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The EU ETS and Aviation: Evaluating the Effectiveness of the EU Emission Trading System in Reducing Emissions from Air Travel

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Abstract

Over the past 30 years, the aviation industry has seen record-breaking growth whilst enjoying exemptions from most taxes and VAT charges. Currently, the aviation sector is considered one of the fastest-growing greenhouse gas emissions sources. Attempting to reduce these emissions in a cost-effective manner, the EU decided in 2012 to include all flights entering and leaving the EU in their Emission Trading System (EU ETS). It was quickly changed to only include travel within the EU. Nevertheless, as the largest cap-and-trade system in the world, the purpose of the EU ETS is to control the growth of emissions by issuing pollution permit rights. The idea is that by setting an emission ceiling and allowing trade between sectors, emission abatement will happen where it is cheapest and easiest to do. This paper explores whether the EU ETS succeeded in reducing the aviation sector emissions over the period 2012–2018 by employing a General Synthetic Control model to estimate a counterfactual scenario. When using jet fuel consumption as a proxy for emissions, the results indicate that on average the EU ETS led to a 10 per cent increase in jet fuel consumption relative to a scenario where it was not implemented. However, the paper fails to conclude a causal relationship between EU ETS and jet fuel consumption due to drawbacks with the data. Nevertheless, it provides a starting point for future ex-post research concerned with aviation and carbon pricing in the European market.

Keywords: Emissions trading system; aviation industry; General Synthetic Control model; greenhouse gas emission; air pollution

JEL Classification: C20, L93, Q20, Q35, Q52, Q53, Q58, R41

Introduction

The EU's Emission Trading System (EU ETS) is the largest cap-and-trade scheme globally and was implemented to combat climate change and reduce greenhouse gas (GHG) emissions in a cost-effective manner. It covers more than 11,000 energy-intensive installations in 31 countries, in addition to airlines operating between these countries, accounting for approximately 45 per cent of EU's GHG emissions. For convenience, throughout the paper, the term "EU" will include all EU-28 countries plus Iceland, Liechtenstein, and Norway, unless explicitly stated otherwise (see **Annex 1**).

The EU ETS was developed to facilitate the goals set out in the Kyoto Protocol. The Kyoto Protocol required emission reductions in industrialised countries, and the common EU-wide target was set at an 8 per cent reduction in GHG emissions by 2012 compared to 1990 levels (Transport and Environment, 2016). How to achieve the EU-wide reductions was left up to the member states, and in 2003 the EU agreed to an emission trading scheme across borders (EC, 2003, Directive 2003/87/EC). The member states received emission permits, called EU Allowances (EUAs), by the European Commission (EC) after submission and approval of their National Allocation Plans (NAPs) outlining the reduction target and regulated installations. The ETS sets an emission cap which is slightly reduced every year with the intention of polluters having to either reduce their emissions or purchase additional allowance which should progressively grow scarcer and more costly. The first phase of the EU ETS (2005–2007) was used as a trial period to develop experience and find potential improvements for later stages, whereas phase II (2008–2012) coincided with the Kyoto commitment goals made by the EU (Wråke et al., 2012). Phase III (2013–2020) is a continuation of the previous two phases, including more sectors and a single EU-wide cap than the national caps previously used. The next trading period, phase IV (2021–2030), adopts emissions targets in line with the Paris Agreement for 2030 (EC, n.d.).

Since the start of the EU ETS, its scope has expanded in terms of geography, sectors, and type of greenhouse gases. The first two phases of the EU ETS included the most GHG-intensive sectors in the power and manufacturing industry (EC, 2015). During Phase I, the focus of emission reduction was solely put on CO_2. However, in Phase II, other GHG emissions, such as nitrous oxide, was included by several countries. When referring to "emissions" throughout this paper, it can be assumed this only includes CO_2 emissions, unless explicitly stated.

Although the EU ETS marks the first international ETS, there are up to 61 carbon pricing initiatives worldwide (World Bank, 2020). It includes 31 ETS's and 30 carbon taxes. Collectively they cover around 22 per cent of global GHG emissions. Out of the 61 initiatives; however, only the EU, China and the Republic of Korea have ETS's that cover the aviation sector.

In 2008 it was agreed that aviation should be included in the EU ETS from 2012 (EC, 2009, Directive 2008/101/EC). It resulted from the forecasted rapid growth in the industry and the International Civil Aviation Organization (ICAO) failing to adopt a global measure for aviation (Transport & Environment, 2016). Initially, it was set out to cover all flights departing or arriving in the EEA area — however, due to strong foreign (non-EU) and industry objections it was decided shortly after implementation that only intra-EU flights (flights departing *and* landing in EU) were subject to the policy. The legislation referred to as "stop the clock", exempts international (extra-EU) flights from submitting pollution permits. It was initially set to last until 2016; however, it was extended until 2024 to support the development of a global measure by the ICAO (EC, 2015).

The emission cap for aviation is separate from the overall EU ETS cap, with individual permits called EU Aviation Allowance (EUAA). It is set at 97 per cent and 95 per cent of historical emission between 2004 and 2006, for 2012 and 2013–2020, respectively. Out of these, 82 per cent are granted for free, whilst 15 per cent are auctioned. The remaining 3 per cent are reserved for fast-growing airlines and new entrants. Based on verified tonne-kilometre data for 2010, airlines have received approximately 0.6422 allowances per 1,000 tonne-kilometre flown between 2012–2020 (ibid).

Commercial aviation, mainly international, has historically enjoyed exemptions from most taxes and VAT charges, unlike other transportation methods. It is partially due to the restrictions set out in the Chicago Convention, in addition to ICAO's recommendations (EASA et al., 2019). Furthermore, air travel is closely associated with economic growth, with many papers indicating the contribution of aviation to economic growth directly linked to traffic volume (Marazzo et al., 2010; PwC 2017; Dimitrious & Maria, 2018). Global air travel supports $ 2.7 trillion in world economic activity, equivalent to 3.6 per cent of global gross domestic product (GDP), and would rank 20th in the world in terms of GDP if it was a country (ATAG, n.d.). Taxing airlines, either directly or through a market-based measure (MBM) like the EU ETS, in the hope to reduce emissions, will arguably lead to more substantial economic issues associated with GDP growth. Recognising that depleting air traffic growth could essentially hurt economic prosperity, the EC, in addition to their generous cap, allows a one-way trade between aviation and stationary sources to facilitate the growth in the sector. The aviation sector can purchase EUAs from all actors; however, it can only sell their permits to other airlines (Kopsch, 2012).

The aviation sector is considered among the fastest-growing sources of GHG emission. GHG emissions from international aviation have increased by 141 per cent from 1990 to 2018 and accounted for 167 million tonnes of CO_2 equivalent emissions in 2018 (EEA, 2020a). The EU is one of the world's largest aviation emitters, and intra-EU flights are predicted to grow by over 80 per cent relative to 2005 levels by 2030. Without action, emissions can expect growth up to 300 per cent by 2050 (ICAO, n.d), threatening the 2°C target set by the Paris Agreement. Since the inclusion in EU ETS, aviation emissions have increased by 28 per cent[1] in absolute terms and now represent approximately 3.6 per cent of total EU emissions.

In comparison, other ETS sectors have seen a decrease in GHG emissions by 19.7 per cent[2] (Transport & Environment, 2020b). Even with 17 member states in the EU levying VAT or taxes on domestic aviation, arguments that stronger measures are needed to address the negative environmental externalities exist. Hemmings (via Transport & Environment, 2020a) claims that the EU aviation industry is still severely under-taxed and under-charged. They suggest that Europe should levy fuel taxes, ticket taxes and/or VAT at a higher price than today.

An emission trading scheme intends to reduce emissions by affecting firms' marginal costs. It establishes a right to emit and allows for permit trade across sectors, leading the market towards the ultimate cost-effective allocation of permits (Montgomery, 1972). The incentive for trade exists as long as marginal abatement cost differ. As the cap tightens, permits grow scarcer, and it becomes more costly for actors to pollute, thus it creates an incentive for environmental-friendly innovation (Porter, 1991).

Due to certain characteristics, the aviation sector is not fully comparable to other sectors of the economy (EASA et al., 2019). Unlike other forms of transport, or other industries, the primary energy source of aviation (jet fuel) is not readily substitutable (Stern, 2007). Technological progress in aircraft design and flight operations has been successfully achieved over the past 30 years, and average fuel consumption per passenger kilometre (PKP) has reduced by 24 per cent since 2005 (Fukui & Miyoshi, 2017). The number of passengers carried in Europe has increased by over 60 per cent in the same period (EASA et al., 2019). Thus, even with "green" innovation and technological improvements, the emissions associated with forecasted growth in the sector is unlikely to be offset (EASA et al., 2019; Nava et al., 2018). Nevertheless, aviation still needs to deliver more in-sector emissions reductions than currently witnessed.

The one-way trade in the EU ETS allows airlines to compensate for their emissions by purchasing allowances from sectors where abatement is cheaper and more easily attainable (EASA et al., 2019). However, the increased costs of these permits should have positive environmental effects. Vespermann and Wald (2011) outlined that the increased cost associated with the pollution permits should lead to airlines increasing ticket prices or reducing supply. Either way, it suggests less demand, thus reducing fuel consumption, ultimately reducing emissions. A counterfactual needs to be calculated to analyse the relationship between ETS and emission reductions. Only looking at absolute values makes it easy to conclude that EU ETS has not led to abatement. However, one cannot merely conclude the EU ETS is the cause of CO_2 reductions, or increments in this case, by looking at differences in total CO_2 emissions during the period. These outcomes could have happened in the policy's absence due to technological considerations, exogenous shocks, or other macroeconomic factors. Instead, to assess the EU ETS's effectiveness, a counterfactual need to be calculated. That is, the emissions that would be observed had the EU ETS not been in place, sometimes called the Business-as-Usual (BAU) scenario.

This paper attempts to evaluate whether aviation's inclusion in the EU ETS has led to emissions reductions relative to a BAU scenario. It will do so by estimating a counterfactual using a Generalized Synthetic Control (GSC) model proposed by Xu (2017), which have proved effective in addressing policy impacts on aggregate values, where heterogeneous effects of unobserved confounders are likely to exist. Using jet fuel consumption as a proxy for emissions, aggregate values are collected for 45 countries, with 30 being subject to the EU ETS and the remaining 15 acting as control variables (see **Appendix 2** for list of countries).

Literature Review

The following section will review literature aimed at assessing the effectiveness of the EU ETS in its various phases. Due to this study's macroeconomic nature, the papers examined also focus on sector and countrywide effects. The review includes an overview of the cap-and-trade system. The first two phases of the EU ETS is discussed, followed by literature focusing on the impacts of carbon pricing on aviation.

[1] Between 2013 and 2018.

[2] Compared to 1990 levels.

The Idea Behind EU ETS (Cap-And-Trade Market)

The EU ETS' main objective is to "promote reductions of greenhouse gas emissions in a cost-effective and economically efficient manner" (EC, 2003, Art. 1). Theoretically, carbon markets reduce emissions at the lowest cost, making it the most appealing method (Aldy & Stavins, 2011). Wagner (2003) observes that there are mainly three instruments used for environmental regulation; (1) Standards/emission limits, (2) Environmental taxes and charges, and, (3) Tradable and transferable emission permits and certificates. Instruments are also distinguished between market-orientated and judicially-orientated (command-and-control). Command-and-control regulatory standards are generally technology-based or performance-based. According to Aldy and Stavins (2011), neither tend to achieve a cost-effective solution.

When assessing the different regulatory instruments mentioned above Wagner (2003) finds that permits yield the most favourable results in terms of (cost) efficiency, dynamic incentive effects, structural and regional policy effects, distortions of competition and environmental effectiveness. Besides, they are also more likely to lead to the effects proposed in Porters hypothesis — which state that properly constructed regulatory standards aiming at outcomes will encourage companies to innovate, leading to less pollution, lower cost and better quality (Porter, 1991; 1995).

Although the empirical literature does not support Porters hypothesis due to its special assumptions about company and market functions (Brännlund & Lundgren, 2009), the hypothesis does provide arguments for preferring incentive-based over command-and-control type regulations. As an incentive-based regulation, a trading emission permit system encourages firms to reduce emissions through innovation, provide cost-effective allocation and abatement solutions, and, as a result, is less likely to limit the profitability of a firm (Wagner, 2003).

Moreover, the market-based system allows firms to value the emission allowance that reflects the cost of emission reductions possibly avoided by surrendering that allowance — famously called 'opportunity cost' (Aldy & Stavins, 2011). Thus, carbon's market price is equal to the lowest marginal abatement cost among all controlled sources (Egenhofer et al., 2011), and not explicitly fixed by an authority. Egenhofer et al. (2011) also highlight that the reason EU opted for the cap-and-trade system might be due to previously failed implementation of other instruments — drawing on examples like the rejected 1992 carbon tax proposal and poor voluntary agreements covering EU industries.

The EU ETS Phase I and Phase II

One of the first to evaluate the impact of the EU ETS on CO_2 abatement was Ellerman and Buchner (2008). The authors created a counterfactual using NAP data and found abatement efforts of about 7–8 per cent compared to a BAU scenario. Even if they found significant abatement in the period, there exist drawbacks in their calculations. Namely, the data used to calculate the counterfactual was collected voluntarily, sometimes unverified, and due to different estimations standards, the data was not perfectly comparable across countries. Furthermore, industries' incentive to exaggerate emission numbers as their allowance (EUAs) allocations were based on these unverified reports. A previous study by Ellerman and Buchner (2007) found an overallocation of allowances during the pilot phase — most prominently seen as CO_2 emissions were about 3 per cent lower than the allocated allowances. Although it is unlikely that there was no abatement during the pilot phase, Ellerman and Buchner (2008) result most likely contain an upward bias.

To improve their previous study, Ellerman, Convery and de Perthuis (2010) used United Nations Framework Convention on Climate Change's (UNFCCC) Common Reporting Format (CRF) data as a second source to estimate their counterfactual calculations. Herold (2007), being the first to investigate the legitimacy of using UNFCCC data as a proxy, find the two datasets (UNFCCC CRF and EU ETS verified emissions) to not match perfectly due to the scope of the EU ETS sectors and the different source categories in the CRF data. However, he concludes that since the share of CO_2 emissions reported by EU ETS is similar across the Member States in the UNFCCC data, there is proof of consistency between the datasets. Ellerman et al. (2010) conclude that even if their evidence suggests the EU ETS created emissions reductions of between 2–5 per cent during 2005–2007, the strongest evidence of the effectiveness of the EU ETS is that sector emissions stopped growing despite continued economic growth and development in relative fuel prices that would otherwise have led to higher emissions.

Anderson and Di Maria (2011) were interested in testing both the abatement of CO_2 and whether over/under allocation took place during the first phase. Contrary to Ellerman and Buchner (2008), they use historical data from Eurostat and match past emissions classified by NACE codes to the sectors participating in the EU ETS. Using a dynamic panel data estimation that controls historical data on European industrial emissions, industrial economic activity levels, weather effects, and energy prices, they estimate the counterfactual. Their results show overall GHG abatement in Phase I to be 2.8 per cent.

Extending the analysis of Ellerman et al. (2010), Egenhofer et al. (2011) estimate emission abatement during the first two years of Phase II. They used the average emission intensity[3] improvement from the pilot phase to create the counterfactual projecting BAU in 2008–09. Even though they find reductions to be higher in Phase II than the pilot phase, the abatement under this simplified approach depends to a large extent on the BAU assumptions. They point out several drawbacks with their study. Firstly, sector-level analysis is needed to confirm the macro trends. Secondly, there exist emission intensity fluctuations among sectors. Thirdly, Phase I data might not be reliable for BAU projections due to the economic crisis. Finally, the basis of two years being too short of forming a robust projection. Nevertheless, even if causality remains a problem, they conclude the EU ETS being correlated with emission reductions.

Bel and Joseph (2015) used historical emissions and a dynamic panel data approach to evaluate the EU ETS impact on GHG emissions during the first two trading periods. Their key finding is that most emissions reduction was due to the great recession in 08/09, not the EU ETS. Their main critique of previous studies is that they tend to over-estimate the emission reduction attributed to the ETS since they do not account for the economic recession in their calculations. Since the shock was not foreseen, this specifically affects the BAU-conditions that has been estimated. It is not to say the EU ETS led to zero-emission reductions. However, the emission abatement magnitude is likely to be smaller than previously estimated. Indeed, several other authors conclude the economic recession was the main reason for a decline in emissions in Phase II (Cooper, 2010; Kettner et al., 2011).

Dechezleprêtre et al. (2018), look at the causal impact of EU ETS on carbon emissions focusing on four countries due to data limitations: France, Netherlands, Norway, and the United Kingdom. They indicate that their sample is a relatively good representation of the rest of the EU, although strictly speaking their findings cannot be extended beyond these countries. Focusing on data from the first and second phase, they match installations with similar emissions before implementing EU ETS. Further, they use a difference-in-difference model on the 240 EU ETS-installations and 160 non-ETS installations and find that the policy led to a 10–14 per cent emission reduction. This number is the average for the two trading periods; however, their estimations suggest most reductions happened in Phase II.[4] It supports the findings from both Wagner et al. (2013), and Petrick and Wagner (2014), who look at manufacturing plants in France and Germany, respectively.

Bayer and Aklin (2020), using a generalized synthetic control approach, concluding that the EU ETS lead to a reduction of 1.2 billion tonnes of CO_2, or 3.8 per cent relative to total emissions in the period 2008–2016, compared to a world without EU ETS. The authors look at sectors like energy, metal chemicals and minerals and find that emissions decreased between 20 and 25 per cent against the counterfactual. They also check for abatement effort in the transportation sector, which is considered unregulated, however, concludes that no significant emission reduction was found. They do not include aviation emission in any of their calculations.

Not surprisingly considering the emission trading scheme's nature, abatement has not evenly occurred across either member states or sectors. Ellerman et al. (2010) concluded that 80 per cent of abatement happened in EU-15 in Phase I. Further, Delarue et al. (2008; 2010) conclude the major abatement taking place in the power sector, with

[3] Emissions per unit of GDP.

[4] 6 per cent insignificant reductions in Phase I and 15 per cent significant reduction in Phase II.

fuel switching being the main driver of emission reductions during the first phase. The industry sector has also seen increasing abatement levels, despite the over-allocation of permits — most likely attributed to the trade of allowances with the energy sector (Ellerman et al., 2010). As mentioned previously, if the price of carbon permits (EUAs) is higher than an industry's marginal abatement cost, then it would be advantageous for them to trade the allowances given and invest in abatement efforts instead.

It has been argued that the EU ETS has not been as efficient in generating emission abatement due to the oversupply of EUAs (Dechezleprêtre et al., 2018; Ahmad, 2015; de Perthuis & Trotignon, 2014; Anderson & Di Maria, 2011). The issue with an oversupply of allowances surfaced already in Phase I. It was mainly due to the allowances (and cap) of Phase I being based on poorly verified estimates, resulting in the total amount of allowances issued exceeding actual emissions (EC, 2015). Consequently, the price of EUAs fell to zero in 2007. In Phase II the cap on allowances was reduced, as actual data was available. However, the recession in 2008/09 led to emission reductions much greater than anticipated — again leading to a large surplus of allowances. Even if the European Commission has tried to counteract these outcomes by delaying the auction of about 900 million EUAs to 2019/20, the response to the generally oversupplied market has been a low EUA price. As pointed out by Dechezleprêtre et al. (2018), a cap-and-trade system effectively reduces emissions so long as the cap is set tightly enough. Therefore, a surplus of allowances amounting to 2.1 billion in 2013 can be argued not to send the right incentives to participants to invest in low-carbon technology (de Perthuis & Trotignon, 2014). Despite this, there has been a total reduction in emissions.

The EU ETS and Aviation

Most studies that have addressed the inclusion of aviation in the EU ETS were published before the implementation. To my knowledge, no paper to-date attempts to analyse the impact of the inclusion of aviation in the EU ETS directly concerning CO_2 abatement in an ex-post fashion.

Anger (2010) analyses the aviation industry at an aggregate level using a data-driven model based on historical data combined with econometric forecasting, called E 3ME. To assess the short- and medium-run GHG mitigation, the author assumes based on the EC's then-current proposal. Furthermore, the author assumes aviation activity to grow by 2.5 per cent annually, with 1 per cent fuel efficiency improvement. Considering ICAO (2010) forecasted annual growth to be 4.8 per cent from 2010 onwards, in terms of revenue passenger kilometres (RPK), the growth prediction is relatively conservative. Anger (2010) concludes, assuming a 100 per cent cost pass-through rate, that including aviation in the EU ETS result in a yearly increase of CO_2 emissions by 0.09 and 0.24 per cent under the low and medium allowance prices, € 5 and € 20 respectively, but a decrease of 0.30 per cent with a high allowances price, € 40, in 2020 compared to a no-action scenario.

Schaefer et al. (2010), using a DLR-developed simulation model, analyse how the EU ETS will affect the air transport sector economically and ecologically. Based on 3.4–6 per cent forecasted growth in RPK and an assumed price of EUAs of € 40–55 for the period 2012–2020, they conclude the total cost for the aviation sector is expected to range between € 1.9 and € 3.0 billion in the year 2012 alone. Additionally, if successful in integrating non-EU carriers, the regulation will cover roughly one-third of global aviation emissions. It means that the aviation industry will need to buy allowances worth the equivalent of 48.1 million tonnes of CO_2 from stationary sources.

Vespermann and Wald (2011) employed a simulation model to estimate the effects of the EU ETS policy. Using input variables such as allowance price, average ticket price, efficiency gains, market growth, transport activity, and the price elasticity of demand, they find the financial burden on the industry to average € 3 billion a year but mentions that this number might vary according to fluctuating allowance prices and demand growth. They expect the cost of carbon permits to account for about 1.25 per cent of total industry costs. Further, they conclude the annual growth rate of CO_2 emissions to be 1 per cent lower under EU ETS than an unrestricted scenario — with emission reductions starting at 0.9 per cent in 2013 and rising to 7.7 per cent in 2020. The authors point out that the ETS system's ecological effects assume less air transportation demand due to increased costs will entail reduced fuel consumption because of less air traffic activity, thereby reducing emissions.

Although the restriction of growth in the aviation sector is not met — being a net buyer of EUAs, the industry will likely induce emission reductions in stationary sectors instead.

There has been no ex-post study that explicitly analyses EU ETS's effects on competitiveness in the aviation sector. However, Nava et al. (2018) develop a microeconomic model to explore the effects of applying EU ETS to the aviation sector. They conclude that two main factors influence airline profits; the share of allowances distributed for free, and the airlines' abatement effort costs. The latter negatively impacted, and the former quite intuitively a positive one. Anger (2010) asserts that it would be advantageous for non-EU airlines if they were exempt from the scheme, as they would be able to gain market share.

In contrast, Schaefer et al. (2010) point out that the competitive disadvantage for EU-airlines will happen when non-EU airlines are included in the scheme. It is because non-EU airlines operate mainly long-haul flights, which have comparably lower specific emissions under the ETS. Thus, the percentage of allowances allocated for free would be lower for EU-airlines than non-EU airlines. Vespermann and Wald (2011) believe competition distortions to be low, although dependent on the cost of EUAs.

In general, ex-post studies done on other sectors covered by the EU ETS do not find a significant negative impact on economic performance (Anger & Köhler, 2010; Commins et al., 2011; Chan et al., 2013; Martin et al., 2016; Dechezleprêtre et al., 2018), suggesting that the general concern for the loss of competitiveness might be exaggerated. Dechezleprêtre et al. (2018) imply that the insignificant effect on economic performance tends to be a combination of generous free allocation and low carbon prices.

Several authors (Anger, 2010; Schaefer et al., 2010; Vespermann & Wald, 2011) correctly anticipated that the aviation industry would be a net buyer of allocation emissions. Scheelhaase et al. (2012) estimated the EU ETS cost for airlines to be significant within the sector, amounting to € 20,502 million in 2012–2020. However, as with most research, the permits' allowance price has been grossly overstated. Instead of an allowance price of € 20, as generally assumed (Scheelhaase, et al., 2012; Albers et al., 2009; Anger & Köhler, 2010; Barbot et al., 2014; Malina et al., 2012; Schaefer et al., 2010; Pagoni & Psaraki-Kalouptsidi, 2016), between 2013–2017 the average price of an EU allowance varied between € 4 and € 6 and has not until recently increased above € 15 (EEX Group, 2020). The total cost for aircraft operators purchasing allowances needed for their emissions levels increased from € 89 million in 2013 to € 189 million in 2017 (EASA et al., 2019)—both numbers substantially smaller than the € 1.9 billion estimated by Schaefer et al. (2010). Moreover, for intra-EU operators, these costs only represent about 0.3 per cent of total operating costs (EASA et al., 2019). The operating costs have likely increased after the price jump in 2018. However, no report has yet been released confirming this.

While the research mentioned above is useful, it is all based on modelling scenarios of future events. There is still little known in practice about carbon pricing's effectiveness to reduce aviation emissions (Markham et al., 2018). All simulation studies rely on strong assumptions of EUA price, cost pass-through rates and demand elasticities, and unsurprisingly none predicted the "stop the clock" legislation to come into place.

Markham et al. (2018), analyse the effect of the Clean Energy Future (CEF) policy levied in Australia between 2012 and 2014. Using an OLS model with per capita RPK being the outcome variable, they found the carbon price (ranging between \$ 23.00AUD to \$ 24.15AUD per tonne of CO_2 equivalent) did not affect domestic air travel reduction. They suggested that infeasible fuel source switching and insignificant price signal generated by the carbon price in a very turbulent period to be partly reasons for this result. On the other hand, González and Hosoda (2016), analyzing a domestic fuel tax reduction in Japan, find that CO_2 emissions increased significantly (by 9.7 per cent) compared to a counterfactual scenario after the reduction date. Using a causal impact approach, a Bayesian structural time-series model proposed by Brodersen et al. (2015), they constructed the counterfactual time series with a set of covariates explaining jet fuel consumption behaviour before implementation.

Larsson et al. (2019) highlight that almost half of the EU population is subject to an air passenger tax. Although the taxes do not stimulate technological change the same way a carbon price intends to, it can reduce demand for air travel and emissions. To support this, Falk and Hagsten (2018), using a difference-in-difference model, investigate the impact of a flight departure tax introduced in Germany and Austria in 2011. They find that the tax, which leads to an increase in airfares, reduces the number of passengers — however, this is predominantly seen in airports used by low-cost airlines.

Fageda and Teixidó-Figueras (2020) provide the first complete ex-post evaluation of the EU ETS applied to the aviation sector. They investigate the causal impact of EU ETS on aviation supply. For data availability reasons, they measure aviation supply as available airline seats offered per route. They argue that due to the increased cost for regulated airlines, they will react by reducing supply and increasing prices, resulting in less demand. Similar to Falk and Hagsten (2018) they find that the overall effect of the policy has had a significant impact on low-cost carriers (LCC), resulting in LCCs supplying 7 per cent fewer seats than the counterfactual scenario (Fageda & Teixido-Figueras, 2020). The supply effects that occur can be due to LLCs withdrawing certain connections because of the tax. It has been seen done by Ryanair in several European countries when a passenger/flight tax was introduced, namely Germany (Zuidberg, 2015), England (Malighetti et al., 2016) and Norway (Halpern, 2018).

The effect of EU ETS on ticket prices has yet to be investigated. However, Pagoni and Psaraki-Kalouptsidi (2016) simulate how a market-based measure (MBM) in the American aviation industry would impact ticket prices and corresponding market shares. The carbon fee is incorporated in the airlines' marginal cost, and the increased cost forces airlines to adjust ticket prices to maximize profits. They find that ticket fares would increase by 1.2–11.8 per cent depending on the carbon price. A 1.2 per cent ticket increase represents a carbon price of $ 10 per tonne of CO_2; for an average Ryanair ticket fare in 2016, this would mean a price increase of approximately € 0.5. The authors also find that travel demand would at most decrease by 2.6 per cent under a high carbon price scenario ($ 100), so competition distortions are expected to be rather low. These findings reinforce what other researchers have concluded when analysing environmental policies in European and other markets (Anger, 2010; Malina et al., 2012; Miyoshi, 2014; Scheelhaase et al., 2010).

Methodology

This section presents a macroeconomic model intended to capture an emission trading system's causal impact on jet fuel consumption. The theory underlying the hypothesis will be explained, and the research design and data limitations of the estimation method outlined. The Generalized Synthetic Control method used to estimate the counterfactual and find the average treatment effect of the treated will be given in more detail before the model specification, and a summary of the data is shared.

Hypothesis

The permit price generated by the ETS becomes part of an airline's cost structure. Regardless of the allowance being purchased or freely allocated, the opportunity cost remains the same. In the margin, the freely allocated EUA has an opportunity cost equal to the revenue earned if sold. Thus, emitting an extra tonne of CO_2 means the airline either must buy an allowance or forgo the possibility of selling a freely allocated one. A profit-maximizing firm will factor these costs into their output and price decision (Fageda & Teixido-Figueras, 2020). Brueckner and Zang (2010) point out that the permit price (the EUA price) is effectively added to fuel price. Hence the ETS can be viewed as a carbon-tax scheme applied to aviation. Therefore, the effect of this policy should work in the same way a fuel-price increase would.

Intuitively, a carbon tax increases carbon-based production cost, leading to a decreased demand or a substitution between production or technologies. The latter is mainly seen in stationary sectors (Martin et al., 2016; Dechezleprêtre et al., 2018). As appropriately pointed out by Markham et al. (2018), in air travel, an initial effect of carbon pricing should lead to decreased travel demand since technology improvements such as replacing aircraft fleets cost time and money. An effective carbon price should theoretically reduce aviation emissions by increasing the airlines' cost, leading to less supply and less demand. Even if the ETS system's cost is wholly or partially passed through to the passenger, the resulting higher ticket prices should lead to the same reduction in demand (Vesperman & Wald, 2011). Fageda and Teixido-Figueras (2020) shared this view, who predicts that the increased cost of the EU ETS should result in airlines lowering their supply. Therefore, it is reasonable to assume that the same increased cost will negatively impact jet fuel consumption due to the lowered transportation activity, hence reducing emissions.

Emissions produced by aircraft primarily come from jet fuel combustion, where CO_2 accounts for approximately 70 per cent whilst the rest is mainly made up of water vapour (EUROCONTROL, 2018). Airlines reporting to the EU ETS calculate their emissions by multiplying jet fuel consumption (in tonnes) by 3.15, which is IPPCs default emission factor. Therefore, this paper uses jet fuel consumption as a proxy for emissions.

It is known that overall emissions have increased in the aviation sector over the past 30 years, mainly attributed to strong passenger growth and limited technology improvements. Even though we assume the cost imputed by the ETS system should discourage emissions, most studies conclude the EU ETS is having a relatively small impact on aviation emissions, generally due to the high marginal abatement costs (Malina et al., 2012). Further, if the general assumption is that market prices should equal the social cost of carbon (Nordhaus, 2017), when a mismatch is seen it is logical to conclude that market prices are not high enough to encourage abatement. Following this, even if the hypothesis suggests a negative impact, with the recent trend of EUA prices, it is unlikely that any evidence of abatement attributed to the EU ETS will be found. However, Bayer and Aklin (2020) point out that even if the oversupply of permits leads to low prices, the reverse might not be true. Prices can be low because of decreasing demand for carbon permits; therefore, market prices should not be relied on when evaluating a policy's effectiveness.

Accordingly, this paper will explore the EU ETS hypothesis, leading to a reduction in jet fuel consumption by implementing a GSC method to estimate the counterfactual.

Research Design

Many factors impact an aircraft's fuel consumption; these can be technological, operational, socio-economic and/or fuel-specific (Singh & Sharma, 2015). Papers concerned with modelling aviation fuel demand tend to focus on factors like economic growth (GDP), fuel price, airline traffic data, and efficiency gains (Mazraati & Faquih, 2008; Mazraati & Alyousif, 2009; Chèze et al., 2011b; Singh & Sharma, 2015; Lo et al., 2020).

GDP is the economic driver of passenger traffic and deemed the most important determinant for leisure travellers (Gately, 1988; Eyers et al., 2004; Mazraati & Faquih, 2008; Lee et al. 2009). The real GDP growth rate is also shown to be correlated with a growth rate of Passenger Kilometre Performed (PKP) (Mazraati & Faquih, 2008). PKP is strongly associated with air traffic and provides information on a number of kilometres travelled by all passengers (EUROCONTROL, 2018).

The number of passengers carried by aircraft, in terms of weight, and the flight's length play an important role in terms of fuel consumption. It is logical to assume that fuel consumption will increase if the total kilometres flew increases and/or if the aircraft's weight increases (Fukui & Miyoshi, 2017). An aircraft's efficiency gains tend to focus on fuel consumption used per passenger kilometre flown. The less energy an aircraft can spend on moving a set amount of passengers from A to B, the more efficient the aircraft is (Jordão, 2016). Fuel efficiency is related to the type of aircraft used and the type of flight. Short-haul flights are generally less fuel-efficient than longer-haul flights due to the more frequent take-off and landing phases and offer higher daily frequency and lower average passenger load factors[5] (Chèze et al., 2011b; Miyoshi, 2014; Jordão, 2016).

It would be ideal for including PKP to control air traffic, as some countries experience more traffic than others due to tourists' higher levels. Additionally, considering fuel consumption per mile flown has decreased over the past 25 years (Fukui & Miyoshi, 2017), it would be intuitive to adjust total consumption by the length of flights. Unfortunately, this data is either sparse, behind payment walls or reported differently than the outcome variable.[6]

Ticket prices are also an important consideration measuring consumers' willingness to pay, or price-demand elasticity. Since ticket prices are primarily driven by jet fuel price (Chèze et al.,

[5] Load factor measures the capacity utilization of an aircraft, that is, the average ratio of available seats to passengers carried.

[6] Generally reported as scheduled traffic of airlines registered in the country — and not the total number of passengers departing the country.

2011b), one can use jet fuel price as a proxy for measuring the relative changes.

When analysing a policy implementation, it is crucial to have data containing values, both pre- and post-treatment. The method used in this paper, the Generalized Synthetic Control, uses information from the pre-treatment period to create a counterfactual. As Ellerman and Buchner (2008, p. 277) point out, "*forming a good estimate of the counterfactual is complicated by the lack of historical data corresponding to the installations included in the scheme*".

Ex-post studies done on a sectorial level tend to use the UNFCCC CRF data as a proxy for EU ETS sectors' historical emissions (Ellerman & Feilhauer, 2008; Ellerman et al., 2010; Egenhofer et al., 2011; Bayer & Aklin, 2020). Aviation activities, being a non-stationary emission source, lack an explicit agreement among countries of *who* is responsible for emission from flights crossing borders. The UNFCCC divides aviation activities into two groups: Domestic Aviation, and International Aviation, with the latter not counted in any national inventories, rather it is part of an "international bunker" category. UNFCCC (1996) outlined eight options to allocate GHG emissions from international bunker fuels (see **Appendix 3.1**). The EU ETS uses option (4) for data gathering and permit distribution purposes, whilst the UNFCCC uses option (3) in their CO_2 emission data reporting. Therefore, looking at emission data in the overlapping period (2012–2018), the EU Transaction Log (EUTL) data far from corresponds with UNFCCC observations.

Thus, this study encounters two major issues: (1) there exists no source distinguishing intra-EU flights from extra-EU flights at an aggregate level; and (2), there exists no freely available source that reports emission data, or jet fuel consumption data, in the same format as EUTL.

Unfortunately, the data gathering needed to get past these issues is too complicated and time-consuming for this project. Instead, this paper will focus on whether aviation's inclusion in the EU ETS has impacted aggregate jet fuel consumption in the member states. The jet fuel consumption will refer to all jet fuel sold in a country for international or domestic (commercial) travel or freight transport. However, this paper recommends gathering data on the specific airlines and affected routes for a more accurate analysis of EU ETS's impact on CO_2 abatement in the aviation sector for future research.

It is worth noting that since the analysis will include all air travel, and not just the one directly affected by the EU ETS, it will be difficult to conclude any causal relationship. The results produced will, therefore, have to be interpreted with caution. Since the EU ETS covers a whole region, the effects being picked up merely reflect a growth pattern in the affected area that differs from the control countries.

Because of the nature of the aviation market, specifically in terms of market maturity, the dataset includes observations from OECD and Annex I countries (see **Appendix 2**). In addition to data availability, these countries will likely show similar trends in growth, technology- and efficiency improvements due to their economic situation. Previous studies modelling jet fuel demand have also distinguished between developing and OECD regions (Mazraati & Alyousif, 2009) or, matured and growing markets (Mazraati & Faquih, 2008). The latter authors, supported by Chèze et al. (2011a), point out that variables affecting demand for aviation, hence fuel, differ in magnitude depending on the market's maturity and economic development.

According to a report from Transport & Environment (2020b) the top six EU emitting groups are Germany, Spain, Nordics, Benelux, France and Italy, account for 73 per cent of intra-EU fuel burn. The UK is also part of this group, with the largest emissions in EU-28, at 18 per cent. Considering the EU ETS only regulates intra-EU flights, a sub-group including these countries is separately analysed. Their total fuel consumption could potentially "pick up" the ETS effect better due to their high share in intra-EU fuel burn.

Empirical Strategy

The analysis in this paper aims to explore whether the inclusion of aviation activity in the EU ETS has led to emission abatement relative to a counterfactual where the EU ETS was not implemented. Issues with the counterfactual estimations have been prominent throughout most EU ETS studies.

The difference-in-difference (DiD) method is one of the most used empirical designs in social science, specifically on a micro-level. Several studies use DiD trying to draw a causal inference of the EU ETS on ecological or economic factors using firm-level data (for example Martin et al., 2016; Dechezleprêtre et al., 2018; Fageda & Teixido-Figueras, 2020). However, when data becomes aggregate, the assumptions underlying the DiD method are likely to fail. Most prominent is the parallel trend assumption, where treated and control units follow parallel paths in the pre-treatment period. This assumption most likely fails due to unobserved time-varying cofounders (Xu, 2017), thus leading to biased estimates (Abadie, 2020). The synthetic control method first proposed in Abadie (2003) and further developed in Abadie, Diamond and Hainmueller (2010; 2015) was created to deal with this and handle estimated effects of aggregate interventions. That is, interventions affecting a small number of large units (like cities, regions, countries etc.) (Abadie, 2020). In fact, due to the limitations of traditional regression analysis techniques, it is not possible to claim any causality using aggregate data on country or sector level — rather it produces estimates on the economy- and sector-wide effects (Dechezleprêtre et al., 2018).

The basic idea behind synthetic control is to provide a combination of control units compared to the unit exposed to the intervention, rather than one control unit. Furthermore, to ensure a parallel trend, treated and control units are matched based on pre-treatment covariates and outcomes (Abadie, 2020). The "synthetic control unit" created is thus a combination of reweighted control units. The drawback is that it is only applicable to data with one treated unit. As mentioned previously, Bayer and Aklin (2020) focus on the impact of EU ETS on CO_2 emissions at the sector and country levels. They argue that due to their data's nature, as the simultaneous implementation of the EU ETS in multiple countries, the best estimation technique is the Generalized Synthetic Control (GSC).

The Generalized Synthetic Control method was developed by Xu (2017) to further build on the method developed by Abadie et al. (2010). Similar in spirit to the synthetic control, the GSC uses a reweighting scheme to construct the counterfactual. However, instead of matching, it estimates a linear interactive fixed effects (IFE) model using only the control variables before assigning weights. The IFE model, proposed initially by Bai (2009), is another way to model unobserved time-varying cofounders, called latent factors. The latent factors represent common shocks, like the financial crisis, and their heterogeneous impact on countries' economies. If the appropriate control variables are included, the model can also pick up other legislation and policies affecting the outcome variable, like a carbon tax. The GSC, therefore, links synthetic control and IFE to addresses several treated units whilst accounting for heterogeneous treatment effects (Xu, 2017).

Empirical Model

To estimate the average treatment effect of the treated (ATT), this study follows the procedures outlined in Xu (2017). Firstly, we have $N = N_{tr} + N_{co}$ number of units, where N_{tr} and N_{co} are the numbers of treated and control units, respectively. All units are observed for $t = 1,\ldots,T_0,\ldots,T$ periods, and all treated units are exposed to the treatment at the same time, T_0.

A linear factor model gives the functional form of the model:

$$Y_{it} = \delta_{it} D_{it} + X'_{it} \beta + \lambda'_i F_t + \varepsilon_{it},$$

where the treatment indicator D_{it} equals 1 if unit i has been exposed to the treatment at the time $t \geq T_0$ and equals 0 otherwise. δ_{it} is the heterogeneous treatment effect on unit i at time t; X_{it} include observed covariates, and β represent their unknown parameters; F_t is the unobserved common factors (time-varying coefficients) and λ_i is their unknown factor loadings (unit-specific intercepts). Finally, ε_{it} represents unobserved idiosyncratic shocks for unit i at time t, with an assumed mean of zero.

The factor component of the model, $\lambda'_i F_t$, takes a linear, additive form by assumption. So long as the unobserved random variable can be decomposed into a multiplicative form, it will be absorbed. However, the factor component does not capture unit-independent unobserved confounders.

The GSC estimator for the treatment effect of treated unit i at time $t \geq T_o$ is given by the difference between the actual outcome and the estimated counterfactual: $\hat{\delta}_{it} = Y_{it}(1) - \hat{Y}_{it}(0)$. Xu (2017, pp. 62–63) refers to it as an out-of-sample prediction method based on Bai's (2009) factor augmented model. $Y_{it}(1)$ denotes the actual observed outcome of treated units and $\hat{Y}_{it}(0)$ is the estimated counterfactual. The counterfactual is calculated in three steps:

$Y_{it} = X_{it}\beta + \lambda_i F_t + \varepsilon_{it}$, for control group data N_{co}, $t = 1, \ldots, T$,

$Y_{it} = X_{it}\hat{\beta} + \lambda_i \hat{F}_t + \nu_{it}$, for treatment group data N_{tr}, $t < T_0$,

$\hat{Y}_{it}(0) = X_{it}\hat{\beta} + \hat{\lambda}_i \hat{F}_t$, for treatment group data N_{tr}, $t \geq T_0$.

The first step estimates the IFE model using only the control group data to obtain $\hat{\beta}, \hat{F}$. The second step estimates factor loadings, $\hat{\lambda}_i$, for each treated unit by minimizing the mean squared error of the predicted treated outcome in pre-treatment periods. The third step uses $\hat{\beta}, \hat{F}, \hat{\lambda}_i$ obtained previously to calculate the counterfactual $\hat{Y}_{it}(0)$ for the treated had they not been subject to treatment. The average treatment effect (ATT) for all treated units will thus be:

$$\widehat{ATT}_t = \left(\frac{1}{N_{tr}}\right)\sum_{i \in T}\left[Y_{it}(1) - \hat{Y}_{it}(0)\right] for\ t \geq T_o.$$ [7]

One additional strength to this method is that the data algorithm developed to use a cross-validation procedure to select the number of factors included in a model that gives the most accurate predictions before estimating the causal effect. It works well in practice where limited knowledge of exact numbers of unobserved factors often is a problem.

Model Specification

The output variable, Y_{it}, is *Jet fuel consumption per capita*. It is an annual measure of all jet fuel (in metric tonnes) sold for commercial use in a selected country i for the period $t = [1990, \ldots, 2019]$. The model specification used in this analysis is as follows:

$$\left(\frac{Jet\ fuel\ consumption}{Population}\right)_{it} = \hat{\delta}_{it}\ ETS_{it} + \hat{\beta}X_{it} + \hat{F}\hat{\lambda}_i + \varepsilon_{it} \quad (1)$$

Where $ETS_{it} = \{1, 0\}$ is the binary treatment indicator, and X_{it} is a vector of control variables, $\hat{F}$ represents common shocks and $\hat{\lambda}_i$ picks up the heterogeneous impact of these shocks on country i. Finally, ε_{it} is the country-specific error term of output.

When we use macroeconomic data, the control variables should include important drivers for the dependent variable (Bai, 2009). Therefore, in a similar fashion to Bayer and Aklin (2020), the main specification includes *GDP per capita* and *GDP per capita*^{2} as control variables (Model 1). Although simple, the model captures the data's variability well, especially when allowing interactive fixed effects. It is common to assume the underlying relationship between GDP and jet fuel consumption to be concave. It is also the expected relationship if following the Environmental Kuznets Curve (EKC) hypothesis.

A second model specification includes *inbound tourists* as an additional control variable (Model 2). It adjusts for a high jet fuel consumption per capita in countries with the strong tourism industry. Although the measure includes all overnight tourist entering the country via any transportation method, since over half of all international tourists fly to their destinations (ATAG, n.d.), it will hopefully control some of the effects of aviation passengers. This control variable enforces the results seen in the first specification, thus providing robustness to the results.

Other factors previously identified as good determinants of jet fuel consumption should be picked up as latent factors due to the IFE estimations' mechanisms. It includes jet fuel price and efficiency gains, as they are both common regressors. Further, ticket prices cannot be easily measured at an aggregate level; instead, GDP per capita acting as a proxy for household income should represent general affordability (Markham et al., 2018). Finally, exogenous shocks either affecting economic activity, or the aviation industry specifically, do not need to be explicitly modelled as all regions will experience them. The IFE will pick up the heterogeneous effects of these.

Like most econometric methods, the GSC works best when the model is correctly specified. Xu (2017) performs Monte Carlo exercises to test the method and find that in the presence of decomposable time-varying confounders the GSC has less bias than the two-way fixed effects estimator, where DiD is a specific version. Further, it corrects the IFE estimator's bias when the treatment effect is heterogenous; and finally, it is generally

[7] For further explanations and step by step calculations, please refer to Xu (2017).

more efficient than the SC method. However, it is worth noting that insufficient data — either a short pre-treatment period or a small number of control units[8]—can cause bias in the estimated treatment effect. Due to this dataset's characteristics, this is something to be cautious of when interpreting the results.

Data

Data on annual jet fuel consumption, measured in 1000 metric tonnes, is downloaded from U.S Energy Information Administration. Across the 45 countries included in the sample, the panel data is slightly unbalanced with 1,297 observations in total for Model 1, and 1,053 observations for Model 2. Figures 1 and 2 show an overview of the missing observation in the two models, in addition to control and treatment countries.

Annual data for GDP, GDP per capita and Population are all obtained from the World Bank Development Indicators database. GDP and GDP per capita are expressed in current US dollars. Finally, numbers on international inbound tourists are also taken from the World Bank database and refer to the number of overnight tourists arriving in a country other than those they usually reside.

Jet fuel consumption per capita is established by first multiplying jet fuel consumption by 1000 to change the measurement from mmt[9] to metric tonnes (mt). It is then divided by the corresponding population measurement.

Although it is correct to assume that EU ETS came into effect in 2012, the original directive included all routes to and from the EU. The "stop the clock" legislation was only applied right before airlines were supposed to surrender their allowances for 2012, with backdating properties. Therefore, it was not until 2013 when officially only flights within the EU were affected. Because of there being no clear control group in 2012, in the estimations, 2013 is regarded at the official start of the EU ETS (Fageda & Teixido-Figueras, 2020).

Descriptive statistics are reported for the entire period by treatment and control group in **Appendix 3.2**, and for the pre-treatment period in **Appendix 3.3**. As seen in both tables, the mean values for control and treatment groups are quite different. It supports using a GSC method rather than a DiD method, as the parallel trend assumption would be violated.

Results

The results from the GSC estimation are shown in Table 1. The ATT coefficient row shows the aggregate average treatment effect, which is the difference between the treated countries' average outcome against its estimated counterfactual. Although it is reported as one number, the treatment effect is not constant over years or countries and would differ depending on the country, or year looked at.

The programming code, *gsynth*, provided by Xu (2017) includes an option to implement the Expectation Maximization (EM) Algorithm developed by Gobillon and Magnac (2016). The EM method uses pre-treatment information for the treated group, thus providing more precise estimated coefficients. Applying this method leads to a better pre-treatment fit and improves the results' significance. Considering the sample includes more treated than control variables, using pre-treatment information of treated units can prove important when calculating the counterfactual. Therefore, all results reported are calculated using the EM method.

A parametric bootstrapping with 1000 runs is used to generate a 95 per cent confidence interval around the ATT estimates, following what was implemented in Xu (2017, p. 65). Due to the small sample size of treated variables, it is impossible to approximate this nonparametrically, without risking biased results. An appealing alternative to bootstrapping when the number of treated units is small is a jack-knife resampling (Liu, Wang & Xu, 2020). Although it might not provide better uncertainty estimates, it can offer a worthwhile robustness check to see whether a single observation is driving our results due to our sample size. The results from using a jack-knife resampling reinforce the legitimacy of the findings below and a full description is provided in **Appendix 4.1**.

All specifications outlined in Table 1 impose additive country and year fixed effects. In addition to the two model specifications outlined earlier, column (1) runs the estimation with no controls included. When controlled for the covariates included in (2) and (3) are assumed to have a con-

[8] $t < 10$ and $N_{co} < 40$.

[9] Reported by the EIA source to equal 1000 metric tonnes.

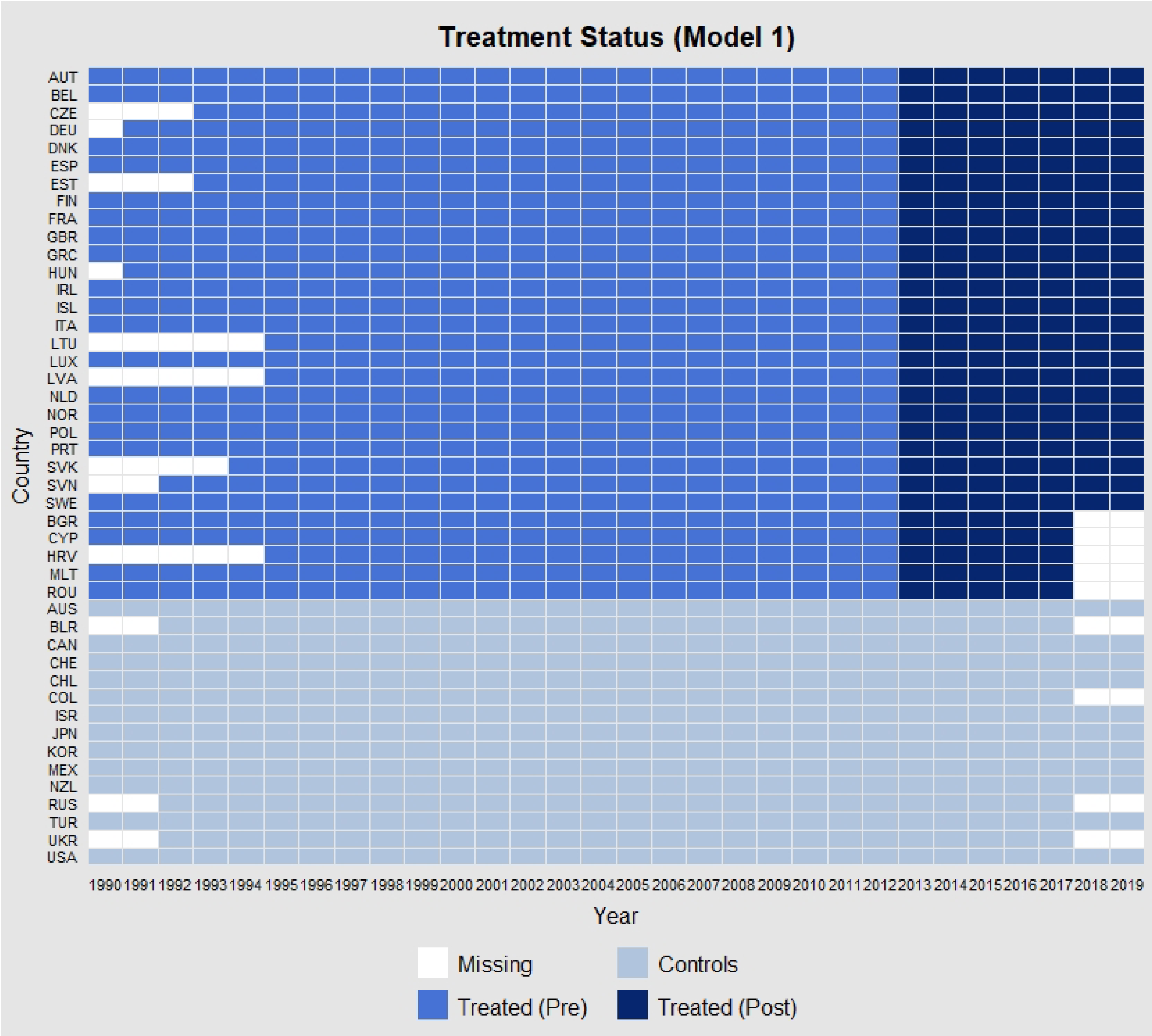


Fig. 1. Observations and treatment status Model 1

stant effect on the outcome variable. Three unobserved factors are found to be important with both specifications, using the cross-validation scheme. Focusing on the main model (1), the estimated ATT predicts jet fuel consumption per capita to increase by 0.01531 when countries are subject to the EU ETS. Dividing the ATT by the mean jet fuel consumption per capita seen in treated units for the post-treatment period, reported in **Appendix 3.4**, we find that the EU ETS is associated with a statistically significant increase of 10.2 per cent in jet fuel consumption per capita.

Figure 3 show the dynamics of the estimated ATT.[10] The left figure depicts the mean path for actual jet fuel consumption per capita figures for treated countries (solid line) relative to a counterfactual scenario (broken line). The average consumption and the average predicted consumption match well before treatment before diverging after EU ETS took effect. It demonstrates that the statistical method has provided a good counterfactual. The right figure reinforces that that gap is essentially zero before treatment and the effects happen after implementation. Since the GSC method minimizes gaps between the actual and predicted outcomes in pre-treatment periods, this result is not surprising. However, it is surprising that the EU ETS has led to affected countries having a higher jet fuel consumption (per capita) than what is estimated had the EU ETS not come into effect. It goes against the theoretical hypothesis outlined above.

The results for each of the 30 countries subject to the EU ETS are reported in **Appendix 4.3**. Approximately 14 are experiencing a negative ATT differing in significance, though the pre-treatment fit for some of these countries is debatable. In

[10] The period shown in the figures have been limited to 1995–2017, where a perfectly balanced panel dataset is present.

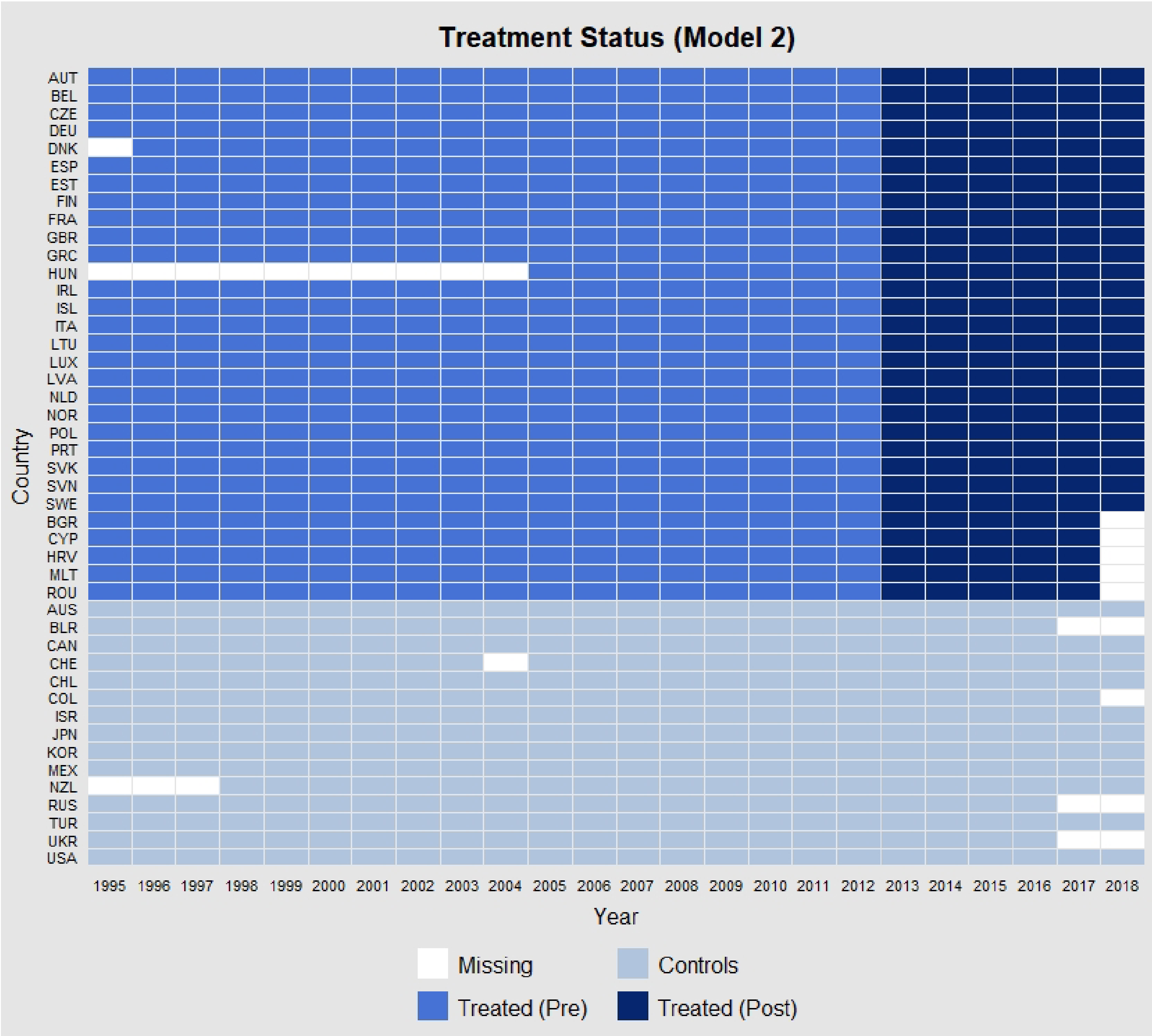


Fig. 2. Observations and treatment Status Model 2

general, better plots tend to follow the positive trend shown above. Overall, countries with larger jet fuel consumption values have a clear pattern, driving counterfactuals results.

In addition to looking at the treated and counterfactual averages, the estimated factors and factor loadings produced by the GSC method are shown in Figure 4. Figure 4a plots the three estimated factors. The x-axis shows the year and the y-axis the magnitude of the factors. Figure 4b depicts the estimated factor loadings for each treated and control variable, with the x-and y-axes indicating the magnitude of the loadings for the respective factors. The estimated factors might not be directly interpretable, as they are, at best, linear transformations of the true factors (Xu, 2017). Factor 3 in (a) looks to plot out the negative relationship between jet fuel consumption and jet fuel price. The negative impact after the year 2000 corresponds to the sharp price increase between 2000–2009. Jet fuel consumption responded positively to the short drop in prices after 2008/09. However, the negative trend associated with high prices continued until around 2015, where prices started to fall considerably. Factor 1 and 2, set almost orthogonal to each other, seem less interpretable, although both point to a positive effect on jet fuel consumption post-2013. The estimated factor loadings (b) of the treated units tend to overlap the control units. It is a reassuring finding, as it shows more reliable interpolations rather than extrapolations mostly estimate the counterfactuals produced.

Often researchers log variables to either normalize the values or reduce the influence of outliers. The main model estimations have been repeated for a log-log specification, with results reported in **Appendix 4.2,** to explore whether

Table 1
Results

Outcome Variable: Jet Fuel Consumption per capita (mt)	**(0)**	**(1)**	**(2)**
ATT Coefficient	0.01745***	0.01531***	0.01581***
Standard Error 95% Confidence Interval	(0.00457) [0.00898–0.0271]	(0.003842) [0.009349–0.02416]	(0.003218) [0.00874–0.02138]
GDP per capita[a]		1.813*** (0.2185)	1.317*** (0.217)
GDP per capita^{2} [a]		−0.000006568* (0.000002274)	−0.00000261 (0.000001741)
Inbound tourist[a]			−0.00007903 (0.0001187)
Country & Year fixed effects	Yes	Yes	Yes
Unobserved factors	2	3	3
Observations	1297	1297	1039
Treated countries	30	30	29[b]
Control countries	15	15	15

Notes.
***, **, and * denotes significance at 1%, 5%, and 10% levels, respectively.
Standard errors are presented in parentheses, and 95% confidence intervals are presented in brackets.
a: values are adjusted for visualisation purposes and should be multiplied by 10^{-6} to show true results
b: Hungary is dropped from the sample due to too few (< 12) pre-treatment observations.

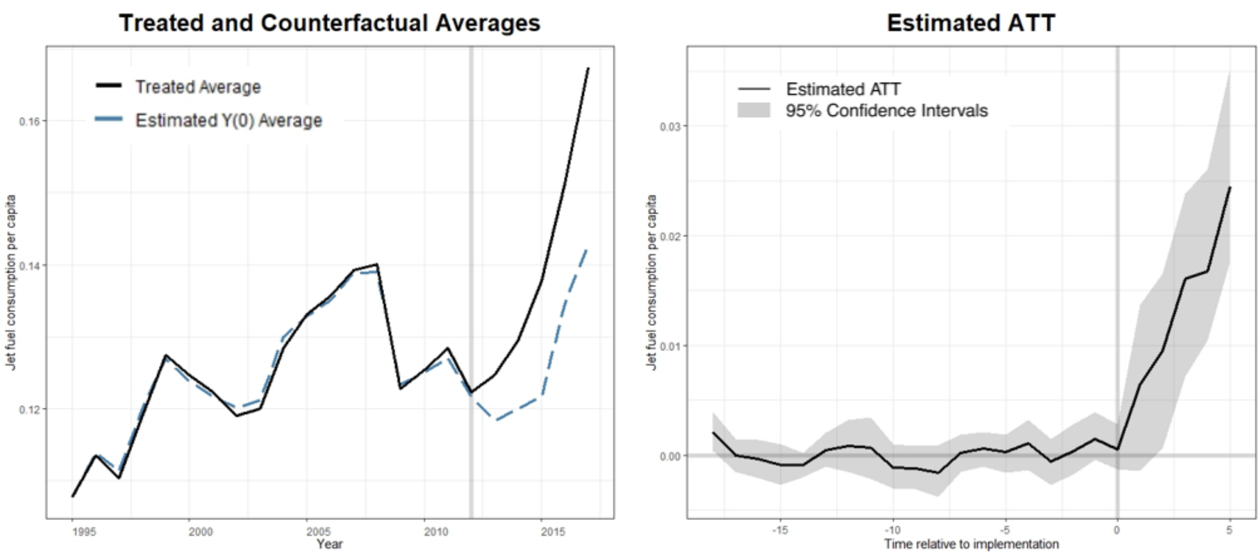
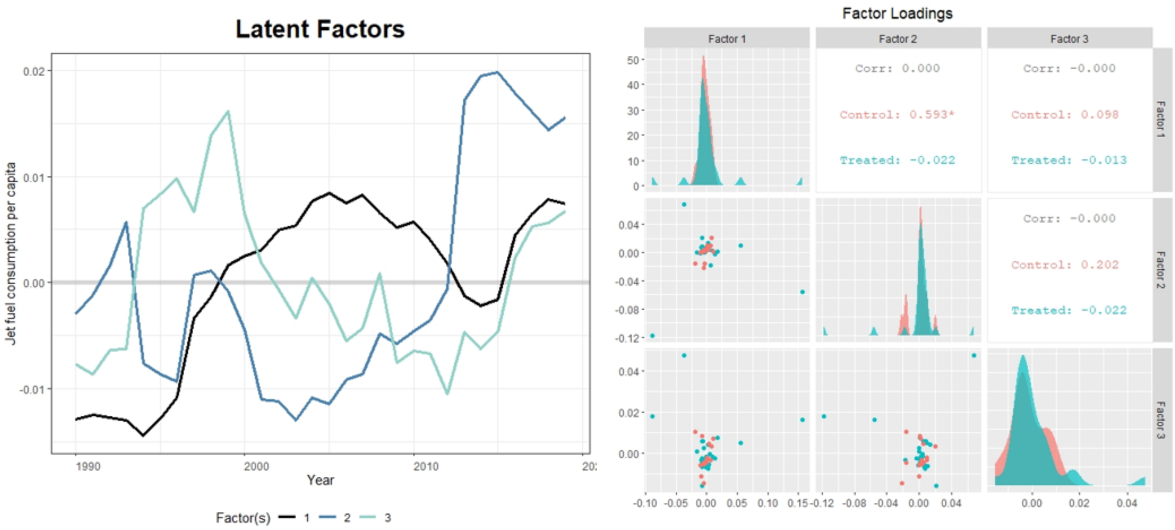


Fig. 3. The effect of the EU ETS over time, sample averages

this would affect the results. The log-log model results underpin the findings above, although the ATT varies in magnitude. Convincingly, the level model presents a "cleaner" result, with easier interpretable coefficients. Moreover, by adjusting aggregate jet fuel consumption by population, it captures consumption relative to a country's size and makes some control units, like the USA, more comparable to smaller countries. Nevertheless, there remain outliers in the sample with reported values much higher than the rest. However, with the GSC method assigning both positive and nega-



(a) Factors (b) Loadings

Fig. 4. The estimated factors and factor loadings produced by the GSC method

tive weights and not relying on a parallel trend assumption, this should not be a significant issue.

To strengthen the robustness of the GSC model results, Xu (2017) recommends benchmarking the results with estimates from the IFE model, if possible. Using a programming code, *fect*, developed by Liu, Wang, and Xu (2020), the IFE model is estimated. The IFE estimations are run only including GDP per capita as a control variable due to estimation issues when including a square value. The estimation yields a positive ATT, very similar to the one in the GSC estimation, although not statistically significant. Finally, a placebo test will run on the IFE model to test whether the estimated ATT is significantly different from zero for the range –3 and –5 years before the ETS implementation. The test returns the desired result, indicating that the policy's effect was not significantly different from zero before treatment. However, considering the IFE model results' insignificance, the placebo test does, unfortunately, not contribute to any valuable insights. The result and figure for the IFE model and the placebo tests figures are included in **Appendix 4.4** and **4.5**, respectively.

Sub-Group

As mentioned in the methodology, due to their high share of intra-EU fuel burn, 12 treated countries[11] are evaluated in a separate sample. Table 2 outlines the results. An overview of missing observations and treatment status is found in **Appendix 4.6.**

Following the same model specifications and estimation techniques as the full sample, the ATTs reported in Table 2 represent a negative effect after including controls (column 2–3). However, the results are not statistically significant. The ATT of the main model (1) represent a 1.5 per cent decrease in jet fuel consumption per capita for the countries affected by the EU ETS in the sub-sample, relative to a counterfactual.

Figure 5 shows the effect of the EU ETS over time. Again, a good-pre-treatment fit is seen in both panes, and the effect looks to take off right after implementation. However, this time the magnitude of the EU ETS is not as clear, including both negative and positive spikes, thus not ruling out its effect being zero.

Limitations and Discussion

Carbon pricing is an approach used to reduce carbon emissions by impacting firms' marginal costs, regardless of being delivered through carbon taxes or cap-and-trade systems. The results obtained from the full sample model, however, contradicts this.

There are several liable reasons why the effects were seen opposite from the predictions, most prominent is the limitations regarding the data. Not being able to distinguish jet fuel consumption used for intra-EU travel from consumption used for extra-EU travel makes it difficult to at-

[11] Belgium, Denmark, Finland, Germany, France, Italy, Luxembourg, Netherlands & Norway.

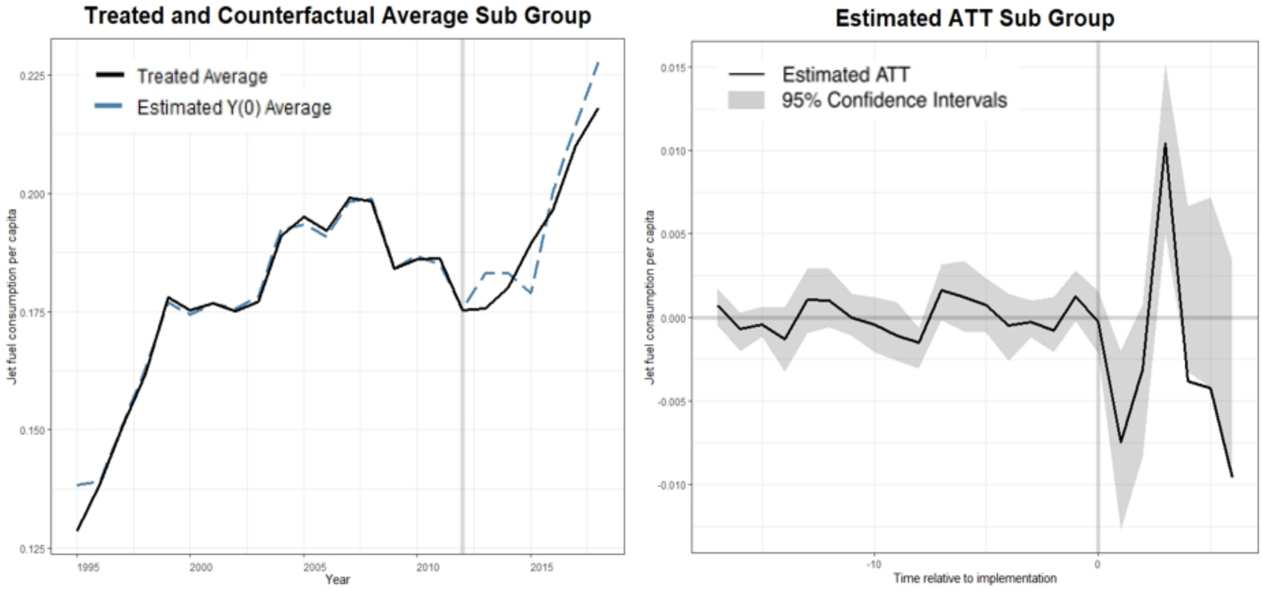


Fig. 5. The effect of the EU ETS over time, sub-group sample averages

Table 2
Sub-group Results

Outcome Variable: Jet Fuel Consumption per capita (mt)	**(0)**	**(1)**	**(2)**
ATT Coefficient	0.00007498	−0.002971	−0.004158
Standard Error 95% Confidence Interval	(0.005167) [−0.01153–0.008304]	(0.001876) [−0.003595–0.003336]	(0.001819) [−0.004648–0.002513]
GDP per capita[a]		0.831*** (0.1034)	0.6185*** (0.1035)
GDP per capita^{2} [a]		0.000002192*** (0.000000754)	0.000003539*** (0.0000007591)
Inbound tourist[a]			−0.0004237*** (0.00006808)
Country & Year fixed effects	Yes	Yes	Yes
Unobserved factors	2	4	4
Observations	636	636	636
Treated countries	12	12	12
Control countries	15	15	15

Notes.
***, **, and * denotes significance at 1%. 5% and 10% levels, respectively.
Standard errors are presented in parentheses, and 95% confidence intervals are presented in brackets.
a: values are adjusted for visualisation purposes and should be multiplied by 10^{-6} to show true results.

tribute the whole treatment effect to the EU ETS. Moreover, the EU ETS measures emission from airlines registered in a country, rather than all flights departing from that country as reflected in this papers' outcome variable. Therefore, it is likely that the treatment variable picks up impacts on jet fuel consumption caused by confounding variables not included in the model. Not accounting for all confounding variables violates the assumption of strict exogeneity and generates the results to be biased.

As previously mentioned, the factor component cannot capture unobserved confounders independent across units. Knowing that many of the countries included in the sample levies either a ticket tax or an exercise duty on domestic jet fuel, including a factor variable indicating whether a country has such a tax, and when it came into effect, might affect the results. Researchers have found both a tax on domestic fuel (González & Hosoda, 2016) and a flight departure tax (Falk & Hagsten, 2020) to have adverse effects. A ticket tax can be a reason why the sub-group estimates resulted in a negative ATT. A report from CE Delf and EC (2019) points out that the highest average aviation tax rates are found in the UK, Italy, Norway, Germany, and France. Ticket taxes have recently been included in Sweden as well. Although it should be possible to control such a factor in theory, it was left out of the model due to the data programming proving too difficult.

Assuming that the model is correctly specified and none of the assumptions underlying it is violated, one can argue that the EU ETS has failed its goal to reduce emissions in aviation. Although many researchers have concluded that the EU ETS has led to emission reductions during its first three phases, these studies have solely been based on stationary sources with abatement primarily seen in the power sector (Martin et al., 2016). In contrast, the aviation sector analysis has found inconclusive evidence that a carbon price has led to increased abatement efforts (Seetaram et al., 2014; Markham et al., 2018; Fageda and Teixido-Figueras, 2020). Significant, albeit small, reductions have been concluded through stimulations studies, although all assume a high allowance price (€ 50 and up).

Although this does not answer why a cap-and-trade system like the EU ETS should cause airlines to increase their emissions relative to a scenario where it was not implemented, the results are somewhat in line with Anger's (2010) predictions. When a relatively small permit price is seen (< € 20), a yearly increase of CO_2 emissions was calculated to be positive. Although Angers' (2010) estimations were smaller in magnitude than what this paper reports, the growth rate assumed in the paper is also one-third of actual passenger growth seen over the past seven years. Statista (2020) reports passenger traffic growth associated with all domestic and international flights by European airlines during 2013–2019 to average 6.2 per cent yearly, with fuel efficiency seeing an annual average improvement of 2.3 per cent (Enviro.aero, 2019). Thus, it is not unreasonable to believe that if the growth rate in Angers' estimations was increased, it could reflect similar results to what is seen in this paper.

The EC published a report (CE Delf & EC, 2019) that concluded that on average a 10 per cent increase in ticket prices would lead to a 9–11 per cent reduction in demand followed by a similar reduction in emissions, in the 27 member states included in the analysis. Empirical ex-post analysis of ticket taxes has found similar results (Falk & Hagsten, 2020). In contrast, IATA (2019a) argues that no government has demonstrated that a ticket tax has led to reduced emissions. Considering the highly competitive market that airlines operate in, instead of contributing to the decarbonizing of the aviation industry, taxes with "green" incentives have negative financial impacts on airlines hence limiting their ability to invest in newer, cleaner, and quieter technology. Arguably, without a tax, airlines already have an incentive to maximize fuel efficiency, considering fuel represents up to 30 per cent of operational costs (IATA, 2019b). The estimated costs of purchasing permits for intra-EU airlines in 2017 only represented about 0.3 per cent (EASA et al., 2019). Consequently, compared to large market swings in jet fuel prices, a tax set with a modest price, is thus expected to have little effect.

It underlines that the effectiveness of the ETS is reliant on EUA prices. When prices are set at an appropriate level, the incentives to abate are higher. Further, when the permit market is competitive, an appropriate price ensures no more profitable trade opportunities exist (Thomson Reuters Point Carbon, 2012). In turn, prices rely primarily on supply and demand. The EU ETS has arguably been oversupplied with allowances for most of its existence, limiting its economic and environmental impact. One could wonder whether the situation of allowances and the "willingness to purchase" these by the aviation sector would differ with a tighter cap.

Nonetheless, even if EU ETS has not had the desired impact on emission reductions in the aviation industry, it can still be effective. Returning to a carbon tax; it should encourage emitters to adopt the cheapest GHG abatement measures available to them. The EU ETS has proved that the cost of marginal abatement for airlines is far greater than the market price of permits, especially with continued growth in passenger traffic. Thus, this can be positively interpreted as the market-based mechanism working as intended. That is, emission abatement primarily taking place in sectors where it is cheapest and easiest to do so, whilst other industries, with little to no low-carbon substitutions, continue to pay to pollute (Markham et al., 2018). During 2012–2019 the aviation industry has purchased over 172 million tonnes worth of CO_2 equivalents either via auctions or other industries (EEA, 2020c). In a way, by purchasing emission allowances from stationary sources — the aviation sector is effectively offsetting their emissions.

Ahmad (2015) states that although the success of unilateral measures, like the EU ETS, is limited — it has led to ICAO speeding up its processes toward reducing emissions from international civil aviation. CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation) was ratified by the 39th ICAO assembly in October 2016. Another market-based measure, CORSIA realise that emission abatement is unlikely in the aviation sector with continued positive passenger growth. Thus its focus is on making sure aviation growth is offset elsewhere. CORSIA was agreed by 192 countries and marked the first MBM covering an entire international sector. Participation in voluntary until 2026, and as of 5th November 2018, 76 States have indicated that they will volunteer — representing 76 per cent of international aviation activity in terms of RTKs (EASA et al., 2019).

Conclusions

This paper has attempted to evaluate the effectiveness of the EU ETS by analysing whether the aviation industry's inclusion in 2012 has led to emission abatement. The GSC model results show that a 10 per cent increase in fuel consumption per capita is associated with being regulated by the EU ETS relative to a counterfactual scenario. Although the result is surprising, there is reason to believe that taxing aviation does not have the intended effect theory predicts. Since 2005 passenger kilometres flow have increased by 60 per cent, whilst average fuel consumption for commercial flights has decreased by 24 per cent. Thus, with the continued growth of passengers and limitations for technological improvement, there is no reason to believe a carbon tax will effectively lead to this trend changing. Instead, a tax might reduce the already low-profit margins and push airlines into financial difficulties with increasing operations costs.

However, the 10 per cent ATT predicted by the model fails to distinguish between intra- and extra-EU travel. Therefore, this leaves inconclusive results regarding the effects actually being attributed to the ETS. Attempting to account for this a separate model (including only the top intra-EU fuel burner countries) was estimated, and showed the effect, although insignificant, of the EU ETS to be −1.5 per cent. It is more in line with the theoretical hypothesis and other research suggesting a carbon tax, or cap-and-trade system, will effectively suppress demand (Fageda & Teixido-Figueras, 2020; Falk & Hagsten, 2020; González & Hosoda, 2016).

Arguably, even if EU ETS has not led to direct emission abatement through reduced jet fuel consumption, the aviation industry has still achieved emission reductions up to 172 million tonnes CO_2 equivalents in other sectors. It has also helped speed up the process of implementation of an international MBM, CORSIA. Whether CORSIA, including up to 76 per cent of all international aviation, will be more successful than the EU ETS remains to be seen.

This study is limited by data availability, and because of the likelihood of biased estimates, fails to conclude a causal impact of the EU ETS on aviation emissions. However, what is shown is that countries regulated by the EU ETS are associated with an increase in jet fuel consumption per capita, whether this is due to the EU ETS or other macroeconomic trends cannot be disentangled. Air travel is best analysed at the route level, as that is where competition occurs. By using aggregate values, the route-specific trends will not be picked up. Therefore, for all future research, it is recommended that data is gathered on the airline and/or route level.

Furthermore, one should distinguish the analysis by network and low-cost airlines and short, medium, and long-haul flights, as the different characteristics are likely to cause different results. There is still a lack of ex-post research concerned with aviation and carbon pricing. Some areas to address for future research can include; evaluating emissions directly; analysing changes to tickets prices, and; estimating effects on airlines revenue.

References

Abadie, A. (2003). Semiparametric instrumental variable estimation of treatment response models. *Journal of Econometrics*, *113(2)*, 231–263.

Abadie, A. (2020). Using Synthetic Controls: Feasibility, Data Requirements, and Methodological Aspects. *Journal of Economic Literature*, forthcoming.

Abadie, A., Diamond, A., & Hainmueller, J. (2010). Synthetic control methods for comparative case studies: Estimating the effect of California's tobacco control program. *Journal of the American Statistical Association, 105(490)*, 493–505.

Abadie, A., Diamond, A., & Hainmueller, J. (2015). Comparative politics and the synthetic control method. *American Journal of Political Science*, *59(2)*, 495–510.

Ahmad, M.T. (2015). Evaluating the Effectiveness of the European Union Emissions Trading System to Reduce Emissions from International Civil Aviation. *McGill International Journal of Sustainable Development Law and Policy*, *11(1)*, 115–181.

Air Transport Action Group (ATAG). (n.d.). *Adding value to the economy*, ATAG. Available at https://aviationbenefits.org/economic-growth/adding-value-to-the-economy/ [Accessed 20 September 2020]

Albers, S., Bühne, J.A., Peters, H. (2009). Will the EU-ETS instigate airline network reconfigurations? *Journal of Air Transport Management*, *15(1)*, 1–6.

Aldy J.E., Stavins, R. N. (2011). The promise and problems of pricing carbon: Theory and experience. *The Journal of Environment & Development*, *21(2)*, 152–180.

Anderson, B., Di Maria, C. (2011). Abatement and Allocation in the Pilot Phase of the EU ETS. *Environmental and Resource Economics*. *48 (1)*, 83–103.

Anger, A. (2010). Including aviation in the European emissions trading scheme: Impacts on the industry, CO2 emissions and macroeconomic activity in the EU. *Journal of Air Transport Management*, *16(2)*, 100–105.

Anger, A., Köhler, J. (2010). Including aviation emissions in the EU ETS: Much ado about nothing? A review. *Transport Policy*, *17(1)*, 38–46.

Bai, J. (2009). Panel Data Models With Interactive Fixed Effects. *Econometrica*, *77 (4)*, 1229–1279.

Barbot, C., Betancor, O., Socorro, M.P., Viecens, M.F. (2014). Trade-offs between environmental regulation and market competition: Airlines, emission trading systems and entry deterrence. *Transport Policy*, *33*, 65–72.

Bayer, P., Aklin, M. (2020). The European Union Emissions Trading System reduced CO emissions despite low prices. *Proceedings of the National Academy of Sciences of the United States of America*, *117(16)*, 8804–8812.

Bel, G. & Joseph, S. (2015). Emission abatement: Untangling the impacts of the EU ETS and the economic crisis. *Energy Economics*, *49*, 531–539.

Brännlund, R. & Lundgren, T. (2009). Environmental Policy Without Costs? A Review of the Porter Hypothesis. *International Review of Environmental and Resource Economics*, *3(2)*, 75–117.

Brodersen, K. H., Gallusser, F., Koehler, J., Remy, N., Scott, S.L. (2015). Inferring Causal Impact Using Bayesian Structural Time-Series Models. *The Annals of Applied Statistics*, *9(1)*, 247–274.

Brueckner, J. K., Zhang, Anming, A. (2010). Airline emission charges: Effects on airfares, service quality, and aircraft design. *Transportation Research Part B: Methodological, 44 (8–9)*, 960–971.

CE Delf and European Commission (EC). (2019). *Taxes in the field of aviation and their impact*. Directorate-General for Mobility and Transport, European Commission, Brussels. Available at https://op.europa.eu/en/publication-detail/-/publication/0b1c6cdd-88d3–11e9–9369–01aa75ed71a1 [Accessed 01 September 2020].

Chan, H.S., Li, S., Zhang, F. (2013). Firm competitiveness and the European Union emissions trading scheme. *Energy Policy, 63(C)*, 1056–1064.

Chèze, B., Gastineau, P., Chevallier, J. (2011a). Forecasting world and regional aviation jet fuel demands to the mid-term (2025). *Energy Policy*, *39(9)*, 5147–5158.

Chèze, B., Gastineau, P., Chevallier, J. (2011b). Air traffic energy efficiency differs from place to place: New results from a macro-level approach. *Economie Internationale*, *126 (2–3)*.

Commins, N., Lyons, S., Schiffbauer, M., Tol, R. (2011). Climate Policy & Corporate Behavior. *The Energy Journal*, *32(4)*, 51–68.

Cooper, R. (2010). Europe's Emissions Trading System. *Harvard Project on International Climate Agreements Discussion Paper 2010–19*, Cambridge, Mass.: Harvard Environmental Economics Program.

de Perthuis, C., Trotignon, R. (2014). Governance of CO_2 markets: Lessons from the EU ETS. *Energy Policy*, *75(C)*, 100–106.

Dechezleprêtre, A., Nachtigall, D., Venmans, F. (2018). The joint impact of the European Union emissions trading system on carbon emissions and economic performance. *OECD Economics Department Working Papers*, No. 1515. OECD Publishing, Paris.

Delarue, E., Ellerman, A.D., D'haeseleer W. (2010). Short-term CO2 abatement in the European power sector: 2005–2006. *Climate Change Economics, 1(2)*, 113–33.

Delarue, E., Voorspools, K., D'haeseleer, W. (2008). Fuel switching in the electricity sector under the EU ETS: Review and perspective. *Journal of Energy Engineering*, *134*, 40–46.

Dimitrios, D., Maria, S. (2018). Assessing air transport socio-economic footprint. *International Journal of Transportation Science and Technology, 7 (4)*, 283–290.

EEA (European Environment Agency). (2020a). *Annual European Union greenhouse gas inventory 1990–2018 and inventory report 2020*. Copenhagen, Denmark. Available at https://www.eea.europa.eu/publications/european-union-greenhouse-gas-inventory-2020 [Accessed 3 August 2020].

EEA. (2020b). *EEA greenhouse gas — data viewer*. Available at https://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer [Accessed 17 August 2020].

EEA. (2020c). *EU ETS Data viewer*. Available at https://www.eea.europa.eu/data-and-maps/dashboards/emissions-trading-viewer-1 [Accessed 23 September 2020].

EEX Group. (2018). Market Data — Environmental Markets.

Egenhofer, C., Alessi, M., Georgiev, A., Fujiwara, N. (2011). *The EU Emissions Trading System and Climate Policy Towards 2050: Real Incentives to Reduce Emissions and Drive Innovation?* Available at https://papers.ssrn.com/abstract=1756736 [Accessed: 21 July 2020].

Ellerman, A. D., Convery, F. J., de Perthuis, C. (2010). Pricing Carbon: The European Union Emissions Trading Scheme. Cambridge University Press.

Ellerman, A. D., Buchner, B. K. (2007). The European Union Emissions Trading Scheme: Origins, Allocation, and Early Results. *Review of Environmental Economics and Policy*, *1(1)*, 66–87.

Ellerman, A. D., Buchner, B. K. (2008). Over-Allocation or Abatement? A Preliminary Analysis of the EU ETS Based on the 2005–06 Emissions Data. *Environmental Resource Economics*, *41*, 267–287.

Enviro. Aero. (2019). *Tracking aviation efficiency, Factsheet 3*. ATAG. Available at https://aviationbenefits.org/media/166506/fact-sheet_3_tracking-aviation-efficiency.pdf [Accessed 18 September 2020].

EUROCONTROL. (2018). *D 2.3 European Aviation Fuel Burn and Emissions Inventory System for the European Environment Agency.* Whiteley, M., (ed.). EUROCONTROL. Available at https://www.eurocontrol.int/sites/default/files/content/documents/201807-european-aviation-fuel-burn-emissions-system-eea-v2.pdf [Accessed 13 September 2020].

European Commission (EC). (2003). *Directive 2003/87/EC* of the European Parliament and of the Council of 13 October 2003 establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC. Available at http://data.europa.eu/eli/dir/2003/87/oj

European Commission (EC). (2009). *Directive 2008/101/EC* of the European Parliament and of the Council of 19 November 2008 amending Directive 2003/87/EC so as to include aviation activities in the scheme for greenhouse gas emission allowance trading within the Community. Available at http://data.europa.eu/eli/dir/2008/101/oj

European Commission (EC). 2015. *EU ETS Handbook*, European Union. Available at https://ec.europa.eu/clima/sites/clima/files/docs/ets_handbook_en.pdf [Accessed 3 August 2020].

European Commission (EC). (n.d.). *EU Emissions Trading System (EU ETS),* European Union. Available at https://ec.europa.eu/clima/policies/ets_en [Accessed 3 August 2020].

European Union Aviation Safety Agency (EASA), EEA, EUROCONTROL, 2019. *European Aviation Environmental Report*. [online] Available at: https://doi.org/ 10.2822/309946 [Accessed 22 August 2020].

Eyers, C., Norman, P., Middel, J., Plohr, M., Michot, S., Atkinson, K., & Christou, R. (2004). AERO2k Global Aviation Emissions Inventories for 2002 and 2025. *QINETIQ Report to the European Commission*, December, UK.

Fageda, X., & Teixido-Figueras, J. J. (2020). Pricing Carbon in the Aviation Sector: Supply Effects of the European Emissions Trading System. *SSRN Electronic Journal*.

Falk, M., & Hagsten, E. (2019). Short-run impact of the flight departure tax on air travel. *International Journal of Tourism Research*, *21(1)*, 37–44.

Albers, S., Bühne, J. A., & Peters, H. (2009). Will the EU-ETS instigate airline network reconfigurations? *Journal of Air Transport Management*, *15 (1)*, 1–6. doi: 10.1016/j.jairtraman.2008.09.013.

Anger, A., & Köhler, J. (2010). Including aviation emissions in the EU ETS: Much ado about nothing? A review. *Transport Policy, 17 (1)*, 38–46. doi: 10.1016/j.tranpol.2009.10.010.

Barbot, C., Betancor, O., Socorro, M.P., & Viecens, M.F. (2014). Trade-offs between environmental regulation and market competition: Airlines, emission trading systems and entry deterrence. *Transport Policy, 33*, 65–72. doi: 10.1016/j.tranpol.2014.02.008.

Fukui, H., & Miyoshi, C. (2017). The impact of aviation fuel tax on fuel consumption and carbon emissions: The case of the US airline industry. *Transportation Research Part D: Transport and Environment*, *50*, 234–253. doi: 10.1016/j.trd.2016.10.015.

Nava, C.R., Meleo, L., Cassetta, E., & Morelli, G. (2018). The impact of the EU-ETS on the aviation sector: Competitive effects of abatement efforts by airlines. *Transportation Research Part A: Policy and Practice, 11*, 320–34. doi: 10.1016/j.tra.2018.03.032.

Scheelhaase, J., Schaefer, M., Grimme, W., & Maertens, S. (2012). Cost impacts of the inclusion of air transport into the European emissions trading scheme in the time period 2012–2020. *European Journal of Transport and Infrastructure Research*, *12 (4)*, 332–348. doi: 10.18757/ejtir.2012.12.4.2973.

Gately, D. (1988). Taking off: the US demand for air travel and jet fuel. *The Energy Journal*, *9(2)*, 93–108.

Gobillon, L., & Magnac, T. (2016). Regional Policy Evaluation: Interactive Fixed Effects and Synthetic Controls. *The Review of Economics and Statistics*, *98(3)*, 535–551.

González, R., & Hosoda, E.B. (2016). Environmental impact of aircraft emissions and aviation fuel tax in Japan. *Journal of Air Transport Management*, *57*, 234–240.

Halpern, N. (2018). Airport business strategy. In Graham, A., & N. Halpern, (eds.), *The Routledge companion to air transport management*, (154–170). Abingdon, Oxon: Routledge.

Herold, A. (2007). Comparison of verified CO_2 emissions under the EU Emission Trading Scheme with national greenhouse gas inventories for the year 2005. *ETC/ACC Technical Paper no. 2007/3.* European Topic Center on Air and Climate Change, Bilthoven.

International Air Transport Association (IATA). (2019a). *Taxes & the environment — Fact Sheet.* IATA. Available at https://www.iata.org/contentassets/c4f9f0450212472b96dac114a06cc4fa/fact-sheet-greentaxation.pdf [Accessed 18 September 2020].

International Air Transport Association (IATA). (2019b). *Fuel — Fact Sheet*. IATA. Available at https://www.iata.org/contentassets/ebdba50e57194019930d72722413edd4/fact-sheet-fuel.pdf [Accessed 18 September 2020].

International Civil Aviation Organization (ICAO). (2010). *ICAO Environmental Report 2010.* Aviation and Climate Change. Available at https://www.icao.int/environmental-protection/Documents/Publications/ENV_Report_2010.pdf [Accessed 24 August 2020].

International Civil Aviation Organization (ICAO). (2019). *ICAO Environmental Report 2019*. Aviation and Climate Change. Available at https://www.icao.int/environmental-protection/Documents/ICAO-ENV-Report2019-F1-WEB%20(1).pdf [Accessed 24 August 2020].

International Civil Aviation Organization (ICAO). (n.d.). *Trends in Emissions that affect Climate Change*. ICAO. Available at https://www.icao.int/environmental-protection/Pages/ClimateChange_Trends.aspx [Accessed 24 August 2020].

Jordão, T.C. (2016). Analysis of fuel efficiency of the largest European airlines in the context of climate change mitigation. *International Journal of Global Energy Issues*, *39 (3–4)*, 253–270.

Kettner, C., Kletzan-Slamanig, D., & Köppl, A. (2011). The EU Emission Trading Scheme. Allocation Patterns and Trading Flows. *WIFO Working Papers 408/2011.* Vienna, Austria.

Kopsch, F. (2012). Aviation and the EU Emissions Trading Scheme — Lessons learned from previous emissions trading schemes. *Energy Policy*, *49(C)*, 770–773.

Larsson, J., Elofsson, A., Sterner, T., & Åkerman, J. (2019). International and national climate policies for aviation: a review. *Climate Policy*, *19(6)*, 787–799.

Lee, D.S., Fahey, D.W., Forster, P.M., Newton, P.J., et al. (2009). Aviation and global climate change in the 21st century. *Atmospheric Environment*, *43(22–23)*, 3520–3537.

Liu, L., Wang, Y., & Xu, Y. (2020). A Practical Guide to Counterfactual Estimators for Causal Inference with Time-Series Cross-Sectional Data. *SSRN Electronic Journal*. doi: 10.2139/ssrn.3555463.

Lo, P.L., Martini, G., Porta, F., & Scotti, D. (2020). The determinants of CO2 emissions of air transport passenger traffic: An analysis of Lombardy (Italy). *Transport Policy*, *91(1)*, 108–119.

Malighetti, P., Paleari, S., & Redondi, R. (2016). Base abandonments by low-cost carriers. J*ournal of Air Transport Management, 55*, 234–244.

Malina, R., McConnachie, D., Winchester, N., Wollersheim, C., et al. (2012). The impact of the European Union emissions trading scheme on US aviation. *Journal of Air Transport Management*, *19(1)*, 36–41.

Marazzo, M., Scherre, R., & Fernandes, E. (2010). Air transport demand and economic growth in Brazil: A time series analysis. *Transportation Research Part E: Logistics and Transportation Review*, *46(2)*, 261–269.

Markham, F., Young, M., Reis, A., & Higham, J. (2018). Does carbon pricing reduce air travel? Evidence from the Australian 'Clean Energy Future' policy, July 2012 to June 2014. *Journal of Transport Geography*, *70*, 206–214.

Martin, R., Muûls, M., & Wagner, U.J. (2016). The Impact of the European Union Emissions Trading Scheme on Regulated Firms: What Is the Evidence after Ten Years? *Review of Environmental Economics and Policy, 10(1)*, 129–148.

Mazraati, M., & Faquih, Y.O. (2008). Modelling aviation fuel demand: the case of the United States and China. *OPEC Energy Review*, *32(4)*, 323–342.

Mazraati, M., & Alyousif, O.M. (2009). Aviation fuel demand modelling in OECD and developing countries: impacts of fuel efficiency. *OPEC Energy Review*, *33(1)*, 23–46.

Miyoshi, C. (2014). Assessing the equity impact of the European Union Emission Trading Scheme on an African airline. *Transport Policy*, *33*, 56–64.

Montgomery, W.D. (1972). Markets in licenses and efficient pollution control programs. *Journal of Economic Theory*, *5(3)*, 395–418.

Nava, C.R., Meleo, L., Cassetta, E., & Morelli, G. (2018). The impact of the EU-ETS on the aviation sector: Competitive effects of abatement efforts by airlines. *Transportation Research Part A: Policy and Practice*, *11(3)*, 20–34.

Nordhaus, W.D. (2017). Revisiting the social cost of carbon. *Proceedings of the National Academy of Sciences of the United States of America*, *114(7)*, 1518–1523.

Pagoni, I., & Psaraki-Kalouptsidi, V. (2016). The impact of carbon emission fees on passenger demand and airfares: A game theoretic approach. *Journal of Air Transport Management*, *55*, 41–51.

Petrick, S., & Wagner, U. J. (2014). The impact of carbon trading on the industry: Evidence from German manufacturing firms. *Kiel Working Paper No.1912.* Kiel, Germany: Pontoglio,

Petrick, S., Rehdanz, K., & Wagner, U.J. (2011). Energy use patterns in German industry: Evidence from plant-level data. *Journal of Economics and Statistics, 231(3)*, 379–414.

Porter, M.E. (1991). America's green strategy. *Scientific American*, *264(4)*.

Porter, M.E., & Linde, C. van der. (1995). Toward a New Conception of the Environment-Competitiveness Relationship. *Journal of Economic Perspectives*, *9(4)*, 97–118.

Pw C. (2017). *Connectivity and Growth 2017 Edition.* Pw C. Available at https://www.pwc.com/gx/en/industries/assets/connectivity-and-growth-2017-edition.pdf [Accessed 20 September 2020].

Schaefer, M., Scheelhaase, J., Grimme, W., & Maertens, S. (2010). The economic impact of the upcoming EU emissions trading system on airlines and EU Member States-an empirical estimation. *European Transport Research Review*, *2(4)*, 189–200.

Scheelhaase, J., Grimme, W., & Schaefer, M. (2010). The inclusion of aviation into the EU emission trading scheme — Impacts on competition between European and non-European network airlines. *Transportation Research Part D: Transport and Environment*, *15(1)*, 14–25.

Scheelhaase, J., Schaefer, M., Grimme, W., & Maertens, S. (2012). Cost impacts of the inclusion of air transport into the European emissions trading scheme in the time period 2012–2020. *European Journal of Transport and Infrastructure Research*, *12(4)*, 332–348.

Seetaram, N., Song, H., & Page, S.J. (2014). Air Passenger Duty and Outbound Tourism Demand from the United Kingdom. *Journal of Travel Research*, *53(4)*, 476–487.

Singh, V., & Sharma, S.K. (2015). Fuel consumption optimization in air transport: a review, classification, critique, simple meta-analysis, and future research implications. *European Transport Research Review*, *7(2)*, 1–24.

Statista. (2020). *Commercial airlines change in passenger traffic in Europe 2013–2020*. Available at https://www.statista.com/statistics/658701/commercial-airlines-passenger-traffic-change-europe/ [Accessed 18 September 2020].

Stern, N. (2007). *The economics of climate change: The stern review*. Cambridge University Press. doi: 10.1017/CBO9780511817434.

Thomson Reuters Point Carbon. (2012). *Carbon Pricing, Emissions Trading and Linking Emissions Trading Schemes*, European Bank for Reconstruction and Development (EBRD). Available at www.ebrd.com/documents/climate-finance/carbon-pricing-emissions-trading-and-linking-emissions-trading-schemes.pdf?blobnocache=true [Accessed 05 September 2020].

Transport & Environment. (2016). *Aviation ETS — gaining altitude*; *An analysis of aviation EU ETS 2013–2015*. J. Dings, ed. Available at https://www.transportenvironment.org/sites/te/files/2016_09_Aviation_ETS_gaining_altitude.pdf [Accessed 03 August 2020].

Transport & Environment. (2020a). *Taxing Aviation Fuel in Europe. Back to the Future?* B. Hemmings, ed. Available at https://www.transportenvironment.org/sites/te/files/publications/2020_06_Study_for_TE_Taxing_aviation_fuel_final.PDF [Accessed 16 August 2020].

Transport & Environment. (2020b). *State of The Aviation ETS*. Available at https://www.transportenvironment.org/state-aviation-ets [Accessed 2 August 2020].

U.S Energy Information Administration (EIA). (2020). *Petroleum and Other Liquids — annual*, electronic dataset, U.S EIA. Available at https://www.eia.gov/international/data/world [Accessed 12 August 2020].

Vespermann, J., & Wald, A. (2011). Much ado about nothing? — An analysis of economic impacts and ecologic effects of the EU-emission trading scheme in the aviation industry. *Transportation Research Part A: Policy and Practice*, *45(10)*, 1066–1076.

Wagner, M. (2003). *The Porter Hypothesis Revisited: A Literature Review of Theoretical Models and Empirical Tests*. Available at www.uni-lueneburg.de/csmwww.uni-lueneburg.de/umanagement [Accessed: 2 August 2020].

Wagner, U. J., Muûls, M. R., Martin, R., & Colmer, J. (2013). An evaluation of the impact of the EU emissions trading system on the industrial sector. Plant-level evidence from France. Paper presented at the AERE Conference. Banff, Canada.

World Bank database. (2020). *World Development Indicators*, electronic dataset, The World Bank Group. Available at https://databank.worldbank.org/ [Accessed 19 August 2020].

World Bank. (2020). *State and Trends of Carbon Pricing 2020*. Washington, DC. Available at https://openknowledge.worldbank.org/handle/10986/13334

Wråke, M., Myers, E., Burtraw, D., Mandell, S., et al. (2010). Opportunity Cost for Free Allocations of Emissions Permits: An Experimental Analysis. *Environmental and Resource Economics, 46*, 331–336. doi: 10.1007/s10640–010–9343-z [Accessed 2 August 2020].

Xu, Y. (2017). Generalized synthetic control method: Causal inference with interactive fixed effects models. *Political Analysis*, *25(1)*, 57–76.

Zuidberg, J. (2015). The implications of air travel taxes. *Journal of Airport Management*, *10(1)*, 64–72.

APPENDIX

Appendix 1. EU enlargement glossary

Country	Part of EU enlargements:
Austria	EU-15, EU-25, EU-27_2007, EU-28, EU-27
Belgium	EU-12, EU-15, EU-25, EU-27_2007, EU-28, EU-27
Bulgaria	EU-27_2007, EU-28, EU-27
Croatia	EU-28, EU-27
Cyprus	EU-25, EU-27_2007, EU-28, EU-27
Czechia (former Czech Republic)	EU-25, EU-27_2007, EU-28, EU-27
Denmark	EU-12, EU-15, EU-25, EU-27_2007, EU-28, EU-27
Estonia	EU-25, EU-27_2007, EU-28, EU-27
Finland	EU-15, EU-25, EU-27_2007, EU-28, EU-27
France	EU-12, EU-15, EU-25, EU-27_2007, EU-28, EU-27
Germany	EU-12, EU-15, EU-25, EU-27_2007, EU-28, EU-27
Greece	EU-12, EU-15, EU-25, EU-27_2007, EU-28, EU-27
Hungary	EU-25, EU-27_2007, EU-28, EU-27
Ireland	EU-12, EU-15, EU-25, EU-27_2007, EU-28, EU-27
Italy	EU-12, EU-15, EU-25, EU-27_2007, EU-28, EU-27
Latvia	EU-25, EU-27_2007, EU-28, EU-27
Lithuania	EU-25, EU-27_2007, EU-28, EU-27
Luxembourg	EU-12, EU-15, EU-25, EU-27_2007, EU-28, EU-27
Malta	EU-25, EU-27_2007, EU-28, EU-27
Netherlands	EU-12, EU-15, EU-25, EU-27_2007, EU-28, EU-27
Poland	EU-25, EU-27_2007, EU-28, EU-27
Portugal	EU-12, EU-15, EU-25, EU-27_2007, EU-28, EU-27
Romania	EU-27_2007, EU-28, EU-27
Slovakia	EU-25, EU-27_2007, EU-28, EU-27
Slovenia	EU-25, EU-27_2007, EU-28, EU-27
Spain	EU-12, EU-15, EU-25, EU-27_2007, EU-28, EU-27
Sweden	EU-15, EU-25, EU-27_2007, EU-28, EU-27
United Kingdom	EU-12, EU-15, EU-25, EU-27_2007, EU-28

Appendix 2. Countries included in analysis

id	Country	Country Code	Treatment status	Specification
1	Australia	AUS	Control	
2	Austria	AUT	Treated	
3	Belarus	BLR	Control	
4	Belgium	BEL	Treated	Sub-group
5	Bulgaria	BGR	Treated	
6	Canada	CAN	Control	
7	Chile	CHL	Control	
8	Columbia	COL	Control	
9	Croatia	HRV	Treated	
10	Cyprus	CYP	Treated	
11	Czechia (former Czech Republic)	CZE	Treated	
12	Denmark	DNK	Treated	Sub-group
13	Estonia	EST	Treated	
14	Finland	FIN	Treated	Sub-group
15	France	FRA	Treated	Sub-group
16	Germany	DEU	Treated	Sub-group
17	Greece	GRC	Treated	
18	Hungary	HUN	Treated	
19	Iceland	ISL	Treated	
20	Ireland	IRL	Treated	
21	Israel	ISR	Control	
22	Italy	ITA	Treated	Sub-group
23	Japan	JPN	Control	
24	Latvia	LVA	Treated	
25	Lithuania	LTU	Treated	
26	Luxembourg	LUX	Treated	Sub-group
27	Malta	MLT	Treated	
28	Mexico	MEX	Control	
29	Netherlands	NLD	Treated	Sub-group
30	New Zealand	NZL	Control	
31	Norway	NOR	Treated	Sub-group
32	Poland	POL	Treated	
33	Portugal	PRT	Treated	
34	Romania	ROU	Treated	
35	Russian Federation	RUS	Control	
36	Slovakia	SVK	Treated	
37	Slovenia	SVN	Treated	
38	South Korea	KOR	Control	
39	Spain	ESP	Treated	Sub-group
40	Sweden	SWE	Treated	Sub-group
41	Switzerland	CHE	Control	
42	Turkey	TUR	Control	
43	Ukraine	UKR	Control	
44	United Kingdom	GBR	Treated	Sub-group
45	United States	USA	Control	

Note. Monaco and Liechtenstein are omitted as they do not have a commercial airport.

Appendix 3.1. Allocation options for emissions from bunker fuel use (UNFCCC, 1996)

Option 1	No allocation, as in the current situation
Option 2	Allocation of global bunker sales and associated emissions to Parties in proportion to their national emissions
Option 3	Allocation to Parties according to the country where the bunker fuel is sold
Option 4	Allocation to Parties according to the nationality of the transporting company, or to the country where a ship or aircraft is registered, or to the country of the operator
Option 5*	Allocation to Parties according to the country of departure or destination of an aircraft or vessel; alternatively, the emissions related to the journey of an aircraft or vessel could be shared by the country of departure and the country of arrival
Option 6*	Allocation to Parties according to the country of departure or destination of passenger or cargo; alternatively, the emissions related to the journey of passengers or cargo could be shared by the country of departure and the country of arrival
Option 7*	Allocation to Parties according to the country of origin of passengers or owner of a cargo
Option 8*	Allocation to the Party of all emissions generated in its national space

Notes.
* Options considered to be less practical because of data requirements or inadequate global coverage.
All information is taken directly from UNFCCC (1996) under paragraph 27.

Appendix 3.2. Descriptive Statistics, mean values for 1995–2018

Variable	Control	Treated
Jet fuel consumption (mt)	8011341 (17857040)	1649801 (2696242)
Jet fuel consumption (mt) per capita	0.10741 (0.08)	0.133771 (0.17)
GDP (Current million US $)	1736569 (3587576)	506667.4 (813998.1)
GDP per capita (Current US $)	23058.5 (20101.8)	29210.83 (21349.05)
Inbound Tourists	13673150 (15548100)	13115280 (18023720)
Population	66568990 (76855470)	17185150 (22365270)
Number of observations	349	693
Number of countries	15	30

Note. Standard deviations in parentheses.

Appendix 3.3. Pre-treatment mean values, for period 1995–2012

Variable	Control	Treated
Jet fuel consumption (mt)	7746432 (17763680)	1583855 (2612476)
Jet fuel consumption (mt) per capita	0.1 (0.08)	0.13 (0.16)
GDP (Current million US $)	1531127 (3143231)	468677.8 (763313.5)
GDP per capita (Current US $)	20108.28 (18050.84)	26792.1 (19909.79)
Inbound Tourists	11872060 (13486310)	11882140 (16771540)
Population	65391440 (74906220)	17079850 (22173390)
Number of observations	266	518
Number of countries	15	30

Note. Standard deviations in parentheses.

Appendix 3.4. Post-treatment mean values, for period 2013–2018

Variable	Control	Treated
Jet fuel consumption (mt)	8860325 (18236010)	1845000 (2929423)
Jet fuel consumption (mt) per capita	0.12 (0.09)	0.15 (0.2)
GDP (Current million US $)	2394975 (4702911)	619116.7 (941767.4)
GDP per capita (Current US $)	32513.35 (23306.18)	36370.26 (23788.09)
Inbound Tourists	19445320 (19847020)	16765390 (20934490)
Population	70342840 (83161830)	17496840 (22985690)
Number of observations	83	175
Number of countries	15	30

Note. Standard deviations in parentheses.

Appendix 4.1. Results for Jack-knife resampling

Outcome Variable: Jet Fuel Consumption per capita (mt)	(0)	(1)	(2)
ATT Coefficient	0.002102	0.01531	0.01581
Standard Error 95% Confidence Interval	(0.01459) [−0.0265–0.0307]	(0.02403) [−0.03178–0.0624]	(0.01675) [−0.01703–0.04865]
GDP per capita[a]		1.813 (1.674)	1.317 (1.369)
GDP per capita^2 [a]		-0.000006568 (0.00002457)	-0.00000261 (0.00001702)
Inbound tourist[a]			-0.00007903 (0.000822)
Country & Year fixed effects	Yes	Yes	Yes
Unobserved factors	4	3	3
Observations	1297	1297	1039
Treated countries	30	30	29[b]
Control countries	15	15	15

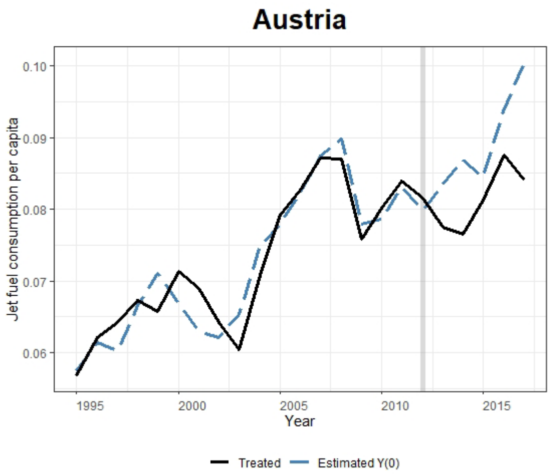
Notes.
***, **, and * denotes significance at 1%. 5% and 10% levels, respectively.
Standard errors are presented in parentheses, and 95% confidence intervals are presented in brackets.
a: values are adjusted for visualisation purposes, and should be multiplied by 10^{-6} to show true results.
b: Hungary is dropped from the sample due to too few (< 12) pre-treatment observations.

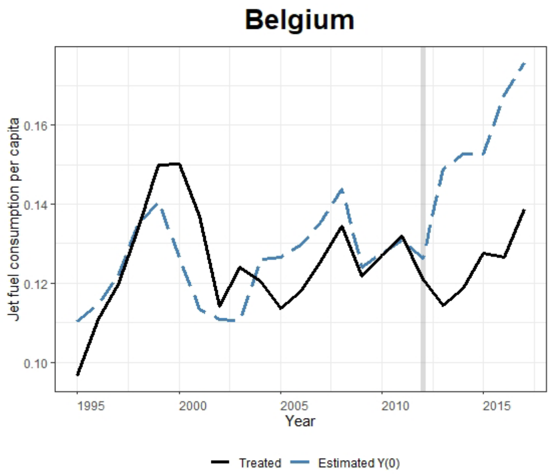
Appendix 4.2. Results from the log-log model

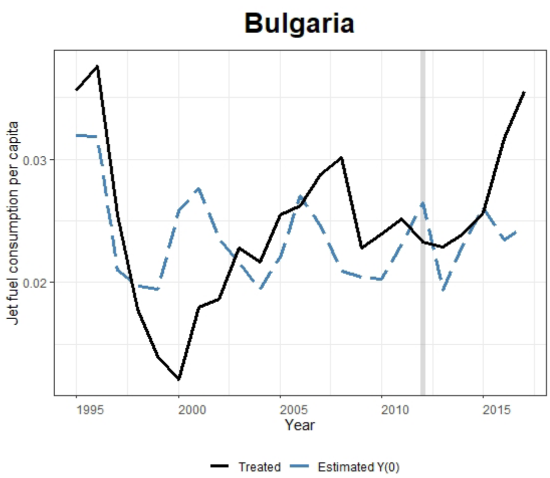
Outcome Variable: Log (Jet Fuel Consumption per capita (mt))	**(0)**	**(1)**	**(2)**
ATT Coefficient	0.1513***	0.143***	0.08925***
Standard Error 95% Confidence Interval	(0.01442) [0.1658–0.2214]	(0.01895) [0.1668–0.2398]	(0.01675) [–0.01703–0.04865]
Log(GDP per capita)		-1.0625*** (0.060357)	-0.32516*** (0.056749)
Log(GDP per capita)^2		0.0819*** (0.003701)	0.04039*** (0.003459)
Log(Inbound tourist)			-0.17046*** (0.007701)
Country & Year fixed effects	Yes	Yes	Yes
Unobserved factors	5	5	5
Observations	1297	1297	1039
Treated countries	30	30	29[b]
Control countries	15	15	15

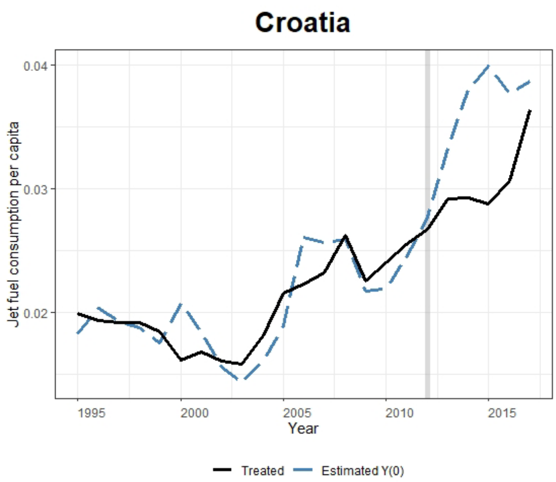
Notes.
***, **, and * denotes significance at 1%, 5%, and 10% levels, respectively.
Standard errors are presented in parentheses, and 95% confidence intervals are presented in brackets.
b: Hungary is dropped from the sample due to too few (< 12) pre-treatment observations.

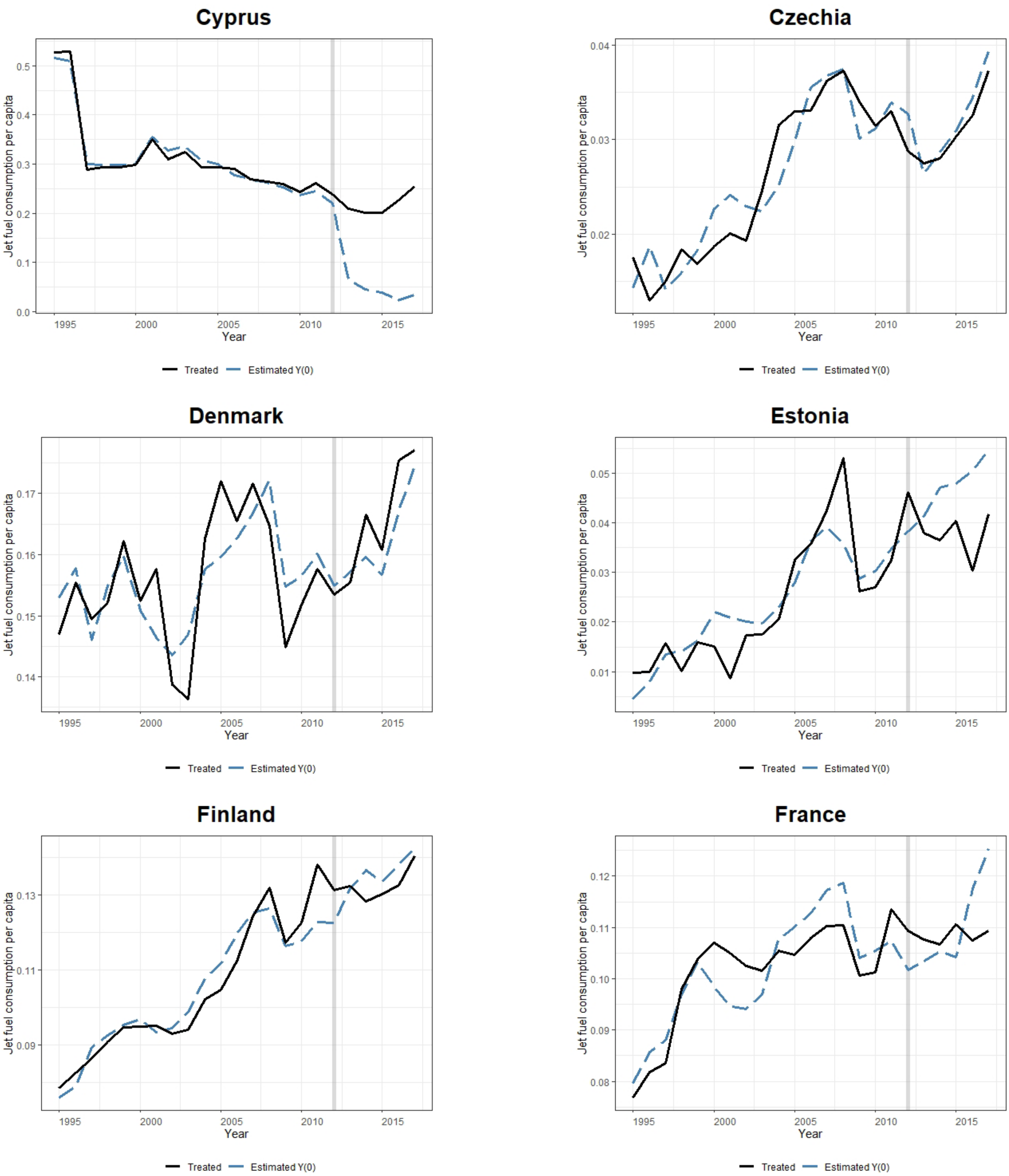
Appendix 4.3. The effect of the EU ETS over time, country-specific results

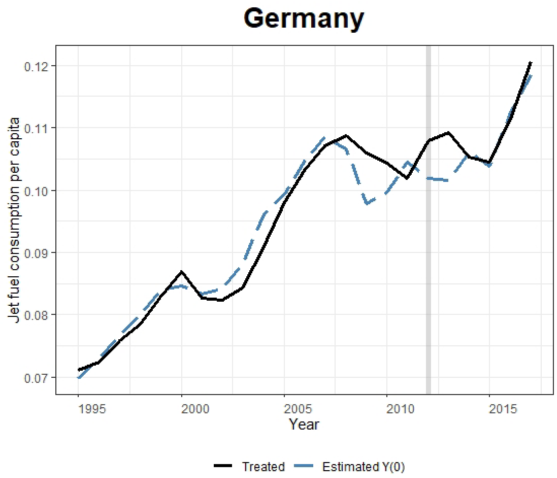


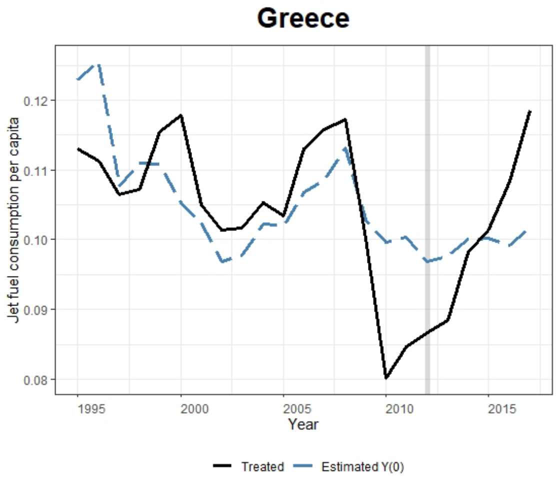


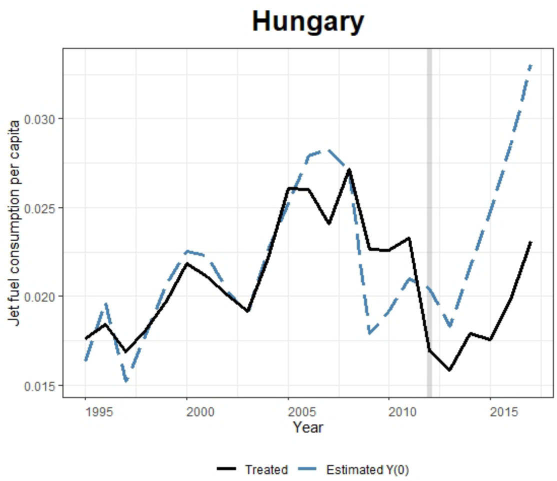


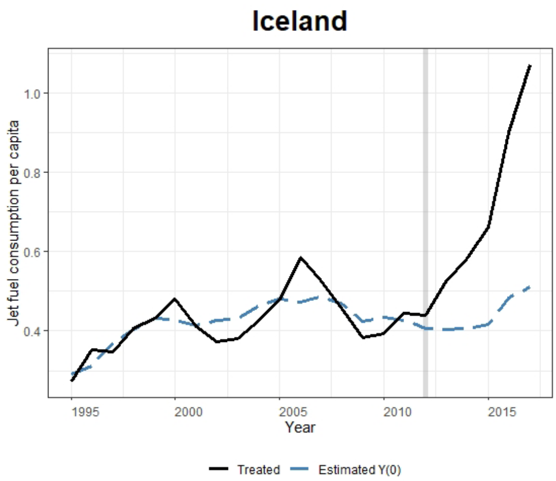


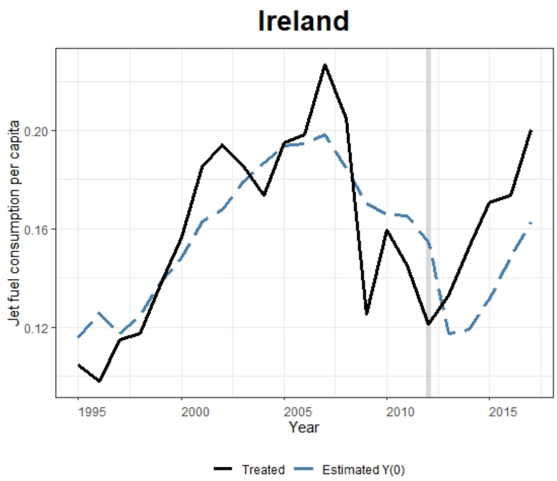

Cyprus
Czechia
Denmark
Estonia
Finland
France
Jet fuel consumption per capita
Year
Treated
Estimated Y(0)

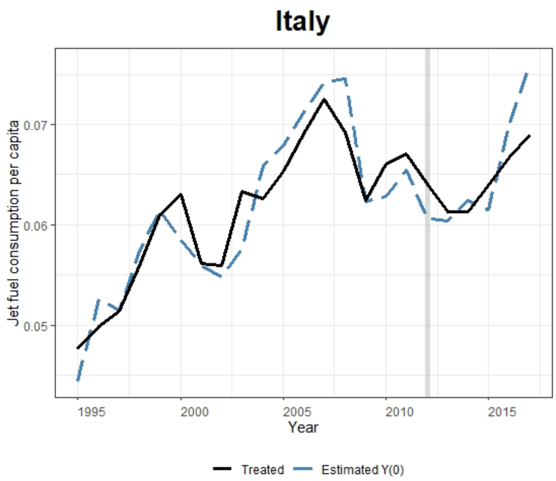

Germany
Jet fuel consumption per capita
0.12
0.11
0.10
0.09
0.08
0.07
1995
2000
2005
2010
2015
Year
Treated
Estimated Y(0)

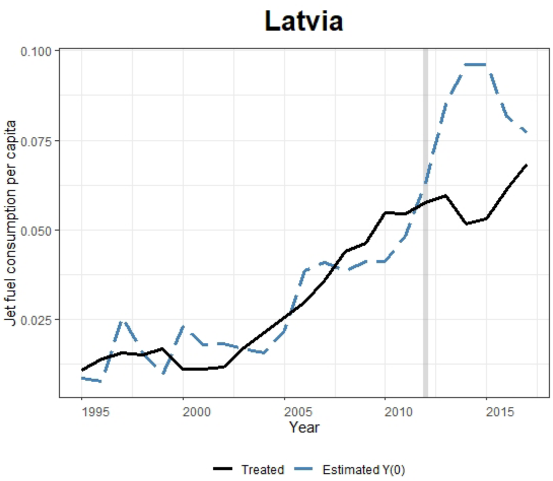

Greece
Jet fuel consumption per capita
0.12
0.11
0.10
0.09
0.08
1995
2000
2005
2010
2015
Year
Treated
Estimated Y(0)

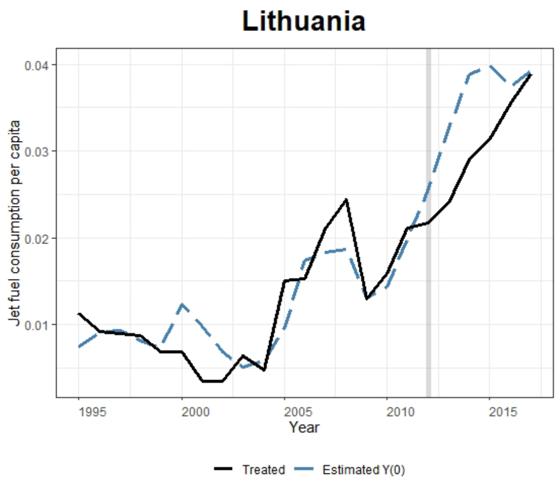

Hungary
Jet fuel consumption per capita
0.030
0.025
0.020
0.015
1995
2000
2005
2010
2015
Year
Treated
Estimated Y(0)

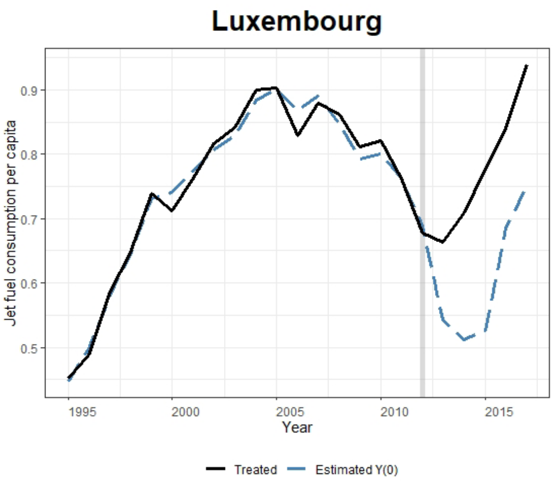

Iceland
Jet fuel consumption per capita
1.0
0.8
0.6
0.4
1995
2000
2005
2010
2015
Year
Treated
Estimated Y(0)

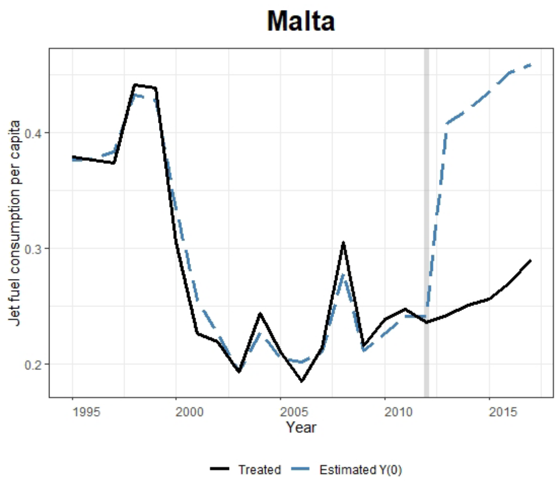

Ireland
Jet fuel consumption per capita
0.20
0.16
0.12
1995
2000
2005
2010
2015
Year
Treated
Estimated Y(0)

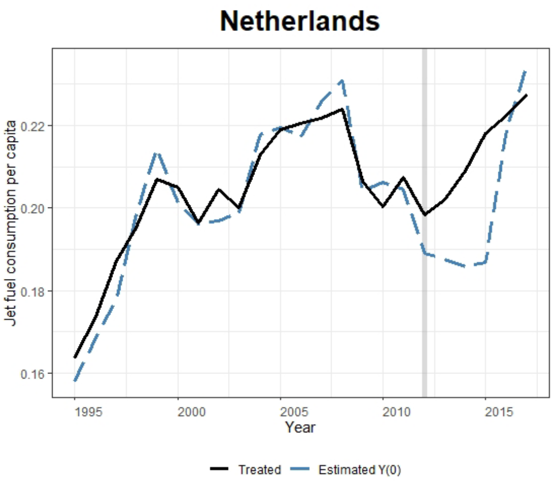

Italy
Jet fuel consumption per capita
0.07
0.06
0.05
1995
2000
2005
2010
2015
Year
Treated
Estimated Y(0)

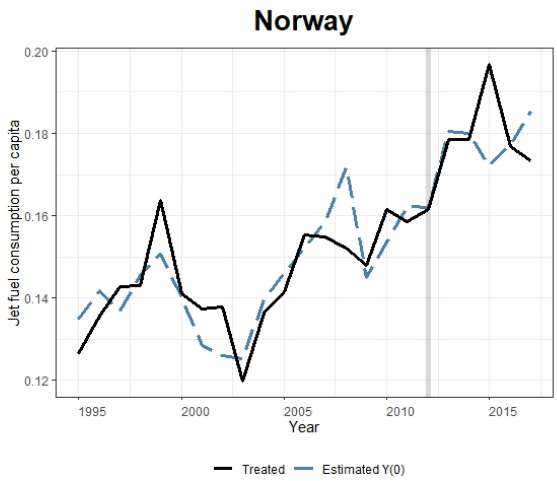

Latvia
0.100
0.075
0.050
0.025
Jet fuel consumption per capita
1995 2000 2005 2010 2015
Year
Treated
Estimated Y(0)

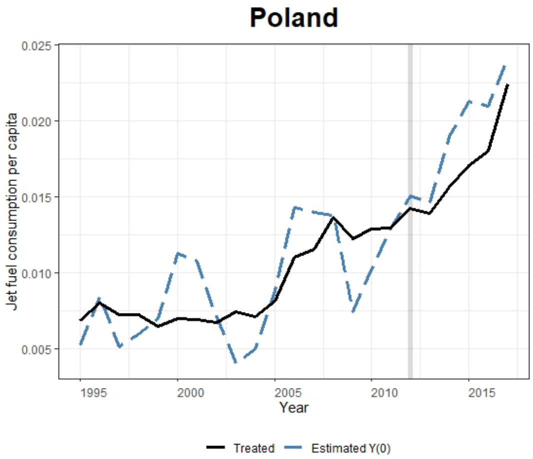

Lithuania
0.04
0.03
0.02
0.01
Jet fuel consumption per capita
1995 2000 2005 2010 2015
Year
Treated
Estimated Y(0)

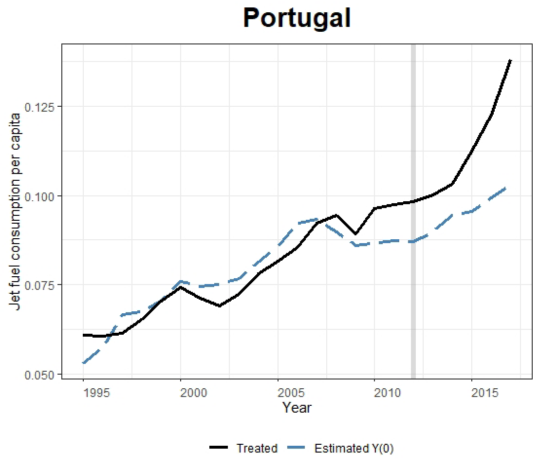

Luxembourg
0.9
0.8
0.7
0.6
0.5
Jet fuel consumption per capita
1995 2000 2005 2010 2015
Year
Treated
Estimated Y(0)

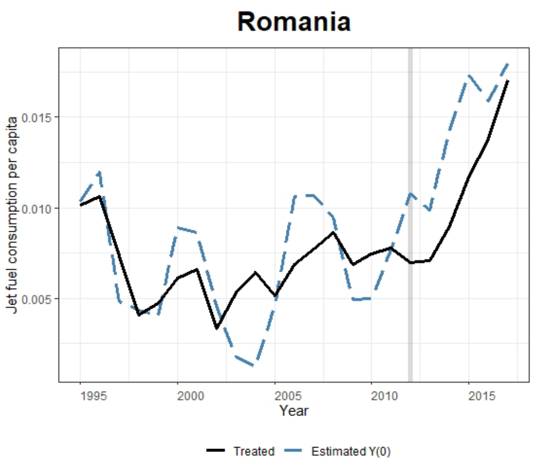

Malta
0.4
0.3
0.2
Jet fuel consumption per capita
1995 2000 2005 2010 2015
Year
Treated
Estimated Y(0)

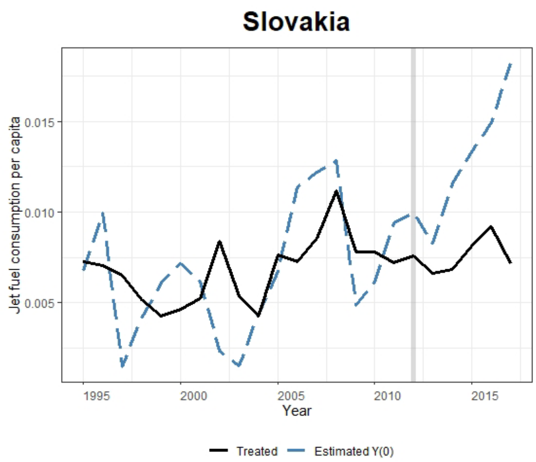

Netherlands
0.22
0.20
0.18
0.16
Jet fuel consumption per capita
1995 2000 2005 2010 2015
Year
Treated
Estimated Y(0)

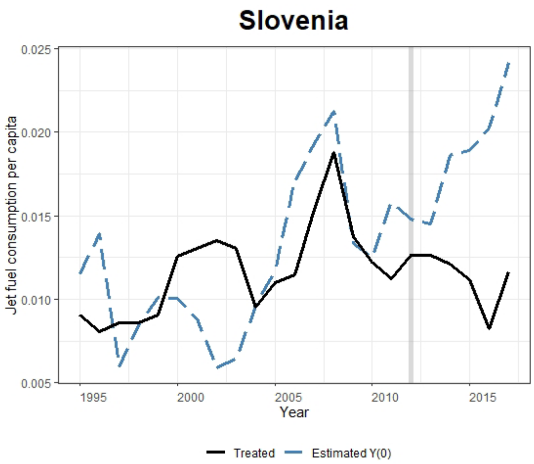

Norway
0.20
0.18
0.16
0.14
0.12
Jet fuel consumption per capita
1995 2000 2005 2010 2015
Year
Treated
Estimated Y(0)

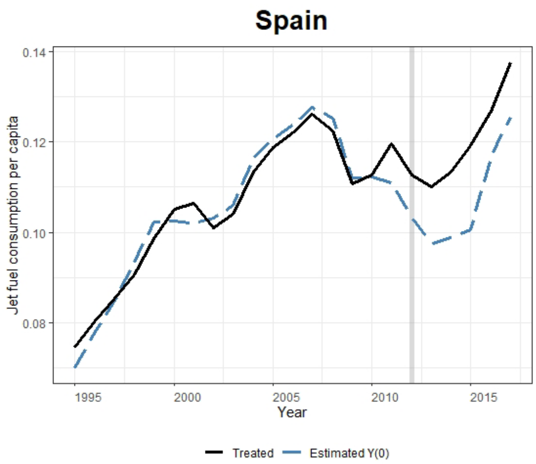

Poland
Jet fuel consumption per capita
0.025
0.020
0.015
0.010
0.005
1995
2000
2005
2010
2015
Year
Treated
Estimated Y(0)

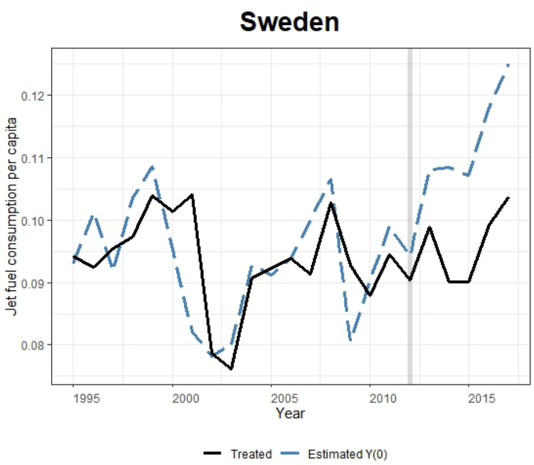

Portugal
Jet fuel consumption per capita
0.125
0.100
0.075
0.050
1995
2000
2005
2010
2015
Year
Treated
Estimated Y(0)

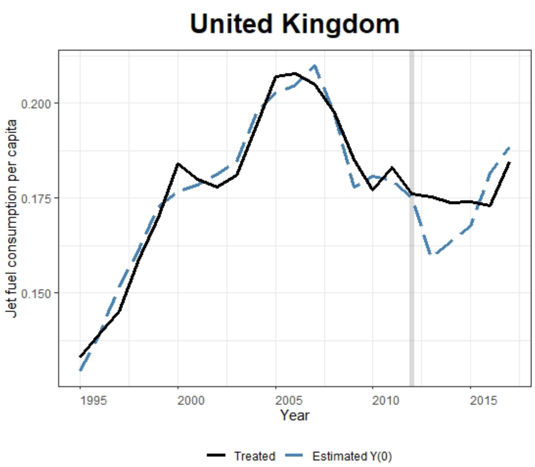

Romania
Jet fuel consumption per capita
0.015
0.010
0.005
1995
2000
2005
2010
2015
Year
Treated
Estimated Y(0)


Slovakia
Jet fuel consumption per capita
0.015
0.010
0.005
1995
2000
2005
2010
2015
Year
Treated
Estimated Y(0)


Slovenia
Jet fuel consumption per capita
0.025
0.020
0.015
0.010
0.005
1995
2000
2005
2010
2015
Year
Treated
Estimated Y(0)


Spain
Jet fuel consumption per capita
0.14
0.12
0.10
0.08
1995
2000
2005
2010
2015
Year
Treated
Estimated Y(0)


Sweden
Jet fuel consumption per capita
0.12
0.11
0.10
0.09
0.08
1995
2000
2005
2010
2015
Year
Treated
Estimated Y(0)

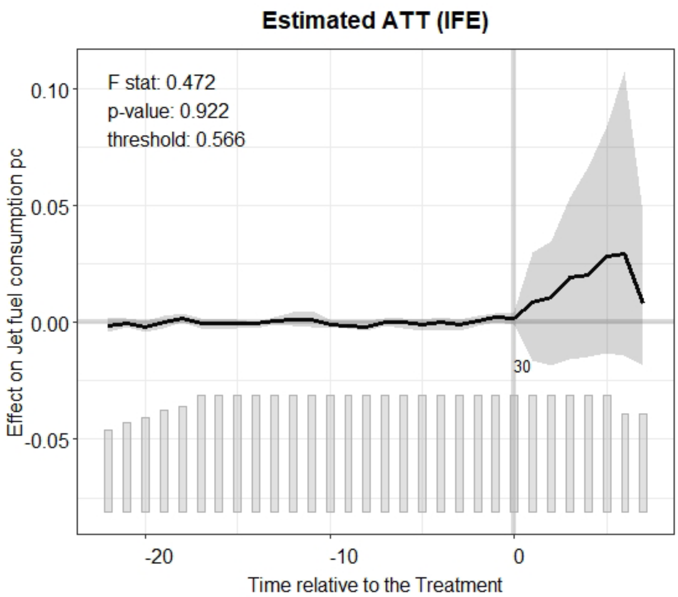

United Kingdom
Jet fuel consumption per capita
0.200
0.175
0.150
1995
2000
2005
2010
2015
Year
Treated
Estimated Y(0)

Appendix 4.4. IFE model results and plot

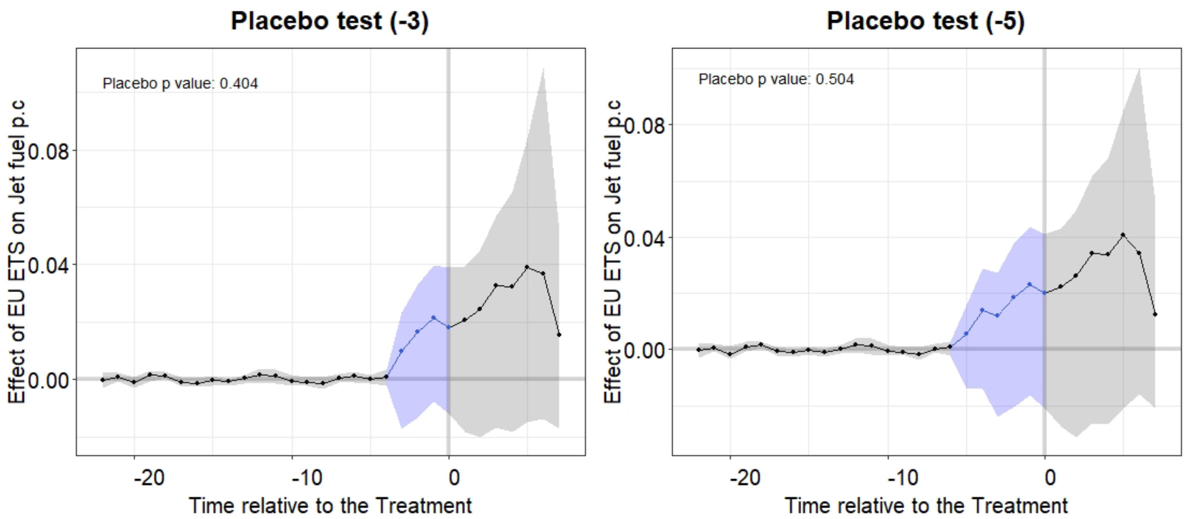
Outcome Variable: Jet Fuel Consumption per capita (mt)	IFE MODEL
ATT Coefficient	0.01777
Standard Error 95% Confidence Interval	(0.01728) [−0.009431−0.05675]
Control	GDP per capita
Country & Year fixed effects	Yes
Unobserved factors	3[a]
Observations	1297
Treated countries	30
Control countries	15

Notes.
a: Manually enforced based on GSC results.
Note: it is impossible to estimate the IFE model with a squared variable; thus, only one control variable is included.

The effect of EU ETS on Jet fuel consumption estimated by the IFE model follows a similar pattern to that of the GSC model. The downward trend after 2017 is likely due to missing observations when treated countries drop from 30 to 25. The GSC model better accounts for missing observation than the IFE model.

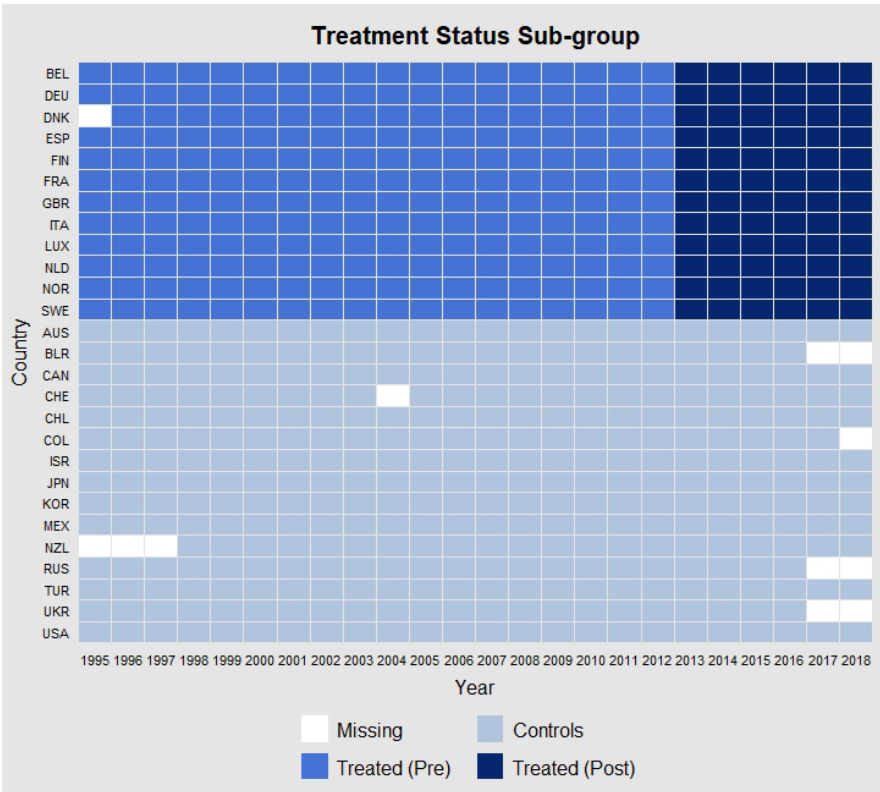


Appendix 4.5. Placebo test results from IFE model



In both cases, we reject the null hypothesis that the ATT is different from zero before implementation.

Appendix 4.6. Overview of treatment and missing observation in sub-group



Система коммерциализации выбросов Евросоюза (EU ETS) и авиация: оценка эффективности системы торговли квотами на выбросы в Евросоюзе для сокращения выбросов от авиаперелетов

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Аннотация. В настоящее время авиационный сектор считается одним из наиболее быстрорастущих источников выбросов парниковых газов. Пытаясь сократить эти выбросы рентабельным образом, Евросоюз в 2012 г. решил включить все рейсы, прибывающие и вылетающие из Евросоюза, в свою Систему коммерциализации выбросов (EU ETS). Идея ETS состоит в том, что, установив потолок выбросов и разрешив торговлю квотами между секторами, заниматься сокращением выбросов можно там, где это дешевле и проще всего сделать. В какой мере EU ETS, используя модель общего синтетического контроля для оценки противоположного сценария, удалось сократить выбросы авиационного сектора в 2012–2018 гг.? Результаты исследования свидетельствуют: при использовании расхода реактивного топлива как показателя выбросов применение ЕС ETS привело к 10%-ному увеличению расхода данного вида топлива по сравнению со сценарием, в котором он не был критерием.
Ключевые слова: система коммерциализации выбросов; авиационная индустрия; модель общего синтетического контроля; выбросы парниковых газов; загрязнение воздуха