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Research Article

Are the European manufacturing and energy sectors on track for achieving net-zero emissions in 2050? An empirical analysis

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A B S T R A C T

The European Green Deal has established a 2050 net-zero emissions target to tackle climate change. The manufacturing and energy sectors account for at least 40% of European emissions and are central in the transition to a low-carbon economy. Thus, devising suitable strategies for reaching net-zero emissions requires a comprehensive analysis of emissions reductions achieved by the two sectors. This paper has a two-fold aim: firstly, to empirically analyse European energy and manufacturing facilities' abatement results; secondly, to expose whether the two sectors are on track to achieve net-zero emissions by 2050. We used European Union Emissions Trading System data from 2005 to 2017 from France, Germany, Italy, Spain, and the United Kingdom to analyse the homogeneity of mitigation performances and the distribution of emissions among installations. The results indicate that a large share of installations have not decreased emissions yet, although there is substantial variety in units' contribution to total carbon releases. A smaller bundle of units (from 13 to 23%) containing super-polluters is responsible for up to 95% of emissions. The findings highlight that achieving net-zero emissions by 2050 will require additional policies that are tailored to super-polluters and also support installations that have not started their decarbonisation pathway.

1. Introduction

The Paris Agreement target of net-zero carbon emissions by 2050 calls for a deep decarbonisation of economic activities (Forster et al., 2020). Unlike other environmental issues, where emissions under a certain threshold are enough to ensure a safe operating space, the concentration of greenhouse gases (GHG) in the atmosphere cannot be allowed to increase if humans want to limit global warming at 1.5 °C (IPCC, 2018; Knutti et al., 2016; Rockström et al., 2009; Tvinnereim and Mehling, 2018). Energy-intensive manufacturing industries and power plants are responsible for around 50% of global GHG emissions and are central to pursuing carbon neutrality (IPCC, 2018). Extensive use of carbon capture and storage techniques will be necessary if the energy and manufacturing sectors fail to decarbonise, but these technologies are not yet fully developed (Forster et al., 2020; Knutti et al., 2016).

Launched in 2005, the European Union Emissions Trading System (EU ETS) is the leading policy for decarbonising the energy and manufacturing sectors at the European level. The EU ETS provides the most comprehensive and detailed database on the two sectors' GHG emissions. However, the literature still lacks studies that assess the mitigation progress of EU ETS installations after 2013 (Teixidó et al., 2019). For this reason, we empirically analysed facilities' carbon emissions data from 2005 to 2017, focusing on the five largest European economies (France, Germany, Italy, Spain, and the United Kingdom). Our aim is two-fold: firstly, to assess the abatement results of installations from the energy and manufacturing sectors; secondly, to expose whether the two sectors are on track to achieve net-zero emissions by 2050. Identifying facilities with poor mitigation results is crucial to avoiding a costly decarbonisation process and jeopardising the low-carbon transition (Erickson et al., 2015; Janipour et al., 2020). Our results provide valuable empirical evidence on what aspects ought to be targeted by future policymaking to create a comprehensive decarbonisation process with sufficient speed (Bertram et al., 2015; Rosenbloom et al., 2020; Tvinnereim and Mehling, 2018).

The paper is organised as follows: the next section provides a background on the EU ETS—the main policy instrument for decarbonising the manufacturing and energy sectors. Section 3 details the three steps of the analysis: investigating emissions reductions and their sources, assessing installations' individual performances, and evaluating emissions distribution. Section 4 presents the results, exposing the disparities

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among installations' performance and emission levels, while discussing the implications for achieving net-zero emissions. The final remarks emphasise the urgency of adopting additional policy instruments that allow for a deep decarbonisation of high-emitting installations.

2. Background

Since its inception in 2005, the EU ETS has represented an ambitious attempt to reconcile economic growth with the reduction of emissions from the manufacturing and energy sectors (Meckling and Allan, 2020; Verbruggen et al., 2019). The policy works as a cap-and-trade system where installations can use the trade of carbon credits to compensate for emissions above the cap established (European Commission, 2015). The core idea is that the financial impact of buying carbon credits will foster investments in low-carbon technologies (Verbruggen et al., 2019). The EU ETS has undergone three phases, with each one altering the design to improve the system and increase its stringency (Bel and Joseph, 2018). However, empirical studies so far have only covered the EU ETS data up through Phase 2, which finished in 2012. They have concluded that the carbon emission bills generated by the EU ETS were lower than expected and insufficient to induce an overall innovation process (Ellerman et al., 2016; Narassimhan et al., 2018; Verbruggen et al., 2019). Phase 1 of the EU ETS was a pilot from 2005 to 2007 and had carbon prices as low as a few euro cents (Trading View, 2021). The price remained between €15 and €20 during Phase 2 (2008–2012) but dropped significantly to around €4 upon the introduction of Phase 3 (2013–2020) (Trading View, 2021). The carbon price did not exceed €9 during the first five years of Phase 3, but since 2017, it has recovered and now reaches peaks of €30 (Trading View, 2021).

The EU ETS is now finishing its Phase 3, with the goal of reducing emissions across the whole system by 21% through 2020 (using 2005 as the baseline year) (European Commission, 2020). Phase 3 removed the free allowances of emissions for the energy sector and sought to reduce allowances for the manufacturing sector from 80% to 30% until 2020 (European Commission, 2020). The changes adopted in Phase 3 should have increased pressure on installations to achieve emissions targets and adopt low-carbon innovation (Teixidó et al., 2019). Phase 4 of the EU ETS will start in 2021, with the goal of reducing emissions by 43% until 2030 (compared to 2005 levels). The free allocation of emissions will still be granted to industries with higher carbon leakage risk (Leipprand et al., 2020), but for all others, this allowance will be progressively removed until the end of Phase 4 in 2030 (European Commission, 2020).

The structure of the EU ETS has successfully engaged crucial sectors and a range of countries in decarbonisation (Leipprand et al., 2020); however, the trading system now has a much more complex end-goal of advancing net-zero emissions. Although initially designed to promote incremental mitigation results, the system now needs to foster a transition from fossil fuels in a 30-year time frame (Leipprand et al., 2020; Meckling et al., 2017). Fossil fuels represent around 80% of all energy produced worldwide and have shaped the technological development of economic activities for two centuries (Seto et al., 2016). For this reason, scholars have argued that the trading system alone lacks the instruments necessary to start a deep decarbonisation process (Ellerman et al., 2016; Narassimhan et al., 2018; Verbruggen et al., 2019). Transitioning away from fossil fuels involves complex structural changes that demand technological development and a stable institutional environment that assists with this goal (Geels et al., 2017; Seto et al., 2016; Tvinnereim and Mehling, 2018).

Previous studies show that, in order to reduce their GHG emissions, the manufacturing and energy sectors have mainly switched to less carbon-intensive fossil fuels (Bel and Joseph, 2018; Teixidó et al., 2019). Although fuel switching reduces emissions, it is a limited solution that will unlikely reduce emissions above 80% (Wilson and Staffell, 2018). This context also exposes a persistent carbon dependence and carries the risk of firms switching back to more pollutant fuels if external conditions make it convenient (Wilson and Staffell, 2018). Mitigation results related to increments in efficiency can produce partial emission reductions, but will not suffice for deep decarbonisation (Åhman et al., 2017). The true depth and breadth of emissions reductions remain unclear, but it is paramount to understand these particularities in order to design adequate strategies for achieving net-zero emissions by 2050.

3. Method

The analysis observed the period from 2005 to 2017, which comprises three phases of the EU ETS. The emissions in the EU ETS database are reported as equivalent tons of CO_2 and account for carbon dioxide, nitrous oxide, and perfluorocarbons (European Commission, 2015). The countries included in the analysis were the five largest European economies: France, Germany, Italy, Spain, and the United Kingdom. The analysis focused on the sectors of energy (electricity generation and steam and air conditioning supply) and energy-intensive manufacturing industries (chemicals, ceramics, glass, mineral oil, pulp and paper, iron and steel, cement and lime, and nonferrous metals). The database does not contain all industrial facilities, since only the ones above a specific size or with emissions higher than 25.000 tCO_2e per year are obliged to participate in the EU ETS (Verde et al., 2019). However, the industries and power plants included in the database are responsible for the majority of sectoral emissions. Table 1 presents the number of installations for each country divided by their sectors, using 2017 as the reference year. The empirical analysis had three main goals: i) identify the magnitude of overall emissions reductions for each country and sector, as well as the share related to installations exiting the program; ii) classify the emissions reduction performance of installations, and iii) evaluate the distribution of emissions among installations.

3.1. Evaluation of emissions reduction and influence of installations' exit from EU ETS

We split the database based on whether installations were from manufacturing industries or the energy sector. We divided the analysis between the two sectors because they have different technological alternatives available and, accordingly, the EU ETS applies different standards to accommodate their particularities. We first calculated the yearly total emissions and number of installations for both sectors, and then produced a second total sum of historical emissions that only included installations in the EU ETS in 2017. This sum allowed us to identify the share of emissions reductions for both sectors that stemmed from installation exits. An installation was considered no longer part of the trading system when it stopped reporting data. An installation can exit the EU ETS when the industrial unit closes, relocates, or has emissions below the threshold for mandatory participation (25.000 tCO_2e per year).

3.2. Assessment of the individual performance of manufacturing and energy units

We analysed the individual performance of installations by following the steps presented in Fig. 1. We used the first year of reporting as the baseline year for calculating a facility's total reduction. We classified installations' mitigation performance into five categories (Fig. 1): the first two were the reduction targets proposed by EU ETS (as guiding thresholds); reducing emissions up to 21% by 2020 and 43% by 2030. Additional categories were added, being a reduction higher than 80% the last one. We considered reductions above 80% as a mitigation performance consistent with deep decarbonisation (Bataille et al., 2016), which is necessary for achieving the target of net-zero emissions by 2050 adopted by the IPCC (IPCC, 2018) and the European Green Deal (European Commission, 2019).

Table 1
Number of installations part of the EU ETS database in 2017 divided by country and sector.

Sector	Subsector	France	Germany	Italy	Spain	United Kingdom
Energy	Power and Heat	278	690	260	189	180
Manufacturing	Cement and Lime	45	75	57	48	27
	Ceramics	52	138	117	186	25
	Chemicals	104	181	56	82	45
	Coke Ovens	0	3	1	2	0
	Combustion	392	288	264	178	452
	Glass	46	76	50	25	21
	Iron and Steel	48	115	65	38	23
	Mineral oil	9	22	16	10	9
	Nonferrous metals	8	43	12	11	4
	Pulp and paper	81	128	125	61	28
Total		1063	1759	1023	830	814

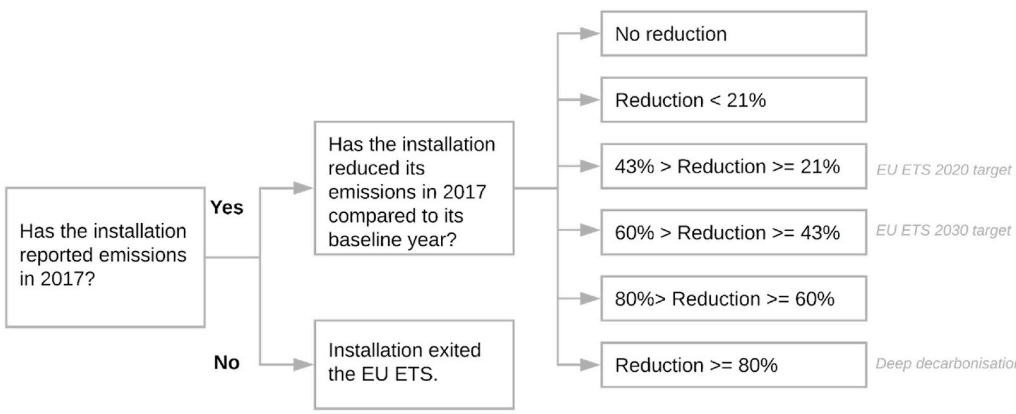

Fig. 1. Scheme of the individual installations' performance analysis.

3.3. *Evaluation of the distribution of emissions among installations*

We also analysed the distribution of 2017 emissions (the most recent data point) among installations. To this end, we constructed a distribution curve that contained the cumulative percentage of emissions from the installations of each country. The curve illustrated each installation's contribution to total emissions and their concentration per category. Additionally, we classified the installations from the five countries and two sectors according to their emissions level. We performed the analysis separately for each sector and country because of the different magnitudes in total emissions. The categories used were low (under the mean), high (above the mean by less than one standard deviation), very high (one standard deviation above the mean), and super-polluters (two standard deviations above the mean, following Tong et al., 2018). We also identified if manufacturing installations with emissions levels above average were from one of the subgroups classified as exposed to carbon leakage (according to the 2014/746/EU directive). Super-polluting installations were further characterised by their opening year, emission reduction performance, sector, and geographical location. We assembled a map that highlighted the super-polluting installations from both the energy and manufacturing sectors.

4. Results and discussion

Each of the following sections will detail the three key findings of the analysis. First, Section 4.1 demonstrates the different overall emissions reductions achieved by the energy and manufacturing sectors. The energy sector presented a better performance in all countries, whereas the emissions abatement from the manufacturing sector was a product of units exiting the EU ETS. This discrepancy among sectors will also be present in Section 4.2, demonstrating how the individual performance of installations from the energy sector was better than the manufacturing one. Nevertheless, a heterogenous decarbonisation process can be found in all countries and sectors, with many installations not yet reporting reductions in emissions. Finally, Section 4.3 presents another imbalance regarding the distribution of emissions among installations: namely, that a small share of installations is responsible for most of the total emissions. This finding has implications for measuring mitigation progress and should be considered when elaborating future instruments to support the achievement of net-zero emissions.

4.1. *Analysing historical patterns of emissions of EU ETS installations from the manufacturing and energy sectors*

Fig. 2 presents a global view of GHG emissions from the manufacturing facilities (MF) and energy facilities (ME) in the five analysed countries from 2005 to 2017. The graphs differentiate among total emissions and emissions solely arising from installations that were still part of the EU ETS record in 2017. Overall, the energy sector achieved better results than the manufacturing one, which reduced its emissions marginally. The countries that reduced total emissions from the manufacturing sector (red line) were Italy (−24,37%), France (−16,61%), and Spain (−9,67%); on the other hand, emissions increased for Germany (+25,11%) and the United Kingdom (+5,61%). France and Germany incremented their EU ETS manufacturing installations by 41% in 2013. These new facilities have impaired emissions reduction results, particularly for Germany, where only two new installations have reduced emissions. Meanwhile, the total emissions from the energy sectors (orange line) declined for the United Kingdom (−60,27%), Italy (−35,47%), Spain (−35,24%), France (−22,30%), and Germany (−17,30%).

Previous studies had not evaluated Phase 3 of the EU ETS (2013–2020), which is partially covered by our data. Policymakers

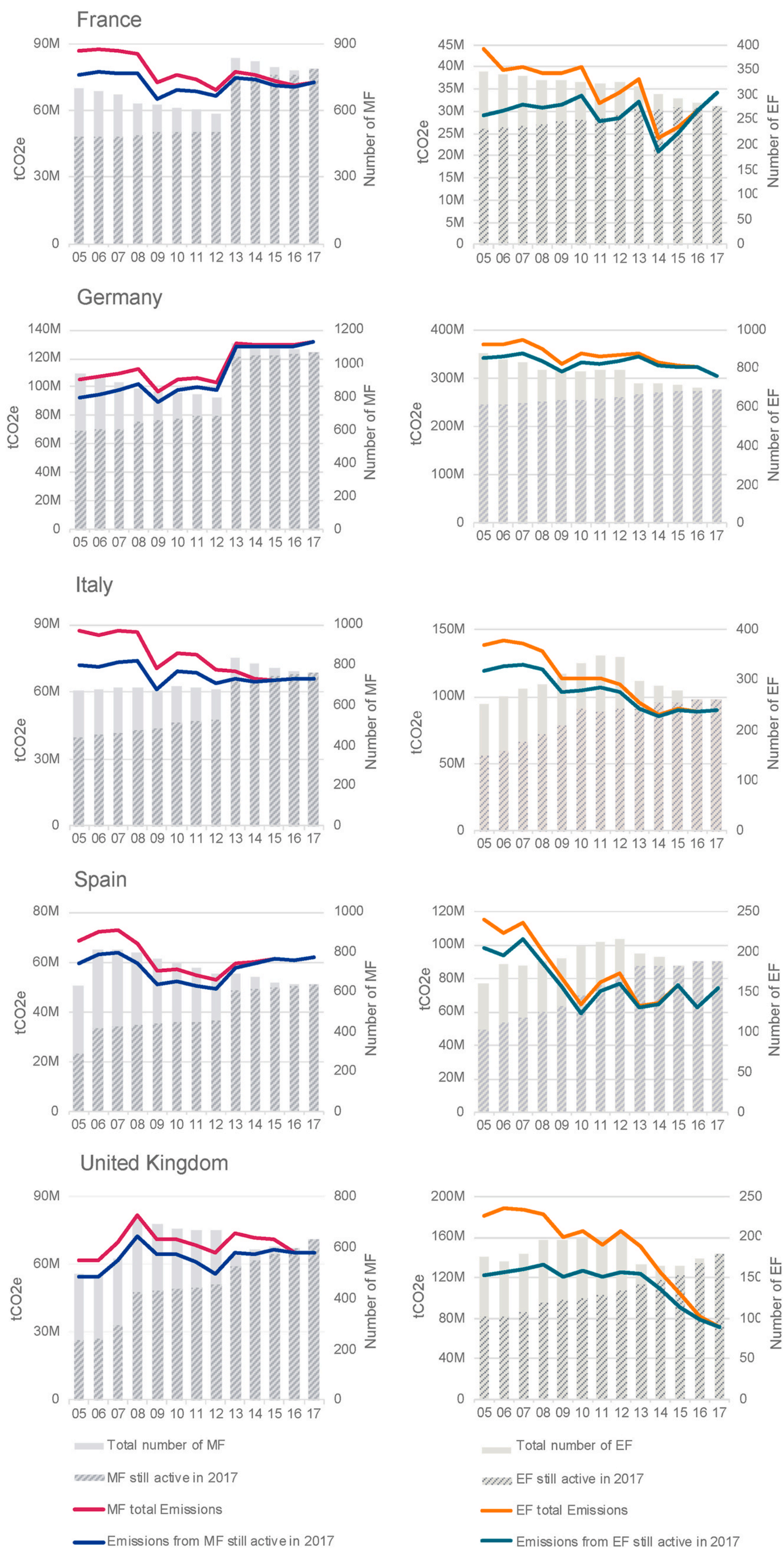

Fig. 2. Global view of GHG emissions and installation exits of the energy (right column) and manufacturing (left column) sectors in France, Germany, Italy, Spain and the United Kingdom.

expected that changes made in the trading system for Phase 3 would result in better mitigation performances (Teixidó et al., 2019). Our findings suggest, however, that Phase 3 presented inferior results for most countries, with emissions even increasing for Germany's manufacturing sector (+1,39%) as well as Spain's energy (+18,16%) and manufacturing (+3,41%) sectors. The manufacturing (−13,28%) and energy (−52,63%) sectors of the United Kingdom, along with the energy sector of Germany (−12,89%), were the only ones that improved reductions in Phase 3. The energy sector of the United Kingdom has produced a sharp reduction in emissions that started in 2013. This reduction can be attributed to a widespread switch from coal to natural gas in the energy sector, enabled by country-specific technological, economic, and policy aspects (Wilson and Staffell, 2018).

Table 2 illustrates the percentage of installations from the energy (E) and manufacturing (M) sectors that have exited the EU ETS in each phase. Evidently, the number of exits was lower in Phase 3, especially in the manufacturing sector. The reduction in installation exits also coincides with a decrease in emissions reductions. Fig. 2 illustrates how the marginal results achieved by the manufacturing sector disappear after accounting for emissions related to installation exits. It is essential to delineate emissions reductions that are a product of installation exits because they are not necessarily mitigation results. Installations might exit the EU ETS because their emissions are below the threshold for mandatory participation of 25.000 tCO2e per year (Verde et al., 2019), or because they relocated or closed. The EU ETS database does not provide information on why an installation exited, but emissions would only cease to exist if an installation closed. Installations that leave the EU ETS because their participation is not mandatory, or relocate outside of its jurisdiction, are still producing GHG emissions but are no longer reporting. Information on the motive for installations' exit is essential to adequately account for emissions abatement results. Identifying that an exit resulted from relocation is also valuable for monitoring carbon leakage.

4.2. *Differences in mitigation performances of individual installations*

Emissions reductions results were marginal in many cases; however, some installations experienced significant improvements in their performance. The relationship between the number of installations that were open annually since 2005 and total emissions underscores that a larger group of installations is producing a consistent level of emissions over the years. Even if the installations improved their efficiency, there were no reductions in the total amount of GHG discharged in the atmosphere. Fig. 3 presents the individual performance of installations from the manufacturing (M) and energy (E) sectors, demonstrating the extent and magnitude of the mitigation. The numbers in Fig. 3 refer to the total of units in each category.

Fig. 3 shows that many installations from both sectors have increased emissions or made reductions below the 2020 target of 21%. In contrast, a smaller share of installations has achieved emissions reductions higher than 60% or 80%. When we analyse the different manufacturing subsectors in detail, all have facilities that reduced emissions by more than 80%. Manufacturing activities with emissions derived from industrial furnaces were the most successful in reducing emissions, probably due to a fuel switch. Considering other manufacturing processes, most installations that reduce emissions by more than 80% are from the pulp and paper, chemicals, and ceramics subsectors. Thus, installations in all sectors are at very different levels of decarbonisation. National figures that showed emissions reduction were not a product of collective improvement and derived from punctual performances. The analysed countries have not yet started a comprehensive decarbonisation process of the energy and manufacturing sectors. The manufacturing sector presented a lower level of performance compared to the energy one. The percentage of installations that reduced emissions above 20% (the first EU ETS target) is on average 29% for the manufacturing sector and 47% for the energy one. A possible factor that could explain the contrasting performances might be the different regulatory pressures on the two sectors (Bel and Joseph, 2018; Teixidó et al., 2019). Manufacturing industries, for instance, might be entitled to receive free emissions allowances to prevent their relocation outside the EU ETS jurisdiction (Hildingsson et al., 2019; Verbruggen et al., 2019; Wesseling et al., 2017). Free allowances mean that instead of buying carbon credits to offset their exceeding emissions, these installations get credits for free. The energy sector had free allowances terminated in 2013, which increased the pressure to adopting low-carbon alternatives. However, the energy sector already has more access to developed alternatives than the manufacturing sector, which motivated the maintenance of the free allowances for the latter (Rosenbloom et al., 2020).

Gerres et al. (2019) reviewed decarbonisation roadmaps for the

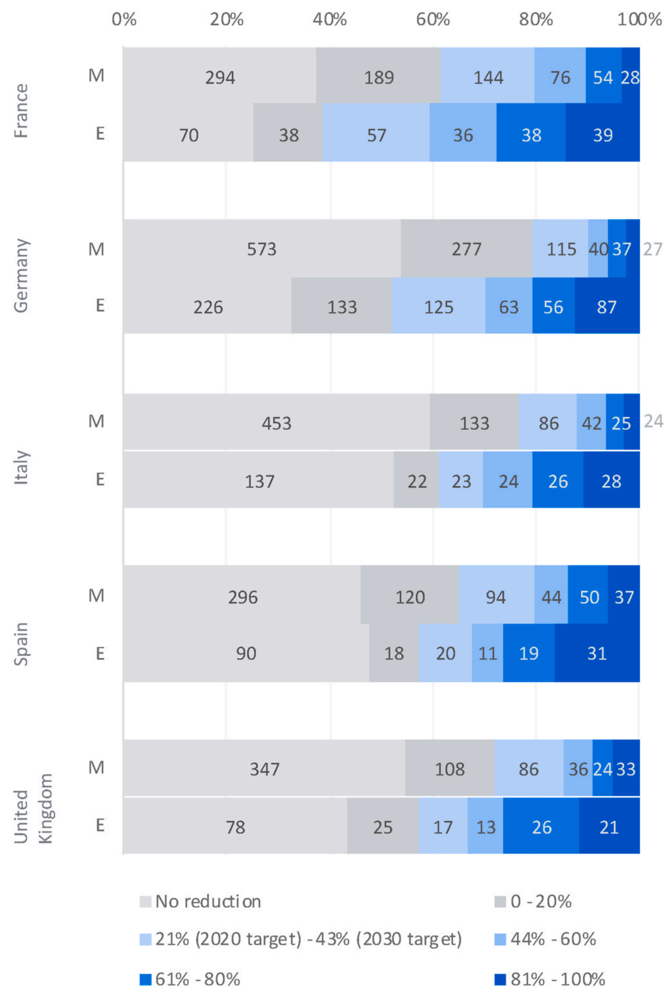

Fig. 3. Analysis of manufacturing and energy sector units' decarbonisation performance (2005–2017) from Italy, France, Germany, Spain and the United Kingdom.

Table 2
Percentage of installations that exited in different phases of the ETS by country.

	Phase 1 (2005–2007)		Phase 2 (2008–2012)		Phase 3 (2013–2017)	
	M	E	M	E	M	E
France	11.14%	8.41%	14.94%	12.54%	5.62%	13.97%
Germany	16.81%	12.11%	15.80%	13.10%	4.72%	7.17%
Italy	7.75%	6.32%	16.93%	17.24%	7.77%	12.08%
Spain	7.64%	7.50%	31.27%	17.46%	6.22%	6.60%
United Kingdom	22.65%	9.14%	17.51%	20.92%	4.69%	9.58%

manufacturing sector and concluded that there is still much uncertainty regarding what technologies should be adopted and their potential for reducing emissions. The most promising low-carbon technologies identified in those roadmaps were membrane technology in the petrol and chemical industry, carbon-neutral steelmaking, alternative feedstock for cement production, and carbon capture & storage (CCS). The number of manufacturing industries that have not reduced emissions suggests that many installations probably have no access to alternatives. However, it does not mean that alternatives do not exist, since manufacturing industries from all subsectors presented mitigation results higher than 80%. This contrast suggests that the availability of technological alternatives is only one of the factors influencing facilities' decarbonisation; market or policy barriers might also be relevant. Previous studies of specific manufacturing subsectors have highlighted a carbon lock-in reality where systemic interactions among technologies and institutions inhibit the replacement of fossil fuel-based infrastructure with low-carbon alternatives (Janipour et al., 2020; Wesseling and Van der Vooren, 2017).

The lack of maturity in low-carbon technologies for manufacturing industries requires appropriate incentives to foster their adoption; after all, novel technical options have high costs and high risks (Åhman et al., 2017; Gerres et al., 2019; Wesseling et al., 2017). Manufacturing industries also have long investment cycles (at least 20 years); as such, plans to retrofit industrial plants need to be elaborated now to achieve future targets such as net-zero emissions by 2050 (Gerres et al., 2019). Choosing to delay deep decarbonisation increases the risk of no decarbonisation at all. Because of these industries' relevance to their regional economies, designing tailored policies is a necessary course of action (Wesseling et al., 2017). The findings from the next section will shed light on what plants should be targeted by such policies.

4.3. The existence of super-polluters and its implications for the 2050 net-zero emissions target

The data presented in Section 4.2 revealed that many installations, especially from the manufacturing sector, are not reducing their emissions. Achieving the net-zero goal by 2050 will thus require understanding the distribution of emissions among installations. Fig. 4 presents the relationship between the percentage of installations and total emissions in each country for both sectors. The relationship is represented with a 2017 cumulative emissions curve that adds the individual units' contribution to total emissions. The curves reveal an unbalanced scenario for all countries in both sectors. The considerable disparity among individual levels of emissions warrants the classification among low, high, very high, and super-polluters (Table 3). The emissions related to each one of these categories exposes how smaller groups of installations with high polluting levels can have an enormous impact on total mitigation results. Installations with high, very high, and super levels of emissions accounted for between 77% and 95% of total emissions in 2017, considering all countries and both sectors. Consequently, there is a large majority of installations (from 77% up to 87%) responsible for a small share of emissions. Such disparities in emissions levels pose implications for monitoring the decarbonisation progress and making policy aimed at deep decarbonisation.

The implications for monitoring the decarbonisation process are that an unequal setting can hide units that are not reducing emissions. A reduction in emissions from high-emitting installations is enough to achieve EU intermediary mitigation targets. The EU ETS 2030 target of reducing GHG emissions by 43% compared to 2005 levels, for example, can be achieved with the deep decarbonisation of very high and super-polluters. Thus, the milestone would be accomplished while installations with high and low emission levels (on average 93% of installations in both sectors and all countries) produce the same level of emissions and use fossil fuels. Progress evaluations need to consider if all installations are reducing emissions to promptly address carbon lock-in settings. Overlooking carbon lock-in and failing to take adequate action can impair the achievement of the net-zero emissions target by 2050.

Policymaking also needs to consider installations' different levels of contribution to total emissions. Adopting identical emissions reduction targets might not be adequate in a context where installations have such a disproportional influence on mitigation results. As Table 3 shows, there are very different potential contributions to GHG emissions reduction among low, high, very high, and super-polluters. Thus, the deep decarbonisation of different manufacturing and energy units will have distinct impacts on overall abatement results. On average, 82% of the installations are low polluters, and the decarbonisation efforts of this vast majority cannot impact total reduction figures by more than 20%. In contrast, the deep decarbonisation of super-polluters (an average of 2,5% of installations for all countries and both sectors) can reduce emissions up to 52% in the energy sector and 45% in the manufacturing one. The deep decarbonisation of all is necessary to achieve net-zero emissions, but it is especially impactful among high, very high, and super-polluters. The number of emissions concentrated in these installations makes them crucial to the decarbonisation process.

At the present moment, super-polluting installations need to comply with the same reduction targets as low-polluting ones. These

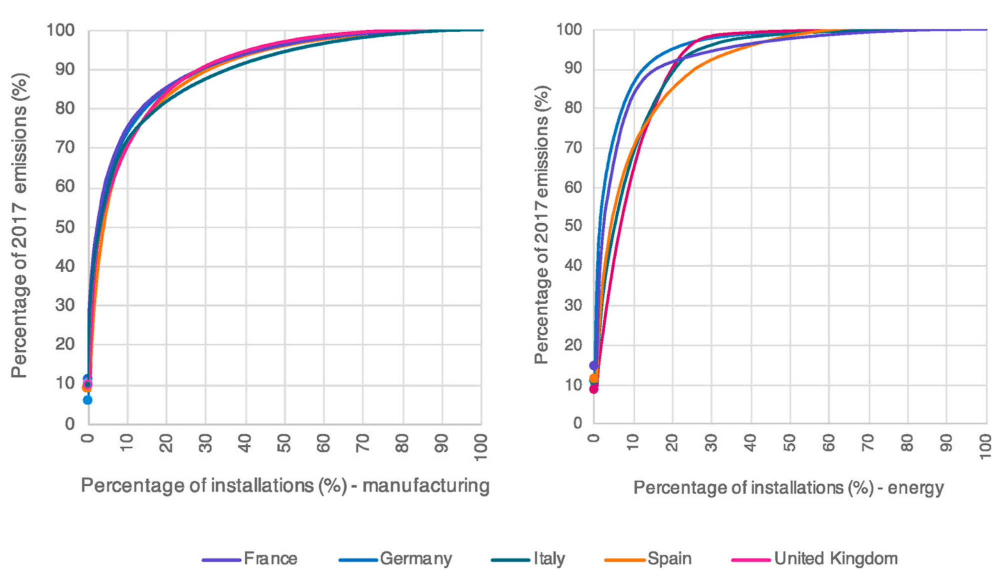

Fig. 4. The relationship between installations and total share of emissions.

Table 3
Classification of installations according to their level of pollution and their respective total emissions share.

Level of pollution		France		Germany		Italy		Spain		United Kingdom	
		N[a]	PE[b]	N	PE	N	PE	N	PE	N	PE
Manufacturing	Super ($x > \bar{x}+2\sigma$)	11 (1,4%)	41,2%	26 (2,4%)	45%	11 (1,4%)	38,5%	16 (2,5%)	41,8%	12 (1,9%)	43,4%
	Very high ($x > \bar{x}+\sigma$)	14 (1,8%)	12,8%	28 (2,6%)	15,5%	14 (1,8%)	12,2%	17 (2,6%)	15,9%	8 (1,3%)	7,9%
	High ($x > \bar{x}$)	91 (11,6%)	27,1%	91 (8,5%)	20,4%	80 (10,5%)	25,7%	75 (11,7%)	22,7%	100 (15,8%)	31,9%
	Low ($x < \bar{x}$)	669 (85,2%)	19%	902 (84,4%)	19%	658 (86,2%)	23,6%	533 (83,1%)	19,5%	514 (81%)	16,7%
Energy	Super ($x > \bar{x}+2\sigma$)	6 (2,2%)	50,3%	11 (1,6%)	52,4%	7 (2,7%)	37,6%	7 (3,7%)	47,3%	10 (5,6%)	44,4%
	Very high ($x > \bar{x}+\sigma$)	8 (2,9%)	17,3%	10 (1,4%)	10,9%	12 (4,6%)	22,6%	5 (2,6%)	12,3%	11 (6,1%)	26,1%
	High ($x > \bar{x}$)	22 (7,9%)	20,3%	68 (9,8%)	27%	39 (15%)	32%	25 (13,2%)	25%	21 (11,7%)	24,2%
	Low ($x < \bar{x}$)	242 (87%)	12,1%	601 (87%)	9,7%	202 (77,7%)	7,8%	152 (80,4%)	16,3%	138 (76,7%)	5,2%

[a] : number of installations;
[b] : percentage of total emissions.

installations are critical to the decarbonisation process and likely to their regional economies. That said, they may also be extremely inefficient and produce low economic output (Freudenburg, 2005). In any case, these installations demand extraordinary measures to ensure their emissions abatement while preventing their relocation. Fig. 5 illustrates super-polluting units' location, level of emissions, and sector. All the analysed countries have power and heat installations that drive super-polluters' emissions. This situation is pronounced for Germany, where 73% of super-polluter emissions stem from power and heat installations. Even in the United Kingdom, where the energy sector has aggressively reduced total emissions, 52% of super-polluter emissions come from energy facilities. Granted, those emissions may be dealt with in time due to ongoing advancements in the transition away from coal. But for all countries, strategies will be needed to address the second- and third-largest sectors for super-polluter facilities—the manufacturing activities of iron/steel and mineral oil.

The iron and steel sector is the second largest contributor to super-polluter emissions in France. Those emissions come from two facilities from ArcelorMittal (one in Dunkerque and the other in Fos sur Mer) that account for 34% of emissions. Six iron and steel facilities, two of them from ArcelorMittal, also compose the second-largest super-polluter sector in Germany. In Italy, Spain, and the UK, mineral oil refineries account for 23% of emissions on average and represent their second-largest super-polluters category. Those emissions come from no more

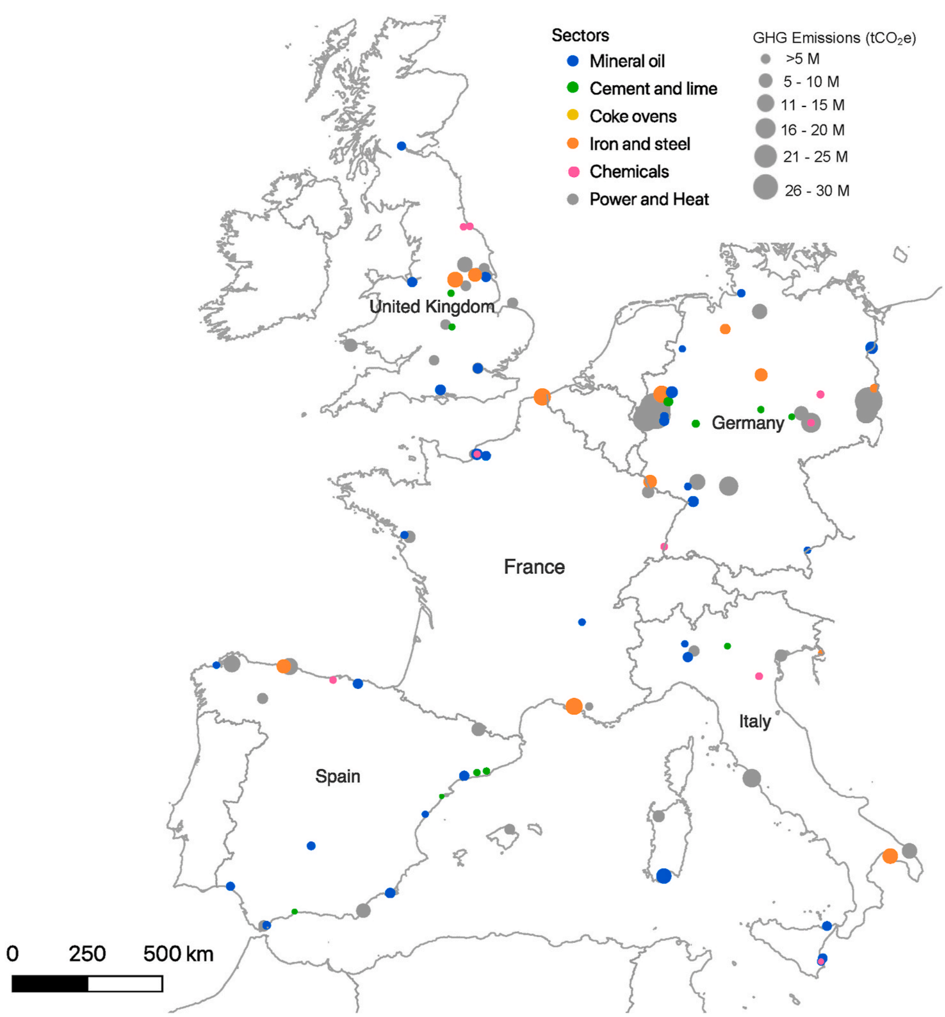

Fig. 5. Location, sectors, and level of emission of super-polluting installations.

than twenty facilities that belong to international oil companies like ExxonMobil, ISAB, Eni, Repsol, and BP. The sectors of cement and lime, chemicals, and coke ovens together account for less than 10% of super-polluter emissions for all countries. Glass, ceramics, pulp and paper, and non-ferrous metals are also part of the EU ETS and had no facilities classified as super-polluters. The complete list of super-polluter facilities is available in Appendix A.

The EU ETS was designed to compensate for pollution inequality when installations with high levels of emissions suffer the substantial financial impact of buying carbon credits. However, there was apprehension that large carbon budgets could provoke the relocation of manufacturing units outside the EU ETS and result in carbon leakage (Verbruggen et al., 2019). To counter this possibility, the system granted free allowances to manufacturing subsectors exposed to carbon leakage (European Commission, 2020). This measure has possibly been effective: one previous study found no linkage between the EU ETS and the relocation of installations outside the EU (Martin et al., 2013).

Free allowances seem successful in avoiding carbon leakage, but they can be a severe threat to decarbonisation. All super-polluting manufacturing installations are from sectors classified as exposed to carbon leakage and entitled to free allowances. As a result, any deep decarbonisation efforts will be much more related to other motives than avoiding an expensive carbon bill. The entitlement to free allowances also occurs for the vast majority (94% of the installations on average) of manufacturing units classified as high and very high polluters. If free allowances prevent action among units with high levels of emissions, then the achievement of even partial mitigation targets is at risk. Free emissions allowances are a short-term solution to avoid economic loss but will unlikely promote transition. Granting these allowances empties the carbon tax principle of ‘polluters pay’ and possibly foments carbon lock-in. The European Green Deal proposes the adoption of a carbon border adjustment mechanism for sectors exposed to carbon leakage. Measures like this are undoubtedly necessary given the limited capacity of the current EU ETS structure to promote a transition (as shown by this study and others: Teixidó et al., 2019). Policies tailored to installations with high levels of pollution are also necessary for promoting sustainable decarbonisation. Targeting super-polluting installations from both manufacturing and energy sectors is an appropriate starting point.

5. Conclusion and policy implications

This paper used EU ETS data from 2005 to 2017 (comprising three EU ETS operational phases) to empirically analyse the mitigation progress of the five largest European economies. Our findings demonstrate that few installations have proactively sought to deeply decarbonise after thirteen years of carbon emissions regulation, whereas many have augmented emissions instead. In most of the analysed cases, the inferior emissions reduction performances after 2013 indicate that the increased stringency of EU ETS Phase 3 did not translate to emissions abatement. Instead, additional policies are likely necessary to achieve carbon neutrality by 2050.

Many units from both sectors increased emissions since 2005 or produced reductions below the 2020 target. This finding signals that decarbonisation is onerous for several installations that might be struggling with technological and institutional constraints that inhibit the adoption of low-carbon alternatives. This constrained reality is more pronounced in the manufacturing sector than the energy one. The insufficiency of technological alternatives is likely one of the main factors behind the manufacturing sector’s inferior mitigation results. However, since manufacturing firms performing the same activities presented results ranging from no reduction to more than 80% of emissions abatement, it is unlikely that the lack of alternative technologies is the sole reason for poor mitigation results. More research is needed to understand the barriers that companies are facing. During the analysed period, the exit of installations from the EU ETS was the primary driver of overall emissions abatement from the manufacturing sector. Emissions reductions related to installation exit cannot be considered mitigation results since they can be a product of relocations or closures. The establishment of the cap-and-trade system was crucial to kickstarting the decarbonisation pathway of many facilities, but European policymakers need to go much further to achieve the magnitude of emissions reductions that have been politically agreed to (Hildingsson et al., 2019; Tvinnereim and Mehling, 2018).

Notably, all countries and both sectors exhibited a clear-cut inequality in emission levels from different units. A share of units from 13 to 23% (depending on the country and sector) containing super-polluting installations was responsible for up to 95% of total emissions. As a result, the achievement of current EU ETS targets is possible without transversal efforts and can produce a false sense of an economy in transition. The unequal level of emissions present among installations requires mitigation targets oriented towards these distinct realities. Moreover, achieving deep decarbonisation will require policy efforts that address the outsized impact of a smaller share of installations on total emissions. Meeting the magnitude of this challenge demands cooperation between government, industry, and academia. Action must be taken promptly, as 30 years is a short time frame for installations with long life cycles.

Our analysis stopped after 2017 and it might be that the following three years saw a shift in the trend. Further, the findings obtained here cannot be generalised to all member states of the EU ETS. It would be helpful to extend the analysis to other countries to confirm if the same distinct emissions levels exist and if reduction performances were also heterogeneous. Moreover, future research should investigate the factors that allowed some units to deeply decarbonise while many others remained carbon-dependent.

We can also make recommendations for reporting carbon mitigation. Adding information about the reasons for installations’ exit from the EU ETS database can assist in adequately characterising mitigation sources. Knowing the exit reason is helpful for flagging the occurrence of carbon leakage, evaluating the comprehensiveness of the decarbonisation process, and identifying the occurrence of carbon lock-in. The EU ETS database has become a crucial resource for evaluating progress towards a low-carbon economy and research on transition; thus, a more comprehensive database can only add value to future studies and policymaking.

CRediT authorship contribution statement

Leticia Canal Vieira: Conceptualization, Methodology, Formal analysis, Writing – original draft, Visualization. **Mariolina Longo:** Conceptualization, Resources, Writing – review & editing, Supervision. **Matteo Mura:** Conceptualization, Resources, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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