Technology diffusion in carbon markets: Evidence from aviation

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Abstract: Carbon pricing has been found mainly to foster low-carbon innovation but not low-carbon technology adoption. Focusing on the aviation sector, we find novel evidence that the EU's Emission Trading System is responsible for a greater diffusion of available low-carbon technologies. We find a small improvement in emission intensities in the sector driven by the modest substitution of aircraft – more fuel-efficient planes – and the sizeable effect of aircraft retrofitting – use of winglets – compared to the counterfactual. We conclude that while carbon pricing satisfies theoretical predictions in terms of cost-effective emission reductions, complementary policies are required to ensure full decarbonization is achieved in time.

Keywords: carbon pricing; EU ETS; aviation; technology diffusion, diff-in-diffs

JEL Codes: Q54; D22; L93

1. Introduction

As the world emerges from the pandemic, fighting climate change would appear to be more urgent than ever. However, the fight requires a considerably stronger global political consensus given that the aggregate effort resulting from COP26 is calculated to be insufficient to keep global warming below 2 ºC by the end of the century (IPCC 2022). Against this backdrop, technology change is even more critical in efforts to tie mitigation pledges to climate targets consistent with the 2 ºC threshold. In theory, when faced with a carbon price, firms avail themselves of abatement options whose costs are below the carbon price. This incentivizes polluting agents to pick the most cost-effective options to reduce their emissions, with organizational and behavioral changes leading the way. Alternatively, firms may seek to accommodate their output to their new marginal costs so as to continue to maximize profits. In the long run, this search for cost-effectiveness is expected to induce investment in low- and zero-carbon technologies that should further reduce the costs of compliance. This paper examines technology adoption in response to carbon pricing by the EU's Emission Trading System (EU ETS).

The technology response to carbon pricing may take the form of the invention and innovation of new low-carbon technologies or, alternatively, the adoption of existing low-carbon technologies, i.e. the diffusion of innovation. In this regard, the EU's Emission Trading System (EU ETS) has been reported as providing more innovation than adoption (Teixidó et al., 2019). However, to exploit and generalize full abatement possibilities, the adoption of new technology is critical. Firms faced with having to pay a carbon price have been found to invest more heavily in R&D and to register more low-carbon patents than they would have done had the carbon price not been in place (Calel, 2020; Calel & Dechezleprêtre, 2016). However, changes in emission intensities, which would indicate the adoption of these or other low-carbon technologies, have not been reported for these same firms (Calel, 2020) nor have they been found in country-specific analyses (Jaraite & di Maria, 2016; Klemetsen et al., 2020; Löfgren et al., 2014). When found, reductions in emission intensity are explained by behavioral and operational changes, such as fuel switching, mainly in the electricity sector (Berghmans et al., 2014; Delarue et al., 2008; Ellerman & McGuinness, 2008), and other energy optimization processes in manufacturing (Petrick & Wagner, 2014; Wagner et al., 2014). But, importantly, all these analyses fail to present any evidence of a technology upgrade being responsible for a fall in emissions. This distinction is relevant because, unlike the short-run responses of organizational change or output reductions, technology changes also improve the emission reduction rate and do so in a more permanent fashion, and it is here that the key to bridging the climate targets gap lies.

This lack of empirical support for the effect of carbon pricing on the diffusion of low-carbon technology casts doubts on its dynamic efficiency (i.e. its long-run cost-effectiveness), suggesting that its virtues in this regard are only theoretical (Lilliestam et al., 2021, 2022). Various explanations have been offered including the argument that the technology is not yet available as it appears to have been in earlier contexts (Calel, 2020); the presence of bounded rationality in some sectors (Pintos & Linares, 2018); dynamic increasing returns and network externalities (Jaffe et al., 2005); or an array of other institutional and infrastructural barriers, including regulations and firm-specific characteristics (Snyder et al., 2003, Popp, 2010, Horbach et al., 2012). Additionally, data availability and the time spans considered in previous studies may have also played a role here. Ideally emission intensity should be measured by emissions per output; however, these figures are rarely available and, where they are, they tend not to be readily comparable across sectors (certainly not in the case of manufacturing, which has been the main focus of such studies). This means existing evidence tends to measure carbon intensity in terms of emissions per employment level or per $1,000 of gross output, which is not free of drawbacks.

In this paper, we investigate the effect of the EU ETS on actual technology diffusion using reliable, comparable metrics of technology change. To do so, we focus on the European commercial aviation sector and analyze how the EU ETS affects actual emission intensity (kg of CO_2 per seat-km), aircraft model choice and aircraft retrofit decisions (winglets). We use data on the universe of flights in Europe and neighboring countries.

To identify the impact of the EU ETS, we exploit the policy change introduced when limiting the scope of the scheme for aviation: the so-called ‘stop-the-clock’ law. Originally (that is, from January 1st, 2012), any flight landing or taking off from an airport in the European Economic Area (EEA) was subject to EU ETS compliance and, hence, faced a carbon price. However, this generated considerable resistance among international carriers who deemed the regulation unlawful and a breach of the sovereignty of non-EU countries. In the face of significant international pressure, in April 2013 the European Commission proposed ‘stopping the clock’ on the ETS regulation for the aviation sector and limiting the scope of the EU ETS directive, retrospectively, to flights *within* the EEA, regardless of airline’s nationality. This policy change, previously exploited by Fageda and Teixidó (2022), therefore, provides us with a group of flights that can be used as a control for our analysis, i.e. a natural experiment. We use a difference-in-differences strategy to compare changes in terms of technological and retrofitting available options in the aircraft fleets operating on the EU ETS regulated routes with those made by our control group between 2010 and 2019.

Our results show that the EU ETS improved average emission intensity (kg of CO_2 per seat-km) by a statistically significant, but environmentally negligible, 2–4%. This is in line with the literature reporting null or weak effects in other sectors. However, in this case, the effect does not seem to be attributable (solely) to organizational changes in the sector’s operations, but rather to the timing of the effects of technology diffusion: The average effect is low because technology change only has an impact a few years after policy implementation;

yet, this technology change occurs earlier than it would have done without a carbon pricing policy in place.

The most sizeable effect is that originated by the retrofitting of aircraft. We find an average increase of 8% in the share of aircrafts with winglets, with point estimates scaling to 12–13% three to five years after policy implementation. Winglets (the curved tips at the end of the wings), the main retrofit in the air industry, improve a plane's aerodynamics by reducing drag and, consequently, fuel consumption.[1] In 2010, before the introduction of carbon pricing, they appeared on about 10% of planes in Europe, but by 2019 this share had increased to above 30%.[2] Here, we show that the EU ETS is responsible for big share of this notable increase in the adoption of winglets.

We also find, albeit at a lesser magnitude, that the EU ETS has encouraged aircraft substitution. More carbon intense regional aircraft are being slowly retired in favor of larger, more carbon efficient narrow body planes. Indeed, today, narrow body aircraft account for more than 80% of the market.

Moreover, the EU ETS has had an impact on the adoption of more efficient aircraft models. On average, the EU ETS has increased the use of those aircraft considered as being the most efficient, for given years and route distances, by 4–5%. These effects, although low in average terms, are increasing in time and reached point estimates close to 10% in 2019.

Our results contribute to the broader literature examining the impact of carbon pricing on technology change, with a primary focus on innovation. To date, carbon pricing has only been found to be effective in terms of increased R&D and low-carbon patents, but without any evidence that these developments have resulted in technology diffusion. Here, we identify a causal link between

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[1] The concept was first devised in 1897, although the first Boeing and Airbus winglet models would not be employed until 1985

[2] This refers to narrow body aircraft which is the most popular aircraft type in European Market (with one aisle seats and concentrating around 80% of flights)

carbon pricing and the diffusion of low-carbon technologies, an effect that has traditionally been linked to environmental regulations (such as, technology standards), but not to pricing instruments (Clarke et al., 2006; del Río González, 2009; Kerr & Newell, 2003; Popp, 2010; Snyder et al., 2003). Indeed, technology standards can provide fast, dependable outcomes; however, they lack the continuous incentives and cost-effectiveness that pricing instruments can offer. Technology diffusion is, after all, a slow, gradual process (Schumpeter, 1942). Here, we show that carbon pricing can accelerate it.

The results reported here refer to a single sector and, hence, precluding the generalization of effects to other sectors, sectorial details matter. However, by focusing on the aviation sector, we are able to exploit data on salient, comparable technology choices that can be measured and we are, moreover, not constrained in this exercise to a single country. In the specific case of the aviation sector, Fageda and Teixidó (2022) and Kang et al. (2022) report evidence of the short-run effect of the EU ETS in reducing the number of flights in response to carbon costs. To date, this supply effect is today the strongest channel of emission reduction in the sector. De Jong (2022), in a comparison of EU and US carriers, finds that the EU ETS fosters the early retirement of old (narrow body) aircraft. Here, we identify the onset of a long-run response, which is better characterized by retrofitting actions and earlier technology upgrades.

Aviation is the most climate-intensive mode of transport and while today it accounts for only 6% of global climate impact[3], its projected growth – 2050 flights are projected to be between 20 and 76% higher than 2019 levels – means its global GHG contribution is set to grow critically in the coming years (IATA, 2022; ICCT, 2020). The main value added by our research, in this regard, derives from demonstrating that carbon pricing does indeed play a role in the diffusion of low-carbon technology; however, our study also shows that the incentives provided are insufficient to offset the sector's emission growth

[3] The climate impact of aviation extends beyond CO_2 emissions, given that non-CO_2 emissions at high altitudes have been found to multiply this impact (Lee et al., 2021).

trends, at least they are not enough to ensure climate targets are consistent with the 2 ºC threshold, which is what ultimately matters. To meet this target, aviation emissions (depending on the scenario) need to be between 41 and 96% lower than their 2005 levels by 2050 (Cames et al., 2015); however, they continue to grow.

The rest of this paper is organized as follows. Section 2 reviews the literature and basic theory on the economics of induced technology change related to both the EU ETS and to aviation. Section 3 presents our data and empirical strategy, which includes a descriptive analysis and our identification strategy. Section 4 reports our main results and Section 5 concludes and discusses policy implications.

2. EU ETS-induced technology diffusion

2.1 Background

Technology change was described by Joseph Schumpeter (1942) as the result of three independent steps: *invention*, that is, the original development of a new technical idea; *innovation* or the penetration of the new technology into the market, thereby generating profits and/or a monopolistic position, and *diffusion*, that is, when the new technology is widely adopted by other firms in the market. Thus, the key difference between innovation and diffusion is that while the former can be seen as a shift of the technological frontier, diffusion occurs as firms move towards that technological frontier (Jaffe et al., 2005). Here, we are specifically concerned with the latter. The EU ETS has been reported as playing a role in both invention and innovation, consistent, that is, with the induced-innovation hypothesis, i.e. the change in the relative price of a factor spurs innovation aimed at economizing the use of said factor (Hicks, 1932). But, here, our interest lies in testing the induced-diffusion hypothesis (Popp, 2010).

While innovation can be "disruptive" (Schumpeter, 1942), the diffusion of a new technology tends to be a slower process. Typically, adoption of a new technology follows an S-curve: an initial stage characterized by a handful of early adopters is followed by a period of mass-adoption, but when the market reaches maturity, the final phase returns to the earlier slow adoption rate (Geroski, 2000). In the case of environmental technologies, empirical research indicates that the adoption of cleaner technologies only occurs when there is a need to comply with environmental policies, what the literature refers to as the induced-diffusion hypothesis (Kerr & Newell, 2003; Popp, 2010). What is not clear, however, is which instruments are best suited to achieve this goal (Popp et al., 2010; Lilliestam et al., 2021) and, to the best of our knowledge, empirical evidence shows that while the EU ETS induces low-carbon innovation, the strategy does not stimulate technology diffusion (through adoption).

Calel & Dechezleprêtre (2016) report that the EU ETS increased innovation – measured in terms of the number of low-carbon patents – in the manufacturing sector. EU ETS firms generated 10% more patents of this nature than the counterfactual. Similarly, Calel (2020) reports a 25% increase in low-carbon patents in the UK manufacturing sector and a similar impact on R&D spending. However, the same author fails to find any significant effect on emission intensity, which is relevant as this would point to the adoption of new technologies. The absence of any impact on emission intensity is further confirmed for Norway (Klemetsen et al., 2020), Sweden (Löfgren et al., 2014) and Lithuania (Jaraite & di Maria, 2016). However, a reduction in emission intensity can originate from sources other than the adoption of new technologies: in Germany (Petrick & Wagner, 2014) and France (Wagner et al., 2014), the EU ETS has been found to reduce emission intensities by 18 and 8%, respectively, because of fuel switching and other energy optimization processes. Yet, these authors also find the effect not to be statistically different from zero when they focus specifically on technology upgrades. Similarly, empirical studies conducted for the power sector highlight the effect of the EU ETS on encouraging firms to switch from coal to gas to generate electricity (Berghmans et al., 2014; Delarue et al., 2008; Ellerman & McGuinness, 2008). However, while this might be considered a case of adoption, it does not represent an actual technology upgrade but rather a reranking of generation technologies, i.e. a merit-order effect.

The diffusion of low-carbon technologies ensures longer, more sustained emission reductions than those originating from operational changes and reductions in output, especially if the policy-induced technology is zero-carbon as opposed to low- carbon technology (Lilliestam et al., 2022). The EU ETS has been found to reduce emissions in the power sector (Delarue et al., 2008), manufacturing (Abrell et al., 2011, Petrick and Wagner, 2014; Wagner et al., 2014; Klemetsen et al., 2020) and aviation (Fageda and Teixidó, 2022; Kang et al., 2022). These effects, however, can be reversed if, as is the case of aviation, an external shock causes an increase in the supply of flights, or, as recent geopolitical events in Europe have shown, rising energy and carbon prices have seen Germany returning to coal as an energy source in response to the Russian invasion of Ukraine. Emission reductions are likely to be more sustained when they involve technology changes that go beyond operational changes or output reductions. When an airline renews its aircraft fleet with more efficient planes, the emission reductions achieved cannot be reversed[4], especially if the new technology used is carbon free.

2.2 Induced technology diffusion and the aviation sector

As of today, some potentially applicable disruptive technologies, including laminar flow control, open-rotor propulsion, and double-bubble designs, have still to overcome major technical and economic obstacles which means they are not viable options for commercial aviation in the immediate future (Graham et al., 2014). Likewise, the use of green hydrogen is a long way from being technically feasible.

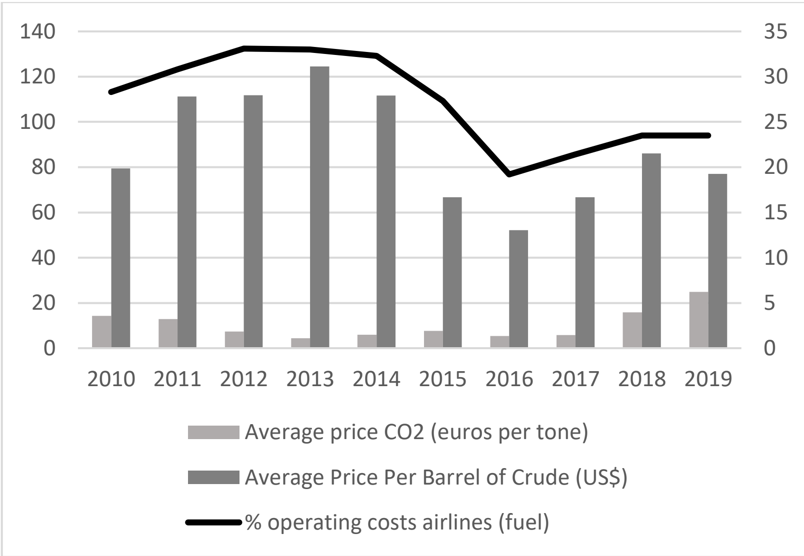
[4] Unless there is a rebound effect triggered by this higher efficiency which makes flying cheaper, hence, creating an increase in demand (the so-called Jevons paradox). However, this is not the case as the number of flights has fallen compared to the counterfactual (Fageda and Teixidó, 2022; Kang et al., 2022).

The two main channels for reducing aircraft emission intensity over the next few years depend on improvements in aircraft technology and the use of biofuels. The abatement cost associated with biofuels ranges from $46 to $652/t CO_2 (Winchester et al., 2015) and this is without considering such challenges as prices rising higher than those of jet fuel, a lack of sufficient feedstock and the need for major capital investment in bio-refining infrastructure (Staples et al., 2018). These challenges mean that biofuels represent less than 0.1% of total aviation fuel consumption. This leaves retrofitting options and in-time aircraft substitution as more rational options for the sector, even though their fleets continue to depend on petroleum-based fuels.

Because fuel consumption represents between 20 and 25% of airlines' total operating costs, there are strong economic incentives to operate with the most efficient aircraft possible (see Figure 1). In practice, the ETS represents an increase in fuel costs, so that the airlines most affected by the trading system are likely to have even stronger incentives to operate with more efficient aircraft. In this regard, there has been an abrupt increase in CO_2 prices in recent years. By way of illustration, Figure 2 shows the cost of CO_2 per aircraft for selected narrow body aircraft[5] using 2019 prices and 1,500 km. Considering that a single aircraft in this distance range usually makes around 3,000 flights per year, the total CO_2 costs for airlines are far from negligible. Note also that airline decisions regarding their aircraft fleets are based not only on current prices but also on future price expectations.

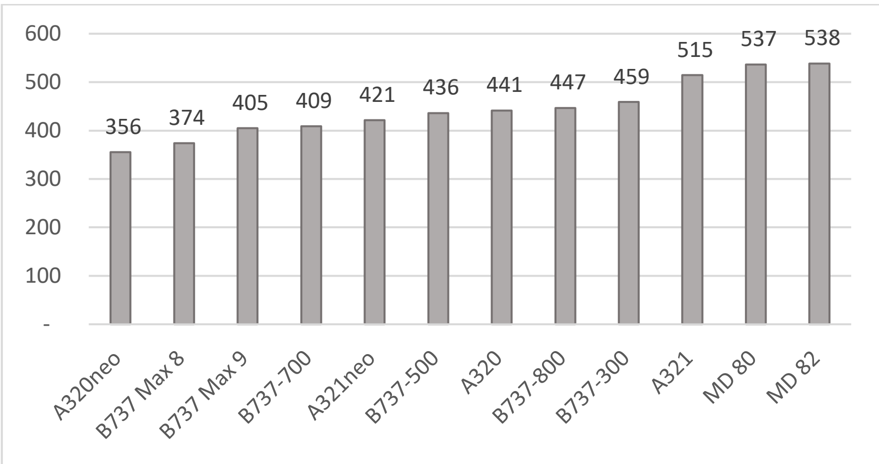
[5] Mainline jets include narrow (with a single aisle of seats) and wide-body (two or more aisles of seats) airplanes. Regional planes are smaller planes (with fewer than 100 seats) and include regional jets and turboprops. Narrow body aircraft concentrate around 80% of flights in the European market.

Figure 1. CO_2 and oil prices



Notes: This figure plots carbon prices (euros/ton on the left axis) and fuel jet prices (US$ on the left axis). The line shows fuel costs as a share of the airlines' total operating costs on average (right axis)

Figure 2. CO_2 costs per selected narrow body aircraft



Note: This figure plots CO_2 costs (euros per flight) for a flight of 1500 km and the average carbon price in 2019.

As a result, airlines affected by the EU ETS may have greater incentives to reduce aircraft emission intensities and, hence, use newer, more efficient planes or, at least, the most efficient models for a particular distance range. Similarly, the EU ETS may spur airlines to withdraw old aircraft at an earlier date or, in a context of traffic growth, to absorb traffic growth with more efficient aircraft (e.g. the use of narrow body aircraft as opposed to regional aircraft). Finally, the retrofitting of existing aircraft, including installation of winglets (or sharklets), may be more intense on ETS routes. This, moreover, has the advantage of not requiring the substitution of aircraft.

In the following sections, we analyze the extent to which carbon pricing has affected the adoption of available technology, in particular, aircraft replacement and the fitting of winglets.

3. Data and methods

We use annual data for the period 2010 to 2019 for all flights within Europe at the airline–route level, where the route is the airport-pair. We record, at this level, the total number of seats, frequencies, aircraft size, distance flown, the operating airline and the aircraft model used.[6] Data have been obtained from RDC aviation (Apex schedules). To estimate emissions at the airline–route level we use Eurocontrol's small emitter tool (SET), designed to assist aircraft operators in their monitoring and reporting obligations for the EU ETS. The SET is based on fuel burn samples of real flight operations and provides accurate estimates of emissions for any given distance and aircraft model. With the aircraft model, the number of seats per aircraft and the route distance, we can estimate emissions per seat-km at the airline–route level per year.[7]

We have also collected urban population data for the points of origin and destination of all routes. For urban areas with more than 300,000 inhabitants, data have been obtained from the UN's World Urbanization Prospects database. For urban areas in the European Economic Area, Switzerland and Turkey with

[6] Unfortunately, data for cargo flights are not available. However, note that a significant amount of cargo is handled by passenger flights.
[7] When different aircraft are used by an airline on the same route, we compute the corresponding mean values weighted by the number of flights made by each aircraft. Low-cost airlines generally operate routes with a single aircraft model, but it is usual that network airlines operate with different models on the same route.

fewer than 300,000 inhabitants, we have collected data from Eurostat (NUTS 3). For urban areas in the remaining countries with fewer than 300,000 inhabitants, we have collected data from their respective national statistics agencies. We also consider income per capita at both endpoints of the routes at the country level. Data have been obtained from the World Bank Development Indicators database. Additionally, we have used supply data to construct an indicator of the intensity of competition, namely the Herfindahl-Hirschman index (HHI), which is based on the sum of the square of the share of flights of airlines operating a route. Additionally, a dummy variable taking a value of one is included for city-pairs with high-speed rail services (speeds over 200 km/hour). We obtained information about each line from the International Union of Railways.

The routes considered may be operated by different types of airlines, primarily low-cost or network.[8] Alternatively they might be operated by charter airlines offering scheduled flights, regional carriers operating independently of network airlines, or airlines with a mixed business model. However, network and low-cost airlines concentrate around 90% of flights.

The analysis of the choice of aircraft is based on a sample at the aircraft–airline–route level, totaling 632,377 observations. The analysis of aircraft emission intensity is based on a sample at the airline–route level (as for emission intensity we do not need to split airline-route level observation in terms of aircrafts). Here, we have collected data for 80,698 airline–route pairs, totaling 333,023 observations. To minimize the distortions of those flights that respond to contingent or circumstantial events, we restrict our sample to airline–route pairs with at least one flight per week. Since some airline–route pairs do not

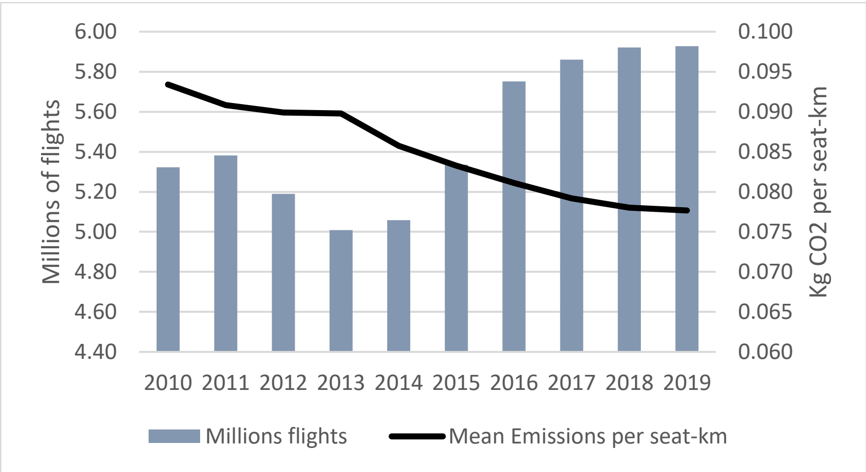
[8] Chapter 5.1 of the Manual on the Regulation of International Air Transport published by the International Civil Aviation Organization (ICAO) defines a low-cost airline as "an air carrier that has a relatively low-cost structure in comparison with other comparable carriers and offers low fares and rates". Based on these criteria, the ICAO provides a list of low-cost airlines that we use here to establish our category of low-cost airlines. Network airlines are airlines integrated in one of the three global airline alliances (oneworld, Star Alliance, SkyTeam).

have a flight or have fewer than one flight per week in a particular year, our resulting dataset is an unbalanced panel of 416,847 observations when the sample used is at the aircraft–airline–route level and 131,807 observations when sampled at the airline–route level.

3.1. Trends in aircraft emissions

Figure 3 shows the evolution in flights and the mean emission intensity in the European aviation market from 2010 to 2019. Despite some temporary shocks, such as the financial crisis of the last decade and the COVID-19 pandemic, the long-term trend in the sector is one of traffic growth. There was an 11% increase in flights in 2019 compared to 2010 and it is expected that traffic will recover pre-pandemic levels by 2024 (IATA, 2022). Environmentally, this growth appears to be only slightly offset (note, sectorial emissions continue to grow) by a 17% improvement in average emission intensity.

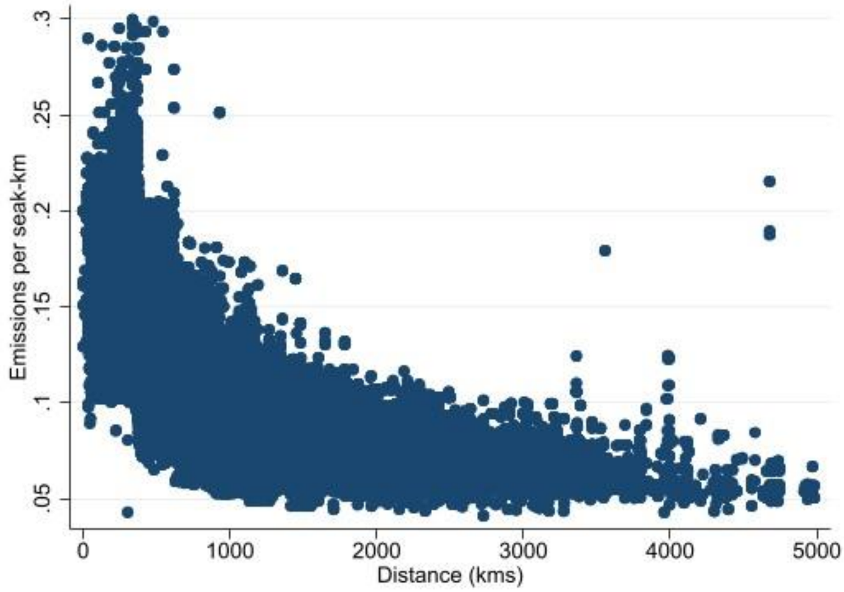
Figure 3. Flights and emission intensity in the European aviation market



Notes: This figure plots in bars the evolution in the number of flights in Europe (left axis) and the evolution in average emission intensity, as measured by kg of CO_2 per seat-km (right axis). The lower emission intensities have not offset the emissions from increased sector growth.

Emission intensity not only depends on the specific aircraft model used but also on the distance flown because fuel consumption is particularly high during landing and take-off, so the shorter the flight the more intense the use of fuel per seat-km. Figure 4 shows this negative relationship between emission intensity and distance, highlighting the fact that the variability within the same distance range is mainly explained by aircraft choice and to a lesser extent by seat configuration.[9]

Figure 4. Emission intensity (CO_2 per seat-kms vs distance)



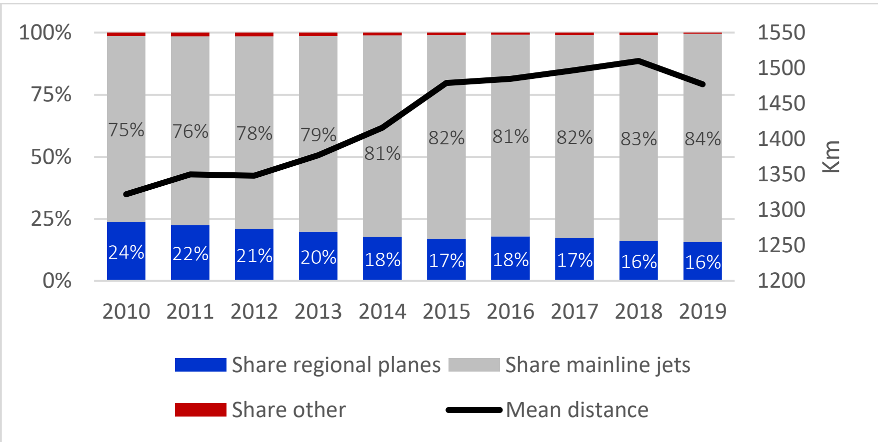
Notes: The scatter plot correlates aircraft emission intensity, as measured by kg of CO_2 per seat-km, with the average distances flown by those aircraft. Aircraft choice -in terms of emissions per seat-km- is especially relevant in the case of shorter distances.

Figure 5 shows aircraft types available according to their capacity and share of flights over the years. Mainline jets – including both narrow and wide body aircraft[10] – dominate the European market with a share of 74% in 2010 rising to 84% in 2019. This is not surprising given that many routes in the European market are medium-haul routes for which the most efficient option for an airline

[9] Denser seat configurations may mean lower emission intensities per seat-km.
[10] Narrow body airplanes only have a single aisle of seats, whereas wide body planes have two or more aisles of seats.

is to operate a narrow body aircraft. In contrast, wide body aircraft have only a marginal presence, given that they are mainly used for long-haul flights. Regional aircraft, in contrast, are only used for short-haul routes and their use has declined in the market from 24% in 2010 to 16% in 2019. In part, this decline can be explained by an increase in the mean distance flown (from 1,322 km in 2010 to 1,477 km in 2019), which makes larger planes (narrow body, in the main) more appropriate. Only on very short flights are regional aircrafts likely to be more efficient.

Figure 5. Share of flights by type of aircraft in the European Aviation market.



Notes: Regional planes include regional jets and turboprops. Mainline jets include narrow body and wide body aircraft. Other includes very small vehicles (helicopters, private aviation, pistons, etc.).

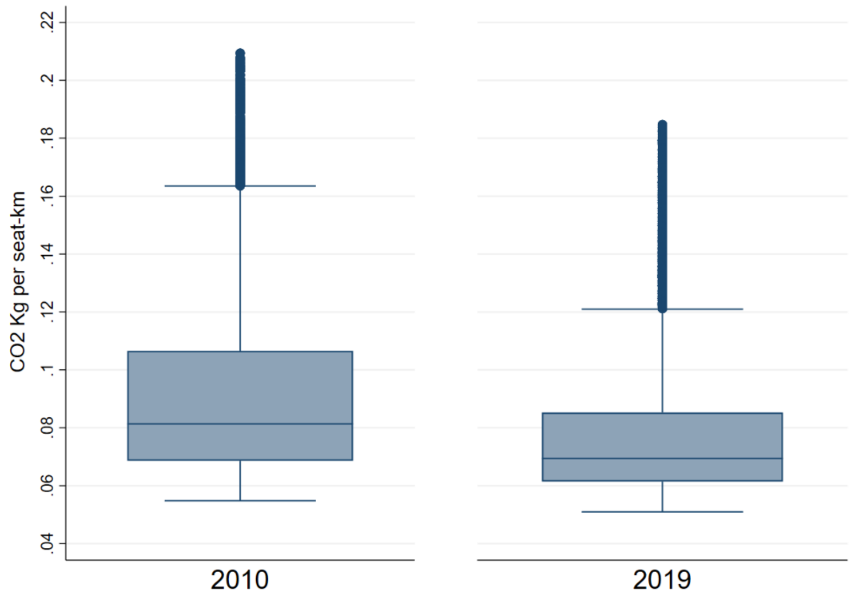
Newer aircraft are, in general, more efficient than older planes, tending to have lighter airframes, improved aerodynamics, and more efficient engines (Abrantes et al., 2021; Graham et al., 2014; Bravo et al., 2022). The Airbus A-320 and the Boeing B737-800 are the two most frequently used planes in Europe. Their new generation models – i.e. the A-320neo and the B737-MAX – have, respectively, 31 and 18% fewer kg of CO_2 per seat-km.[11] Older models that were popular until the early years of this decade, such as the MD-80,

[11] In the case of the B737-800 the use of winglets by default had already implied a great improvement in efficiency.

generated 24% more emissions per seat-km than a comparable model such as the A319. Yet, before substituting an aircraft, airlines can consider available retrofit measures. One such measure is the fitting of winglets, which have a marked impact on a plane's aerodynamics. As a result of both retrofitting and aircraft substitution, the use of winglets has increased tenfold from 2010 to 2019, with 30% of aircraft using winglets by the latter date.

A clear trend, therefore, emerges as flying has become less carbon intensive over the years. Figure 6 shows boxplots comparing emission intensities in 2010 and 2019: the minimum values, i.e. the emission intensity of cleaner aircraft fell only from 0.06 to 0.05 kg of CO_2 per seat-km. The upper values, in contrast, together with the upper quartiles, show a more prominent downward shift, bringing down the median emission intensity values. As such, the trend in emission intensity appears to be mainly attributable to airlines moving towards the technology frontier rather than shifting it forward.

Figure 6. Emissions per seat-km



Notes: All outliers are excluded (that is, 1% maximum and minimum values)

Technology change has never been disruptive, rather it has focused on the emergence of improved versions of existing models. Within this context, the goal of our empirical strategy is to identify the effect of carbon pricing on this overall pattern, in other words, we seek to isolate the effect of the EU ETS from the sectorial trend described up to this point.

3.2. Determinants of aircraft emission intensity

Before proceeding to an identification of the effects of the EU ETS, we first analyze how our main covariates correlate with emission intensity, paying particular attention to four categories of aircraft: narrow body (as to be compared to smaller regional aircrafts), fuel-efficient, most fuel-efficient in a given year and over a given distance, and those with winglets. Table 1 shows the results. The data here are at the aircraft–airline–route level. We apply weights based on the total number of flights so that aircraft–airline–route combinations with more flights are afforded greater weight in the regression.

As covariates, we consider both distance and aircraft size (in logs). As expected, we find clear evidence of distance economies and economies of vehicle size in terms of fuel consumption (and associated emissions). Indeed, the coefficients of the distance and aircraft size variables are negative and statistically significant. Hence, longer routes and larger planes imply lower emissions per seat-km.

In addition, we consider population and regional income per capita at the airports of origin and destination. Emission intensity is lower on routes with richer and less populated endpoints. However, although the coefficients are statistically significant, they are small in value, suggesting they play only a modest role in explaining the emission intensity.

The emission intensity of low-cost airlines is lower than that of network airlines, suggesting that the former use more efficient planes. Moreover, their lower rates of emission may also be attributed to the denser configurations of their aircraft. Low-cost airlines operate an economy-fare class only, while network airlines also operate business classes, which entails more space and, hence, fewer seats on a plane.

Controlling for all these factors, we find evidence that the plane model operated has a relevant impact on emission intensity. In the first specification, we include a dummy variable for narrow body aircraft. The second regression includes a dummy variable for fuel efficient aircraft, that is, aircraft that on average have less than 0.08 kg of CO_2 emissions per seat-km (hence, lower emissions than the mean values in our sample).[12] We focus here on mainline jets, given that small planes are almost never efficient. The third column considers the most fuel-efficient aircraft in a given year and over a given distance. As such, we identify aircraft with below-average emission intensities for three distance categories – short-, medium- and long-haul routes – and we do this for each year in the sample. Given that we consider small planes as possibly being more efficient on short-haul routes, we use the entire sample. The fourth regression focuses on the most popular aircraft family models (A320ceo and B737 -classic and next generation) and includes a dummy for winglets. This focus on the most popular aircraft family models allows us to separate the effect of retrofitting (upgrades to the current fleet) from the effect of fleet renewal, as new aircraft models usually already have winglets fitted.

[12] According to this definition, fuel efficient aircraft include the following models: A320 & A321 (Standard, Winglet, Neo), B737-800 & B737-900 (Standard, Winglet, Max), B757-200 & B757-300 (Standard, Winglet), and CRJ, B737-700 & B767-300 (Winglet).

Table 1. Determinants of aircraft emission intensity (emissions per seat-km)

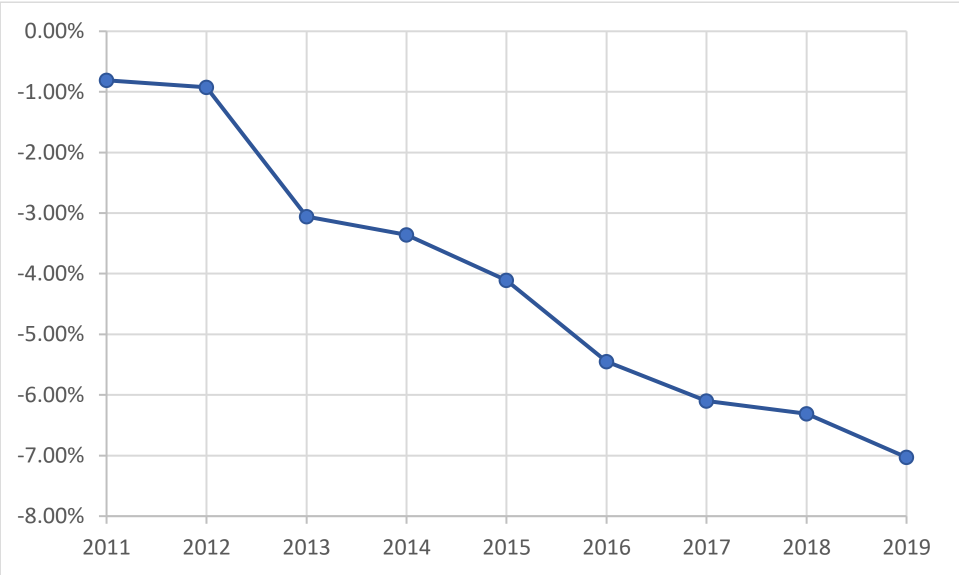
VARIABLES	(1)	(2)	(3)	(4)
ln(Distance)	-0.281	-0.292	-0.269	-0.291
	(0.00282)	(0.00267)	(0.00247)	(0.00239)
ln(Aircraft size)	-0.178	-0.135	-0.131	-0.692
	(0.00452)	(0.0073)	(0.00375)	(0.003142)
Network Airlines	0.0378	0.0163	0.0240	0.0113
	(0.00228)	(0.002175)	(0.00196)	(0.001743)
Low-cost Airlines	-0.0663	-0.0735	-0.0457	-0.0342
	(0.00165)	(0.00143)	(0.00131)	(0.00117)
ln(Income)	-0.0164	-0.0230	-0.0085	-0.0101
	(0.00265)	(0.00291)	(0.00230)	(0.00248)
ln(Population)	0.00974	0.00347	0.00731	-0.00387
	(0.00116)	(0.00119)	(0.00109)	(0.00103)
Narrow body Aircraft	-0.0614			
	(0.00357)			
Fuel efficient Aircraft		-0.158		
		(0.00208)		
Per year-distance fuel efficient aircraft			-0.202	
			(0.00189)	
Winglet				-0.0679
				(0.0007)
Constant	0.512	0.351	0.223	3.249
	(0.0364)	(0.0126)	(0.0338)	(0.0345)
Observations	416,847	374,692	416,847	330,173
R-squared	0.762	0.927	0.839	0.909
Year FE	YES	YES	YES	YES
Sample	All	Large aircraft (>100 seats)	All	Popular aircraft
Airlines	All	All	All	All
Clusters	Route	Route	Route	Route
Weights	Flights	Flights	Flights	Flights

Notes: This table reports the emission intensity regressions. Column 1 includes a dummy variable for narrow body aircrafts, column 2 for fuel efficient aircraft (planes that on average have lower emissions than the mean), column 3 for the most fuel-efficient aircrafts in a given year and over a given distance, and column 4 for winglet fittings. Robust standard errors (in parentheses) are clustered at the route level.

Considering distance and aircraft size, narrow body aircraft have 6% lower emission intensities per seat-km than regional aircrafts, while fuel efficient aircraft have 15% lower emissions per seat-km than other narrow body aircrafts. Fuel efficient aircraft per year and distance have 20% lower emissions per seat-km than other aircrafts. Finally, the use of winglets in the most popular aircraft family models is associated with 6% lower emissions per seat-km.

In Figure 7, we plot the coefficients of the year fixed effects (from the second specification). The results confirm the descriptive evidence reported above – that is, a general decreasing trend in emission intensities.

Figure 7. Coefficient estimates of the year variables (Table 1)



Notes: This figure plots year fixed effects from the second specification in Table 1. It shows that emission intensities per seat-km have tended to decrease over the last decade.

4. Identification

The way in which the EU ETS was unfolded within the aviation sector is central to our identification strategy, and fundamental for interpreting our results. Decarbonizing aviation is especially challenging and not only because of the projected traffic growth and the limited technology options available. The international dimension of the sector is the cause of further difficulties to the extent that the Kyoto protocol determined that aviation abatement be coordinated by the International Civil Aviation Organization (ICAO), a UN agency. However, in view of the lack of progress made by this organization, the EU decided to advance its own targeted climate policies, as did other countries, including Australia and New Zealand.

Under Directive 2008/101/EC of the European Parliament and of the Council of 19 November 2008, the EU decided to include aviation CO_2 emissions within its ETS. This meant that, as of January 1st 2012, all flights from, to, or within Europe – i.e. landing or taking off from an airport in the European Economic Area – were to be regulated under the carbon trading system and, hence, all airlines, regardless of their nationality, would require allowances for every ton of CO_2 emitted during the year. This generated an unprecedented controversy: International carriers refused to adhere to the European law and some countries even forbade their airlines from complying with the EU ETS. US carriers challenged the Directive in the EU Courts arguing that the policy infringed national sovereignty and international agreements. Although the Court rejected these claims, more international pressure was brought to bear. Several Latin American countries, Japan, India, Mexico, Russia, and China signed a joint declaration opposing the inclusion of international aviation in the EU ETS. In November 2012, in response to this pressure, the EU Commission decided to reduce the scope of the EU ETS, retrospectively to January 2012, to flights *within* the EEA. The decision was formally adopted in April 2013 just before the airlines were supposed to pay their allowances for their 2012 emissions.

Thanks to this policy change we can compare ETS and non-ETS flights. Before 2012, no flights were regulated and, hence, we would expect airlines to be using similar aircraft and to be responsible for similar emission intensities across air–routes. Although after 2012 some routes were effectively regulated, it is only since 2013 that existing legislative uncertainties dissipated, and regulation status was clarified. This being the case, we treat 2013 as the first year of the ETS for the aviation sector, but exercise caution when interpreting results for 2012. Crucially for purposes of identification, airlines do not choose their routes conditional on their potential regulatory status. Flights within the EEA (our treated group here) are operated by a variety of carriers that cannot be predicted solely from their treatment status.

We apply the logic of difference-in-differences, a common methodology adopted within the treatment evaluation framework (Angrist and Pischke, 2009; Gertler et al., 2016). Thus, routes affected by the EU ETS are all those connecting two airports within the EEA since 2013, while our control routes include those that connect an EEA airport with a non-EEA airport and those that connect two non-EEA airports.[13] We estimate the following equations for aircraft *a* and route–airline pair *i* in year *t*:

$$\log(Y)_{ait} = \alpha + \beta ETS_{it} + \lambda X_{it} + \gamma_i + \eta_t + hk\varepsilon_{ait} \qquad (1)$$

where Y refers to either emission intensity, aircraft choice or winglet installation. *ETS* is a dummy identifying treated flights after 2013 and *X* is a set of control variables: population and income of the points of origin and destination of the route, the HHI index, and a dummy for high-speed rail services. For our emission intensity regressions, we also control for the average size of the aircraft. All continuous variables are in logs. We add airline–route fixed effects and year fixed effects. Notice that route–airline fixed effects capture the distance effect on emission intensity shown previously. Standard errors are robust to heteroscedasticity and clustered at the route level.

We apply weights based on the number of flights for each aircraft–airline–route or route–airline combination. This allows us to give more weight to those route–airline pairs with more flights, which are thus those route–airline pairs that generate more emissions in absolute values.

[13] The EEA countries include the EU28, Norway and Iceland. The European non-EEA countries include Albania, Armenia, Azerbaijan, Belarus, Bosnia and Herzegovina, Georgia, Macedonia (FAROM), Montenegro, Moldova, Russia, Serbia, Switzerland, Turkey, and Ukraine.

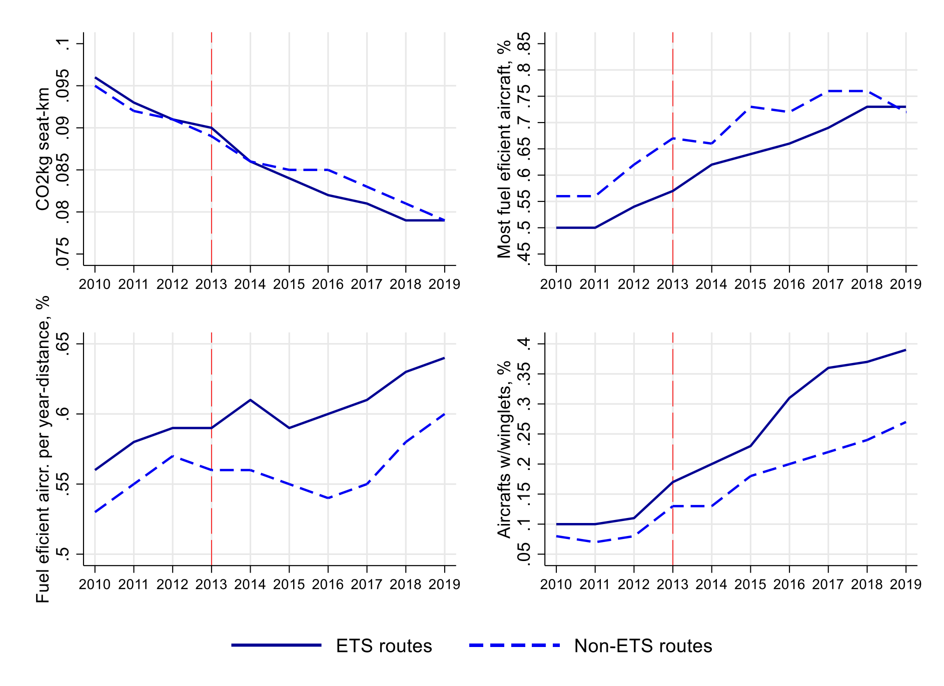
Key to our identification strategy is that the common trend assumption holds. We evaluate this assumption by implementing an augmented difference-in-differences estimator. This involves estimating the impact of the treatment in different years of the sample period (Autor, 2003), by applying the following equation:

$$\log(Y)_{it} = \alpha + \beta_k(D_{it} \times t) + \lambda X_{it} + \gamma_i + \eta_t + \varepsilon_{it} \quad (2)$$

where D is a dummy variable equal to one when the route is in the treated group and t is the year. Thus, β is the coefficient on the treatment effect in year t. The non-significance of the coefficients in the years before 2013 adds plausibility to the common trend assumption in the pre-treatment period, while their significance after 2013 is informative of the durability of the effect over time. However, note here that the results of this analysis must be interpreted with some caution because airline decisions on aircrafts are not made on a year-by-year basis and the average order-delivery time for narrow and wide body jet aircraft is around 2 years (Dray, 2013).

Regarding the plausibility of parallel trends, Figure 8 shows that the treated and the control groups were trending similarly for the key variables in our analysis before the policy implementation in 2013: that is, emissions per seat-km (top-left panel), share of use of the sample's most fuel-efficient aircraft (top-right panel), share of the most fuel-efficient aircraft model per year and distance levels (bottom-left panel), and share of aircraft with winglets fixed (bottom-right panel). This descriptive evidence already suggests that the effect of the EU ETS is especially notable in terms of winglet installations.

Figure 8. Evolution of emission intensities and shares of aircraft used



Notes: Mean values for the different dependent variables used in the difference-in-differences estimator (solid lines for treated and dashed for control routes). The relatively constant gap between treated and control airline-routes before the treatment adds credibility to the parallel trends assumption, i.e. had the policy not been in place, the trends would have continued as before 2013.

5. Results

Table 2 shows the results of the regressions in which the emission intensity of the aircraft operating the route is the dependent variable. In column 1, we show the results for the full sample. We find that emissions on treated routes are 2.2% lower per seat-km than the counterfactual. Although modest, the effect is statistically different from zero, which is quite remarkable in a context in which the trend across the sector is for emission intensity to improve.

In column 2, we show the results for alternative control group samplings by way of a robustness check. It could be that the improvement found in emission intensity is the result of airlines moving their older (or less efficient) aircraft to routes that connect an EEA airport with a non-EEA airport, i.e. to flights in the control group. This would violate the stable unit treatment assumption (SUTVA) and yield biased estimates. More specifically, the results in column 1 would be overestimated, as they would be capturing the reduction of treated routes (obtaining better planes) plus the increase in control routes (being assigned the older planes from the treated routes). In column 2, the control group excludes routes that link an EEA with a non-EEA airport, i.e. the control group is limited to non-EEA airports only. The logic of this is that EEA airlines may simultaneously operate within-EEA routes and routes that link an EEA with a non-EEA airport. However, it is, in fact, very unusual that these EEA airlines operate routes connecting two non-EEA countries: specifically, less than 1% of their flights. As a result, restricting the control group to non-EEA airports greatly reduces these potential SUTVA violations and, therefore, if our results were overestimated, we should see a smaller, not larger, effect in column 2.

However, we find a larger effect of the EU ETS – with -4.3% lower emissions per seat-km – indicating that no strategic movement of planes takes place within airlines.[14] It is also worth mentioning that decreasing trends of emission intensity in both groups is also indicative of the fact that SUTVA is not an issue.

Columns 3 and 4 replicate the same analysis (with a restricted control group) but also limiting the airline type to network airlines. Unlike low-cost and other airlines, network airlines are typically more nationally based. This means EEA network airlines operate just 0.1% of their routes within non-EEA airports. Following the same logic, if there was a SUTVA violation, our effect in column 3 – 4% improvement in emission intensity for treated routes operated by network airlines – would be overestimated, but this ETS effect rises to 7.6% when we limit control routes to non-EEA airports.

All in all, the EU ETS has induced a statistically significant reduction in emission intensities on treated routes without this being the result of an increase

[14] These greater effects of the restricted control groups are therefore attributable to a higher degree of heterogeneity between the treated and (restricted) control groups.

in emission intensities on control routes. However, being statistically significant is not the same as being environmentally significant as the average effect stands at just 2%.

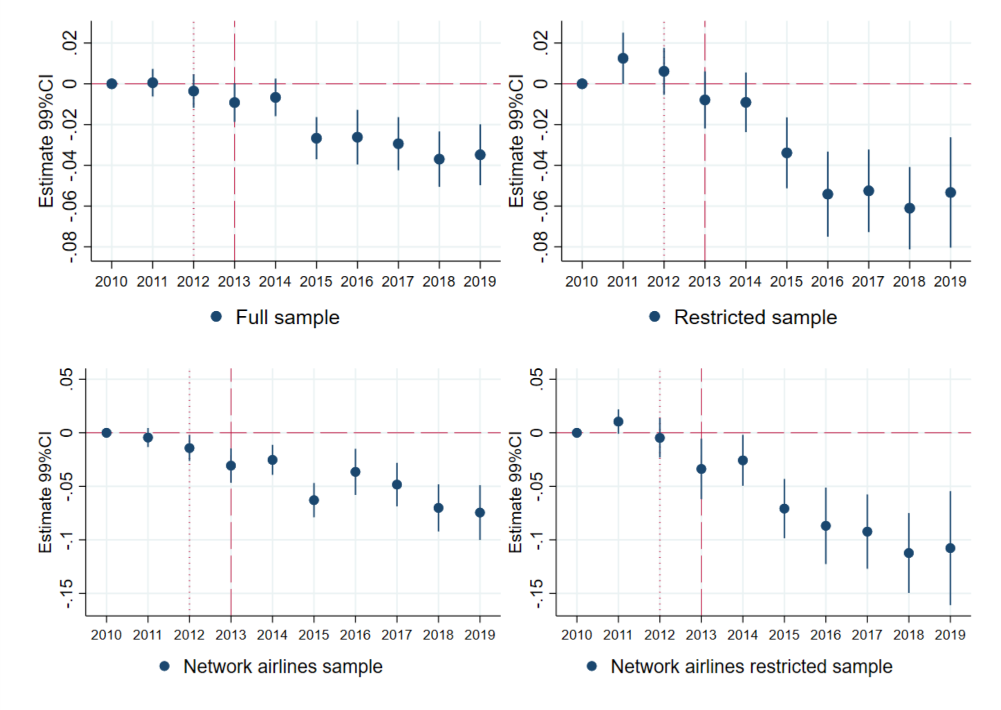
Table 2. EU ETS and emission intensity (emissions per seat-km)

VARIABLES	(1) All	(2) All	(3) Network	(4) Network
EU ETS	-0.0219	-0.0434	-0.0425	-0.0760
	(0.00326)	(0.00507)	(0.00548)	(0.00907)
Constant	0.481	1.037	-0.277	1.788
	(0.464)	(0.507)	(0.8186)	(0.893)
Observations	131,807	112,805	25,279	20,518
R-squared	0.977	0.980	0.957	0.968
Route–Airline FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES
Sample	Full Sample	Restricted	Full sample	Restricted
Airlines	All	All	Network	Network
Clusters	Route	Route	Route	Route
Controls	All	All	All	All

Note: This table shows difference-in-difference coefficients using as our outcome variable a measure of flight emission intensities (emissions per seat-km). Column 1 reports results for the whole sample. To see if this effect is driven by EEA airlines moving more polluting planes to non-regulated routes (SUTVA), column 2 reports results when flights in the control group are limited to flights between non-EEA airports. Because only 0.8% of the routes operated by EEA airlines include flights between non-EEA countries, this alternative control group reduces the chances of a SUTVA violation. In the case of low-cost airlines this percentage is 1%, and in the case of network airlines it is 0.1%. Columns 3 and 4 replicate the same analysis for network airlines only, showing again that a SUTVA violation cannot be significant. Robust standard errors (in parentheses) are clustered at the route level.

Figure 9 shows the event-study estimates of these prior effects illustrating both dynamic effects and the plausibility of the common trends assumption. The EU ETS coefficients prior to the treatment are not statistically significant in any of the regressions. Thus, we provide evidence in favor of the common trends assumption. Point estimates rise to about 4% after 2015, after remaining non-significant during the first two years. This jump in emission intensity can be considered a telltale sign if we consider that aircraft investment is not immediate and that a few years must elapse between a purchase decision and aircraft use.

Figure 9. Event-study estimates of the EU ETS effect on flight emission intensity



Notes: This figure plots the results from an event-study analysis of the differences in emission intensity between the EU ETS regulated air-routes and other comparable air-routes before and after policy implementation. The coefficients reported are derived from equation (2) in which we interact the treatment variable with year indicators. The top-left panel reports the results for the full sample estimates and the top-right panels reports the results when the flights in the control group are restricted to those flying within non-EEA airports. Since airlines in the treated group operate fewer than 1% of their routes between non-EEA airports, this specification controls for potential strategic displacement of polluting aircrafts within an airline. The bottom panels replicate the same analysis for network airlines that are even more nationally based and, hence, network airlines operating treated groups only have 0.1% of their routes connecting two non-EEA airport. Finding greater effect in the restricted samples confirms the EU ETS effect on emission intensity is not driven by strategic aircraft movement to non-regulated routes (in which case, the effect in restricted routes would be smaller than in the full samples). Year 2010 is used as a reference. The confidence interval is set at 99% and standard errors are clustered at the route level.

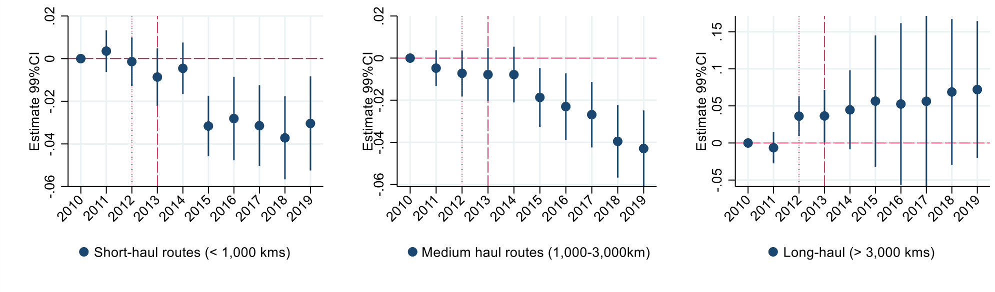
Table 3 provides additional estimates of the EU ETS effect on emission intensity. Because distance is a key characteristic of aircraft choice (see Table 1), we divide the sample in three different distance categories: short-haul routes of less than 1000 km, medium distance flights between 1000 and 3000 km and long-haul routes of more than 3000 km. The effect on the emission intensity of the carbon market appears to be stronger when emission intensity is higher. As detailed above, because landing and taking off are the most carbon intensive phases of flying, short-haul routes are more carbon intensive. EU ETS regulated short-haul flights reduced their emission per seat-km by about 2.5% compared to the non-ETS scenario. This translates into a 1.7% improvement in the case of medium-haul flights and a non-significant effect on long-haul routes (see Figure 10 for the event estimates). This evidence suggests that carbon pricing fosters more intense technology change in contexts of higher emission intensity. Potentially, technology changes on short-haul routes are more cost-effective given that longer routes are already more efficient and, hence, emission intensity improvements are already too expensive in the margin.

Table 3. EU ETS effect on emission intensity (emissions per seat-km) by distance

VARIABLES	(1) Short-haul	(2) Medium-haul	(3) Long-haul
EU ETS	-0.0245	-0.0169	0.0421
	(0.00479)	(0.00369)	(0.0275)
Constant	1.972	-1.605	3.873
	(0.700)	(0.449)	(1.997)
Observations	54,376	71,099	6,458
R-squared	0.962	0.942	0.814
Route–Airline FE	YES	YES	YES
Year FE	YES	YES	YES
Sample	<1000 kms	1000-3000 kms	>3000 kms
Airlines	All	All	All
Clusters	Route	Route	Route
Controls	All	All	All

Note: This table shows difference-in-difference coefficients using as our outcome variable a measure of flight emission intensity (emissions per seat-km). Column 1 reports the results for short-haul routes (distances flown below 1,000 km), column 2 for medium-haul routes (1,000-3,000 km) and column 3 for flights above 3,000 km. Robust standard errors (in parentheses) are clustered at the route level.

Figure 10. Event-study estimates of the effect of EU ETS on flight emission intensities by distance



Notes: This figure plots the results from an event-study analysis of the differences in emission intensity between the EU ETS regulated air-routes and other comparable air-routes before and after policy implementation for subsamples according to different lengths of the route. Year 2010 is used as a reference. The confidence interval is set at 99% and standard errors are clustered at the route level.

Next, we replicate the analysis, focusing now on how the EU ETS affects the kind of aircraft chosen to operate. We are interested in capturing whether this improvement in emission intensity in the EU ETS flights has been driven by induced technology changes.

Table 4 shows estimates for four different dependent variables that identify the characteristics of the aircraft chosen: in column 1, we focus on whether the EU ETS has incentivized the greater use of narrow body planes. This would mean using larger planes and, hence, retiring smaller CO_2-intensive regional planes. In column 2, focusing solely on narrow body planes, we examine the most fuel-efficient aircraft in our sample. These are aircraft whose emissions per seat-km are below 0.08 kg of CO_2, the sample average. However, this overlooks the market dynamics of the diffusion of the aircraft models – i.e. some models might have diffused earlier than others – and it also fails to consider the role played by distance when choosing an aircraft. To account for this, column 3 considers the effect on the use of the most fuel-efficient aircrafts in a given year and over a given distance. Here, we signal aircraft with below-average emission intensity for three distance categories – short-, medium- and long-haul routes – and we do this for each year in the sample. The result is the effect of the EU ETS on using the most efficient aircraft available each year given the route distance. Hence, this provides us with the EU ETS estimates net of the technology trend and diffusion lags of particular models in the whole sector. Finally, column 4 shows the effect on winglet use in the aircraft operated, considering the most popular family planes (the A320ceo and B737 -classic and next generation-). As opposed to the former specifications, this is a retrofit action which, as such, does not require the substitution of aircraft. We focus on the most popular aircraft family models to separate the effect of retrofitting (upgrades to the current fleet) from the effect of fleet renewal, as new aircraft models (ie; A320neo, B737 MAX) usually already have winglets fitted.

According to our results, the EU ETS has incentivized the use of more efficient aircraft in all categories. Airlines on ETS-routes have a 4.4% higher probability of using narrow body aircrafts than airlines on non-ETS routes. Similarly, the EU ETS has also increased the use of fuel-efficient narrow body planes by 4.3%. Taking the dynamics of technology change and distance into account, the EU ETS routes use on average 5.3% more fuel-efficient aircrafts. This difference is motivated by potentially different stages of technology diffusion for some aircraft models. More striking, however, is the effect on winglet fitting, for which the EU ETS has an average effect of about 8%. Arguably, this higher effect derives from the fact that this action consists primarily of a retrofit investment and does not require the purchase of a new aircraft.

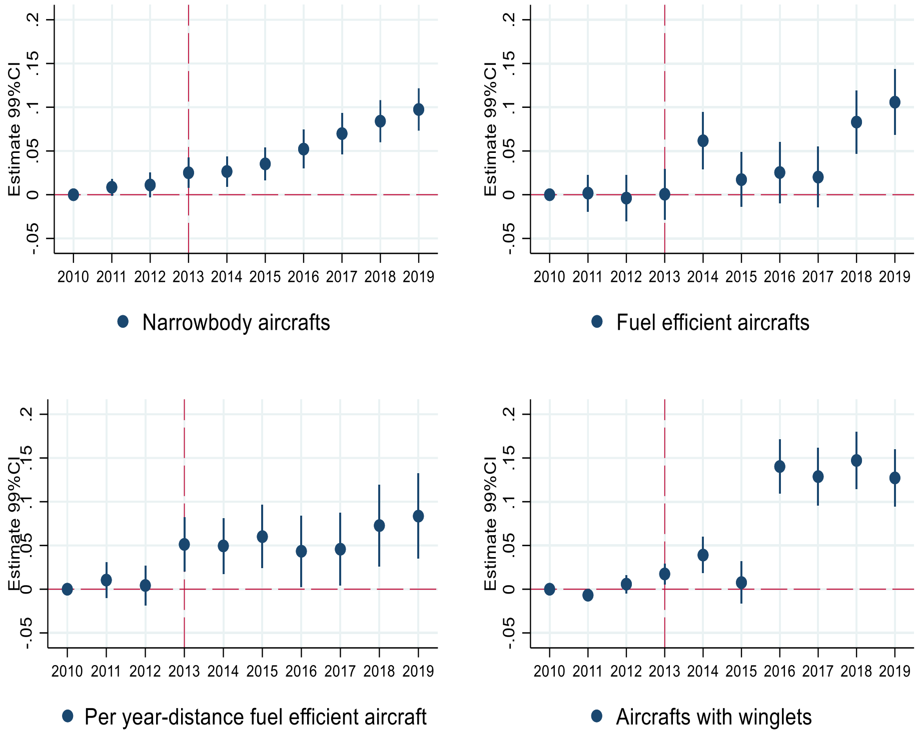
Table 4. EU ETS on aircraft choice

VARIABLES	(1) Narrow body aircraft	(2) Fuel efficient aircrafts	(3) Per year-distance fuel efficient aircraft	(4) Winglets in aircraft
EU ETS	0.0444	0.0430	0.0530	0.0785
	(0.00550)	(0.00908)	(0.0124)	(0.00812)
Constant	4.596	-1.471	-1.157	3.167
	(0.652)	(1.438)	(1.365)	(1.629)
Observations	416,847	374,692	416,847	330,178
R-squared	0.830	0.535	0.712	0.598
Route–airline FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES
Sample	All	Large aircrafts (> 100 seats)	All	Popular aircrafts
Airlines	All	All	All	All
Clusters	Route	Route	Route	Route
Controls	All	All	All	All

Note: This table shows difference-in-difference coefficients using as our outcome variable dummies for the type of aircraft used. In column 1, we consider a dummy variable for narrow body aircrafts, in column 2 for fuel efficient aircraft (aircrafts that on average have lower emission intensities than our mean values), in column 3 for the most fuel-efficient aircraft in a given year and over a given distance, and in column 4 for winglet fittings. Robust standard errors (in parentheses) are clustered at the route level.

Figure 11 shows the evolution of the year-on-year estimates of these effects. The EU ETS coefficients prior to the treatment are not statistically significant, which makes the common trends assumption plausible. It also shows that the effect on aircraft technology adoption is increasing over time, with point estimates close to 10% in 2019 in the four aircraft categories. The 2016 jump for winglet fittings (which do not require as much time as the purchase of an aircraft) might be driven by reforms to the EU ETS approved in 2015 – including the market stability reserve (MSR) – becoming effective in 2019. This reform involves the introduction of a mechanism to avoid an excess of allowances in the carbon market, considered as being the cause of excessively low prices in the years following the financial crisis. It was expected to affect both levels and the volatility of carbon prices (Bruninx et al., 2020; Perino & Willner, 2016), something that appears to have been confirmed by recent high and increasing carbon prices. This could eventually further induce the adoption of more efficient aircraft, especially those already to hand, such as winglets.

Figure 11. Event-study estimates for aircraft choice



Notes: This figure plots the results from an event-study analysis of the differences in the type of aircraft used. The coefficients reported are derived from equation (2) in which we interact the treatment variable with year indicators. The key assumption is that prior to policy implementation (red line at 2013), airlines in the control group show no difference with airlines in the treated group in terms of the particular type of aircraft they were operating. This is supported when the coefficient before policy implementation is not statistically different from zero. The top-left panel shows the annual effects of the EU ETS on the use of narrow body aircrafts, those whose emission intensity mainly derives from increasing the size of the plane. The top-right panel shows the effect on the use of fuel-efficient aircrafts, defined as those with below average fuel efficiency. The bottom-left panel shows the annual effects on the most fuel-efficient aircraft in a given year and over a given distance. The bottom-right panel shows the annual effects on the use of aircraft with winglets, consisting mainly in a retrofit of the aircraft in use. Year 2010 is used as a reference. The confidence interval is set at 99% and standard errors are clustered at the route level.

Altogether, these results show that the EU ETS is responsible for an improvement in the emission that is driven by actual technology change, in particular the fitting of winglets to aircraft in use. In this regard, the size effect on emission intensity (which, as reported above, remains small) seems in this case to be driven more by the timing of the technology adoption (in the main, a few years after policy implementation and potentially accompanying the higher carbon prices) than by small operational or behavioral changes as reported in other sectors. In this sense, technology diffusion is a slow, gradual process that can be accelerated by carbon prices.

6. Discussion and Conclusions

Carbon markets are designed to reduce emissions in a cost-effective manner, a process that includes the spurring of low-carbon innovation and, in the long term, technology diffusion. To date, empirical studies on carbon markets have, indeed, shown that they spur low-carbon innovation, with regulated firms increasing their low-carbon patenting and R&D spending. However, these greater innovation efforts are not being transferred into the greater adoption of these technologies, which ultimately is what will reduce emissions. Without the diffusion of low-carbon technologies, carbon markets are unable to realize their full potential as regards cost-effectiveness in reducing emissions. Here, in the aviation sector, we report some evidence of low-carbon technology diffusion taking place in response to the EU ETS. Thus, while the impact of the system on emission intensity is small, the effect on retrofitting is gaining increasing relevance, due, it would appear, to the rise in carbon prices. Likewise, the replacement of aircraft for more efficient models, although slow, presents a higher substitution rate on ETS routes than on those of the counterfactual.

These results, however, need to be considered in context. Technology advances in the aviation sector have been quite remarkable in recent decades but insufficient to achieve its full decarbonization, as pledged, by 2050. From a policy perspective, the emission reductions achieved to date fall well short of climate targets in this sector: emissions in the aviation sector have yet to stop increasing. The EU ETS has only moderated emission growth by reducing supply and, to a lesser extent, as we show, by spurring adoption of low-carbon technology. The retrofitting of winglets is the main adoption practice identified here as being of any great magnitude, especially after 2015, that is, after carbon emissions started being priced in the sector. The bottom line remains, as economic theory is quick to reminds us, that carbon pricing tends to work only by ‘picking low hanging fruit’, in short, it promotes only those technology changes whose implicit abatement costs are below the effective carbon price. Our findings respond to this same logic. The question that remains to be asked, therefore, is whether, given the sector characteristics and pending climate targets, these ‘low hanging fruit’ are enough to fully decarbonize aviation.

We show that higher carbon prices may well trigger higher levels of low-carbon technology adoption. Here, the marked rise in the fitting of winglets coinciding with the approval of the MSR (and an increase in carbon prices) is consistent with this belief. However, this does not contradict the continuing need to complement carbon pricing with the regulation of technology standards which should further boost the diffusion of technology: while carbon pricing can continue to provide a *continuous* incentive for low-carbon investment, technology standards can guarantee the diffusion of a more readily operative technology, especially when carbon prices are not high enough. This, of course, would not yield cost-effective reductions but it would at least provide dependable reductions, which are just as important today, without major equity concerns insofar as air travel is highly correlated with income (Cass & Lucas, 2022; Gössling & Humpe, 2020; O’Garra & Fouquet, 2022).

Finally, a valid discussion of the matter at hand needs also to consider the difference between low-carbon and zero-carbon technologies. Only the latter are definitive and free of rebound effects, and capable of leading the sector in the direction of full decarbonization, in line, that is, with the Paris-Glasgow agreements. Low-carbon technologies, in contrast, reduce emissions but do not eliminate them, and this is of particular relevance in a context of predicted air traffic growth in which the technology to offset the consequent growth in emissions is unavailable. Here is where high carbon prices can provide the right incentive to develop zero-carbon technologies. However, in the meantime, well informed technology standards could set a technology floor to be made operative over the next decade, at least if climate commitments are to be met.

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