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Pricing carbon in the aviation sector: Evidence from the European emissions trading system

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ABSTRACT

A policy change in the European Union's Emissions Trading Scheme (EU ETS) provides us with a unique opportunity to measure the impact of carbon pricing on aviation, the most climate-intensive mode of transport. We implement a difference-in-differences strategy on a sample based on all flights within Europe from 2010 to 2016 to examine the causal impact of the EU ETS on emissions and supply. We find that the EU ETS reduced emissions by 4.7% in the regulated routes relative to the counterfactual. When we restrict the sample to short-haul flights, routes on which competition from other means of transport may exist (less than 1,000 km), the reduction in emissions is 10.7%. Finally, the reduction in emissions is also high for low-cost airlines (−11%) but it is not statistically significant for network airlines. In sum, the EU ETS has helped to mitigate emission growth by 3 Mt CO_2 per year during the period analyzed, but not to reduce absolute emissions in the sector, as needed.

1. Introduction

Despite the COVID-19 crisis, air traffic levels are expected to recover their 2019 levels by 2024 globally, and two years earlier for short haul traffic (IATA 2020). However, if the 2 °C target set by the Paris Agreement is to be met, international aviation CO_2 emissions will have to be some 41–96% lower than their 2005 levels by 2050 (Cames et al., 2015). Before the pandemic, total global emissions increased by 32% between 2013 and 2018 (Graver et al., 2019) and, although they accounted for about 2.1% of total carbon emissions (3% of EU's emissions),[1] the expected growth of the sector will bring with it a critical increase in the global share of aviation emissions. In absolute terms, projections place them between two to four times their 2015 values by 2050 (Transport and Environment, 2016; ICAO, 2019). Importantly, technological progress in both aircraft design and flight operations is significant and the average fuel consumption per passenger-km flown has fallen in Europe by 24% since 2005. However, this improvement has been cancelled out by the increase in the number of passengers carried, which rose by more than 60% over the same period in Europe (EASA, 2019), and by 114% if we consider the whole world (ICAO, 2019). Even in the most optimistic scenario, technological progress will not be able to offset the emissions from forecasted growth in the sector (EASA, 2019; Nava et al., 2018; Budd and Suau-Sanchez, 2016; Sims et al., 2014).

It was against this backdrop that, in 2012, the European Union acted and included aviation in its Emissions Trading Scheme (ETS),

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[1] However it should be noted that because of non-CO_2 emissions from planes at high altitudes, the actual impact of aviation related CO_2 on the climate should be multiplied by a factor of 1.3–2.9 to obtain the CO_2-equivalent emissions (Azar and Johansson, 2012; Lee et al., 2021). Non-CO_2 emissions are not accounted for in the EU ETS.

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the EU's carbon pricing strategy, thus making CO_2 emissions a new input cost for the aviation industry. However, as the industry's emissions have not stopped growing since that date, the effect of the EU ETS on aviation is considered to have been limited to the offsetting of its own growth in emissions via the purchase of allowances in other EU ETS sectors (electricity and energy intensive industry). Taken together, this would represent a non-significant in-sector effect of the scheme (Transport and Environment, 2016; EASA, 2019). Moreover, a large share of emission allowances is allocated for free based on the airlines' past emissions, making this in-sector effect less plausible. These two considerations, however, overlook the counterfactual reasoning: first, an increase in emissions does not imply that the carbon price had no in-sector effect and, second, despite the free allowance allocation, profit-maximizing firms factor opportunity costs – i.e., the market value of allowances – into their decisions, rather than just the observed costs – i.e., purchased allowances (Fabra and Reguant, 2014; Verde et al., 2019). As a result, therefore, airlines marginal costs will reflect the full market cost of each GHG ton emitted.

The goal of this paper is therefore to evaluate the impact of the EU carbon market on aviation emissions and supply. To achieve this, we draw on a data set of 58,239 airline-route pairs for 44 European countries, on a quarterly basis, from 2010 to 2016, totaling 558,694 observations and use quasi-experimental techniques to measure the causal effect of carbon pricing on CO_2 emissions and flight frequencies at the airline-route level. We also restrict our sample to routes where competition from trains is feasible and distinguish between routes operated by low-cost and network airlines.

Our econometric strategy involves the use of a difference-in-differences approach that exploits a policy change in the EU ETS regulation. Originally, all flights landing at or taking off from an airport in the European Economic Area (EEA) were to be regulated under the EU ETS, regardless of their origin, destination or the airline's nationality. This, however, proved highly controversial and, in the face of significant international pressure, the European Commission backed down and limited the scope of the scheme (the 'stop-the-clock' law) to include only flights within the EEA, regardless of the airline's nationality. In practical terms, this meant that some air-routes were regulated from 2013 onwards – that is, flights within the EEA – while others remain unregulated – that is, flights with at least one endpoint outside the EEA. These are our treated and control groups, respectively. Although the airlines affected are typically to be found in both groups and assignment to the treatment is unrelated to airline-route supply, other factors (such as those arising from route-specific heterogeneity) could potentially confound the EU ETS effect. We refine the comparability of treated and control groups by means of entropy balancing procedures (Hainmueller, 2012), based on a combination of key route characteristics at a flight's destination and origin.

We also augment the difference-in-differences model by interacting treated observations with each year of the period considered to test that the parallel trend assumption holds. In addition, we run regressions on a reduced sample that only considers as control routes those that link non-EEA airports to test the potential distortion that could arise from spillover effects and derived violation of the stable unit treatment value assumption (SUTVA). We also run additional robustness checks to our main results and examine whether the EU ETS has had an influence on airlines' decisions to stop operating routes.

Our main finding is that airlines reduced emissions by −4.7% on average relative to the counterfactual. This translates to 12 Mt CO_2 less than without the EU ETS (3 Mt CO_2 per year). We find this reduction in emissions comes with a similar reduction in the number of flights (−4.9%), indicating the main channel through which carbon pricing operates in the sector is via output reduction, as opposed to aircraft improved efficiency. When we restrict the sample to short-haul routes, where competition from trains is feasible, emissions on regulated routes are 10.7% lower and flights 8.9% less, relative to the counterfactual. This latter result has particularly relevant policy implications as trains are a cleaner transportation option than planes. The reduction in emissions is also high for low-cost airlines (−11%) but it is not statistically significant for network airlines. This difference in behavior across airline types might be explained by the distinct business models employed.[2] These results are robust to different specifications and to alternative control groups.

Earlier studies have identified causal impacts of carbon pricing at the firm level. These, however, have centered mainly on the manufacturing sector and, then, limited to a single country: In Germany, the ETS is reported as reducing manufacturing emissions by 25–28% (Petrick and Wagner, 2014), in France by 13–20% (Wagner et al., 2014), and in Norway by 33% (Klemetsen et al., 2016); while in Lithuania, no significant effect was detected during phase I (Jaraite and Di Maria, 2016).[3] In the US, a 20% reduction has been reported, although not for carbon emissions but for NOx emissions (Fowlie et al., 2012).

Our contribution in this regard is twofold: first, we analyze a sector whose business is not limited to just one country and whose individual firms compete only at the route level. This means, we measure the whole market's reaction to carbon pricing rather than that of individual firms. Moreover, because airlines are highly homogenous in their technologies and sectorial regulations – much more so than most manufacturing firms – causal inferences are more robust.

Second, because of the lack of physical output data or because of output heterogeneity across plants/industries, the effect of carbon pricing on output reduction has been largely underexplored. Nevertheless, reductions in emissions can be achieved both by reducing output and by reducing emissions per output (or both). The previous literature finds the effect of carbon pricing to be mainly driven by an improvement in carbon intensity,[4] as opposed to output reduction. However, these studies measure intensity by using turnover,

[2] Network airlines operate hub-and-spoke route structures and so concentrate traffic in a few hub airports. A high proportion of passengers on their short-haul flights (i.e.; European flights) are connecting passengers whose final destination is a long-haul (non-European) destination. Low-cost airlines, in contrast, operate point-to-point route structures and most (if not all) of the routes they operate are within Europe. In our sample, network airlines account for 46% of total supply, while the low-cost airlines account for 45% of total traffic.

[3] In fact, all these studies coincide in only identifying an abatement effect from phase II onwards (i.e. 2008–2013).

[4] Another branch of the literature has examined the impact on innovation and finds that the EU ETS induces low carbon innovation when measured in terms of patents (Calel, 2020; Calel and Dechezleprêtre, 2014).

number of employees or worked hours rather than quantity produced *per se* (Klemetsen et al., 2016). Given that we observe output and can estimate emissions from that output, our setting offers a unique opportunity to investigate the output channel of emission abatement – which is of particular relevance in key sectors, such as aviation – characterized by an overly steep marginal abatement cost curve.[5]

Our analysis provides the first empirical evidence on the causal impact of carbon pricing on the aviation sector.[6] Our estimates are likely to be relevant regarding the climate neutrality targets for the whole transportation sector—where aviation is expected to contribute—and the upcoming policy debates on the implementation of a global measure to address aviation emissions at international level. We show carbon markets are effective in reducing emissions, even when the prices are low and a significant part of the allowances are granted for free. However, this being the case, it has only achieved mitigating emissions growth in the sector, rather than actually reducing absolute emissions, as is needed.

The paper proceeds as follows. Section 2 provides relevant background on the inclusion of the aviation sector in the EU ETS. Section 3 describes the data used and our research design. Section 4 explains the main results of the empirical analysis. In Section 5, we examine the effects of the EU ETS on the extensive margin. Section 6 is devoted to concluding remarks.

2. The EU ETS and the aviation sector

2.1. The inclusion of aviation in the EU ETS

The EU ETS, launched in 2005, includes around 45% of the EU's GHG emissions and more than 11,000 energy intensive installations and airlines across the EU. The scheme sets a cap on the level of total emissions, which is reduced over time, and determines the number of emission allowances that regulated companies can trade between them as and when required. The tradability of emission allowances is devised as a means of reducing emissions at minimum cost (cost-effectiveness), while the resulting carbon price provides continuous dynamic incentives for the adoption of lower-emitting technologies (Jaffe and Stavins, 1995).

In 2008, the EU decided to include aviation in the EU ETS,[7] meaning that all airlines operating in Europe, that is, landing at or taking off from any EEA airport, would be required to monitor, report and verify their emissions, and to surrender allowances against those emissions from January 1, 2012. The decision, however, generated considerable resistance from international carriers, who considered the EU regulation to be illegal and breach non-EU countries' sovereignty. And while in a case brought by US airlines, the Court of Justice of the EU ruled the EU ETS to be fully consistent with international law, some countries prohibited their carriers from complying with the scheme.[8] As a result, in November 2012, the European Commission issued a proposal to *stop the clock* on the aviation ETS and to reduce, retrospectively to January 2012, the scope of the directive to include only intra-EEA flights. The decision[9] was formally agreed to in April 2013, just before the airlines were required to surrender their allowances for 2012; the first year in which the scheme had been applied to aviation. The decision was justified on the grounds of discussions with the Assembly of the International Civil Aviation Organization (ICAO) and its intention to develop a global market-based mechanism to deal with aviation emissions at international level.[10]

Thus, formally, it was only from 2013 onwards that just flights within the EEA were affected by the EU ETS. Although all air routes from/to EEA airports were first included in the EU ETS in 2012, it is only from 2013, once all legislative uncertainties had dissipated, that the regulatory status of routes under the EU ETS was clarified. These uncertainties, however, may blur our identification strategy. Indeed, since there is no clear control group in 2012, we need to take this into account in our empirical strategy and when interpreting our results. In this regard, we run regressions excluding 2012 to check whether the regulatory uncertainty in 2012 could affect our results. While short-term investments to anticipate the regulation (i.e., renewal of the aircraft fleet) are to be limited given their high costs, these additional regressions will allow us to examine whether those potential investments could be playing any relevant role in our main results.

2.2. Allowance allocation

The number of allowances allocated to the sector is based on historical emissions, corresponding to 95% of average total emissions in the years 2004–2006. This means a yearly constant number of allowances for the years 2013–2020 (phase III); up to 82% of these allowances are granted for free, while the remaining 15% and 3% are auctioned and given to fast-growing airlines and new entrants, respectively. Specifically, each airline's free allowance allocation is based on the ratio obtained by dividing the total number of free

[5] The early retirement of an aircraft costs €1666/tCO_2 (Faber and Brinke, 2011). The cost of biofuels ranges from \$46 to \$652/tCO2 (Winchester et al., 2015), while the carbon price registered in the EU ETS between 2012 and 2018 was always below 10€/tCO_2.

[6] Oesingman and Schneider (2021) analyze the impact of the EU ETS on passenger numbers using a different approach. They use country-pair data for a long-time period but the sample is based exclusively on flights within the EEA.

[7] Directive 2008/101/EC of the European Parliament and of the Council of 19 November 2008 amending Directive 2003/87/EC.

[8] See Transport and Environment (2016) for a more detailed description of this.

[9] Decision 377/2013.

[10] The ICAO proposal CORSIA, that is, Carbon Offsetting and Reduction Scheme for International Aviation, is a new global market-based mechanism offsetting aircraft emissions elsewhere. Some authors consider CORSIA to be less stringent than the EU ETS (Larsson et al., 2019; Scheelhaase et al., 2018).

allowances by the total verified ton-kilometers flown during the benchmark year (established in 2010).[11] Because of the growth in the sector, airlines need to purchase allowances from the other EU ETS sectors, making the aviation sector a net purchaser of allowances in the system.

On balance, because of sectoral growth, free allowances only covered 60% of 2013 emissions and just 51% in 2016 (see Fig. A1 in the appendix).[12] Over the whole period, the aviation sector purchased allowances for up to 98 million tons of CO_2 eq., 74 from other EU ETS sectors and 24 from auctioning within the cap on aviation. This meant a total cost of circa €650 million. However, what is relevant for the aviation supply and derived emissions is how these costs, together with the market value of the allowances allocated for free (i.e., the opportunity cost), shift the airline-route marginal costs.

Importantly, whether allowances are in fact being purchased or freely allocated is irrelevant in terms of their impact on marginal costs, as the opportunity cost remains the same. At the margin, free allowances have an opportunity cost equal to the revenue that would be earned if sold on the market (and the corresponding emissions abated). Emitting an extra ton of CO_2 means the airlines has either to buy an allowance or to forego the possibility of selling a freely allocated allowance. Profit-maximizing firms will therefore factor these costs into their output and price decisions, as occurs in other EU ETS sectors, especially when a loss of competitiveness in favor of non-regulated firms, as is the case for aviation, is not an issue (Fabra and Reguant, 2014; Hintermann, 2016; Verde et al., 2019).

Therefore, airlines under the EU ETS will need to bear additional operating costs per flight, which eventually will affect their output decisions. Fig. 1 shows how carbon allowances—at the period average price of €7.55—factor into airlines marginal cost as a function of the aircraft type and distance flown. This represents a 4% increase over fuel costs (see Fig. A2). Costs are higher for short-haul routes. Besides differences in aircrafts' seat capacity, shorter routes are less carbon efficient and hence relatively more costly than longer routes in terms of allowances.

Notes: This graph shows the average cost per km by main aircraft families (in parenthesis, the % of flights in intra-European routes in 2016). Solid lines plot mainline jets, with capacities between 150 and 180, and dashed lines plot regional jets, with smaller capacities and used mainly on shorter distances and connecting flights. Notice that 77% of flights are operated with the Airbus 320 family (this includes A318, A319, A320 and A321) and Boeing 737 Next Generation family (B737-600/700/800/900).

2.3. The mechanism

Because of the steep marginal abatement cost curve of the aviation sector, with limited new technologies available (EASA, 2019), the expected impact of the EU ETS on emissions is directly related to its effects on supply. A reduction in supply will inevitably lead to fewer CO_2 emissions. Indeed, a carbon price leads to an increase in costs for regulated companies, which, in conditions of imperfect competition, will react by reducing supply and increasing prices so as to maximize profits (André and de Castro, 2017; Brander and Zhang, 1990). Combined with price-demand elasticities, this results in a new market equilibrium that will have fewer emissions relative to the counterfactual, where the EU ETS is not implemented.[13]

A number of previous studies have made ex-ante calculations of the impact of the EU ETS scheme on the aviation market (see Anger and Kohler, 2010, for a review). A common expected result is a fare increase, given that airlines will pass - at least to some extent - the increased costs (including opportunity costs) on to consumers. The cost pass-through rate is uncertain but this rate will essentially determine the distributional effects of the EU ETS scheme between airlines and passengers. Regardless of the extent of the pass-through rate, the expected reaction of airlines is to reduce supply and hence emissions.

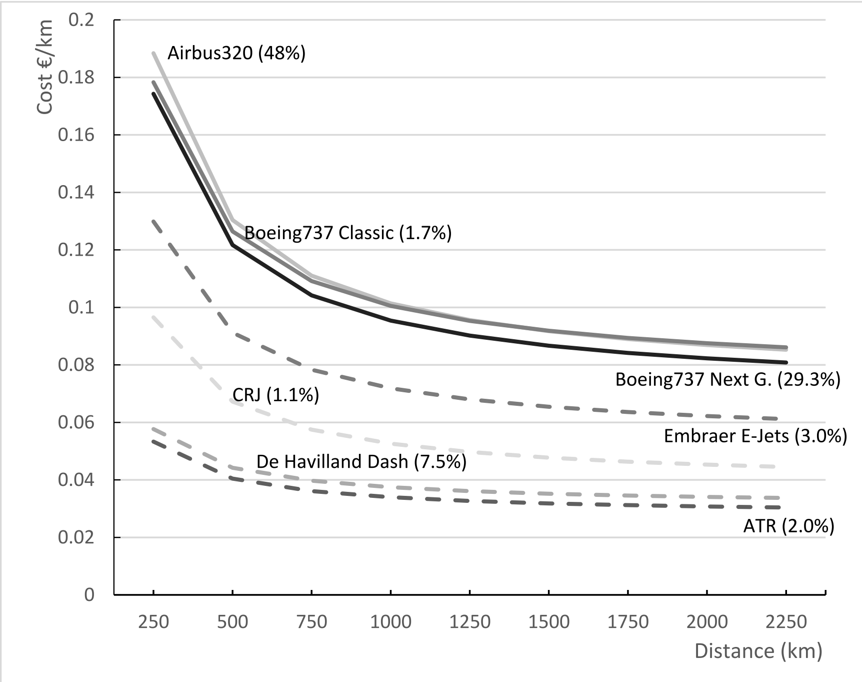
Brueckner and Zhang (2010) add the load factor of the plane as another variable that needs to be taken into account in the supply impacts of the EU ETS. They develop a theoretical framework in which they model the ETS as an increase in fuel costs. This cost rise encourages airlines to reduce flight frequency, keep the size of the aircraft constant and increase the load factor of each flight. Fig. A3 in the appendix shows the evolution of both jet fuel and carbon prices for the period analyzed. Interestingly, the inclusion of aviation into the EU ETS coincides with a reduction in the price of jet fuel.

Finally, differences in the business model of network and low-cost airlines could lead to a different response to the EU ETS. First, they have a different configuration of routes (Berry et al., 1996). Network airlines operate hub-and-spoke networks and most of their passengers are connecting passengers. In contrast, low-cost airlines operate point-to-point routes and most of their passengers are

[11] This resulted in allocating 0.6422 allowances per 1000 ton-kilometers flown in 2010. Hence, each airline receives the number of free allowances corresponding to their ton-kms flown in 2010 multiplied by this benchmark, kept constant during each year of phase III.

[12] The European Commission issued in July 2021 (EC, 2021) a proposal to revise the current legislation regarding the EU ETS aviation scheme. The proposal main amendments include measures to reduce annually the total number of aviation allowances under the ETS linear reduction factor and to accelerate in the reduction of free allowances to reach full auctioning in 2027. In addition, it is set the need to continue intra-European application of the EU ETS while ensuring the implementation of the CORSIA scheme as appropriate to extra-European flights (see https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021PC0552). The objective of these additional measures is to contribute to the European Green Deal objective of reducing transport emissions by 90% by 2050, compared to 1990 levels.

[13] Airlines typically schedule flights for 6-month periods although they can adjust their scheduling decisions by reducing operating routes and frequencies. The only (non-monetary) cost is that they are subject to "the use it or lose it" rule in airports with capacity restrictions. If they do not use 80% of the allocated slots (airport usage rights), they may lose those slots.



Notes: This graph shows the average cost per km by main aircraft families (in parenthesis, the % of flights in intra-European routes in 2016). Solid lines plot mainline jets, with capacities between 150-180, and dashed lines plot regional jets, with smaller capacities and used mainly on shorter distances and connecting flights. Notice that 77% of flights are operated with the Airbus 320 family (this includes A318, A319, A320 and A321) and Boeing 737 Next Generation family (B737-600/700/800/900).

Fig. 1. Carbon costs per km at average carbon price (2013–2016) by aircraft family.

non-stop travelers.[14] Some theoretical works show that the configuration type of routes has relevant effects on the supply choices of airlines (Brueckner, 2004; Flores-Fillol, 2009; Fageda and Flores-Fillol, 2012a). In this regard, empirical studies on the European aviation market find that low-cost airlines tend to operate on thinner routes than network airlines, and that attributes like route distance, competition, population and income of a route's endpoint have a varying influence on their decisions about which routes to operate on and with what capacity (Fageda and Flores-Fillol, 2012b; Calzada and Fageda, 2019). Furthermore, we can expect the price-demand elasticity to be higher for travelers using low-cost than for those using network airline services because the proportion of leisure passengers is generally higher on low-cost airline flights (see Brons et al., 2012 for a meta-analysis of price-demand elasticities in aviation).

3. Research design

3.1. Data

We exploit quarterly data for 2010–2016 on all flights within Europe at the airline-route level. Treated routes (routes within-EEA) are short-haul or medium-haul routes. To have comparable treated and control routes in terms of stage length, we restrict the main dataset to European locations (including all routes from/to Russia and Turkey). Long-haul routes use bigger aircrafts and (with very few exceptions) are operated with many less flights than short-haul and medium-haul routes. Note also that the restriction of the sample to European locations allows us to build a feasible dataset and reduce heterogeneities across airlines, routes and countries. In this regard, although the comparison between the domestic market of United States (US) and the EEA market might be of interest, it would add different sources of heterogeneities to the analysis. Regional services for business passengers are much more prevalent in US than in Europe, whereas services from low-cost airlines in tourist destinations are much more prevalent in Europe (Fageda and Flores-Fillol, 2012b). US airlines are subject to different legislation (i.e., bankruptcy laws-chapter 11) and to different intensity in the competition from rails. In addition, the consolidation process has been much more intense in US in the period considered (i.e., the

[14] Low-cost airlines have been able to reduce the costs of operating short-haul routes by implementing a business model based on the intensive use of aircraft and crews, lower labor costs and a simpler management model, which involves using only one type of plane and a single fare class (Graham, 2009).

merger between American Airlines and US Airways in 2013).

The primary sample includes 558,694 observations. However, to minimize distortions of flights that are not offered in most of the year-quarters of the period considered, we restrict our sample to airline-route pairs with at least one flight per week.[15] Hence, the sample used in the regressions includes 402,589 observations in an unbalanced panel dataset, since some pairs of airline–routes do not have a flight or have less than one flight per week in a particular year-quarter.

We observe, at the airline-route level, the total number of seats, frequencies, aircraft size, distance flown, the operating airline and the aircraft type.[16] Data have been obtained from RDC aviation (capstats statistics). Treated observations are intra-EEA routes; routes where both endpoints are in countries in the EEA. Intra-EEA routes have been affected by the EU ETS since 2013.[17] Control observations are routes where the origin and/or destination is a non-EEA country (see Fig. 2).[18] We then follow the logic of the difference-in-differences estimator.

Notes: This map shows countries in the European Economic Area-EEA (in blue) and other countries sampled (in yellow). Treated routes are those flying *within* the EEA countries.

To estimate emissions at the airline-route level we make use of the 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 flights operations and provides accurate estimates of emissions for any given distance and aircraft type. With the aircraft type, the route distance and the number of flights, we can estimate emissions at the airline-route level per quarter.

Given that emissions are mainly determined by airline's supply decisions, our estimates are based on a supply equation. In aviation studies, it is commonly assumed that airlines first make supply decisions and then they adjust fares according to the evolution of demand. Hence, fares are not considered to be an explanatory variable in supply equations. Given the strong correlation between demand and supply, demand shifters (population, income) are usually included as controls. Distance (which in our setting is captured by route-airline fixed effects) and the intensity of competition are also typically considered major drivers of supply airline choices. Examples of studies that estimate supply equations for air routes include Schipper et al. (2002), Richard (2003), Fageda and Flores-Fillol (2012b) and Brueckner and Luo (2014). Given that in the short-term airlines cannot easily adjust their fleet of aircrafts, supply changes are mainly driven by flight frequency changes.

Thus, we consider the population of the urban areas at the points of origin and destination of the routes. For urban areas with over 300,000 inhabitants, data have been obtained from the UN's World Urbanization Prospects database. For urban areas with less than 300,000 inhabitants in the EEA, Switzerland and Turkey, we have collected data from Eurostat (NUTS 3). For urban areas in the remaining countries with less than 300,000 inhabitants, we have collected data from 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 construct a dummy variable that takes a value of one for monopoly routes. We consider monopoly routes to be those routes on which one single airline controls at least 99% of the total number of seats offered on that route.

To test for a possible different response to the EU ETS, we run separate regressions for routes operated by network and low-cost airlines. Table A1 in the appendix provides the list of network and low-cost airlines considered in our analysis. Network airlines are airlines integrated in one of the three global airline alliances (oneworld, Star Alliance, SkyTeam). 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.

Note that a few routes in our sample may be affected by the overlapping of services of airlines that are within the same group. However, there are no significant changes in the period considered in terms of mergers and cross-investments between airlines. Given that our regressions always include route-airline fixed effects, such relationships between airlines are captured by those route-airline fixed effects.

3.2. Empirical model

To assess the effect of the EU ETS on aviation emissions, we estimate a difference-in-differences model, a common methodology adopted within the treatment evaluation framework (Angrist and Picke, 2009; Gertler et al., 2016). We estimate the following equation (1) for the route-airline pair *i* in quarter *q* and year *t*:

$$\log(emissions)_{iqt} = \alpha + \beta ETS_{it} + \lambda X_{it} + \gamma_i + \eta_t + v_q + \varepsilon_{iqt} \tag{1}$$

where the main dependent variable is the total number of CO_2 emissions, given that the ultimate goal of the EU ETS is to reduce them. We also run regressions using the total number of flights as a dependent variable. To this point, we can directly observe flights while emissions are estimates based on the combination of aircraft type, number of flights and distance. Furthermore, the use of both

[15] We exclude air services with very low frequencies because they usually refer to flights that are offered on an occasional basis.

[16] Unfortunately, data for cargo flights are not available. However, note that a significant amount of cargo is handled on passenger flights.

[17] Croatia was included in the EU ETS one year later, in 2014.

[18] The EEA countries include 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.

Notes: This map shows countries in the European Economic Area-EEA (in blue) and other countries sampled (in yellow). Treated routes are those flying *within* the EEA countries.

Fig. 2. Map with EEA countries and control countries.

dependent variables in complementary regressions allows us to examine where reductions in emissions are mainly achieved by reducing output.

The main explanatory variable is ETS, which is a dummy variable that indicates whether the route-airline pair is affected by the EU ETS at time *t*. X_{it} denotes the set of control variables: income (in a yearly basis), population (in a yearly basis) and a dummy variable for monopoly routes (derived from the Hirshman-Herfindhal concentration index in a quarterly basis). All continuous variables are transformed using logarithms, so that the influence of outliers is reduced and parameter estimates can be interpreted as elasticities.

The data used present a panel structure and so we employ the techniques typically applied within the framework of panel data models. Hence, the specification includes route-airline fixed effects, as well as year and quarter fixed effects. A clear advantage of the route-airline fixed effects model is that it allows us to control for omitted variables that are correlated with the variables of interest and which do not change over time (Verbeek, 2000). The route-airline fixed effects model focuses on the within variation in the data so that it controls for the effect of time-invariant variables, such as, the distance covered, historical links between countries and constant airline heterogeneity. Furthermore, we add year dummies to control for yearly effects that are common to all city-pairs and quarter dummies to control for seasonal effects. Standard errors are robust to heteroscedasticity and clustered at the route level.

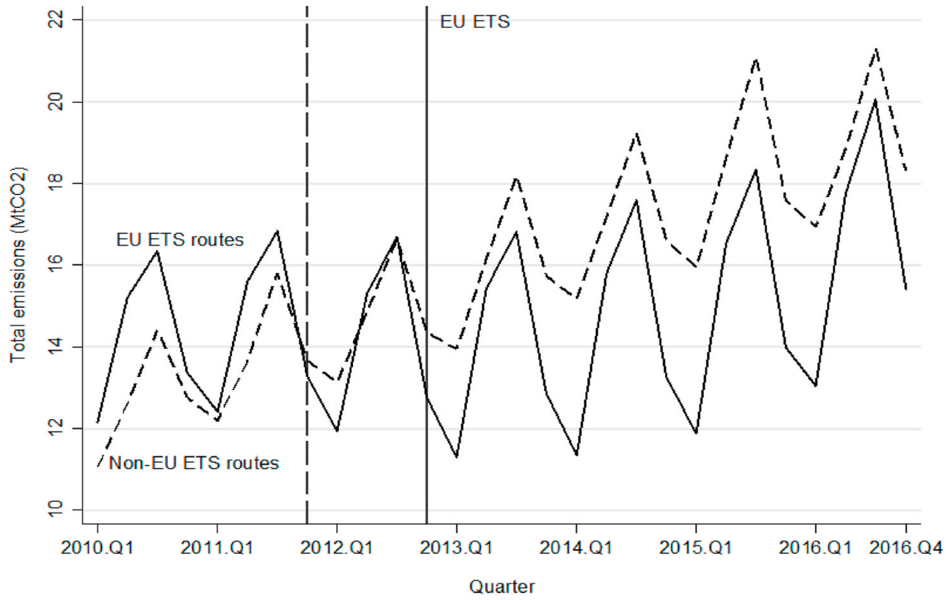
3.3. Entropy balance

Fig. 3 shows the evolution of emissions in treated and control routes in the period analyzed. Before EU ETS implementation, emissions from EU ETS routes were slightly higher than emissions from untreated routes. After 2013, however, the level of emissions on treated routes is clearly lower after what seem a byproduct of slower growth rate of emissions of the EU ETS group as compared to the emissions from untreated routes. Total emissions from treated routes were 241 Mt CO_2 from 2013 to 2016 compared to 172 Mt CO_2 in the three preceding years; this is an increase of 40%. Untreated routes increased from 165 to 281 Mt CO_2; a 70% increase. Assuming this whole difference is driven by the EU ETS, then the carbon market saved around 51.4 Mt CO_2 (241–172 $\times$ 1.7), which is almost the same amount emitted in 2013 by EU ETS regulated aviation (verified emissions in 2013 were 53.4 Mt CO_2). This estimate assumes that untreated routes are an accurate estimate of what would have happened to treated routes without the EU ETS. However, this naïve estimate does not consider control covariates described previously: changes in income, population or monopoly power could also change air traffic and subsequently its emissions. Routes in the untreated groups may not be entirely comparable to treated routes.[19]

Therefore, to identify the causal effect of treatment status on outcomes, we need to compare comparable route-airline pairs. Ideally, our treated and control groups should be defined randomly so that route-airline pairs would appear to be similar *ex ante*. However, route-airline pairs from/to the EEA to/from the rest of Europe or route-airline pairs within Non-EEA countries (control observations) and route-airline pairs within-the EEA (treated observations) may differ in several attributes that can potentially confound the effect of the policy. To ensure comparability, we therefore use entropy balancing (Hainmueller, 2012), a non-parametric matching technique that consists in a reweighting scheme on the sample units so that the covariate distributions of the control group match exactly with those observed on the treated group.

In particular, the control group is reweighted so that its first and second moments of a set of covariates considered relevant match

[19] Because of potential confoundedness, flights from/to and within neighboring countries are not included in the analysis despite these being available in the data source (RDC aviation). North Africa and Middle East countries are not included because of the Arab spring (2010–2012), while Israel is not included because of the open-skies agreement signed with the EU in 2013. Even so, estimates are virtually identical when these flights are added to the sample.



Note: This figure shows total emissions per year-quarter while the main text provides the numbers in annual terms to ease its interpretation

Fig. 3. CO_2 emissions of EU ETS and non-EU ETS air routes from 2010 to 2016. Note: This figure shows total emissions per year-quarter while the main text provides the numbers in annual terms to ease its interpretation.

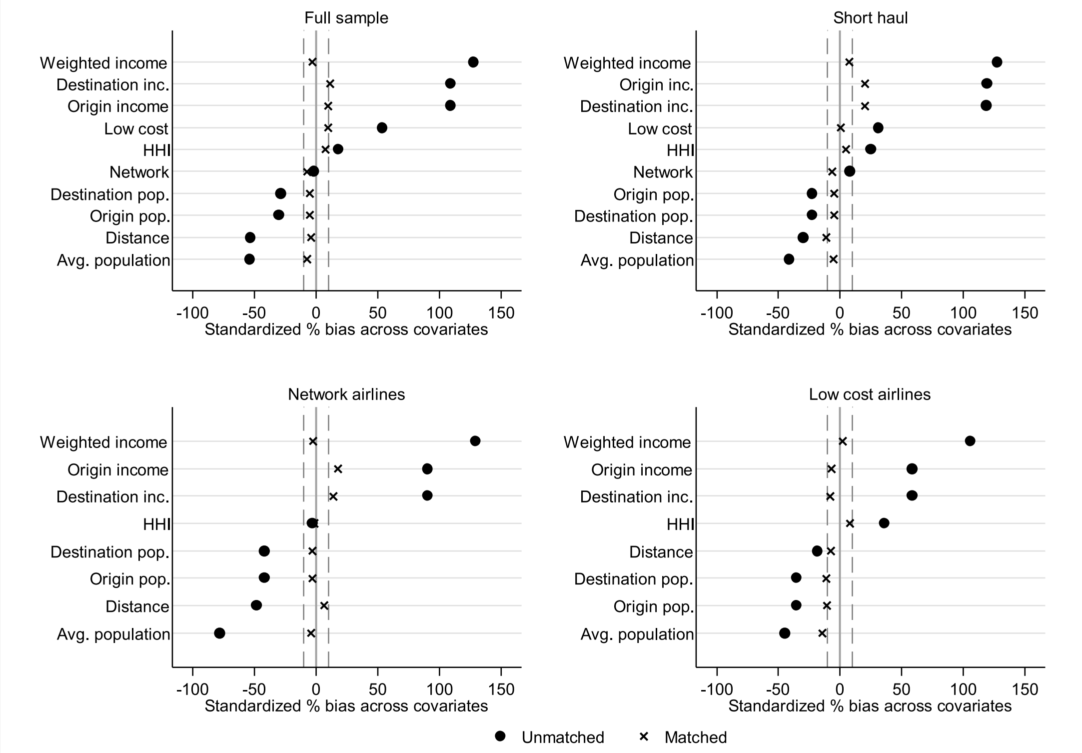
exactly with those observed in the treated group. Moreover, to enhance comparability we apply the procedure separately to each subsample analyzed, all with the following covariates: distance, the weighted mean income between origin and destination (where weights are based on population), the population of origin and destination, the Hirshman-Herfindhal concentration index per route, the average CO_2 emissions, and finally the share of low-cost and network airlines; all these prior to the EU ETS implementation in 2013. This enables us to rule out any potential confounders arising from route-airline specific heterogeneity while reducing model dependence in the subsequent estimation of treatment effects (Abadie, 2005; Hainmueller, 2012; Ho et al., 2007).

Fig. 4 shows the covariate balance obtained by each sample analyzed as measured by the standardized difference in means between the treated and the control group (Rosenbaum and Rubin, 1985; Austin, 2009). All standardized differences are reduced considerably after the entropy balancing procedures, with most being well below 10%.

Notes: This graph plots the standardized differences in % between treated and control routes before 2013. Dots report balance with maximum-entropy reweighting of the control group (Hainmueller 2012) and x without balancing. The grey dashed vertical lines mark the 10% difference, below which differences in means are considered negligible.

Table 1 shows the mean and standard deviation values for the air routes in terms of the most relevant covariates before 2013 across the treated routes (i.e., under the EU ETS) and control groups (European and Russian routes not regulated by the EU ETS), with and without entropy weighting.

Although 2013 is the official year in which aviation was included in the EU ETS, lobbying pressure from many countries throughout 2012 caused a high level of regulatory uncertainty. Given that this might cast some doubt on the strict exogeneity of the treatment variable, for the sake of robustness, we further restrict the matched sample by removing the 2012 observations in some specifications. Moreover, for additional robustness, the difference-in-differences model is then augmented by interacting treated observations (route-airline pairs within EEA) with each year of the period considered. This allows us to verify further that the parallel trend assumption holds. Finally, we also contemplate alternative control groups to rule out potential spillover effects from the EU ETS on control routes (violations of SUTVA). All these complementary specifications reinforce the causal inference.



Notes: This graph plots the standardized differences in % between treated and control routes before 2013. Dots report balance with maximum-entropy reweighting of the control group (Hainmueller 2012) and x without balancing. The grey dashed vertical lines mark the 10% difference, below which differences in means are considered negligible.

Fig. 4. Standardized mean difference for covariates in treated and control routes before and after entropy balance.

Table 1
Means of air-routes by treatment status before 2013.

	Treated		Weighted Control		Unweighted Control	
	mean	sd	mean	sd	mean	Sd
Avg. Population	14.29	1.02	14.32	1.05	14.83	1.16
Origin pop.	13.77	1.18	13.80	1.22	14.12	1.36
Destination pop.	13.77	1.18	13.80	1.22	14.12	1.36
Weighted Income	10.56	0.30	10.57	0.31	9.73	0.68
Origin inc.	10.50	0.45	10.42	0.93	9.67	0.89
Destination inc.	10.50	0.45	10.41	0.95	9.67	0.89
Monopoly	0.53	0.50	0.53	0.50	0.48	0.50
HHI	0.77	0.27	0.77	0.26	0.75	0.26

Notes: This table reports descriptive statistics for both treated and control routes prior to 2013. Control routes are shown as weighted by the entropy balance procedure and as observed.

Table 2
Effect of EU ETS on emissions and supply. Difference-in-Difference estimates.

VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)
	Full sample	Full sample	Full sample	Short haul	Short haul	Short haul
PANEL A: ln(Emissions)						
EU ETS	−0.092***	−0.047***	−0.045**	−0.142***	−0.107**	−0.097*
	(0.007)	(0.018)	(0.019)	(0.013)	(0.050)	(0.051)
Observations	401,147	277,385	233,516	147,896	104,354	87,271
R^2	0.909	0.905	0.905	0.931	0.916	0.914
R^2 adj.	0.899	0.900	0.899	0.925	0.911	0.909
PANEL B: ln(Flights)						
EU ETS	−0.079***	−0.049***	−0.051***	−0.124***	−0.089***	−0.099***
	(0.006)	(0.018)	(0.018)	(0.011)	(0.033)	(0.038)
Observations	402,589	277,385	233,516	148,998	104,354	87,271
R^2	0.905	0.910	0.911	0.909	0.912	0.910
R^2 adj.	0.894	0.904	0.905	0.900	0.907	0.904
Entropy balance	NO	YES	YES	NO	YES	YES
2012 included	YES	YES	NO	YES	YES	NO
Control vars.	YES	YES	YES	YES	YES	YES
Route-airlin. FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
Quarter FE	YES	YES	YES	YES	YES	YES

Notes: This table reports the regression of emissions (panel A) and flights (panel B) on the EU ETS indicator, our difference-in-differences estimator. Columns 1 to 3 estimate the effect of the EU ETS for the full sample: column 1 estimates the difference-in-difference model without any sort of weighting balance, column 2 replicates the latter applying entropy balance to the control group; column 3 replicates the latter but removing 2012 observations, since this year has no neat treatment status. Columns 4 to 6 estimate the same models for a subsample of routes where other means of transportation may be competitive: short-haul routes (with less than 1000 kms) without islands in any endpoint or with a high-speed rail connection. Entropy balance is applied to each specific subsample. Robust standard errors (in parentheses) are clustered at the route level.
***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

4. Results

4.1. Main estimates

Table 2 shows the main results from the difference–in-differences estimator. The effect of our treatment variable can be read as the percentage change in emissions (panel A) or flights (panel B) due to the EU ETS. All regressions include route-airline fixed effects, year and quarter fixed effects. Standard errors are clustered at the route-level.[20]

Focusing on emissions (panel A), column 1 shows that the EU ETS reduced airline emissions by −9.2% compared to the counterfactual. Using the reweighted sample – and, in doing so, controlling for heterogeneity between the treated and control routes— this effect is reduced to −4.7% in column 2. Finally, since the effect for 2012 is not clean-cut in terms of most control and treated groups, the EU ETS effect could be underestimated if some airlines anticipated the outcome of the stop-the-clock law by reducing (or not reducing) the supply of the treated (or control) routes. Column 3 shows the results when excluding observations for 2012 and we find a similar result to the previous one with an average effect of a −4.5% reduction in emissions. All in all, this corresponds to 12 Mt CO_2 saved during the period of analysis; an average of 3 Mt CO_2 per year.

Of particular interest is the effect that the scheme might have had on short-haul routes where competition from trains may be an option (columns 4 and 5). Specifically, the emissions of rail services are much lower than those of aircraft, but their competitiveness will depend on the distance of the trip. High speed rail proves to be highly competitive in terms of time, service attributes and price on routes shorter than 1000 km (see Givoni and Dobruszkes, 2013, and Zhang et al., 2019, for a detailed literature review). Note also that the fuel efficiency of planes increases with distance (Brueckner and Abreu, 2017) so that short-haul flights may be especially detrimental in terms of emissions. Thus, the environmental benefits of not burning jet fuel means short-haul routes are a case of particular relevance to our study of the effects of EU ETS. Columns 4 and 5 show the effect of the EU ETS on short-haul flights that do not have an island as an endpoint or that have a high-speed rail connection.[21] The effect on these routes is twice the effect found for the full sample:

[20] Since the treatment is assigned at the route-level, we cluster errors accordingly. However, results are virtually identical when clustered at the route-airline level. Furthermore, we opted for separate year and quarter fixed effects to have a more parsimonious model: results with quarter-year fixed effects are virtually identical.

[21] We exclude routes with an island as origin and/or destination because surface transportation (roads and trains) is usually more competitive than maritime transportation. Given that our interest here is on routes where surface transportation is feasible, we do not consider as islands those locations where significant infrastructures have made transportation by roads and/or trains viable.

emissions are 10.7% lower than in the counterfactual or 9.7% lower if 2012 is omitted. Panel B reports the same models but considering the number of flights instead of emissions as dependent variable, showing that the bulk of the induced emission reduction is driven by supply adjustment.

Table 3 reports the effect of the EU ETS when looking at routes operated by network and low-cost airlines separately.[22] Taking into account the high heterogeneity of the group of airlines that cannot be considered either network or low-cost airlines, these regressions aim to examine a possible different response from the two dominant business models. In this regard, we apply specific weights to each sample. In addition, as we mention above, previous empirical studies on the European aviation market show that low-cost airlines tend to operate in thinner routes than network airlines and that attributes like route distance, competition, population and income from a route's endpoints have a different influence on their decisions about which routes to operate on and with what capacity. To this point, note that we could also examine the different response to the policy by network and low-cost airlines through a regression with the entire sample adding interaction terms for airline types. However, a single interacted model would not allow to properly apply the entropy balance.

As in the previous table, we show three different specifications for each airline type: one without entropy balancing, another with entropy balancing and the last one with entropy balancing and without 2012 observations. For network airlines, we find that the estimated effect of the EU ETS disappears when we use the balanced sample (column 2) or when we omit 2012 (column 3). In contrast, low-cost airline estimates remain significant with similar size effect when using the balanced sample. The estimate in columns 2 and 3 show a significant 11% reduction in emissions that comes with a similar reduction of supply compared to the counterfactual.

Overall, we find that, despite the sectoral growth observed, the EU ETS has had a relevant impact in terms of restraining the growth of air services and derived emissions within the EEA, even though the measures applied to airlines are relatively soft. Further, while the overall effect of the policy might be modest, it has had a much more marked impact on routes where other means of transport are a competitive option; short-haul routes with no islands as endpoints or with a high-speed rail connection available. Finally, it is apparent that the estimated effect of the EU ETS on emissions has been mainly driven by low-cost airlines.

4.2. Parallel trend assumption

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:

$$\log(emissions)_{iqt} = \alpha + \beta_k(D_{it} \times t) + \lambda X_{it} + \gamma_i + \eta_t + v_q + \varepsilon_{iqt} \tag{2}$$

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. Fig. 5 plots these coefficients for the same samples used in the previous section and shows these coefficients are non-significant before treatment implementation in 2013. This is consistent even when looking at the interactions with quarters (see Fig. A4 in the appendix).[23]

Fig. 5 shows the evolution of emissions in treated routes relative to control routes according to the different samplings. Using the weighted sample with entropy balance procedures at all times, the top-left panel plots equation (2) coefficients β for the full sample and top-right for the sample restricted to short-haul routes; with both confirming our earlier results. Compared to 2010 (the baseline year), differences between treated and control routes remain non-significantly different before treatment, while from 2014 onwards, a year after the policy was introduced, the coefficient becomes significant, at the 90% confidence interval in 2014, and increases in size and significance in the following years. When focusing on short-haul routes, differences between treated and control routes largely and abruptly increase after the EU ETS implementation. The size effect of the EU ETS on these routes (almost double) is especially relevant, given that these flights account for a third of overall emissions and their carbon intensity is about 35% higher than that on medium-haul routes (Graver et al., 2019).

The bottom panels in Fig. 5 focus on network (bottom-left) and low-cost airlines (bottom-right) and here again, the common trend assumption is plausible. It also confirms how the induced emission reduction is mainly driven by low-cost airlines, given that significant changes after the EU ETS implementation are not found for network airlines. In contrast, treated routes operated by low-cost airlines reduced their emissions around 19% (point estimate 2016).

[22] Notice that 28% of our sample are routes whose operating airlines are neither low-cost nor network airlines. Airlines that cannot be considered as either network or low-cost airlines include charter airlines offering scheduled flights, regional carriers operating totally independently of network airlines or airlines with a mixed business model.

[23] To ease graph interpretation, we use 2010 as the baseline year as opposed to the year before policy implementation, as it is more common: 2010 is the first year of the period sample and, in a context of growing emissions, 2010 is the lower emissions year. Furthermore, 2010 was used as the benchmark year to allocate allowances as relative to ton-km flown in 2010. Finally, intra-EEA routes are effectively treated in comparison to non-intra EEA flights in 2013 but, due to the regulatory uncertainty in 2012, it is not entirely clear if the year before the policy was 2011 or 2012.

Table 3
Effect of EU ETS on emissions and aviation supply by airline type. Difference-in-differences estimates.

VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)
	Network	Network	Network	Low cost	Low cost	Low cost
PANEL A: ln(Emissions)						
EU ETS	−0.127***	−0.020	−0.020	−0.106***	−0.110***	−0.110***
	(0.011)	(0.020)	(0.018)	(0.010)	(0.022)	(0.025)
Observations	126,875	103,245	87,288	168,357	107,847	91,155
R^2	0.918	0.930	0.931	0.841	0.861	0.859
R^2 adj.	0.912	0.927	0.927	0.825	0.853	0.850
PANEL B: ln(Flights)						
EU ETS	−0.124***	−0.033	−0.038*	−0.105***	−0.101***	−0.099***
	(0.010)	(0.023)	(0.023)	(0.010)	(0.022)	(0.026)
Observations	126,895	103,245	87,288	168,357	107,847	91,155
R^2	0.916	0.924	0.926	0.864	0.887	0.886
R^2 adj.	0.910	0.920	0.922	0.850	0.880	0.878
Entropy balance	NO	YES	YES	NO	YES	YES
2012 included	YES	YES	NO	YES	YES	NO
Control vars.	YES	YES	YES	YES	YES	YES
Route-airlin. FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
Quarter FE	YES	YES	YES	YES	YES	YES

Notes: This table reports the regression of emissions (panel A) and flights (panel B) on the EU ETS indicator, our difference-in-differences estimator. Columns 1 to 3 estimate the effect of the EU ETS for a sample limited to routes operated by network airlines: column 1 estimates the difference-in-differences model without any sort of matching or weighting balance, column 2 replicates the latter model with entropy balance applied to the control group; column 3 replicates this latter model removing 2012 observations. Columns 4 to 6 replicate the same previous three models on a subsample limited to routes operated by low-cost airlines. Entropy balance is applied to each specific subsample. Robust standard errors (in parentheses) are clustered at the route level. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

4.3. SUTVA

A second major key assumption of our analysis deals with the stability unit treatment value assumption (SUTVA). This requires that the realized outcome (here emissions or flights) of an airline-route depends only on the treatment value of that airline-route, and not on the treatment value of any other airline-route. In other words, the EU ETS does not affect potential supply and emission changes in the control group. However, the existence of several interdependences between our treated and control routes could violate SUTVA.

Our control group includes flights with one end at an EEA airport. This is helpful for our identification strategy insofar it reduces heterogeneity between treated and control groups. However, it could also be problematic if there were strong interdependences of complementarity or substitutability between treated and control routes: for instance, carbon pricing could change the relative price of different destinations and displace demand from treated to control routes. This could be especially relevant for leisure travelers, who more likely use low-cost airline services. In addition, network airlines could shift connection flights from treated to control routes within their hub-and-spoke system. If these cases are abundant, then the EU ETS effect estimated above would be overestimated. Moreover, on the climate policy arena, the existence of such spillover effects would imply carbon leakage, a critical issue in carbon markets: emissions on untreated routes would increase as a direct consequence of the marginal cost increase on the treated routes. On the other hand, the EU ETS effect could also be underestimated if other positive interdependencies took place, for instance, if induced flights reduction interacted positively with control routes through aircrafts' routing: if aircrafts are used across treated and control routes, it could be the case that the induced reduction of a number of flights on a particular ETS regulated route affected, in cascade, other non-regulated routes. This positive spillover would therefore result in underestimating the true effect of the policy.

To deal with this potential SUTVA violation, we restrict the control group to flights that both originate and terminate outside the EEA (Table 4). This allows us to minimize these potential interdependencies, positive and negative, between treated and control routes. We balance treated and control by means of entropy balancing procedures using the same covariates as in previous models. However, convergence is only feasible for the first moment (not for the second) and not achieved at all for routes operated by low-cost and network airlines samples without allowing too high levels of mean differences, or reducing covariates to match on. We therefore restrict the analysis to regressions using the full sample and short-haul routes sample for which we can provide comparable results (with same mean values between treated and control routes).

Results remain consistent with previous estimates in that carbon pricing is much more effective in reducing emissions for short-haul routes than for the whole sample. However, size effects reveal potential underestimation when the control group does include EEA airports. Full sample estimates (column 1) show the EU ETS reduced emissions by −9.8% relative to counterfactual without EEA airports, more than doubling the reduction found in our previous estimates (−4.7%). When focusing on short-haul routes, the EU ETS effect on emissions is −16.9% (column 2), six percentage points higher than before (−10.7%).

Fig. 6 shows the evolution of year-on-year estimates of these effects. EU ETS coefficients prior to the treatment are not statistically

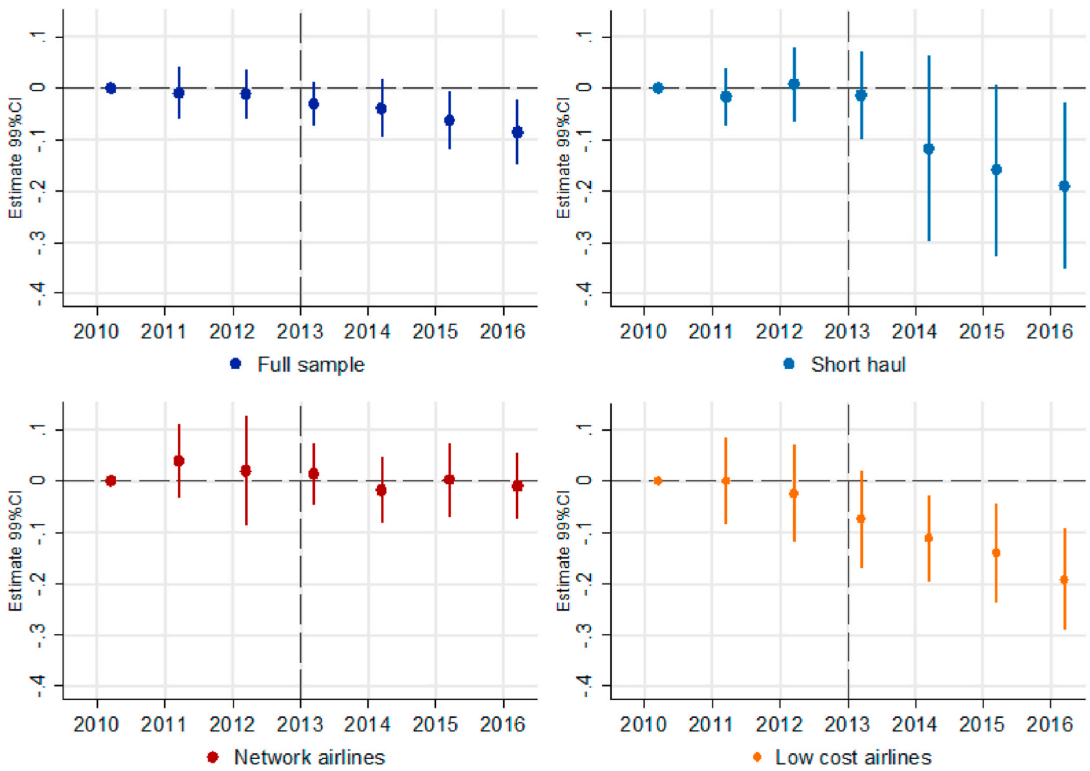


Fig. 5. Year-on-year difference-in-differences estimates. Notes: This figure plots results from an event-study analysis of the difference in the route-airline emissions between EU ETS regulated air-routes and other comparable air-routes before and after the policy implementation. The reported coefficients come from equation (2) where we interact the treatment variable with year indicators. The top-left panel figure reports results for full sample estimates and the top-right panel shows results when the sample is restricted to routes where competition from trains is feasible (i.e., short haul routes without islands at the endpoint or with a high-speed rail connection). The bottom-left panel figure reports results when the sample is restricted to routes operated by network airlines and the bottom-right by low-cost airlines. All four samples use entropy balancing as a reweighting scheme so that first two moments of the control group match with the treatment group of each particular sample (Hainmueller, 2012). The base year is 2010 and the confidence interval is at 99% with standard errors clustered at the route level.

significant, making common trends assumption plausible. The impact of the EU ETS is statistically significant (at the 95% level) from 2014 onwards for the full sample, while estimated differences between treated and control short-haul routes clearly increases after the implementation of the EU ETS. In this latter case, (smaller) differences can also be observed in 2012. Since we are comparing treated routes with non-EEA routes (having both an origin and destination out of the EEA), some effects of the EU ETS in 2012 could arise: control routes here are certainly not to be treated at any point, and hence there is not the same previous uncertainty. In fact, the regulatory uncertainty in the first years of the implementation of the EU ETS – particularly relevant on routes that connect EEA airports with non-EEA airports-, could explain that the estimated impact of the measure is greater when these control routes are excluded from the sample.

4.4. *Robustness checks*

Our results suggest that the EU ETS has induced a reduction in emissions that is concurrent with a reduction in supply, especially on short-haul routes where competition from other transport modes is feasible. Table 5 shows the results of additional regressions for the full sample that provide various robustness checks to our main results. We apply the entropy balancing technique with the same procedure and covariates as outlined in section 3.3. As in the previous analyses, these additional regressions include route-airline fixed effects, year and quarter fixed effects. Furthermore, standard errors are clustered at the route-level.

(i) *Different regulations applying to treated and control groups:* Non-EU countries in the control group may be governed by different regulations, a fact that might account for our results. For instance, the European Single Market or bilateral treatments could induce a reduction in supply on the EU ETS routes. However, insofar as the regulations are time invariant for the period considered, the airline-route fixed effects already control for this potential effect. However, it would be quite a different story if there had been a significant change in regulations during the period of analysis. In particular, aviation taxes (departure taxes) in some countries were modified during the period: Austria and Germany introduced a departure tax in 2011 and 2012,

Table 4
Effect of EU ETS on emissions and aviation supply. Difference-in-differences estimates with alternative control group.

VARIABLES	(1)	(2)
	Full sample	Short haul
PANEL A: ln(Emissions)		
EU ETS	−0.098***	−0.169***
	(0.027)	(0.059)
Observations	237,498	92,339
R^2	0.934	0.957
R^2 adj.	0.930	0.955
PANEL B: ln(Flights)		
EU ETS	−0.073**	−0.146**
	(0.033)	(0.061)
Observations	237,498	92,339
R^2	0.952	0.961
R^2 adj.	0.950	0.959
Entropy balance	YES	YES
2012 included	YES	YES
Control vars.	YES	YES
Route-airlin. FE	YES	YES
Year FE	YES	YES
Quarter FE	YES	YES

Notes: This table reports the regression of emissions (panel A) and flights (panel B) on the EU ETS indicator, using as alternative control group routes that originate and terminate outside EEA countries. Column 1 estimate the effect of the EU ETS for the full sample, while column 2 estimate the effect for a subsample of routes where other means of transportation may be competitive. Entropy balancing is applied to each specific sample. Robust standard errors (in parentheses) are clustered at the route level. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

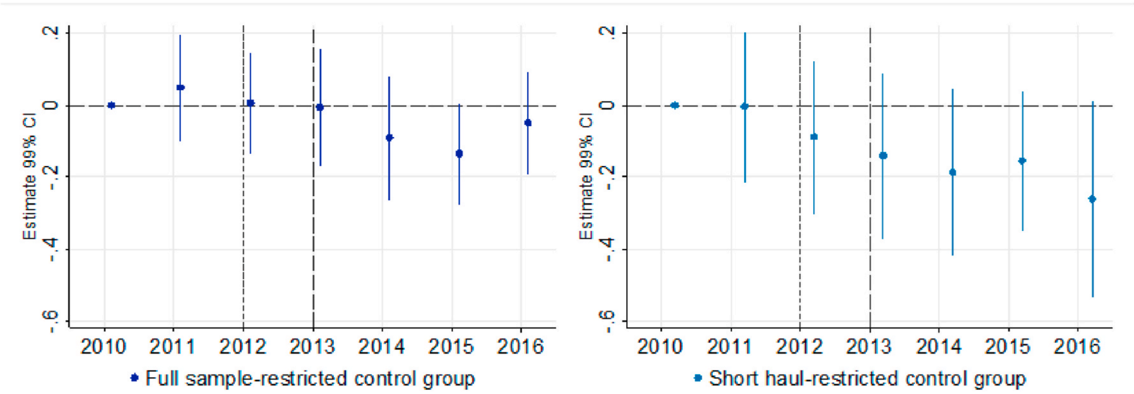


Fig. 6. Year-on-year difference-in-differences estimates with alternative control group. Notes: This figure plots results from an event-study analysis of the difference in the route-airline emissions between EU ETS regulated air-routes and comparable routes between non-EEA airports. The reported coefficients come from equation (2) where we interact the treatment variable with year indicators. The left panel figure reports results for full sample estimates and the right panel shows results when the sample is restricted to routes where competition from trains is feasible (i.e., short haul routes without islands at the endpoint or with a high-speed rail connection). Both samples use entropy balancing as a reweighting scheme. The base year is 2010 and the confidence interval is at 99% with standard errors clustered at the route level.

respectively, and Ireland abolished its aviation tax in 2014. To control for this effect, we include dummy variables from the year of this tax change on routes departing from these countries. Column 1 in Table 5 shows the effect of the EU ETS including departure taxes as explanatory variables (note that all regressions reported in this subsection include departure taxes as covariates).

(ii) *Annual variation of control variables:* The dependent variable in previous analyses is built with data at the quarterly level to account for the strong seasonal variation both in demand and supply that typically affect aviation markets. However, control covariates like population or income per capita have annual variation. To address the possible distortion due to the use of

Table 5
Effect of EU ETS on emissions and aviation supply. Difference-in-differences estimates with different robustness checks.

VARIABLES	(1)	(2)	(3)	(4)
PANEL A: ln(Emissions)				
EU ETS	−0.044**	−0.052**	−0.055***	−0.088***
	(0.018)	(0.023)	(0.020)	(0.021)
Germany departure tax	−0.053**	−0.057***	−0.056***	−0.095***
	(0.021)	(0.020)	(0.020)	(0.035)
Austria departure tax	0.040	−0.026	0.010	−0.109
	(0.025)	(0.033)	(0.024)	(0.069)
Ireland departure tax	0.009	0.039	0.009	0.066**
	(0.022)	(0.027)	(0.022)	(0.031)
Observations	277,385	71,842	272,907	52,114
R^2	0.905	0.931	0.907	0.835
R^2-adj.	0.90	0.915	0.902	0.826
PANEL B: ln(Flights)				
EU ETS	−0.047***	−0.045**	−0.055***	−0.081***
	(0.018)	(0.018)	(0.018)	(0.022)
Germany departure tax	−0.055***	−0.055***	−0.065***	−0.087**
	(0.020)	(0.018)	(0.020)	(0.036)
Austria departure tax	−0.013	−0.078**	−0.020	−0.103
	(0.038)	(0.031)	(0.051)	(0.070)
Ireland departure tax	0.020	0.036	0.023	0.068**
	(0.022)	(0.025)	(0.022)	(0.031)
Observations	277,385	71,842	272,907	52,114
R^2	0.910	0.944	0.909	0.865
R^2 adj.	0.905	0.932	0.904	0.858
Entropy balance	YES	YES	YES	YES
2012 included	YES	YES	YES	YES
Control vars.	YES	YES	YES	YES
Route-airlin. FE				
Year FE	YES	YES	YES	YES
Quarter FE	YES	YES	YES	YES

Notes: This Notes: This table reports the regression of emissions (panel A) and flights (panel B) on the EU ETS indicator using the full sample. Column (1) estimate the effect of the EU ETS including departure taxes as explanatory variables. Column 2 estimates the effect using data at the annual level. Column 3 estimates the effect using data at the city-pair level. Column 4 estimates the effect when treated group is limited to an airline that only operates in EU ETS routes: Ryanair. Entropy balancing is applied to each specific sample. Robust standard errors (in parentheses) are clustered at the route level. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$ nel A) and the number of flights () on the EU ETS indicator, our difference-in-difference estimator, according to.

different time units for the dependent and some explanatory variables, we replicate the previous model using data at the annual level. Column 2 in Table 5 shows the effects of the EU ETS on the full sample using data at the annual level.

(iii) *Definition of routes:* In the main dataset, we define routes as airport-pairs.[24] However, low-cost airlines often operate from secondary airports but still serve the large destination. In addition, this might affect the definition of the dummy variable for monopoly routes. RDC aviation – the source of supply data-also allows us to build a dataset where the unit of observation is the city-pair market. By city-pair market, we mean that multi-airport cities are considered as a single origin and/or destination. Given that RDC aviation provides directly a variable that groups airports that serve the same city, we consider the definition of city-pair markets that is already available in the database. In this regard, we run a regression in which data have been collapsed at the city-pair market. Column 3 in Table 5 estimates the effect of the EU ETS using an alternative definition of route: instead of defining routes at the airport level (e.g. London-Gatwick to Paris-Orly), we show here the effect when the route is defined at city level (e.g. London to Paris).

(iv) *Airline supply shifts from treated to control routes*: In the previous subsection, we have examined a potential violation of the Stable Unit Treatment Value Assumption (SUTVA). In particular, demand changes may drive down the supply of aviation services within EEA routes and drive up supply between EEA and non-EEA locations. We have addressed such potential distortion by defining a specific control group restricted to routes between non-EEA locations. In addition to changes in demand, another potential source of a SUTVA violation could take place from changes in supply decisions. In fact, airlines operate more than one route and potentially on both treated and control groups. If this is the case, a negative shock in the regulated routes could affect unregulated routes. Airlines might respond to carbon pricing by moving aircraft from treated to control routes. To account for

[24] Note that the geographical scale used to build the population variable in the baseline regression always includes the core city and the surrounding region. For example, the variable of population for London Gatwick refers to London.

this, we perform an additional regression in which we limit the treated group to Ryanair, the leading low-cost airline in the EU. Ryanair does not operate routes in the control group so that any impact of the EU ETS on Ryanair cannot be explained by shifting activity to control routes. Column 4 in Table 5 shows the effect of the EU ETS when the treated group is limited to routes operated by Ryanair. This dilutes the potential distortion that airlines on treated routes may shift supply to control routes. However, it must be recognized that control routes may still be affected by supply decisions of other airlines operating on treated routes.

Results of these additional estimates confirm our previous findings. The EU ETS reduced airline emissions and supply in a range that goes from −4.4% to −8.8%. The magnitude of the impact is very similar to that found in main estimates. The regression that constrains the treated routes to Ryanair's flights, confirms that the impact is notably higher for low-cost airlines. Interestingly, the impact of the departure tax in Germany is negative and statistically significant, while Ireland's abolishment of its aviation tax is positive and statistically significant in the regression in which treated routes are operated by Ryanair.

Fig. 7 shows the timing effects of the EU ETS considering the regressions with different robustness checks. The causal impact of the EU ETS is confirmed in all cases given that the reduction in emissions on treated routes is only statistically significant after 2013.

5. Extensive margin

Our previous analyses focus on the intensive margin because the sample used considers route-airline pairs with air services (i.e.; at least one flight per week). In particular, we use a dataset based on airline-route pairs with flights in at least one quarter in the period that goes from 2010 to 2016. Hence, those analyses are based on an unbalanced panel dataset given that some pairs of airline–routes do not have any flights (or have less than one flight per week) in some year(s)-quarter(s). In this regard, the EU ETS could also have an effect on emissions by encouraging airlines to stop operating routes that they did offer before its implementation.

To assess the effects of the EU ETS in the extensive margin, we have built an additional balanced panel dataset in which each airline-route pair with flights in at least one quarter of the period considered has observations for all year-quarters. Observations for airline-route-quarters with no flights are not excluded here from the analysis but we assign them the value zero in the dependent variable. In this regard, regressions using this expanded sample consider as a dependent variable a dummy variable that takes the value one when the airline-route pair has less than one flight per week.[25] We use the same covariates as in equation (1) and we apply the entropy balancing technique with the same procedure and covariates as outlined in section 3.3.[26] As in the previous analyses, regressions include route-airline fixed effects, year and quarter fixed effects. Furthermore, standard errors are clustered at the route-level.

Table 6 shows the results of the estimates. The effect of our treatment variable can be read as the change in the probability of ceasing to offer flights on the route. We run regressions using the full sample and the same subsamples considered previously (i.e.; short-haul routes and routes operate by either network or low-cost airlines). In addition, we also run regressions in which we restrict the control group to flights that both originate and terminate outside the EEA. Recall here that entropy balancing is not applicable to the specific subsamples centered on routes operated by either network or low-cost airlines, so that these latter regressions only use the full sample and the subsample for short-haul routes.

We find a positive and significant impact of the EU ETS on the probability of exits. Columns 1 and 2 show the results when using the full sample. The EU ETS increased the probability of exits by 2.2% compared to the counterfactual. However, such effect is not statistically significant when the control group is restricted to routes between non-EEA countries.

Columns 3 and 4 show the results when using the subsample of short-haul routes. The EU ETS increased the probability of exits by 5% compared to the counterfactual and such impact is even higher (9.7%) when the control group is restricted to routes between non-EEA countries. Columns 5 and 6 also show a positive impact of the EU ETS on the probability of exits when the analysis is centered on routes operated by network (2.8%) or low-cost airlines (2.5%).

Figs. 8 and 9 shows the evolution of year-on-year estimates of these effects. Fig. 8 is centered on regressions using the full sample, and the subsamples based on short-haul routes and routes operated by network and low-cost airlines. All these regressions consider all control routes. Fig. 9 focuses on regressions using the full sample and the subsample based on short-haul routes and that restrain the control routes to routes that link non-EEA airports. In all cases, EU ETS coefficients prior to the treatment are not statistically significant, which provides evidence in favor of the parallel trend assumption. In contrast, the probability of exit on the treated routes compared to the control routes is higher from 2013 onwards.

This pattern is inconsistent only in the regression that uses the full sample and restricts the control group to routes between non-EEA countries. In this case, the differences between treatment and control routes are small both before and after the policy is implemented. Furthermore, differences between treated and control routes follow a more volatile dynamic both before and after 2013 when the analysis focuses on routes operated by low-cost airlines.

Overall, it seems that the EU ETS has contributed to reducing CO_2 emissions on the routes affected by the policy compared to the control routes. This impact operates through the intensive and, more modestly, the extensive margin. In particular, the magnitude of

[25] Air services with less than one flight per week are generally non-scheduled services and are, therefore, offered on an occasional basis (i.e., charter flights, re-routings due to special events or technical incidences, etc.). Hence, these occasional flights could distort the results. For example, a shift from 1 flight per month to 0 cannot be considered a real exit, as opposed to removing a weekly flight.

[26] We use a linear probability model because it eases interpretation. However, using logit models provide consistent results with those shown in Table 6.

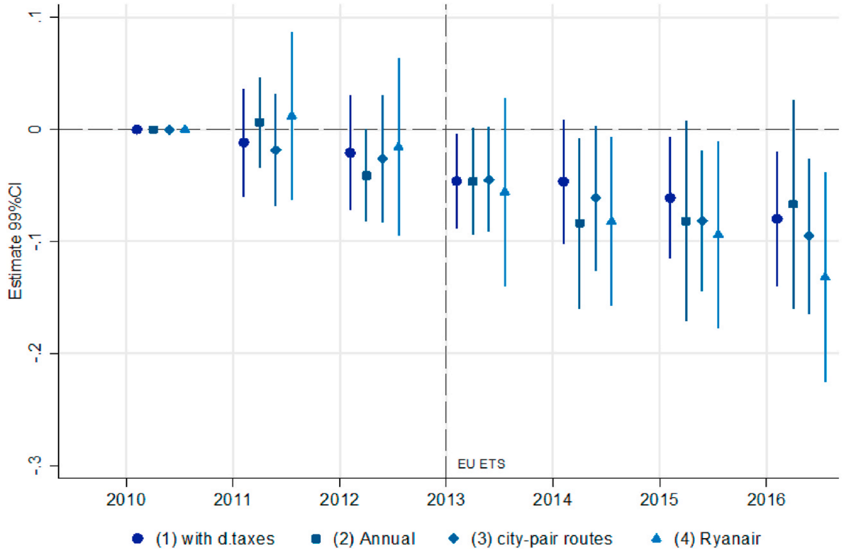


Fig. 7. Year-on-year difference-in-differences estimates with different robustness checks. Notes: This figure plots results from an event-study analysis of the difference in the route-airline emissions between EU ETS regulated air-routes and comparable non-regulated air-routes before and after the policy implementation. The reported coefficients come from equation (2) where we interact the treatment variable with year indicators. We report results for: 1) a regression that include departure taxes as explanatory variables, 2) a regression that uses data at the annual level, 3) a regression that uses data at the city-pair level, 4) a regression in which the treated group is limited to routes operated by Ryanair. Entropy balancing is applied to each specification. The base year is 2010 and confidence interval is at 99% with standard errors clustered at the route level.

Table 6
Effect of EU ETS on airline-route exits. Difference-in-differences estimates.

VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)
	Full sample	Full sample	Short haul	Short haul	Network	Low cost
P = 1 if number of flights are below one per week						
EU ETS	0.022**	−0.013	0.050***	0.097**	0.028***	0.025*
	(0.008)	(0.025)	(0.018)	(0.041)	(0.006)	(0.014)
Observations	337,275	287,688	237,325	207,165	113,976	131,352
R^2	0.454	0.492	0.726	0.770	0.512	0.392
R^2-adj.	0.427	0.467	0.710	0.758	0.489	0.363
Restricted ctrl. group	NO	YES	NO	YES	NO	NO
Entropy balance	YES	YES	YES	YES	YES	YES
2012 included	YES	YES	YES	YES	YES	YES
Control vars.	YES	YES	YES	YES	YES	YES
Route-airlin. FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
Quarter FE	YES	YES	YES	YES	YES	YES

Notes: This table reports linear probability models with an exit measure (0 = a flight per week or more, 1 = less than one flight per week) as a dependent variable and the EU ETS indicator as our difference-in-differences estimator. Column 1 reports effects for the full sample and column 2 replicates the same model but restricting the control group to flights with no end in the EEA countries (to avoid potential SUTVA violations). Columns 2 and 3 replicate the model for short haul samples. Columns 5 and 6 show results for routes operated by network and low-cost airlines without restricting the sample (due to no convergence with entropy balance reweighting procedure for this particular subgroup of routes). Robust standard errors in parentheses (clustered at the route level).
***p < 0.01, **p < 0.05, *p < 0.1.

the impact is particularly remarkable on short-haul routes where competition from surface transportation is viable. This is the case whether we focus on the intensive or extensive margin.

It should also be noted that low-cost airlines have contributed to a greater extent than network airlines to the reduction in supply and emissions as a result of the EU ETS. However, we did not find such clear differences between both types of airlines in relation to the decision to close or not close routes.

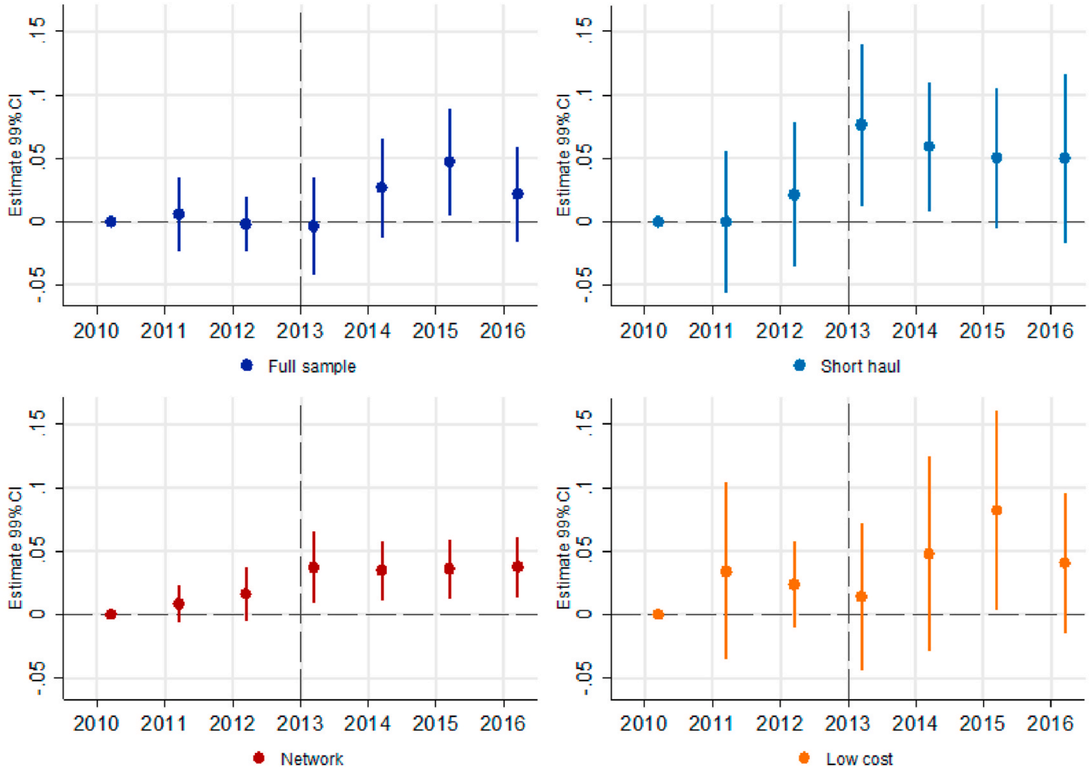


Fig. 8. Year-on-year difference-in-differences estimates (extensive margin). Notes: This figure plots results from an event-study analysis of differences between EU ETS regulated air-routes and comparable non-regulated air-routes before and after the policy implementation. The reported coefficients come from linear probability models with an exit measure (0 = a flight per week or more, 1 = less than one flight per week) as a dependent variable. We interact the treatment variable with year indicators. The top-left panel figure reports results for full sample estimates and the top-right panel shows results when the sample is restricted to routes where competition from trains is feasible (i.e., short haul routes without islands at the endpoint or with a high-speed rail connection). The bottom-left panel figure reports results when the sample is restricted to routes operated by network and the bottom-right by low-cost airlines. Entropy balancing is applied to each specification. The base year is 2010 and the confidence interval is at 99% with standard errors clustered at the route level.

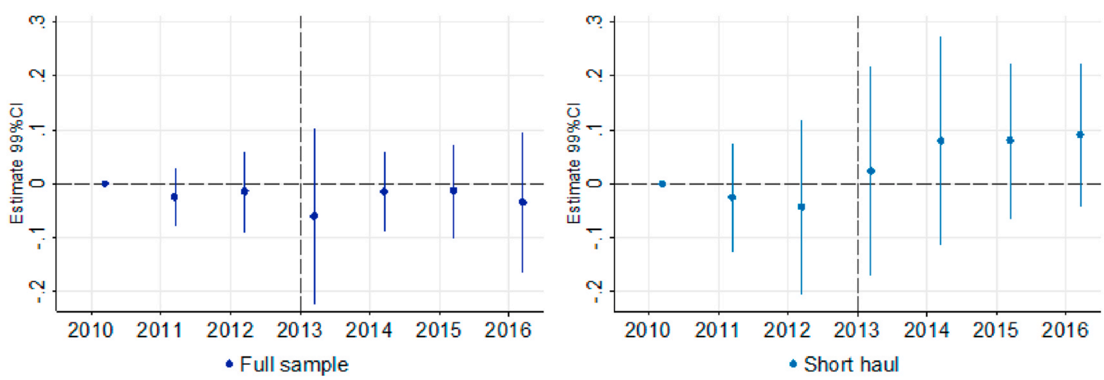


Fig. 9. Year-on-year difference-in-differences estimates (extensive margin with alternative control group). Notes: This figure plots results from an event-study analysis of differences between EU ETS regulated air-routes and comparable routes within non-EEA airports before and after the policy implementation. The reported coefficients come from linear probability models with an exit measure (0 = a flight per week or more, 1 = less than one flight per week) as a dependent variable. We interact the treatment variable with year indicators. The left panel figure reports results for full sample estimates and the right panel shows results when the sample is restricted to routes where competition from trains is feasible (i.e., short haul routes without islands at the endpoint or with a high-speed rail connection). Entropy balancing is applied to each sampling. The base year is 2010 and the confidence interval is at 99% with standard errors clustered at the route level.

6. Conclusions

Carbon pricing, whether delivered by means of carbon taxes or cap-and-trade systems, is expected to reduce emissions thanks to its impact on firms' marginal costs. Such a system encourages both a reduction in emissions per output unit and a reduction in output. The latter is of particular relevance to the aviation sector, considering that its technological improvements are not projected to offset sector growth. In this paper, we have investigated the causal impact of the EU ETS on aviation emissions and we provide the first ex-post evaluation of carbon pricing applied to the aviation sector.

We find that the EU ETS has had a significant impact in containing the growth of air services within the EEA, despite the fact that the measures applied to airlines are relatively soft with around half the allowances received being free. The overall effect of the policy has been modest, but it has had a remarkable impact on low-cost airlines, which concentrate about half Europe's aviation market. The impact is also particularly notable on short-haul routes on which planes may have to compete with other modes of transport, such as the train.

The lower relative growth in emissions on treated routes in comparison to control routes is mainly explained by a lower growth in the number of flights. We have also found that the EU ETS has contributed to the reduction of emissions by encouraging the closure of routes. In the long term, the policy could induce emission reductions through the use of larger and more efficient aircraft. However, changes in the aircraft type do not appear to have played a significant role in the period considered, given that we do not find substantial differences in the results when using emissions or flights as dependent variable. Another mechanism that could explain the reduction in emissions is the redirection of routes to nearby airports, but our analyses regarding the stability unit treatment value assumption suggest that this has not been the case.

From a policy perspective, the finding that airlines respond strongly on short-haul routes suggests that investments, at both national and international level, to improve connectivity by rail (i.e., high-speed trains), should be seen as complementary measures to the ETS scheme to reduce emissions. Besides, expanding rail networks to offset air traffic reduction is a convenient way to avoid the negative economic consequences of such a reduction. Indeed, there is a large body of evidence showing that the contribution of aviation to economic growth is directly proportional to its volume of traffic. This trade-off between economic growth and lower emissions is less explicit on short-haul routes insofar as the reduction in air traffic can be compensated for by an increase in traffic in cleaner alternative modes of transport. These potential benefits, however, need to be balanced with the high costs associated with the building and maintenance of high-speed rail lines.

Although carbon pricing alone may not be enough to deal with climate change, the evidence reported here suggests that tougher measures to increase the price of carbon may be cost-effective in achieving a reduction in emissions in the aviation sector. In this sector, this could well include eliminating the free allocation regime (as it has been recently proposed by the European Commission). In comparison to other sectors, free allowance allocation is not justified in terms of competitiveness, since airlines, regardless of their nationality, compete at the route level. Indeed, given that the airlines' chief capital assets—their planes—are movable, airlines can shift their activity to other non-regulated routes, i.e., carbon leakage. In this regard, expanding the geographical scale of the policy would be particularly effective and would have more certain effects over time. The 'stop-the-clock' law was justified on these grounds: that is, achieving a global scheme. This, however, should be done without breaking the link between emission allowance costs and the airlines' marginal costs, as is entailed by carbon pricing approaches but not by some carbon offsetting measures proposed by international aviation (i.e., CORSIA).

Given data availability, our analysis has focused on the impacts on emissions and supply of the EU ETS. The strong interaction between demand and supply in the aviation sector allows us to hypothesize that the reduction in supply has been accompanied by a reduction in demand and an increase in prices. However, further research needs to assess the impact of the EU ETS on passenger numbers and air fares. In this regard, one factor that could have an effect on demand is a change in airlines' price discrimination strategies or a change in their balance of business vs economy seats. Also, further research needs to assess the long-term effects of the EU-ETS and its contribution to the consolidation process in the airline market.

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Appendices.

Table A1
List of network and low-cost airlines in the sample

Network airlines	Low-cost airlines

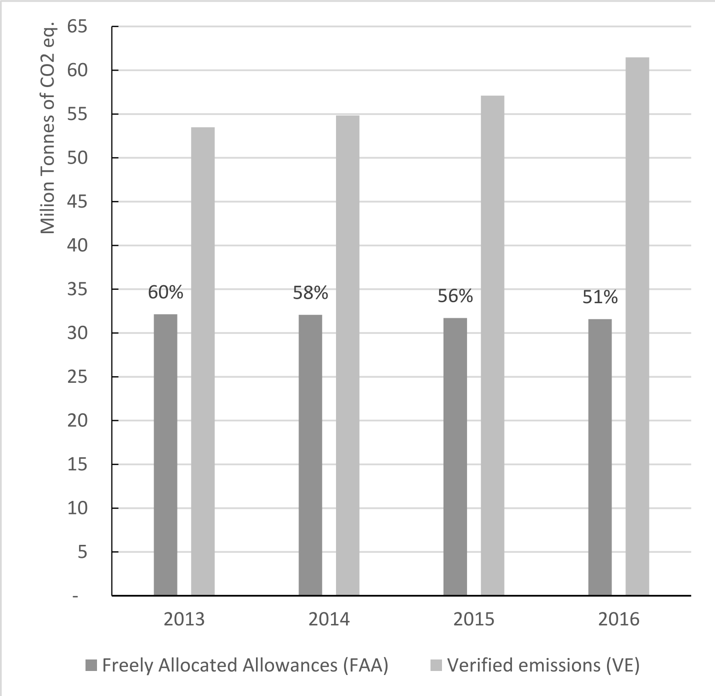
(*continued on next page*)

Table A1 (*continued*)

Network airlines	Low-cost airlines
Adria Airways, Aegean, Aer Lingus, **Aeroflot**, Air Europa, Air France, Air Berlin, Alitalia, Austrian Airlines, British Airways, SN Brussels, Croatia Airlines, Czech Airlines, Finnair, Iberia, KLM, LOT, Lufthansa, Malev, **S7**, SAS, Spanair, **Swiss**, TAP, TAROM, **Turkish Airlines**	**Atlasjet**, **Belle Air**, Blue Air, Blue Panorama, bmibaby, Condor, Easyjet, **Easyjet Switzerland,** Eurowings, Germania, Germanwings**, Helvetic Airways**, Iceland Express, Intersky, Jet 2, Meridiana, Monarch, Niki, Norwegian, **Pegasus**, **Pobeda**, Ryanair, **Sky Express (Russia)**, Smartwings, **Sun Express**, Sun Express Deutschland, Transavia, Tuifly, Volotea, Vueling, Wizzair, Wizzair Bulgaria, **Wizzair Ukraine**, WOW, XL Airways

Notes: Non-EEA airlines in bold.

Notes: This graph plots 2 bars per year, one showing the freely allocated allowances (darker grey bar), which remain constant in the whole phase, and compares it with the actual verified emissions (lighter grey bar). The growing difference depicts the purchased allowances by affected airlines. The number of free allowances will be reduced progressively to reach full auctioning by 2027 (EC, 2021). Source: Data extracted from EU Transaction Log (EUTL).



Notes: This graph plots two bars per year, one showing the freely allocated allowances (darker grey bar), which remain constant in the whole phase, and compares it with the actual verified emissions (lighter grey bar). The growing difference depicts the purchased allowances by affected airlines. The number of free allowances will be reduced progressively to reach full auctioning by 2027 (EC, 2021). Source: Data extracted from EU Transaction Log (EUTL).

Fig. A1. Aviation's free allowance allocation and verified emissions 2013–2016.

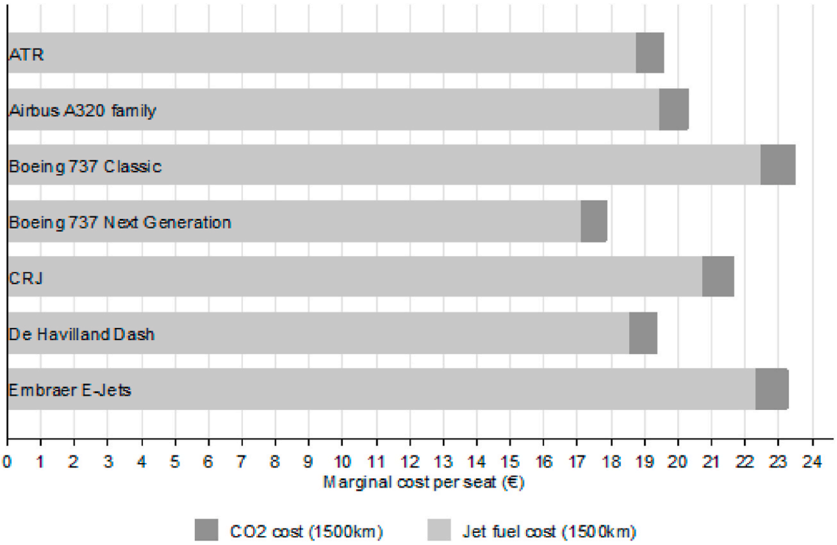


Fig. A2. Fuel and carbon marginal cost per seat by aircraft family. Notes: This figure plots cost per seat of a 1,500 km flight in terms of jet fuel and EU allowances at average prices in the period 2010–2016: €49.4 gallon of jet fuel and €7.55 CO2t.

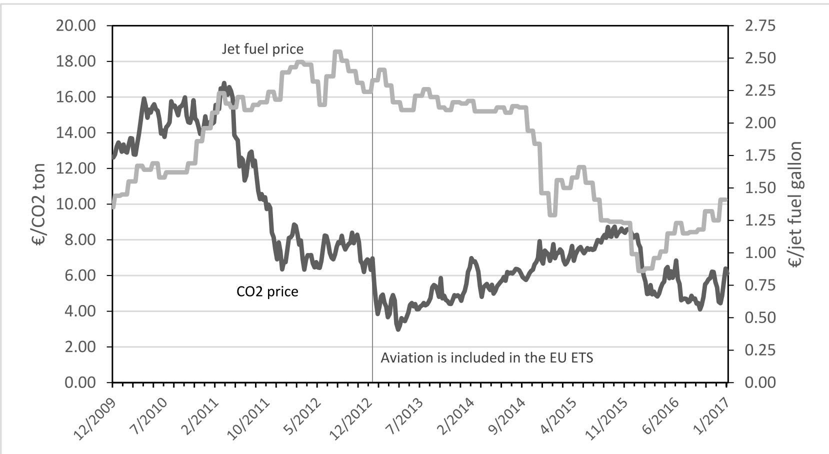


Fig. A3. Prices of jet fuel and EU allowances.

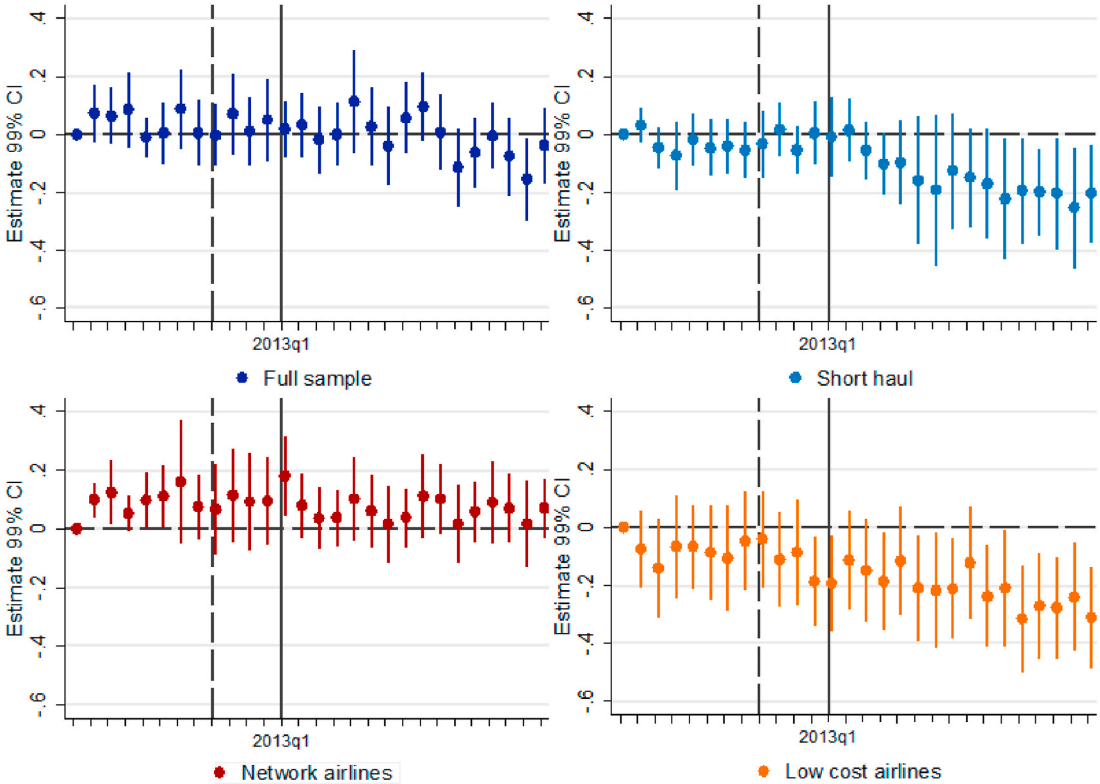


Fig. A4. Quarter-on-quarter difference-in-differences estimates. Notes: This figure plots results from an event-study analysis of the difference in the route-airline emissions between EU ETS regulated air-routes and other comparable air-routes before and after the policy implementation. The reported coefficients come from equation (2) where we interact the treatment variable with quarter-year indicators. The top-left panel figure reports results for full sample estimates and the top-right panel shows results when the sample is restricted to routes where competition from trains is feasible (i.e., short haul routes without islands at the end point or with a high-speed rail connection). The bottom-left panel figure reports results when the sample is restricted to routes operated by network and the bottom-right by low-cost samples. All four samples use entropy balancing as reweighting scheme. The base year is 2010 and the confidence interval is at 99% with standard errors clustered at the route level.

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