from 2019 onwards (European Commission, 2017). The MSR allows the EU ETS Directive to control the volume of EUAs to be auctioned through a 'reserve and release' system (European Commission, 2021a). Initially, the MSR reserved the 900 million of EUAs from 'back-loading to then auction them. Subsequently, 12% of EUAs are reserved when the market has a surplus higher than 833 million. The MSR releases EUAs in yearly batches according to pre-defined rules that are published every year on May 15th (European Commission, 2021d).

In this period, the EU ETS Directive applied changes to strengthen the EUA price. Figure 2 shows eight events and the EUA price development during phase 3. Four of them are considered the most relevant. First, on 6th November 2013 when the all the participating countries ratified the second commitment period of the Kyoto Protocol (European Commission, 2013). The ratification confirmed the determination of the EU to comply with the climate international targets and to strengthen the EU ETS. Second, on 17th February 2015 when the Commission proposed to create the MSR and to become a world leader in the development and man-

[4] CERs are emissions certificates given by the UNFCC and the Kyoto Protocol after countries or companies successfully invest in sustainable projects in developing countries (European Commission, 2015a)

[5] ERUs are emissions credits granted to countries or companies after their complete Joint Implementation (JI) projects (European Commission, 2015a)


**Figure 1:** Weekly price development of EUA during phase II

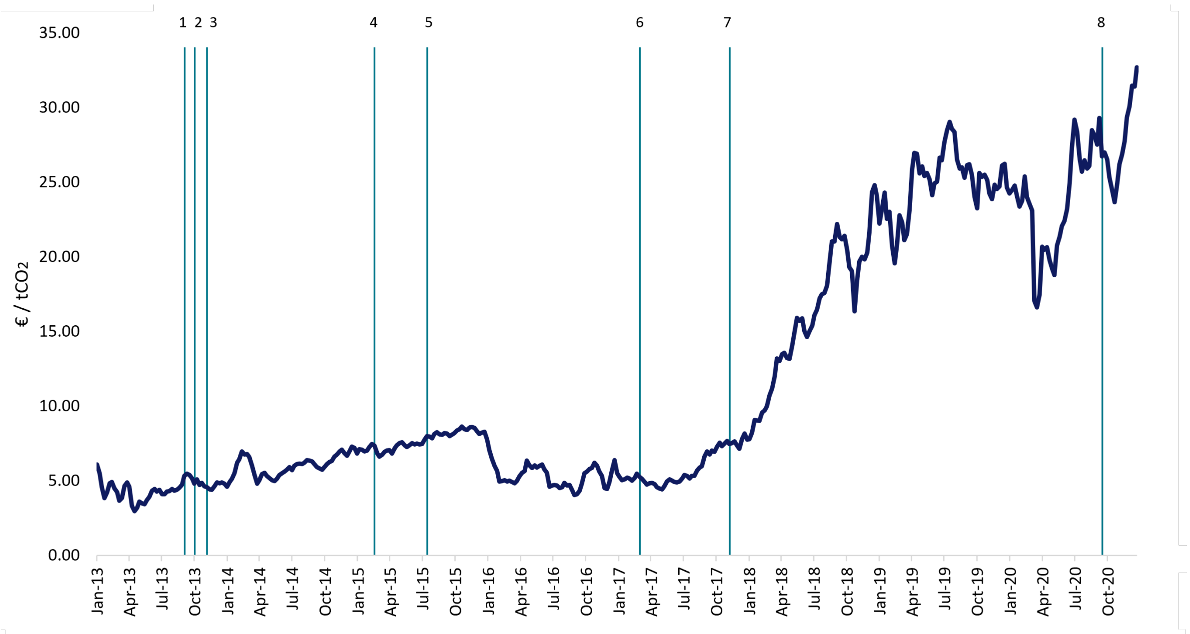
Figure created by the author based on data provided by Sandbag (2021)

ufacture of renewable energy technologies (European Commission, 2015b). These two events were followed by a positive trend in the price. Third, on 9th November 2017, after two years of negotiations, the Commission approved the MSR, applied policies to tackle carbon leakage and support innovation and investment in clean technologies (European Commission, 2017). This policy supported the EUAs significantly, generating a continuity in the positive trend of the price. Fourth, on 17th September 2020, the Commission proposed to increase the reduction of GHG emissions 2030 target to at least 55% (European Commission, 2020). Finally, it is worth noting that the Covid-19 crisis affected the price only temporarily in contrast with the collapse generated during the GFC.

### 3.2. United Kingdom Carbon Price Floor

The UK introduced the United Kingdom Emissions Trading Scheme (UK ETS) in March 2002, three years before the EU (Bourn, 2004). The system was similar to the first EU ETS. Participating companies bid GHG emission reductions from 2002 to 2006 in exchange for a share of £215 million of national incentive funding (Bourn, 2004). Annual GHG emissions revisions were carried during the scheme. The companies' reduction target was calculated as an average of their GHG emissions from 1998 to 2000 (Bourn, 2004). In similarity to the EU ETS, some emissions were overestimated. Therefore, these companies could have received incentive payments even without reducing its GHG emissions. However, four participants that accounted for 50% of the incentive pool reduced their emissions considerably and stated that the system was effective. The UK ETS served many purposes. First, it established and created awareness of emissions trading in the market. Second, it secured 3.96 million tons of $CO_2$ emissions reduction. Finally, it influenced the design of the EU ETS (Bourn, 2004).

In 2009, was the first time that the introduction of a carbon price floor on top of the EU ETS was discussed in the UK (Marion, 2019). However, the Labour party opposed it. In 2010, the Coalition Government put it back on the table. Then, in December 2010, the UK government consulted companies and individuals of the power sector to get their opinion about a carbon pricing proposal (UK Government, 2010). The consultation made some remarks. The unstable and not high enough price of the EUAs had weakened investments in low-carbon technologies (UK Government, 2010) & (Marion, 2019). Renewable energy was more expensive and had higher exposure to price volatility than fossil fuels. Still, substantial investments were required in renewables, carbon capture and storage (CCS), and others to meet their sustainable goals. The Government's objective was to reduce 236 Mt$CO_2$ over all sectors between the periods of 2008-2012 and 2013-2017 (Marion, 2019). Regarding a carbon price, the proposal was to combine the existing EU ETS plus price support. Specifically, it outlined three combined carbon prices (EUA plus UK CPF) of £20, £30, and £40/tCO2 in 2020 that will increase in 2030 to £70/tCO2 (UK Government, 2010). These estimations were based on a carbon price that will keep the increase of global temperature below 2°C. In the Budget of 2011, the Government approved a Carbon Price Support (CPS; also known as CPF) for electricity generation of £16/tCO2 that will reach £30/tCO2 in 2030 (UK Government, 2011). The policy started in April 2013. The tax rate per tCO2 was applied in addition to the EUA price and was expected to increase yearly. This rate will depend on the estimated EUA price (Marion, 2019). In the end, the CPS discontinued its increment after the period 2015-2016 because

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|---|---|---|
| 1 | 05-Sep-13 | Commission clears way for harmonised free allocation to industry for phase three |
| 2 | 04-Oct-13 | The Commission welcomes agreement on global aviation emissions deal |
| 3 | 06-Nov-13 | Climate action: Commission proposes ratification of second phase of Kyoto Protocol |
| 4 | 17-Feb-15 | Speech by Commissioner Arias Cañete at the Lisbon Council "Towards an Effective Energy Union" |
| 5 | 15-Jul-15 | Transforming Europe's energy system - Commission's energy summer package leads the way |
| 6 | 28-Feb-17 | EU Emissions Trading System: Council deal paves way for negotiations with Parliament |
| 7 | 09-Nov-17 | EU ETS: landmark agreement between Parliament and Council delivers on EU's commitment to turn Paris Agreement into reality |
| 8 | 17-Sep-20 | Opening remarks by EVP Timmermans and Commissioner Simson at the press conference on the 2030 climate target plan |

**Figure 2:** Weekly price development of EUA and events during EU ETS phase III

Figure created by the author based on data provided by Sandbag (2021) and the EU Commission (2021)

business representatives complained about their competitive loss. Both industrial and consumers pay higher rates for electricity than other European members. As a result, in May 2014, the European Commission approved compensation for some British electricity users for the extra costs produced by the CPF (European Commission, 2014). The EU Commission agreed that the CPF policy was in line with the goals set in the Environmental and Energy Aid Guidelines, and it was not distorting the competition with the block. As mentioned before, the CPS rate did not increase as announced. Table 1 shows the CPS freeze carried by the UK government in 2015. Because the CPS rate is based on the carbon content of the fuel used for power generation, coal plants were the most affected ones. The system also included Combined Heat and Power (CHP) operators and auto-generators (Marion, 2019). In general, all generators with a thermal input higher than 2 MWth had to pay the CPS. (Marion, 2019) calculates that on average the CPS rate on coal plants is 70% higher in comparison with the tax on natural gas. Likewise, the UK Government estimated that the impacts on Energy Intensive Industries (EIIs) such as steel and chemicals oscillated between 1% and 50% depending on their dependence on fossil fuels (Hirst, 2018). The UK government assures that the UK CPF had decreased the coal production and encouraged the closure of many coal plants. These results will be discussed in the empirical results section of this document.

**Table 1:** UK CPS rates

| Date | CPS Rate per t$CO_2$ |
|---|---|
| 2013-2014 | 4.94£ |
| 2014-2015 | 9.55£ |
| 2015-2016 | 18.08£ |
| 2016-2020 | 18£ |

Source: Hirst, 2018

### 3.3. Electricity production per source

The power generation mix refers to the generation of electricity by different energy sources. It excludes the energy used for transportation and large divisions of housing and industry. Globally, electricity generates 27% of GHG emissions; heating, cooling, and refrigeration 7%; agriculture, and livestock farming 19%, transportation 16%; and cement, steel, and plastic factories together 31% (Gates, 2021). Why is the electricity mix the focus of this study? Because the decarbonization of electricity is the most important one to meet the environmental global goals. Clean electricity can replace the electricity generated from fossil fuels to transport people, cool buildings, and produce products (Gates, 2021).

However, one of the largest challenges is that clean electricity needs to be generated reliably. That means, as long as large-scale storage is not available, electricity generation must not depend on weather conditions or time of the day. Renewable sources such as hydro, wind, solar, and biomass cannot ensure that right now. Gates (2021) states that nuclear is the only carbon-free[6] source that can produce electricity 24 hours a day, 7 days a week, and that can be installed everywhere. Because of its importance as a carbon-free energy source, nuclear is included in this study. However, the political view on this technology is the main difference between the countries analyzed. Therefore, this difference and its implications will be explained in the incoming paragraphs.

Throughout the years, both countries have increased the share of renewables to more than 40%. However, the way both countries have achieved it, and the incoming challenges to meet their environmental goals are different. These would be explained in the following paragraphs. The analysis is divided among the three phases of the EU ETS. Therefore, years from 2005-2020 are taken into consideration, a longer period than the analysis of this study. However, the periods analyzed will show that most changes had happened in the third phase. In Germany, especially, a massive replacement of fossil fuels materialized between 2017-2020, which coincides with the scope of this study. Also, the changes in the $CO_2$ emissions per capita will be presented. The division of the $CO_2$ emissions per person allows the comparison of Germany and the UK in a comprehensible way.

### 3.3.1. Germany

In 2005, when the EU ETS was implemented, Germany had few renewables on their energy mix to generate electricity. Wind, solar, hydro, and other renewables represented 10.3%, while nuclear energy, 26.4%. The relationship between renewables and nuclear energy has reverted throughout time. Figure 3 shows this development. By 2020, the share of renewables in electricity generation had quadrupled to 44.9%, while nuclear had decreased to 11.3%. From 2005 to 2019, $CO_2$ emissions per capita of Germany decreased by 20.84% (Our World in Data, 2021).

The main reason for the decrease in nuclear production is that its phase-out became a reality in 2011 after the Fukushima Disaster (Clean Energy Wire, 2021). The government shut down eight nuclear reactors and approved to cease the rest of them by 2022 (World Nuclear Association, 2021a). According to the World Nuclear Association, by March 2021, Germany had 6 reactors in operation and has closed 30. The gap left by nuclear energy is expected to be met with natural gas production and imports (IEA, 2021). The latter adds pressure on Germany to meet its environmental goals, which include being carbon-free by 2050.

Another reason that explains the shift is the promotion of renewables to substitute both coal and nuclear energy that is part of Germany's energy transformation (*Energiewende* in German). As a consequence, the German Government has subsidized investments in renewable energy (Gugler et al., 2021). For instance, Germany offered low-interest loans to anyone interested in installing solar panels and paid a feed-in-tariff (a fixed price) to anyone who generated it in excess (Gates, 2021). Also, the EU ETS is included as part of the *Energiewende* as an important policy.

At the end of phase I (2005 - 2007), electricity generation increased by 3%. In the generation mix, the share of nuclear energy decreased by 4.3%, wind and other renewables increased by 1.9% and 1.5%, respectively. No significant change was registered for coal nor oil, while gas increased by 0.5%. $CO_2$ emissions per capita of Germany decreased by 1.74% during that time (Our World in Data, 2021). All these minor changes in electricity generation mix and $CO_2$ emissions happened during a stable policy period.

During phase II (2008 - 2012), electricity generation decreased by 2%. In the generation mix, the share of solar increased significantly. It ended up representing 4.2%, after increasing by 3.5%. Consequently, the average cost of photovoltaic rooftop systems decreased by 62.5%, from 4000 € /kWp in 2008 to 1500 € /kWp in 2012 approximately (Wirth, 2021). The share of wind energy grew as in the previous period by 1.8%. The share of nuclear energy fell by 7.4% after the closure of six reactors. Finally, the share of coal increased by 1.2%, while gas decreased by 1.7%. $CO_2$ emissions per capita of Germany decreased by 4.67% during that time (Our World in Data, 2021).

Phase III (2013 - 2020) experienced most of the transformation. The electricity generation decreased by 10%, mainly because of gains in energy efficiency. In the generation mix, the share of renewable energy increased by 20.9%, with wind growing by 15.4% and solar by 4.1%. Wind energy experienced changes in different directions. It grew by 5,000 MW in 2017, but only by 280 MW in the first half of 2019 (Deutsche Welle, 2019). The slowdown is a consequence of wind's decreasing popularity among the citizens who live around the wind farms. New projects' permits have become slower to get due to new rules and longer approval times, which have increased from six months to more than two years (Deutsche Welle, 2019). That is a challenge for the *Energiewende* because wind energy is supposed to represent 65% of the energy mix. On the side of fossil fuels, the share of coal decreased by 21.8% after both lignite and hard coal have decreased significantly in 2019. This reduction is a consequence of less production rather than plant closures (Carbon Brief, 2019). Consequently, the EUA price almost quadrupled from 2017 to 2019. $CO_2$ emissions per capita of Germany decreased by 17.93% during that time (Our World in Data, 2021).

### 3.3.2. United Kingdom

In 2005, fossil fuels (coal, gas, and oil) generated three-quarters of the electricity of the UK. The share of nuclear en-

[6]Not all authors refer to nuclear as carbon-free, but in this paper, we take Gates (2021) approach. His approach considers that nuclear energy needs uranium as a fuel, which is a carbon-free source.

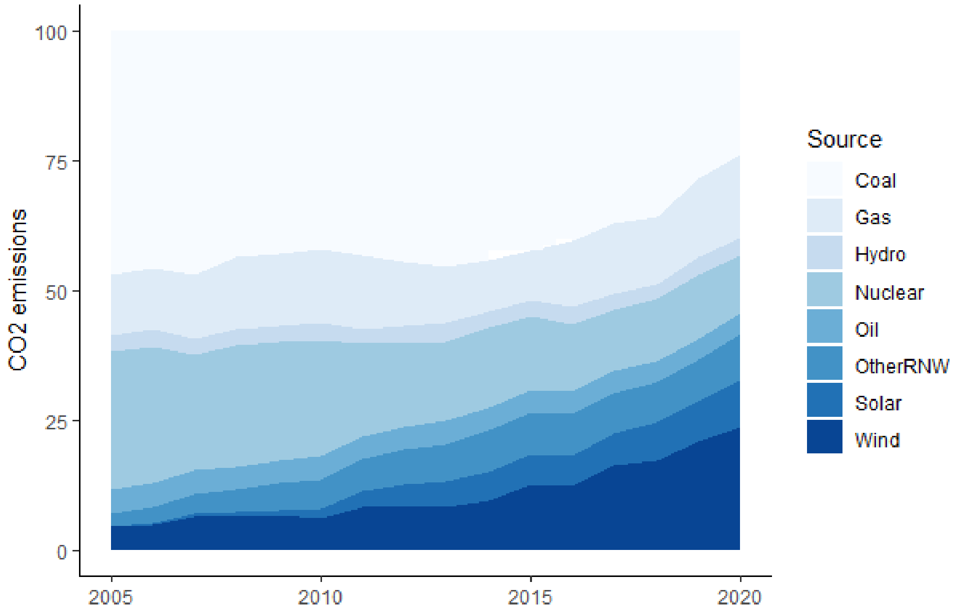


**Figure 3:** Germany: electricity production by source

Source: Our World in Data based on BP Statistical Review of World Energy & Ember
Figure created by the author

ergy was 20.6% and renewables less than 2%. In the same way as Germany, this relationship has changed. Figure 4 shows this development throughout time. Figure 4 shows that since the UK CPF introduction in 2013, the share of coal energy has been undertaken mainly by gas, solar, and wind energy. By 2020, renewables generated 42.4% of the electricity in the UK. However, nuclear energy produced 17% of the electricity in the same year. In contrast to Germany, the British government supported nuclear energy and considers it an important source to meet its climate goals. Currently, the UK is building two nuclear reactors and has strengthened measures to provide long-term support to investors (World Nuclear Association, 2021b). In the same way, natural gas has kept its share of electricity generation, and it is actively supported by the British government. Wind energy grew significantly, increasing from less than one percent in 2005 to 24.2% in 2020. From 2005 to 2019, $CO_2$ emissions per capita of the UK decreased by 42.06% (Our World in Data, 2021).

During phase I (2005 - 2007) electricity generation decreased by one percent. In the generation mix, the share of gas increased by 3.6%, it ended up representing 42.2% of the total. As shown in figure 4, gas undertake the electricity generated by coal. On the other side, the share of nuclear energy decreased by 4.6% after its generation changed from 81 TWh to 63 TWh. This happened during a positive context when the British government approved supportive measures for the industry in 2006 (World Nuclear Association, 2021b). $CO_2$ emissions per capita of the UK decreased by 3.74% during that time (Our World in Data, 2021). This exceeded Germany's reduction by 2%.

During phase II (2008 - 2012), the trend that favored natural energy against coal changed. At the end of this phase, the share of coal was 39.6% after increasing by 7.3%, while the share of natural gas decreased by 18%. Figure 4 shows how coal replaced gas from 2012 to 2014, the time that this shift lasted. It took over the higher share that gas earned from 2005 to 2010. The turning point was the suspension of fracking for several months in 2011 after it was proved that the method caused low-intensity earthquakes in Lancashire (BBC, 2012). The affected company resumed its operations in December of 2012 after the British government established additional preventive measures. On the other side, the share of nuclear and wind energy increased by 5.9% and 3.6%, respectively. Certainly, these policies impacted $CO_2$ emissions per capita of the UK, which decreased by 13.77% (Our World in Data, 2021). British reduction was approximately the triple of the one experienced by Germany. In the same way as Germany, the UK experienced many changes in phase III (2013 - 2020). Electricity generation decreased 14% after gains in energy efficiency. The UK is one of the IEA's leading countries in energy efficiency per GDP due to its policies in the modernization of buildings, transportation, digitalization, and others (IEA, 2019). By 2020 the share of coal on the generation mix was 1.7% after decreasing from 36.7%. Regulations imposed by the Government such as the UK CPF made coal an unprofitable industry since 2015 (IEA, 2019). The gap left by coal was covered by wind, gas, and other renewables after their share of generation grew by 16.2%, 9.6%, and 6.5%, respectively. However, in the long term, the UK expects to reduce its dependency on gas and increase the production of renewable energy (IEA, 2019). Electricity generated by nuclear decreased by 27% because of plant closures. The Government considers nuclear as fundamental for the country, and the technology will increase its development in the long term. $CO_2$ emissions per capita of the UK decreased by 25.52% during that time (Our World in Data, 2021).

### 3.4. Carbon Price Comparison (2013 - 2020)

Since the introduction of the CPF, the price that the British had to pay for electricity increased substantially. Figure 5 shows this difference in Euro per ton of $CO_2$. In 2013, British consumers and companies pay double per ton of $CO_2$ than their European counterparts. This relationship oscillated throughout time. In 2016, the UK CPF was equivalent to 4.12x of the EU ETS. However, the final price per electricity did not increase in these rates because the British electricity generation reduced its dependence on coal, the most $CO_2$ intensive energy source. From 2013 to 2015, the share of coal in British electricity generation decreased by 14%, from 36.6% to 22.6%. At the same time, electricity generated by solar, wind, and other renewables increased by 9.1%. In Germany, electricity generated by coal decreased only by 3%. However, in the UK, the largest reduction in coal production happened after April 2015, when the Government duplicated the carbon price support. Figure 5 shows that, in average, the $CO_2$ price in the UK was 30 € /t$CO_2$, while in Germany, it stayed below 10 € /t$CO_2$. As a consequence, many British coal-fired plants closed. From 2013 to 2020, the generation of electricity from coal in the UK decreased by 35% from 36.7% to 1.7%. In Germany, where the price of EU ETS also increased, but less compared to the UK CPF, the coal generation decreased by 21.9% from 45.5% to 23.7%. These numbers show that the effectiveness of the CPF policy, which directly increases the marginal cost of fossil-fired power plants, is high (Abrell et al., 2021) and (Marion, 2019).

The paper will continue as follows: In the next section, the two hypotheses are presented. Then, the paper presents the data. In the section six the methodology is described. In section seven, the empirical findings are discussed, and section eight concludes the study with the main findings and future research directions.

## 4. Hypotheses

### 4.1. H1: There is a larger and significant reduction of GHG emissions due to the UK Carbon Price Floor than only with the EU Emissions Trading Scheme.

Some authors have investigated the impacts of carbon pricing in tackling GHG emissions in Germany and the UK. The comparison of these two countries is well-founded since both had similar electricity generation mixes before the introduction in the UK of the Carbon Price Floor in 2013. The electricity mix of both countries has changed. Currently, the dependency of the UK on coal for its electricity generation had decreased substantially. In 2020, there were 11 days where coal did not generate electricity in the UK. In that same year, coal generated only 1.7% and 23.7% of electricity in the UK and Germany, respectively. This happened while the price of carbon in the UK has significantly higher than in Germany. Flachsland et al. (2020) stated that the EU should establish a price floor for the EUAs because it 1) will increase its effectiveness as a policy tool and 2) it will provide credibility to green investments. Early on, in 2010, the UK Government agreed on both points. It declared that a carbon price floor is fundamental to promote long-term investments in low-carbon technologies (UK Government, 2010). Still, the share of electricity generated by renewables is similar in the UK and Germany. Renewable subsidies given by the German Government helped to close the gap left by a low carbon price (Gugler et al., 2021).

Nevertheless, the $CO_2$ emissions are lower in the UK than in Germany. Two factors explain this outcome. First, the UK switched from coal to gas, which emits less $CO_2$ emissions. According to Gugler et al. (2021), Abrell et al. (2021), Marion (2019), and Wilson and Staffell (2018); the UK CPF was effective in tackling $CO_2$ emissions. Second, the UK did not phase out nuclear energy, a process that Germany started in 2011. This second point has not been investigated by the existent literature. In this paper, the electricity generated by nuclear will be added as an exogenous variable, because it is also carbon-free. The decrease in electricity generated by nuclear may be a relevant factor that explains German $CO_2$ emissions. Especially because nuclear energy has been replaced by other fossil fuels (IEA, 2021). If the coefficient in the model is negative and significant, it means that less nuclear energy increases the $CO_2$ emissions of Germany. This effect, which is independent of the carbon price, would give an alternative explanation. It would mean that even if Germany had a carbon price floor, its effectiveness could have been undermined by the nuclear phase-out policy.

Table 2 presents the correlations between daily variations of the $CO_2$ emissions per fossil fuel and the nuclear electricity production per country. Also, it shows the correlations between the carbon price per country and the $CO_2$ emissions per fossil fuel. The time frame used is from January 2017 to December 2020. The chart shows that, in Germany, there is a high and positive correlation between electricity generated from nuclear and $CO_2$ emissions from coal, gas, and lignite. In the UK, it shows a positive but mild relationship. Hence, the chart justifies the inclusion of nuclear electricity as a relevant exogenous variable to explain the $CO_2$ emissions, especially in Germany. However, the positive correlation does not support the view that nuclear phase-out may have undermined the effectiveness of the EU ETS. Finally, the correlations show in the Table 2 show that the carbon price has a positive relationship with $CO_2$ emissions in Germany, but not in the UK. When we see this information in isolation, we can conclude that the carbon price has been effective in tackling the $CO_2$ emissions only in the UK. This supports the view of Flachsland et al. (2020). However, since there are other factors (i.e. electricity generated by other renewables,

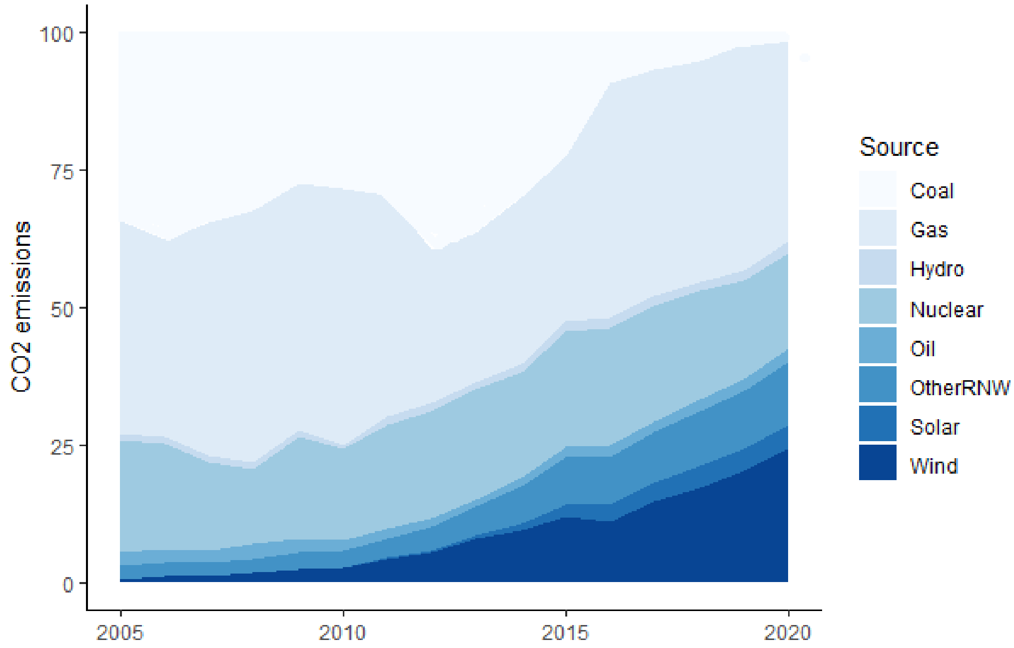


**Figure 4:** United Kingdom: electricity production by source

Source: Our World in Data based on BP Statistical Review of World Energy & Ember
Figure created by the author

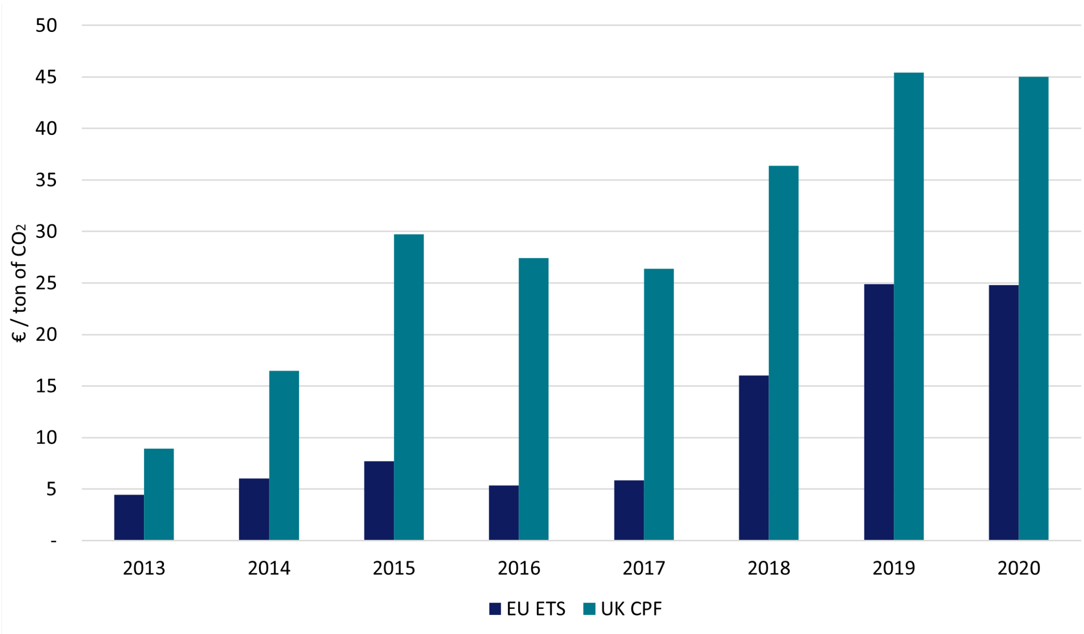


**Figure 5:** Yearly average of the EUA price and UK CPF

Figure created by the author

**Table 2:** Correlations between $CO_2$ emissions and other variables

| | Germany | The UK |
|---|---|---|
| $CO_2$ emissions of Gas and Nuclear electricity | 34% | 1% |
| $CO_2$ emissions of Coal and Nuclear electricity | 38% | 6% |
| $CO_2$ emissions of Lignite and Nuclear electricity | 54% | NA |
| $CO_2$ emissions of Gas and Carbon Price | 1% | -6% |
| $CO_2$ emissions of Coal and Carbon Price | 3% | -1% |
| $CO_2$ emissions of Lignite and Carbon Price | 2% | NA |

Coal-to-Gas ratio, and others) that affect $CO_2$ emissions, an econometric analysis that includes all of them is necessary to make relevant conclusions.

### 4.2. H2: The EU Emissions Trading Scheme is more effective since the Market Stability Reserve implementation

During phase 2 (2008-2012), the EU ETS lost credibility. The 2008 GFC caused a price collapse, and the instrument lost almost 70% of its value. Many studies analyzed the effectiveness of the EU ETS during this crisis. Declercq et al. (2011) and Bel and Joseph (2015) determined that the EU ETS was not resistant to economic shocks. On the other hand, Abrell et al. (2011) concluded that the EU ETS was still slightly effective in periods of economic crisis. After that, the EU Commission implemented new rules that made the EU ETS more resilient. The one of interest in this study is the MSR, introduced in 2019.

As mentioned in section 3.1.3, the MSR allows controlling the volume of EUAs that are in the market (European Commission, 2021a). Therefore, it is designed to avoid oversupply, but its future path is still uncertain because the MSR reacts to the market. Thus, some authors believe that the introduction of a CPF would be more effective to reduce uncertainty and promote long-term investments in clean technologies (Flachsland et al., 2020).

Nevertheless, the price of the EUAs during the Covid-19 crisis was resilient. In contrast with the 2008 GFC, where the price fell from 30 € /t$CO_2$ to 7 € /t$CO_2$ and did not recover; during the Covid-19 crisis, the EUA price fell from 26 € /t$CO_2$ to 16 € /t$CO_2$, but regained its previous value after four months. Moreover, the EUA price continued its uptrend and market a new high in July 2020, sustained by the support of the EU to its 2030 climate goals. Figure 5 shows that during 2015 and 2017, where most coal power plants were closed, the average $CO_2$ price in the UK was between 25 € /t$CO_2$ and 30 € /t$CO_2$. In Germany, during 2019 and 2020, when the MSR was in operation, the average $CO_2$ price was between 25 € /t$CO_2$. Could this policy have acted as a CPF for Germany? Since this discussion is on the table, therefore, an analysis of whether the MSR had acted as a CPF is important for research purposes.

Figure 6 shows the development of the average $CO_2$ of Germany and the UK and highlights the time during the MSR. Also, it shows four simple linear regressions, two for Germany and two for the UK in periods before and after the MSR implementation. This figure displays that the slope of the average $CO_2$ emissions of Germany changed after the MSR introduction. Even though the UK also continued to reduce $CO_2$ emissions, a pronounced shift of slope can be seen only in Germany. Before the MSR, in Germany, the trend of $CO_2$ emissions was slightly positive (+0.11). In the UK, it was neutral (+0.01). After the MSR, the value of these relationships changed. That period is shaded in grey. The slope of Germany's $CO_2$ emissions evolved to -0.35, i.e. it reduced by a factor of 4x. On the other hand, in the UK the slope only changed to -0.09. Nevertheless, factors such as the development of renewable energy, the coal-to-gas price, carbon price, and economic growth also influence the development of $CO_2$ emissions in each country. Therefore, an econometric model that includes these factors is needed to validate this hypothesis. For that purpose, the model of Differences in Differences will be performed.

The paper will continue as follows: In the next section, the data is described. In the section six, the methodology is described. In section seven, the empirical findings are discussed, and section eight concludes the study with the main findings and future research directions.

## 5. Data

This analysis covers the phase III of the EU ETS from 3 January 2017 to 31 December 2020. This period captures different economic developments and policy reforms. In 2017, the price of the EU ETS oscillated between 4.43 - 8.16 € /ton. It increased by € 2.61, in line with the uptrend of the STOXX 600, Europe's market index, which increased by 8.5%. In November of the same year, the EU Commission agreed to strengthen the EU ETS to fulfill the Paris Agreement (European Commission, 2017). As a consequence, the EUA price started an uptrend, which continued due to the introduction of the MSR in 2019. On the other hand, the UK kept its carbon price support at £18.08 during the whole period. Finally, the economic crisis due to Covid-19 started in February 2020, is also captured by the period analyzed.

All the prices used are expressed in Euros. The data used differs depending on the model. For the OLS in panel data, it consists of 1458 observations, which is a robust number for the econometric analysis performed. Table 4 shows the returns of the variables, which are used in the model because the panel data OLS needs stationary variables to be

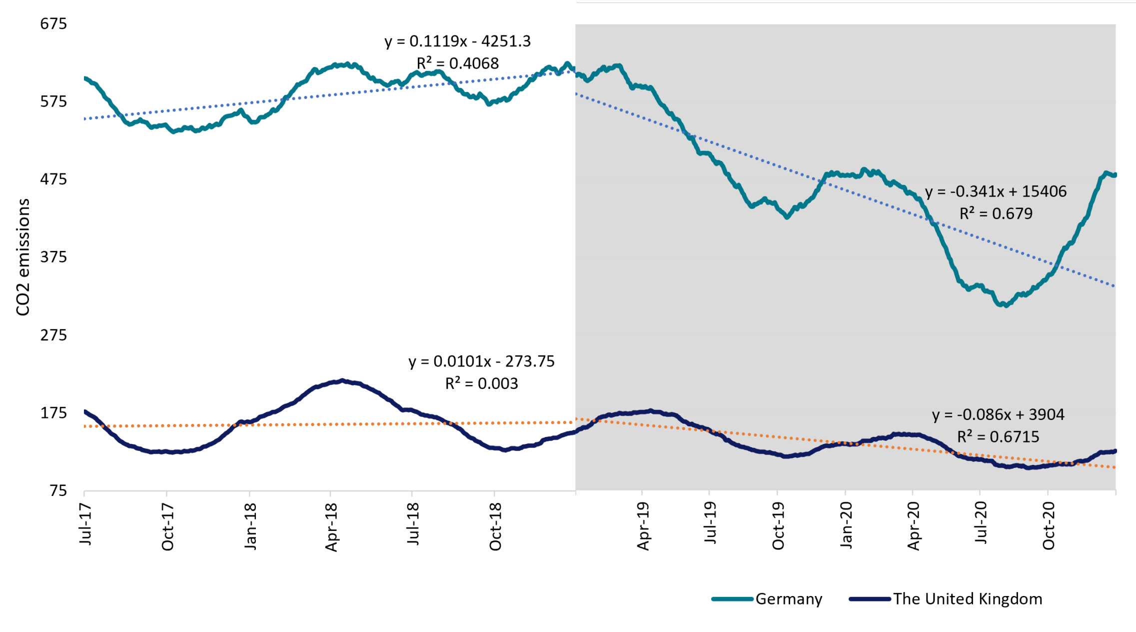


**Figure 6:** Semi-annual average of $CO_2$ emissions of Germany and the UK before and after the Market Stability Reserve

Figure created by the author

performed correctly. For the DD model, the output is expressed in differences, therefore level data is needed. The data used is shown in table 3, it consist of 1459 observations. In general, German variables are more volatile than the British ones. Except for the $CO_2$ emissions of coal in the UK, which have oscillated between 0 and 219 thousand tons, since there are 96 days where coal did not generate electricity in the UK.

Electricity generated by nuclear sources differs between the two countries. Despite the UK produces approximately 50% less electricity than Germany, its nuclear production is as large as the one of Germany, and the Government plans to promote it in the future. The electricity generated by solar and wind sources diverges as well. On average, Germany duplicates the share of the UK in electricity generated by both solar and wind onshore. In summary, nuclear energy in the UK represents the double than in Germany. However, Germany produces twice electricity from solar and wind onshore than the UK. For the purpose of the second analysis with the DD model, the electricity production is grouped by *$CO_2$ neutral sources*. It includes electricity produced by wind onshore, wind offshore, solar, and nuclear.

**EUA price:** The EUA price used is emitted by the ICE Futures Europe ECX. It is a continuous contract based on spot-month calculations. In this contract, each participant must either make or take delivery of the EUAs at the expiration date (Dhamija, Yadav, & Jain, 2018). As futures trade in higher volumes than spot carbon emissions they are more liquid (Dhamija et al., 2018). The EUA price is obtained from Sandbag, a non-profit think tank that focuses on climate change. Authors such as Abrell et al. (2021) and Marion (2019) have used the EUA future prices, as well.

**Electricity demand by source:** The electricity demand is obtained from the European Network of Transmissions System Operators for Electricity (ENTSO-E). The quantities used are under the denomination of Actual Generation per Production Type. They were found in 15-minute frequency for Germany and 30-minute frequency for the UK. Both were expressed in gigawatts and transformed to gigawatts per hour (GWh). The data that is divided per production type allowed the differentiation of two more variables: 1) the electricity generated by nuclear, solar, wind offshore and wind onshore; and 2) the $CO_2$ emissions. The $CO_2$ emissions were calculated using the $CO_2$ emission factors provided by *Umwelt Bundesamt*. These factors have a yearly frequency and are differentiated by fossil fuels: coal, gas, and lignite.

**Stock Market Prices:** National stock market indices are used as economic variables. For Germany, the DAX 30 is used. This index represents the 30 largest companies listed in the Frankfurt Stock Exchange. It is traded in euros and has high liquidity. For the UK, the FTSE 100 is employed. It represents the 100 largest companies listed on the London Stock Exchange. It is traded in British pounds, but in this document is valued is converted to euros. Both indices are total return indices. Thus, they include dividends. The data of both indices and the exchange rate are obtained from Investing in a daily frequency.

**Coal-to-Gas Price Ratio:** Finally, the Coal-to-Gas price ratio is included in the analysis. The coal price used is the Rotterdam Coal Futures (ATW). Each contract represents 1,000 metric tons of thermal coal. It is expressed in US Dollars. The natural gas price used is the UK Natural Gas Futures (NBP).

The contract size is 1,000 therms of natural gas, which are equivalent to 29,307-kilowatt-hours. It is expressed in British pounds. Both prices are first converted to Euros and then transformed to Euro/MWh. Since the final calculation is a ratio, the units are 1. All prices and exchange rates are obtained from Investing.

The paper will continue as follows: In the next section, the methodology is described. In section seven, the empirical findings are discussed, and section eight concludes the study with the main findings and future research directions.

## 6. Methodology

This paper has two main objectives: first, to show whether the UK CPF has been more effective in tackling the $CO_2$ emissions in the UK than the EU ETS in Germany. A coefficient between the carbon price and the $CO_2$ emissions will be calculated to determine the magnitude of this relationship in each country. Second, test whether the effectiveness of the EU ETS has increased since the implementation of the MSR in 2019. For this purpose, the difference between the $CO_2$ emissions of Germany and the UK will be estimated with a model of Differences in Differences (DD). The DD method is a variation of the linear panel data. This model will evaluate the change of GHG emissions in these two countries since the MSR was introduced. For this purpose, a dummy variable will be created. The MSR is a reform of the EU ETS to reduce oversupplies and to make the instrument resilient to economic shocks. Therefore, the consideration of the Covid-19 crisis helps to prove the last point. Finally, the day of the week effect is being considered for both countries.

Daily returns of energy and economic variables are used. The daily returns are calculated as (i) $r_{i,t} = ln(P_{i,t}) - ln(P_{i,t-1})$, where $P_{i,t}$ is the price of the index $i$ at time $t$. This approach goes in line with (Gugler et al., 2021), who test the effectiveness of carbon pricing in Germany and the UK. The authors estimated the $CO_2$ emissions of Coal and Natural Gas power plants. Still, the difference is that in this paper, daily returns are used. In this paper, the $CO_2$ emissions are calculated based on the national electricity generation. For that purpose, the energy variables employed are returns of natural gas, coal, EU ETS and UK CPF, the electricity demand, the electricity production from solar, wind, and nuclear sources; and $CO_2$ emissions of Coal, Natural Gas, and Lignite. The Coal-to-Gas price ratio has been used by (Gugler et al., 2021), (Abrell et al., 2021), and many others because it represents the cost relationship between the two most important electricity fuels. (Gugler et al., 2021) and (Koch et al., 2014) utilized the production from renewable sources in their models, as well. The electricity production from renewables is relevant because their marginal cost is (almost) always lower compared to the one from fossil-fuel power plants. Therefore, they are ranked first in the merit order curve. The economic variables used are the prices of the Financial Times Stock Exchange 100 (FTSE 100), which represents the 100 biggest companies listed in the London Stock Exchange, and the *Deutscher Aktien Index* (DAX), which represents the 30 largest companies listed in the Frankfurt Stock Exchange. Several authors have included economic variables in their analysis of the carbon price. For example, (Koch et al., 2014) employed the returns of the European stock exchange and concluded that the EU ETS was not affected by demand shocks. Still, there is not a homogeneous consensus of the effects of an economic recession on the carbon price.

As the $CO_2$ emissions are time varying and are caused by many factors, it is crucial for its correct modeling to 1) identify the variables that influence on them and 2) use enough data that allows the application of the central limit theory. For both points, the two models of linear regression for panel data used in this paper are useful (Phillips & Moon, 1999). For the first point, both models applied in this paper will use five exogenous variables to estimate the $CO_2$ emissions of each country. The results of the models are coefficients that show long-run average relationships between the variables tested (Phillips & Moon, 1999). Since the both hypotheses of the model are to test whether the Carbon Pricing of the UK has been more effective in tackling the $CO_2$ emissions of the UK in comparison with the one implemented in Germany, the linear regression for panel data answers precisely that. For the second point, the data use in this paper are daily returns and daily values that make up a total of 1458 and 1459 observations, respectively, for each of the models and countries. The advantage of the linear panel data model is that seasonality can be added. Day of the week effects are considered in the first model for both countries. This addition goes in line with (Gugler et al., 2021).

*Ordinary Least Squares for Panel Data*

To test the first hypothesis, the panel data linear model is used. It is based in the models presented by Drukker (2003), Metcalf and Stock (2020), and Gugler et al. (2021). It is as follows:

(ii) $y_{it} = \alpha + X_{it}\beta_1 + y_{t-1}\beta_2 + W_j\delta_1 + Z_i\delta_2 + \varepsilon_i t$
where $i \in \{1, 2, ..., N\}, t \in \{1, 2, ..., T_i\}, j = 7$

In the equation (ii), $y_{it}$ represents the dependent variable. In the analysis of this paper, that represents the $CO_2$ emissions from Coal and Gas of the UK and Coal, Gas and Lignite of Germany, each in one independent equation. $X_{it}$ represents a matrix of independent variables, which are time-varying. The size of the matrix is $(8xK_1)$, because eight exogenous variables are used in the analysis. $y_{t-1}$ represents the past returns of the dependent variable. This addition was based in the paper presented by (Metcalf & Stock, 2020). $W_t$ represent a matrix of time-invariant covariates. The size of the matrix is $(1x7)$. It represents the day of the week effect, which goes from 1 to 7, where 1 represents Sunday and 7 Saturday. (Gugler et al., 2021) considered daily and monthly effects in their analysis. The parameters $\alpha, \beta_1$, and $\delta_1$ represent the relationship between the dependent and each of the independent variables. $\varepsilon_i t$ is the idiosyncratic error. All variables used in the equation (ii) are logarithmic returns calculated according to the equation (i).

*Differences in Differences (DD) for Panel Data*

**Table 3:** Summary of Statistics of daily data

Germany

| | Mean | Std. Dev. | Min | p25 | p50 | p75 | Max |
|---|---|---|---|---|---|---|---|
| $CO_2$ emissions of Gas (thousands of tons) | 51 | 26 | 9 | 29 | 47 | 70 | 134 |
| $CO_2$ emissions of Coal (thousands of tons) | 126 | 80 | 20 | 56 | 108 | 183 | 343 |
| $CO_2$ emissions of Lignite (thousands of tons) | 345 | 98 | 90 | 281 | 377 | 420 | 496 |
| Electricity generation by Nuclear (GWh) | 189 | 31 | 99 | 160 | 188 | 216 | 247 |
| Electricity generation by Solar (GWh) | 113 | 73 | 5 | 44 | 108 | 173 | 290 |
| Electricity generation by Wind Offshore (GWh) | 60 | 36 | 1 | 29 | 58 | 88 | 145 |
| Electricity generation by Wind Onshore (GWh) | 258 | 188 | 13 | 114 | 207 | 351 | 914 |
| EUA (€ /t$CO_2$) | 17.9 | 8.4 | 4.3 | 7.9 | 20.6 | 25.1 | 33.3 |
| Electricity demand (GWh) | 1409 | 193 | 885 | 1265 | 1420 | 1551 | 1890 |
| DAX (€ ) | 12285 | 833 | 8442 | 11890 | 12382 | 12902 | 13790 |
| Coal-to-Gas Ratio (1, used for both countries) | 0.67 | 0.2 | 0.44 | 0.55 | 0.64 | 0.71 | 1.82 |

United Kingdom

| | Mean | Std. Dev. | Min | p25 | p50 | p75 | Max |
|---|---|---|---|---|---|---|---|
| $CO_2$ emissions of Gas (thousands of tons) | 122 | 38 | 3 | 93 | 122 | 149 | 242 |
| $CO_2$ emissions of Coal (thousands of tons) | 27 | 37 | 0 | 3 | 13 | 35 | 219 |
| Electricity generation by Nuclear (GWh) | 154 | 26 | 64 | 139 | 155 | 174 | 206 |
| Electricity generation by Solar (GWh) | 30 | 20 | 1 | 13 | 27 | 45 | 81 |
| Electricity generation by Wind Offshore (GWh) | 53 | 34 | 2 | 25 | 46 | 75 | 151 |
| Electricity generation by Wind Onshore (GWh) | 76 | 39 | 1 | 44 | 72 | 105 | 194 |
| UK CPS (€ /t$CO_2$) | 38.3 | 8.4 | 25.1 | 28.3 | 40.9 | 45.6 | 53.1 |
| Electricity demand (GWh) | 714 | 115 | 243 | 638 | 703 | 784 | 1040 |
| FTSE 100 (€ ) | 7071 | 588 | 4994 | 6940 | 7291 | 7454 | 7877 |

The DD model is useful to see the effect that a treatment (i.e. a government policy) had in a group versus another (Angrist & Krueger, 1999). It has been applied to test policies in economics (Angrist & Krueger, 1999), education (Schwerdt & Woessmann, 2020), and carbon price (Abrell et al., 2021) and (Marion, 2019). The method is called differences in differences because it takes a double difference. It is the difference of the outcome's estimation without the government policy versus the outcome after the policy implementation (Angrist & Krueger, 1999). For this study, two periods and two groups are required (Schwerdt & Woessmann, 2020). In the first period, none of the groups is affected by the treatment. In the second period, only one of them is. The group that is not exposed, is called the control group. In this paper, that is the United Kingdom. Even though the UK was also affected by the MSR, its trend of $CO_2$ emissions did not change after the policy implementation. On the other hand, the trend of $CO_2$ emissions in Germany changed after the MSR. That condition allows the use of the DD model in this comparison (Schwerdt & Woessmann, 2020). The fact that the UK had a high enough carbon price before the policy explains this difference. Gugler et al. (2021) found that in the UK, a carbon price above 38€ /ton was less effective because it affected fewer coal-fired power plants. Thus, in the UK, the MSR had almost no impact, contrary to its effect in Germany.

As mentioned before, the DD method is a variation of the OLS for panel data. It is specified as follows:

(iii) $y_t = \alpha + T_t\beta_1 + S_t\beta_2 + (T_t * S_t)\beta_3 + Z\delta_1 + \varepsilon_t$
where $t \in \{1, 2, ..., T\}$

In the equation (iii), $y_t$ represents the total $CO_2$ emissions of each country. $T_t$ is a dummy variable that represents the treatment. It takes the value of 1 during the years 2019 and 2020 when the MSR was active. $T_t$ is a dummy variable that represents the country affected by the policy. It takes the value of 1 for Germany and 0 for the UK. Therefore the $T_t * S_t$ represents Germany when the MSR was active. As in the OLS panel data, the parameters $\alpha, \beta_1, \beta_2, \beta_3$ and $\delta_1$ represent the relationship between the dependent and each of the independent variables. Finally, $\varepsilon_i t$ is the idiosyncratic error. Figure 7 shows the intuition behind the model. In the x-axis is represented by $T_t$, where the years 2017-2018 take the value of 0 and 2019-2020 the value of 1. The y-axis represents the daily average of $CO_2$ emissions for each country. Finally, the bold grey line represents the differences in differences. The model optimization allows to determine 1) the size of the differences in differences and 2) its significance.

In this paper, specification tests will be carried out. In the incoming paragraphs, an explanation of each of them will be presented.

*Analysis of Variance (ANOVA)*

To get the right model, each exogenous variable must have a self-explanatory power. That means that each of them must be independent of the other. Otherwise, it should be eliminated from the model. The ANOVA test allows comparing

**Table 4:** Summary of Statistics of daily returns

Germany

| | Mean | Std. Dev. | Min | p25 | p50 | p75 | Max |
|---|---|---|---|---|---|---|---|
| $CO_2$ emissions of Gas (thousands of tons) | 0.00 | 0.34 | -1.26 | -0.19 | -0.01 | 0.15 | 1.16 |
| $CO_2$ emissions of Coal (thousands of tons) | -0.00 | 0.49 | -1.62 | -0.26 | -0.02 | 0.20 | 1.75 |
| $CO_2$ emissions of Lignite (thousands of tons) | -0.00 | 0.22 | -1.10 | -0.06 | -0.00 | 0.07 | 0.96 |
| Electricity generation by Nuclear (GWh) | 0.00 | 0.06 | -0.40 | -0.01 | -0.00 | 0.01 | 0.34 |
| Electricity generation by Solar (GWh) | 0.00 | 0.39 | -1.66 | -0.21 | 0.00 | 0.20 | 1.68 |
| Electricity generation by Wind Offshore (GWh) | -0.00 | 0.81 | -4.00 | -0.42 | -0.01 | 0.42 | 3.29 |
| Electricity generation by Wind Onshore (GWh) | -0.00 | 0.66 | -2.42 | -0.43 | -0.01 | 0.42 | 2.36 |
| EUA (€ /$tCO_2$) | 0.00 | 0.02 | -0.19 | -0.01 | 0.00 | 0.01 | 0.13 |
| Electricity demand (GWh) | -0.00 | 0.10 | -0.35 | -0.06 | -0.01 | 0.05 | 0.33 |
| DAX (€ ) | 0.00 | 0.01 | -0.13 | -0.00 | 0.00 | 0.01 | 0.24 |
| Coal-to-Gas Ratio (1, used for both countries) | -0.00 | 0.03 | -0.34 | -0.01 | 0.00 | 0.01 | 0.24 |

United Kingdom

| | Mean | Std. Dev. | Min | p25 | p50 | p75 | Max |
|---|---|---|---|---|---|---|---|
| $CO_2$ emissions of Gas (thousands of tons) | 0.00 | 0.30 | -2.28 | -0.16 | -0.01 | 0.18 | 3.21 |
| $CO_2$ emissions of Coal (thousands of tons) | 0.07 | 1.04 | -9.70 | -0.28 | 0.03 | 0.45 | 7.24 |
| Electricity generation by Nuclear (GWh) | -0.00 | 0.05 | -0.35 | -0.01 | 0.00 | 0.02 | 0.31 |
| Electricity generation by Solar (GWh) | 0.00 | 0.60 | -2.55 | -0.30 | 0.01 | 0.30 | 2.44 |
| Electricity generation by Wind Offshore (GWh) | -0.00 | 0.64 | -2.38 | -0.40 | -0.01 | 0.38 | 2.65 |
| Electricity generation by Wind Onshore (GWh) | -0.00 | 0.55 | -1.97 | -0.33 | -0.00 | 0.33 | 4.01 |
| UK CPS (€ /$tCO_2$) | 0.00 | 0.01 | -0.10 | -0.00 | 0.00 | 0.00 | 0.06 |
| Electricity demand (GWh) | -0.00 | 0.10 | -0.71 | -0.05 | -0.01 | 0.04 | 0.78 |
| FTSE 100 (€ ) | -0.00 | 0.01 | -0.12 | -0.00 | 0.00 | 0.00 | 0.09 |

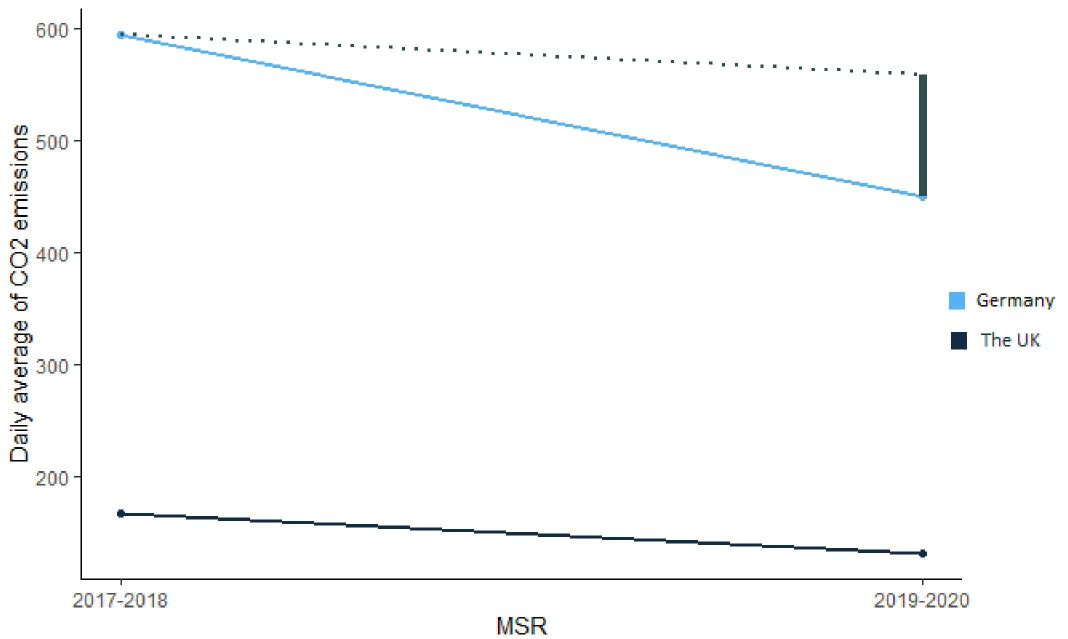


**Figure 7:** DD between Germany and the UK after the MSR implementation

Figure created by the author

models, with the objective to get the best fit (Faraway, 2002). All the models presented in this paper have approved the

ANOVA test. In the case of the UK, the test eliminated the Coal-to-Gas price ratio and the FTSE 100, because both were considered not relevant to estimate the $CO_2$ emissions of coal nor gas. In the case of Germany, the returns of the DAX were eliminated from the three models. However, the Coal-to-Gas ratio was considered significant to explained the $CO_2$ emissions of Lignite.

*Quantile-Quantile Plot for Residuals*
The quantile-quantile (Q-Q) plot is a graphical tool. It shows whether the results of the model are normally distributed or not (University of Virginia, 2015). It plots two sets of quantiles together. In the case that both are normally distributed, the points will be located near the line (University of Virginia, 2015). For the models used in this paper, all the residuals showed a normal distribution. The results of the Q-Q plots can be found in the Appendix.

*Durbin-Watson Test for the Residuals*
The residuals of the model employed in this paper must be independent. This assumption allows a valid interpretation of the model, even if the observations used are serially correlated (Durbin & Watson, 1950). The Durbin-Watson test checks two assumptions: 1) if the error is independently distributed of the exogenous variables with a mean of zero and a constant variance, and 2) if successive errors are independently distributed of one another (Durbin & Watson, 1950). Table 5 shows the Durbin-Watson results for the models computed in this paper. All the models accept the null hypothesis that the residuals are not autocorrelated at a significance level of 99%.

**Table 5:** Results of Durbin-Watson Test

| Germany | |
|---|---|
| | p-value |
| $CO_2$ emissions of Gas | 1 |
| $CO_2$ emissions of Coal | 0.9998 |
| $CO_2$ emissions of Lignite | 0.9909 |
| **The United Kingdom** | |
| | p-value |
| $CO_2$ emissions of Gas | 1 |
| $CO_2$ emissions of Coal | 0.9884 |
| **Differences in Differences** | |
| | p-value |
| Panel model | 1 |

The paper will continue as follows: In the next section, the empirical findings are discussed. Then, the last section of the document concludes the study with the main findings and future research directions.

## 7. Empirical results

The interpretation of the results in the tables (6-8) is as follows. First, the adjusted R-squared is shown. That number reveals how much of the mean return of $CO_2$ emissions per fossil fuel per country is explained by the independent variables. Second, the standard error shows the average distance between the observed values and the ones estimated by the model or coefficient. A smaller value is always preferable, but it is expressed in relative terms. This means that a larger coefficient will tend to have a larger standard error. The degrees of freedom are the difference between the number of observations and the independent variables. Also, the coefficient of each variable is shown. Since it is expressed in returns, the coefficient indicates how the variation of each variable affects the $CO_2$ emissions. The t-value shows the significance level of each estimator. The asterisks are based on the confidence levels that are shown at the end of the tables. Finally, it is worth mentioning that only significant variables are shown in the models since we follow the ANOVA test.

After the estimation of the panel OLS and DD models with the software R, the results obtained are shown in tables 6 to 8. For the UK, the results are shown in Table 6. Following the ANOVA test, the Coal-to-Gas price ratio, the FTSE 100, the day of the week effect of Sunday, Wednesday, and Thursday were eliminated, because they were not significant. For the UK, the positive coefficient of days Monday and Tuesday shows that electricity generated by coal increased in those days. While, on Friday and Saturday, it decreased. Both are explained by the interaction of cost and demand. Since coal is the most expensive fossil fuel in the merit-order curve for the UK, its production increases only when there is a jump in demand (i.e. on Mondays and Tuesdays). On the side of gas, its generation decreases on Mondays but increases on Saturdays. Nevertheless, both effects in natural gas are weak. Finally, the $CO_2$ emissions from coal and gas are explained by 24.9% and 78.8%, respectively.

Table 7 shows the results obtained for Germany. The $CO_2$ emissions from coal, gas, and lignite are explained by 66.2%, 66.2%, and 52.4%, respectively. Following the ANOVA test, the DAX, and the day of the week effect for Wednesday and Thursday were eliminated. For all fossil fuels, there is a negative coefficient on Sundays, Fridays, and Saturdays. As in the UK, the position of these fossil fuels on the merit order explains this. Since they are more expensive, when the demand is lower, renewable energies cover the demand. On Mondays and Tuesdays, these fossil fuels are used since the demand is higher. The model that estimates the $CO_2$ emissions from lignite has a different output. The lagged returns, the electricity produced by solar and wind offshore, and the electricity load were removed for the estimation. However, the Coal-to-Gas price ratio was considered significant and reveals that the average of $CO_2$ emissions from lignite decreases 0.24% when coal gets more expensive than gas by 1%. Finally, the results of the DD model are presented in table 8. For this estimation, the ANOVA method eliminated the market indices. The DD model explains 97.9% of the difference in $CO_2$ emissions between Germany and the UK. Despite the difference in the R-squared, the tests presented in the methodology validate all models.

The rest of the results will be explained in detail in the next paragraphs. The analysis will comprise the hypothesis 1 and 2, nuclear, solar, and wind energy.

### 7.1. Hypothesis 1

The findings provide empirical evidence that there is a link between the carbon price in the UK and the $CO_2$ emissions. This link is negative for coal and positive for gas, following the results found by Gugler et al. (2021), Abrell et al. (2021), Marion (2019), and Wilson and Staffell (2018). These authors concluded that the UK CPF has been effective in reducing the $CO_2$ emissions in the UK. Moreover, that the UK CPF promoted the switch from coal to gas, because its coefficient (impact) is negative on coal, but positive on gas. Table 6 shows the coefficients and its significance. For coal, the magnitude of its coefficient is large, as well. It means that an increase of 1% on the carbon price will decrease the $CO_2$ emissions from coal by 4%. On the side of gas, an increase of 1% on the carbon price will increase its $CO_2$ emissions by 0.5%. This difference in magnitude makes sense when the increase in renewable and nuclear energy is included. Because both increased. The differences between this paper and those mentioned above are 1) the period analyzed was from 2017 to 2020 2) this paper took national electricity generation variables (not production per power plants), and 3) the exclusion of electricity produced by nuclear energy. The latter proved to be a significant variable across both countries and fossil fuels.

Conversely, the results of Germany show that the EU ETS does not explain its $CO_2$ emissions during the period analyzed. As observed in table 7, the carbon price was found not significant across the three fossil fuels analyzed. This result is not directly comparable with the literature described in this paper, because no studies were analyzing the impact of the EU ETS in Germany. However, the results agree partially with Gugler et al. (2021). The authors compared the effectiveness of carbon pricing and renewables subsidies in the UK and Germany, respectively. They concluded that carbon pricing has been more effective because the British price was high enough. The latter did not happen in Germany during all the period analyzed. Figure 5 shows that the average price of carbon in Germany was 5.8 € /t$CO_2$ in 2017. According to Gugler et al. (2021), 8 € /t$CO_2$ is the minimum effective carbon price for Germany. However, the carbon price oscillated between 16 € /t$CO_2$ and 24 € /t$CO_2$ during three-quarters of the data analyzed. Three factors can explain this difference. First, the period analyzed. This paper analyzed data from January 2017 to December 2020, while Gugler et al. (2021) took data from January 2017 to June 2018. Second, they took electricity generation per power plant, while in this paper was at national levels. Third, the inclusion of nuclear energy.

### 7.2. Hypothesis 2

Since the DD model is expressed in differences, some clarifications have to be mentioned to interpret the results correctly. First, a negative coefficient means that the reduction of $CO_2$ emissions was larger in Germany than in the UK. This is validated by Figures 6 and 7. Both figures exclude the alternative interpretation that the UK had reduced its emissions more. Second, three conditional variables are considered. First, the variable *Germany (2017-2020)* is not a difference. It only considers the $CO_2$ emissions of Germany during the whole sample. Second, *MSR (2019-2020)* shows the joint average of $CO_2$ emissions of both Germany and the UK. Third, *Germany (2019-2020)* shows the difference in $CO_2$ emissions of Germany and the UK, when the MSR was active. The latter is the one of interest for this paper. Nevertheless, it is complemented with both variables: *Germany (2017-2020)* and *MSR (2019-2020)*.

The findings provide empirical evidence that there is a link between the introduction of the MSR and the $CO_2$ emissions in Germany. This link is negative and statistically significant. As shown in Table 8, only because of the MSR implementation, Germany decreased its daily $CO_2$ emissions by 39.5 tonnes in comparison with the UK. However, two additional effects resulted. First, the MSR also impacted the $CO_2$ emissions of the UK. On average, each country reduced its emissions by 17.7 during this time. Second, Germany alone reduced its average daily $CO_2$ emissions by 178.6 during the years from 2017 to 2020. In summary, the MSR helped the $CO_2$ emissions of both Germany and the UK, but its impact on Germany was larger. This happened during years where the average carbon price of the UK and Germany, was 50 € /t$CO_2$, and 25 € /t$CO_2$, respectively. The latter goes in line with Gugler et al. (2021). The authors resolved that in the UK when the carbon price was above 38 € /t$CO_2$, its marginal benefit started to decline. The latter happened during the years 2019 and 2020. As shown in Figure 5, the average carbon price in the UK changed from 36 € /t$CO_2$ in 2018 to 45 € /t$CO_2$ in both 2019 and 2020. Finally, the coefficient *Germany (2019-2020)* is significant and negative despite the development of the Covid-19 crisis that starts in February 2020. This result agrees with the conclusions of Gerlagh et al. (2020), who found that the MSR was a good stabilizer during the Covid-19 crisis.

The control variables use in the DD model increase its statistical power and allow to see how other factors affect the difference in $CO_2$ emissions. The carbon price shows that Germany emitted on average an additional of 1.9 $CO_2$ tonnes in comparison with the UK. This makes sense because the carbon price of the UK was higher than the one in Germany during the years analyzed. The generation of electricity by renewables and nuclear sources has a negative coefficient. It means that Germany reduced an additional of -0.7 tonnes of $CO_2$ emissions because of its generation of clean electricity. This is supported by the fact that during the years analyzed, Germany increased its share of clean electricity by 10.86% compared with 8.64% of the UK (Our World in Data, 2021). Finally the positive coefficient of electricity generation shows

**Table 6:** United Kingdom - Results of the panel OLS on $CO_2$ emissions

| | Coal | | | Gas | | |
|---|---|---|---|---|---|---|
| Adj. R-squared | 24.9% | | | 78.8% | | |
| Residual st. error | 0.89 | | | 0.14 | | |
| Degrees of freedom | 1443 | | | 1445 | | |
| | Estim. | Std. Err. | t-val | Estim. | Std. Err. | t-val |
| Lagged (t-1) | -0.23 | 0.02 | -9.33*** | NA | NA | NA |
| Nuclear | -1.09 | 0.55 | -1.97** | -0.70 | 0.09 | -8.02*** |
| Solar | -0.07 | 0.04 | -1.94* | -0.05 | 0.01 | -7.50*** |
| Wind Onsh. | -0.24 | 0.06 | -4.17*** | -0.15 | 0.01 | -16.49*** |
| Wind Offsh. | -0.17 | 0.05 | -3.51*** | -0.11 | 0.01 | -14.62*** |
| Carbon Price | -3.93 | 1.97 | -2.0** | 0.53 | 0.3 | 0.09* |
| Load | 2.57 | 0.38 | 6.73*** | 2.55 | 0.06 | 42.63*** |
| Day Week: Monday | 0.38 | 0.08 | 4.68*** | -0.06 | 0.01 | -4.71*** |
| Day Week: Tuesday | 0.15 | 0.06 | 2.32** | 0.01 | 0.01 | 0.55 |
| Day Week: Friday | -0.11 | 0.06 | -1.82* | 0.01 | 0.01 | 1.11 |
| Day Week: Saturday | -0.29 | 0.07 | -3.83*** | 0.05 | 0.01 | 4.27*** |
| Confidence Levels:<br>*: 90%<br>**: 95%<br>***: 99% | | | | | | |

**Table 7:** Germany - Results of the panel OLS on $CO_2$ emissions

| | Coal | | | Gas | | | Lignite | | |
|---|---|---|---|---|---|---|---|---|---|
| Adj. R-squared | 66.2% | | | 66.2% | | | 52.4% | | |
| Residual st. error | 0.28 | | | 0.20 | | | 0.15 | | |
| Degrees of freedom | 1443 | | | 1443 | | | 1447 | | |
| | Estim. | Std. Err. | t-val | Estim. | Std. Err. | t-val | Estim. | Std. Err. | t-val |
| Lagged (t-1) | -0.05 | 0.02 | -2.62*** | -0.08 | 0.02 | -3.94*** | NA | NA | NA |
| Nuclear | 0.71 | 0.14 | 5.06*** | 0.68 | 0.10 | 7.04*** | 1.30 | 0.07 | 17.73*** |
| Solar | -0.11 | 0.02 | -5.77*** | -0.08 | 0.01 | -6.00*** | NA | NA | NA |
| Wind Onsh. | -0.38 | 0.02 | -21.5*** | -0.23 | 0.01 | -18.88*** | -0.11 | 0.01 | -18.10*** |
| Wind Offsh. | -0.06 | 0.01 | -5.23*** | -0.01 | 0.01 | -1.74* | NA | NA | NA |
| Carbon Price | -0.17 | 0.3 | -0.57 | 0.09 | 0.21 | 0.43 | -0.05 | 0.16 | -0.31 |
| Load | 2.04 | 0.15 | 13.53*** | 0.68 | 0.10 | 6.53*** | NA | NA | NA |
| Coal-to-Gas | NA | NA | NA | NA | NA | NA | -0.24 | 0.13 | -1.90* |
| Day Week: Sunday | -0.09 | 0.02 | -3.69*** | -0.12 | 0.02 | -7.54*** | -0.05 | 0.01 | -5.18*** |
| Day Week: Monday | 0.32 | 0.03 | 9.93*** | 0.32 | 0.02 | 14.62*** | 0.17 | 0.01 | 15.81*** |
| Day Week: Tuesday | 0.10 | 0.02 | 4.10*** | 0.10 | 0.02 | 6.13*** | 0.03 | 0.01 | 3.46*** |
| Day Week: Friday | -0.07 | 0.02 | -3.48*** | -0.04 | 0.01 | -3.18*** | -0.02 | 0.01 | -2.07** |
| Day Week: Saturday | -0.24 | 0.03 | -9.42*** | -0.27 | 0.02 | -15.05*** | -0.13 | 0.01 | -12.51*** |
| Confidence Levels:<br>*: 90%<br>**: 95%<br>***: 99% | | | | | | | | | |

that Germany produced more $CO_2$ emissions in comparison with the UK. As explained in section 3.3.2, the UK is one one of the IEA's leading countries in energy efficiency per GDP (IEA, 2019).

In summary, the DD model validates the second hypothesis. It allows us to conclude that the MSR acted as a carbon price floor for Germany. The model shows that the MSR impacted the $CO_2$ emissions of Germany in a larger and significant way when compared with the UK. Moreover, this happened in times where the economic crisis Covid-19 took place.

### 7.3. Individual analysis of relevant variables

The goal of this paper is to determine whether the CPF in the UK has been more effective in tackling the $CO_2$ emissions. However, both policies, the EU ETS and the UK CPF aim to

**Table 8:** Germany and the UK - Results of DD model

| | | | |
|---|---|---|---|
| Adj. R-squared | 97.9% | | |
| Residual st. error | 33.08 | | |
| Degrees of freedom | 2911 | | |
| | Estim. | Std. Err. | t-val |
| Intercept | -179.4 | 5.4 | -33.2*** |
| Germany (2017-2020) | -178.6 | 4.2 | 42.7*** |
| MSR (2019-2020) | -17.7 | 2.5 | -7.1*** |
| Carbon Price | 1.9 | 0.1 | 14.9*** |
| Renewables + Nuclear | -0.7 | 0.0 | -151*** |
| Electricity Generation | 0.7 | 0.0 | 153.9*** |
| Germany (2019-2020) | -39.5 | 2.5 | -15.9*** |
| Confidence Levels:<br>*: 90%<br>**: 95%<br>***: 99% | | | |

increase investments in renewable energies, too. Therefore, an analysis of the development of nuclear, wind, and solar electricity will be carried out. The coefficients from Tables 6-8 will be used in this analysis.

### 7.3.1. Nuclear energy

As explained in sections 3.3 and 4.1, the inclusion of nuclear energy is meaningful because 1) it represents more than 10% of the electricity produced in both Germany and the UK, and 2) Germany will phase out nuclear energy in 2022, while the UK considers it as fundamental to meet its environmental goals. Accordingly, the relationships between nuclear electricity and $CO_2$ emissions differ per country.

In the UK, there is a negative and significant link between nuclear electricity and $CO_2$ emissions from both coal and gas. Thus, the inclusion of nuclear electricity as a relevant variable is validated. For coal, it means that an increase of 1% of electricity from nuclear decreases $CO_2$ emissions from coal by 1.09%. For gas, an increase of 1% of electricity from nuclear decreases its $CO_2$ emissions by 0.7%. However, during the years analyzed (2017-2020), electricity generation from coal, gas, and nuclear decreased by 5%, 4.5%, and 4.1%, respectively. How can this relationship be explained? According to IEA (2019), despite the UK Government supports nuclear, the technology faces challenges. In June 2018, the UK Government released the Nuclear Sector Deal. The objective of the policy was to deliver affordable and reliable nuclear power, by increasing investments in innovation, supply-chain, and construction of new Nuclear Power Plants (NPPs) (IEA, 2019). However, eight nuclear reactors will be shut down in 2023, and three NPPs have not started to be constructed (IEA, 2019). In summary, the negative coefficients shown in Table 6 indicate that nuclear energy has replaced the electricity generated by coal and gas in the UK.

Conversely, there is a positive and significant relationship between nuclear electricity and $CO_2$ emissions from coal, gas, and lignite. As in the UK, nuclear electricity is a variable that effectively explains $CO_2$ emissions. However, in Germany, additional nuclear electricity increases them. Table 7 shows these coefficients. For lignite, the relationship is the strongest one. It shows that an increase of 1% of electricity from nuclear increases $CO_2$ emissions from lignite by 1.3%. For both coal and gas, the increment is 0.7%. The coefficients indicate that nuclear energy generates electricity in parallel with coal, gas, and lignite. Demand peaks could be an explanation, since they are covered by the most expensive sources, which are fossil fuels. Moreover, the positive coefficients in the model concur with the positive correlations shown in the Table 2. As mentioned in section 3.3.1, Germany will phase out nuclear energy in 2022. Also, it plans to cover the gap left by nuclear with natural gas and imports of electricity (IEA, 2021).

### 7.3.2. Solar and wind energy

The relationship of electricity generated by solar and wind (onshore+offshore) and $CO_2$ emissions is negative and significant across both countries and fossil fuels, excluding lignite. Both findings go in line with the development that Germany and the UK have achieved in solar and wind energy. Currently, solar generation in Germany is one of the highest in the world (Clean Energy Wire, 2020). Also, it counts with the support of the Government as part of the *Energiewende* policy, and it is highly approved by citizens (Clean Energy Wire, 2020). On the other hand, the UK is a leader in wind energy. The country is the world leader in wind offshore by installed capacity (Renewable UK, 2021). The latter is confirmed by its coefficient shown in Table 6, which is the highest across countries.

Wirth (2021) agree that despite PV and wind energy have increased their efficiency, are not capable of replacing fossil fuels in the near future. The lack of electricity storage and weather conditions are among the principal reasons. Gates (2021) agrees with this point and adds another point. Gates (2021) states that the power generated by PV and wind per square meter is limited. On average, fossil fuels generated 500-10,000 watts per square meter. Nuclear between 500-

1,000 (Gates, 2021). However, solar energy generates only between 5-20 watts per square meter, and wind 1-2 (Gates, 2021). About this, Wirth (2021) states that, in Germany, it is possible to have enough space for PV if they are integrated. Integrated PV are part of buildings, automobiles, in parks, roads, and on top of agriculture plantations (Wirth, 2021).

The paper will continue as follows: In the next section, the conclusions of this study and future research directions are presented.

## 8. Summary and Conclusions

This paper analyzed two research questions. First, the impact of carbon pricing on tackling $CO_2$ emissions in Germany and the United Kingdom. Second, whether the Market Stability Reserve introduced in 2019 acted as a Carbon Price Floor (CPF) for Germany.

By using an Ordinary Least Squares (OLS) model for panel data, it was determined that the United Kingdom was more effective in combating $CO_2$ emissions due to its CPF policy. This result supports existing evidence of Gugler et al. (2021), who established that the carbon policy of the UK was more effective in reducing $CO_2$ emissions than the subsidies that Germany gave to boost renewable technologies. Moreover, authors (see (Abrell et al., 2021; Marion, 2019)), who studied the impact of the CPF in the UK, determined that the policy was effective in reducing $CO_2$ emissions. Other authors (see (Edenhofer et al., 2017; Gerlagh et al., 2020)), who studied the EU ETS in Europe, resolved that a CPF would improve the effectiveness of the EU ETS.

To test the second hypothesis, a model of Differences in Differences (DD) for panel data was employed. The model determined that the MSR reduced the $CO_2$ emissions of both countries. However, its impact increased significantly in Germany, enabling its comparison with the CPF of the UK. This result endorsed the findings of Gugler et al. (2021), who determined that when the British carbon price was above 38 € /t$CO_2$, its marginal benefit started to decline. The British carbon price exceeded these levels during 2019 and 2020 when the MSR was in operation. Thus, the MSR was significantly more effective in tackling the $CO_2$ emissions of Germany.

Previous research has mainly focused on evaluating the impact of carbon pricing in $CO_2$ emissions (see (Abrell et al., 2021; Gerlagh et al., 2020; Gugler et al., 2021)) but has excluded one of these two factors: the influence of nuclear energy, and the impact of the MSR in the EU Emissions Trading Scheme (EU ETS). Both factors are considered in this research because nuclear energy is a carbon-free source and the MSR acted as a market stabilizer. Accordingly, the results of this study demonstrate that both factors are relevant for the analysis.

Nuclear energy proved to be a relevant factor of the $CO_2$ emissions across countries and fossil fuels. In the UK, nuclear has a negative relationship with $CO_2$ emissions of both coal and gas. It means that nuclear acted as a substitute for fossil fuels. Since the British Government supports nuclear energy, the finding makes sense. Inversely, in Germany, nuclear energy has a positive link with $CO_2$ emissions of all fossil fuels. It denotes that when Germany produced nuclear energy, it also increased its production from coal and gas by a factor of 0.7, approximately. The link with lignite was stronger, of 1.3x. In summary, nuclear acted as a complementary for fossil fuels. Since Germany has reduced its nuclear generation due to the phase-out in 2022, both fossil fuels and nuclear may have been necessary to fulfill its electricity demand at the same time. Consequently, the link that each country has between nuclear energy and $CO_2$ emissions corresponds to their opposing views on nuclear.

Since the introduction of the EU ETS in 2005, the EU Commission has taken feedback and has actively improved its policy. The MSR established in 2019 was one of the improvements. The MSR controls the supply of European Allowances (EUAs) and avoided a price crash during the Covid-19 crisis. Despite the MSR was active for both countries, this paper has proved that it affected mostly German's $CO_2$ emissions. The DD model resolved that the MSR accounted for a daily reduction of Germany's $CO_2$ emissions by 39.5 tonnes in comparison with the UK. Currently, the discussion of whether the creation of a CPF for the EU ETS is open (see (Gerlagh et al., 2020)). Annalena Baerbock, the leader of the German Green Party, announced that, if elected, her party will raise the carbon price to 60 € /ton by 2023 (NTV, 2021). The finding that the MSR may have acted as a CPF for Germany, adds value to the existing literature and debate.

However, the promotion of renewable energies is the final goal of carbon pricing. Therefore, this paper has included the electricity generation of solar and wind energy in the analysis. The finding is that electricity generation from renewables has reduced $CO_2$ emissions across countries and fossil fuels. For Germany, solar energy and wind onshore have displaced the highest share of coal and gas. Lignite has been significantly affected only by wind onshore. For the UK, both wind onshore and offshore were the most significant sources. The results go in line with each country's development. Germany ranked 4th in the world for its photovoltaic installed capacity (Clean Energy Wire, 2020). While the UK has the largest capacity of offshore wind in the world (Renewable UK, 2021).

Given the results of this paper and prior findings, it is clear that carbon pricing has reduced $CO_2$ emissions and has promoted the development of renewable energies. Also, these findings demonstrate that the reforms taken by the EU Commission to consolidate the EU ETS are effective, too. Still, it is important to mention that in February 2018, the EU Commission approved a reform of the EU ETS for phase 4 (2021 - 2030). The period analyzed in this paper excludes the latest reform. Beck and Kruse-Andersen (2020) run simulations until 2125 to estimate the effects of this reform. They concluded that the new MSR was more effective in the short and long run. The authors stated that the new MSR was being affected by the market demand on EUAs, and thus it was not being set by the EU Commission. The new MSR gives space for further research.

There are some limitations to this research. First, the focus of the research is on analyzing the impact of carbon pricing on $CO_2$ emissions. Investments in renewables and energy efficiency improvements are excluded. The inclusion of electricity load relates partially to energy efficiency, but it is not the same. Second, electricity imports are excluded from the analysis. Marion (2019) points out that it is unlikely that the UK has increased its electricity imports because the UK is not well interconnected. The same cannot be said about Germany.

This study opens two discussion points in carbon pricing. First, the effectiveness of the MSR as a market stabilizer, and therefore as a CPF for Germany. Even though the global economy has not recovered from the Covid-19 crisis, the EU ETS price has kept its uptrend in 2021. From 4th January to 11th August, the EU ETS price has increased from 33.7 € /ton to 57.8 € /ton (Ember Climate, 2021). The latest reform mentioned in the previous paragraph may have improved the effectiveness of the EU ETS. Second, the consideration of national energy policies when two countries are compared. The inclusion of nuclear energy in the model allows us to see that the effectiveness of the UK CPF, when compared to Germany, is positively biased by its nuclear policy.

Despite 191 parties (including the EU) signed the 2015 Paris Agreement, the EU and the UK are pioneers in implementing a carbon market (The United Nations, 2021). These complementary schemes have been analyzed in this study and the results lead to two recommendations for countries that are adopting an ETS (i.e. South Korea and China). First, that the MSR could be as effective as a CPF. Second, to assess their individual country policies (i.e. nuclear policy) when designing an ETS.

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