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Climate Mitigation Strategies for Aviation - A Marginal Abatement Cost Perspective

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Abstract

Aviation is currently responsible for approximately 3 - 5 % of anthropogenic climate warming. Since air traffic is expected to grow in the future, this share is likely to increase in the coming years and decades. In the future, climate-relevant emission reductions in the air transport sector are promised by, among other strategies, the use of sustainable aviation fuels on a large [*]scale, the use of hydrogen and further technical improvements to the airframe and engine. However, the marginal abatement costs in aviation are considerably higher compared to many other emitting sectors. This paper investigates the present marginal abatement costs in air transportation and analyzes their projected development over time. Our results indicate that, as of today, investments in low-carbon technologies and alternative fuels that do not yield operational cost savings are in most cases not economically efficient. Since other sectors competing with aviation in carbon markets - such as those covered by the EU ETS - face lower marginal abatement costs, purchasing allowances remains the most cost-effective option for aviation today. Despite rising carbon market prices and potential economies of scale, many emerging solutions offering great emission reduction potential, including hydrogen-powered aircraft and Power-to-Liquid fuels, are not expected to become economically viable before 2035. As current carbon markets alone are insufficient to drive significant in-sector emission reductions, we provide recommendations that go beyond the regulation by carbon markets, proposing mitigation or policy measures that promote cost-effective mitigation approaches.

Keywords: Marginal Abatement Costs; Sector Comparison; EU-ETS; CORSIA;

1. Introduction

Aviation accounts for approximately 3 – 5% of anthropogenic climate warming (Klöwer et al. (2021), Lee et al., 2009; Lee et al., 2021), a share projected to grow as air traffic increases in the coming years and decades (ICAO,

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2024b). Carbon emissions within the aviation industry are reduced by about 1.9% per year through efficiency gains (Larsson et al., 2019), mainly because fuel costs account for about a third of the sector's total operating costs. Aviation is included in the European Emissions Trading System (EU ETS) for CO_2 and, at the global level, in the ICAO Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) offsetting system.

Carbon markets are designed to reduce greenhouse gas emissions (GHG) to a predefined level usually including different sectors. Cap-and-trade mechanisms like the EU ETS ensure that GHG emissions are reduced in sectors with the lowest additional abatement costs for climate-relevant emissions (marginal abatement costs), while hard-to-abate sectors are purchasing additional permits. Therefore, carbon markets can generally be considered very efficient from an economic point of view (Scheelhaase et al., 2021). Aviation is part of the EU ETS since 2013 including all flights within the European Economic Area (EEA). Flights between the EEA and Switzerland or the UK are subject to either the EU ETS or the Swiss/UK ETS based on a bilateral linkage agreement. CORSIA was developed by the International Civil Aviation Organization (ICAO) and started with a voluntary phase in 2021. It is the first global market-based measure to reduce CO2 emissions from international aviation, aiming to limit the growth of aviation emissions, while aircraft operators offset their emissions in other sectors.

Additional savings in the air transport sector are promised by, among other strategies, the use of sustainable aviation fuels (SAF) and hydrogen (H_2) on a large scale as well as technical improvements to the airframe and engine in the future. In this context, two questions arise: Firstly, how high are the marginal emission abatement costs in air transportation at present and how will these costs develop in the future, also in relation to other emitting economic sectors? Secondly, which additional mitigation or policy measures in aviation can be considered reasonable from an economic efficiency point of view?

For this purpose, section 2 provides a review of the existing literature on marginal abatement costs in and outside aviation. Section 3 describes the methodology used to estimate and evaluate marginal abatement costs. Section 4 provides the results. Economic implications for aviation and potential policy measures will be discussed in section 5, while section 6 analyzes strategies to reduce in-sector emissions and provides recommendations for policymakers.

2. Literature Review

Marginal abatement costs (MACs) can be defined as the costs to obtain an additional unit of pollution reduction (McKitrick, 1999). Initially used to evaluate the relative cost of various electricity saving measures in its early stages, it has become a widely accepted method across sectors to analyze the relative cost of abatement options since. In light of the ambitious emission reduction goals in aviation until 2050, MACs and more precisely MACCs (Marginal abatement cost curves) are used to determine the most economically feasible mitigation measures (Huang et al., 2016).

2.1. Marginal Abatement Costs of Aviation

In principle, there are several options for reducing the climate impact of aviation by technological or operational measures. Mitigation options up to 2050 include the replacement of current fleets with modern aircraft or future aircraft concepts such as hydrogen or electric aircraft, an increase in operational efficiency or the use of alternative low carbon drop-in fuel, such as SAF. In addition to operations (4%-11%) and new aircraft technologies (20%-21%), SAF plays a pivotal role in reducing aviation`s carbon emissions with a potential emission reduction of up to 55% by 2050 (ICAO, 2022a).

Studies on MACs in aviation highlight that a number of carbon mitigation measures can lead to cost savings, resulting in negative MACs. Beyond considering carbon emissions alone, individual studies calculate marginal abatement costs (MACs) relative to CO_2-equivalent (CO_{2eq}) emissions, incorporating other climate-relevant and environmental impacts expressed in CO_{2eq} terms. McKinsey & Company (2023) developed a MACC showing that operational efficiency improvements and fleet renewal can yield significant cost reductions. Schäfer et al. (2015) and Wang et al. (2023) similarly report that several airline operational strategies, such as reduced contingency fuel or an increased seat load factor, as well as Air Traffic Management measures, like single-engine taxiing or inefficiency reductions during cruise, show negative MACs of up to -115 USD_{2010}/t_{CO_2} (Schäfer et al., 2015) and -134 USD_{2019}/t_{CO_2}

(Wang et al., 2023).[†] However, certain operational strategies exhibit notably high MACs. For instance, restricting airlines from carrying excess fuel—a practice known as tankering—can lead to MACs as high as 1,767 USD_{2019}/t_{CO_2} (Wang et al., 2023). This is primarily due to the limited mitigation potential of avoiding tankering, given the variation in fuel prices across the world. Similarly, measures such as surface polishing, while potentially beneficial in reducing drag, involve high operational costs due to the need for frequent washing and polishing. Furthermore, optimizing aircraft-to-mission matching by deploying smaller aircraft for lower-demand routes can improve efficiency but often reduces operational flexibility and incurs additional maintenance and crew training costs. This results in a MAC of approximately 2,193 USD_{2010}/t_{CO_2} (Schäfer et al., 2015). Both studies also highlight that technology options like retrofits with blended winglets or a reduction in cabin weight can reduce fuel consumptions and therefore also show negative MACs. These measures not only significantly reduce emissions but also lower operating costs, providing strong incentives for implementation.

Literature on MACs of the use of H_2 in aviation is limited, as hydrogen-powered aircraft for larger-scale commercial use are not expected to enter into service before 2040, after Airbus delayed its H_2 aircraft project ZEROe. According to the life cycle analysis by Bicer and Dincer (2017), H_2-powered aircraft show great positive overall environmental impacts compared to conventional jet fuel, particularly if the H_2 is produced using renewable sources. Hydrogen aircraft offer positive social impacts through significant climate benefits and the creation of new job opportunities in clean energy and aviation sectors. However, the transition from fossil fuel technologies involves high costs, workforce retraining challenges, and potential public concerns about safety and infrastructure development. For green H_2 production, energy costs, influenced by high energy demand and uncertainty, are a primary driver. Additional costs stem from infrastructure investments at airports and capital expenditures for new aircraft. Martin et al. (2023) calculated levelized cost of carbon abatement, which calculates how much an investment or policy costs per reduced ton of emissions (Friedmann et al., 2020). Abatement costs for green liquid hydrogen (LH_2) combustion in air transport are projected at 1162–1410 €/t_{CO_2} in 2035, decreasing to 533–675 €/t_{CO_2} by 2050, driven by high investments and payload loss increasing transport costs (Martin et al., 2023). Brynolf et al. (2022) estimate lower MACs for LH_2 at 490–950 €/t_{CO_2eq} by 2030. McKinsey & Company (2020) are the only study at hand considering the impact of non-CO2 emissions during flight operations such as contrail-induced climate impacts, estimating MACs between 100–350 USD/t_{CO_2eq} in 2040 for medium- and long-range LH_2-aircraft. For fuel-cell aircraft, estimated MACs range from 20–130 USD_{2040}/t_{CO_2eq} (McKinsey & Company, 2020). However, as with battery-electric aircraft, they are expected to primarily focus on short-range markets and thus offer only limited carbon abatement potential.

Aircraft operators also face high MACs for SAF due to limited availability and high production costs (McKinsey & Company, 2023). SAF, produced from various biological and non-biological feedstocks, varies in carbon abatement potential and costs but has the advantage of being a drop-in fuel compatible with existing aircraft and airport infrastructure. Studies highlight significant cost differences across feedstocks, pathways and regions. Capaz et al. (2021) analyzed the carbon abatement costs of bio-based SAF in Brazil, finding that residue-based pathways have the lowest MACs at 185-370 USD_{2020}/t_{CO_2eq} with fuels derived from used cooking oil being the cheapest abatement option. In studies for the U.S., costs ranged from 181 USD/t_{CO_2eq} for switchgrass to over 444 USD_{2020}/t_{CO_2eq} for corn stover (Fan et al., 2024), while Bullerdiek et al. (2021) reported global MACs of SAF between 150–690 $€_{2020}/t_{CO_2eq}$. For Power-to-Liquid (PtL) fuels, Martin et al. (2023) estimated abatement costs at 1386 €/t_{CO_2} in 2020, declining to 330 €/t_{CO_2} by 2050, aligning with Brynolf et al. (2022), who estimated costs between 400 and 1200 €/t_{CO_2} by 2030. Bullerdiek et al. (2021) provided lower estimates for PtL fuels (290–430 $€_{2020}/t_{CO_2eq}$) based on 2010–2019 conventional jet fuel prices, highlighting the influence of green energy supply on costs.

2.2 Marginal Abatement Costs of Other Sectors

Previous sections indicate high MACs in air transport, especially in the case of SAFs and hydrogen. To put that into context, this section provides an overview of the abatement options and their respective MACs across several

[†] For comparison: the conversion rate Euro – USD was 1,3257 in 2010. In the timeframe 2011 until 2024, this conversion rate was 1,3920 (2011) – 1,0824 (2024) (European Central Bank 2025).

sectors. Amongst the analyzed mitigation options are various operational measures, primarily in the illustrated hard-to-abate sectors, as well as the implementation of emerging technologies such as carbon capture (CC) in existing production processes or as a stand-alone solution (IEA, 2024). Agriculture, energy and road transport show a high share of abatement options with relatively low and even negative MACs. Carbon abatement measures like CC as well as other measures in the steel and cement industry typically show higher abatement costs. A closer examination of the abatement measures can provide some insight into the reasons for the significant cost variations observed across the different sectors.

The abatement cost range of –816 to 58 USD_{2025}/t_{CO_2eq} in the energy sector combines the findings of numerous authors who analyzed various measures covering energy production as well as efficiency improvements in the residential building sector (Björnebo et al. 2018, Das et al. 2021, Farbes et al. 2021, Peng et al. 2018, Van den Bergh 2015). The development of renewable energy sources plays a major role in emission abatement, not only in this sector. Thanks to governmental supporting measures in this area, especially in Europe, costs have decreased gradually over the past two decades. Wind and solar energy, but also district heating systems based on biomass or geothermal energy have seen a rise in popularity since, with production ramping up and prices for investment and operation dropping significantly. However, this positive trend depends heavily on geopolitical stability and reliable global trade relations in future, since the production of renewable technologies relies on resources that are often found only in very remote parts of the world. That is especially the case for Europe; relatively developed in the use of renewables, but extremely reliant on China for some necessary resources (e.g. rare earth metals such as Neodymium and Dysprosium) and the production of the respective technology.

In the case of road transport various measures with a wide range of abatement costs between –302 and 287 USD_{2025}/t_{CO_2eq} have been taken into consideration. Most measures involve electrification of the powertrain of vehicles of different sizes, extending from passenger cars over buses up to heavy-duty trucks. The high share of low-cost abatement options can be explained by the industry's focus on e-mobility and the gradual reduction in cost of electricity from renewables which has dropped by 90 % since 2010 in the case of solar photovoltaic and by over 50 % in the case of wind energy (IRENA, 2024). Excluding fuel/energy carrier replacement, maritime transport also shows a multitude of low cost abatement options, typically operational measures related to travel speed and trajectory like voyage optimization (-138 USD_{2025}/t_{CO_2eq}) or speed reduction (55 USD_{2025}/t_{CO_2eq}) The MAC range of shipping overall is -138-221 USD_{2025}/t_{CO_2eq} excluding new energy carriers, expanding to 459 USD_{2025}/t_{CO_2eq} including fuel replacement and even 1130 USD_{2025}/t_{CO_2eq} including the use of renewable energy sources like solar panels that can provide energy to the auxiliary engines (Longva et al., 2024, Nepomuceno de Oliveira et al., 2022). To round up transport, the cost of rail decarbonization highly depends on the current state of the rail network as well as the geographical circumstances. The switch from fossil fuels like Diesel to electric OCS (overhead catenary system) is very costly, especially in larger countries like the US (full-scale OCS deployment: 455-728 USD_{2025}/t_{CO_2eq}). That is due to the immense infrastructure efforts that have to be undertaken in order to install the OCS systems on these connections, especially in the vast west of the US. Other measures include battery-electric operation (38-134 USD_{2025}/t_{CO_2eq}, depending on battery range) and hydrogen powered train operation where costs range from 77 to 151 USD_{2025}/t_{CO_2eq} (Hernandez et al., 2024).

According to Ge et al. (2024), the highest sectoral CO_{2eq} emissions are caused by the energy sector, followed by agriculture. With most of the agricultural emissions caused by livestock & manure as well as agricultural soils that is what the majority of the observed measures are targeting. Operational measures such as external grazing of livestock but also energy production with agricultural waste were considered for the estimation (De Cara and Jayet, 2001, Schulte et al., 2012). The resulting measure set shows an over 60% share of abatement options with negative MACs, most of them relying on biomass for energy production. With an increasing number of district heating networks working on biomass and further technological improvements to operational efficiency, costs are expected to decrease in the future.

Abatement options in the steel and cement industry show a cost range of 41-347 USD_{2025}/t_{CO_2eq}.. Here, the bundle of measures includes operational improvements up to the use of alternative energy sources in the production process (Kajaste and Hurme, 2016, EWI, 2022). Most commonly mentioned is the substitution of natural gas by hydrogen or biodiesel in the reduction process (Bhardwaj et al., 2025). Closely tied to steel production are certain CC technologies since they are applicable in heavy industries like steel, cement and chemicals (IEA, 2024). In a few cases, the CO_{2eq} emitted by steel production plants is already used in enhanced oil recovery today (EWI, 2022). In principle, this technology is suitable for most polluting production processes and promises a large CO_{2eq} mitigation potential. However, the MACs of the analyzed CC technologies are substantial and on par with steel production itself. According to the literature, costs range from 118 $USD_{2025}/t_{CO_{2}eq}$ for corn ethanol production to 226 $USD_{2025}/t_{CO_{2}eq}$ in the case of Direct Air Capture (DAC) technologies (Johnsson et al., 2020, Farbes et al., 2021).

Remarkably, MACs in the chemical sector are significantly higher than in other producing industries due to its reliance on fossil fuels, predominantly oil and gas derivates. The MACs of our measure set in the chemical industry range from 188 to 410 $USD_{2025}/t_{CO_{2}eq}$ (Rekker et al. 2023, Saygin and Gielen, 2021).

3. Methodology

MACs are calculated by dividing the incremental cost of implementing an abatement measure by the quantity of emissions reduced as a result of that measure as can be seen in equation (1).

$$MAC = \frac{incremental\ costs}{reduced\ CO_2-emissions} \tag{1}$$

Estimating the MACs of the individual mitigation options requires different calculation approaches. For the sectors mentioned in 2.2, we use MACs from the literature. We compare them using USD_{2025} values, accounting for inflation since the source year. We apply a slightly refined approach for the different abatement option groups in aviation. For operational measures we consider several procedural changes that aim towards more efficient aircraft and efficient use of the resources at the airport. They include ground operation, flight planning as well as optimizations and innovations in air traffic management.

While MACs of technological advancements and operational improvements stem from literature, MACs of SAF can be estimated by applying current production costs and lifecycle emissions data. Braun et al. (2024) conducted a meta-analysis of SAF production costs, reviewing 230 observations on minimum selling prices for various pathways, such as Hydroprocessed Esters and Fatty Acids (HEFA), Fischer-Tropsch (FT), Alcohol-to-Jet (ATJ), Hydroprocessed Fermented Sugars to Synthetic Paraffins (SIP), and PtL fuels. Combined with lifecycle emissions data from ICAO (2024a) for bio-based as well as the German Federal Environmental Agency (2022) for PtL fuels - accounting for both core emissions and indirect land use changes (ILUC) - this data provides a robust basis for calculating MACs across SAF pathways. Using feedstock-pathway combinations reviewed by Braun et al. (2024), the specific fuel mass (MS/ER), representing the mass of SAF required (MS) to reduce one metric ton of CO_{2eq} (ER), can be calculated. The SAF mass required to abate one metric ton of CO_{2eq} (MS/ER) is calculated using equation (2) based on the methodology defined by ICAO (2018). Inputs include the Fuel Conversion Factor (FCF = 3.16 kg CO_{2eq} /kg_{fuel}) as well as baseline lifecycle emissions of conventional jet fuel (LC = 89 $g_{CO_{2}eq}$/MJ) and the respective SAF (LSf) (ICAO, 2024a).

$$\frac{MS}{ER} = (FCF * (1 - \frac{LSf}{LC}))^{-1} \tag{2}$$

MACs are then calculated by multiplying the required SAF mass by the difference of the respective SAF price (P_s) and the price for conventional jet fuel (P_c = 690 USD_{2020}/t_{fuel}) obtained from Braun et. al (2024) in equation (3).

$$MAC = \frac{MS}{ER} * (P_S - P_C) \tag{3}$$

The MACs of the aviation sector are compared to the other sectors. In addition, current carbon market prices relevant to the aviation sector are analyzed and compared to the calculated MACs of aviation.

As of today, production of hydrogen-based PtL fuels remains in its early stages. With Airbus postponing its hydrogen aircraft program to 2040 or later, the role of hydrogen in aviation decarbonization is expected to become more relevant closer to 2050 and beyond. Therefore, the MACs of hydrogen in aviation should be assessed in conjunction with the anticipated evolution of carbon markets. In section 5, we will compare projected carbon prices with the MACs of hydrogen-based fuels, allowing for a more realistic assessment of their economic viability in the long term.

4. Results

The results presented in Figure 1 reveal significant variability in the MACs of SAF across pathways and feedstocks, driven primarily by differences in carbon abatement potential and production costs. Rapeseed and palm oil-based fuels show high MACs mainly due to their poor environmental performance. PtL fuels on the other hand show remarkable carbon savings, but also face high production costs, leading to relatively high MACs. Our findings align with the existing literature, reinforcing the potential of Brassica Carinata oil and used cooking oil as cost-effective SAF feedstocks in current carbon markets (Capaz et al., 2021; Bullerdiek et al., 2021; Karami et al., 2022).

Overall, for aviation average MACs of around 276 USD/t_{CO_2eq} have been calculated. This value is modeled by MACs of a range of mitigation measures; including various SAFs, strategic measures such as aircraft retirements, and measures to improve process efficiency (Capaz et al., 2021, Bullerdiek et al., 2021, Liu and Jang, 2023, Morris et al., 2009). Among the abatement measures there are large differences in MACs, as shown in Figure 2. While operational and technology-driven measures have the potential to achieve even negative MACs, measures associated with high operational or investment costs for airlines—as well as those that do not enhance aircraft fuel efficiency—tend to result in significantly higher MACs.

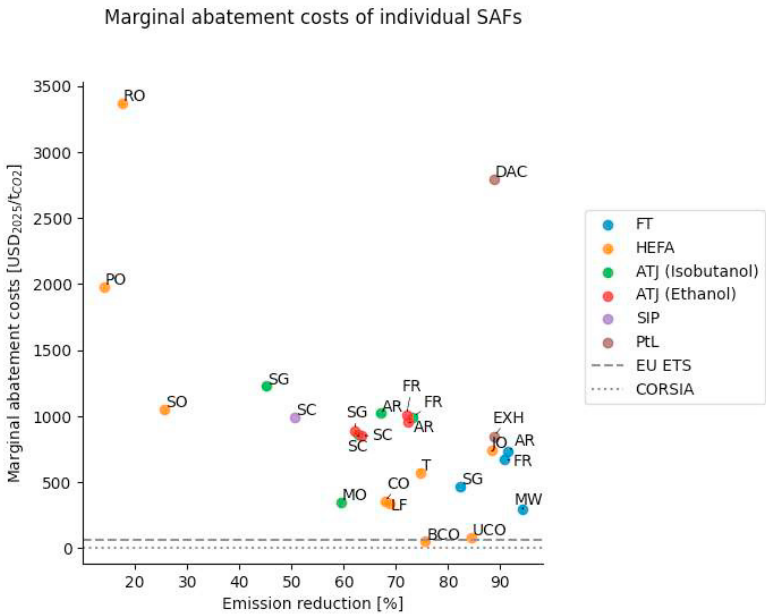

Fig. 1. Marginal Abatement Costs of SAF for Different Pathways and Feedstocks - AR: Agricultural Residues, BCO: Brassica Carinata Oil, CO: Camelina Oil, DAC: Direct Air Capture, EXH: Carbon capture from exhaust gases, FR: Forestry Residues, JO: Jatropha Oil, LF: Lard fat, MO: Molasses, MW: Municipal Waste, PO: Palm Oil, RO: Rapeseed Oil, SO: Soybean Oil, SC: Sugarcane, SG: Switchgrass, T: Tallow, UCO: Used Cooking Oil. Own compilation based on Braun et al. (2024), ICAO (2024a) and German Federal Environmental Agency (2022))

Certain SAFs show significantly lower MACs than others, highly depending on the production process and the feedstocks they originate from. While individual HEFA feedstocks are able to compete in current carbon markets, most SAF feedstocks and pathways show significantly higher MACs than other mitigation options in aviation and competing sectors.

Marginal abatement costs in air transport are comparatively high for several reasons. Firstly, the sector has been optimizing fuel use for decades, as fuel accounts for approximately one-third of total operating costs (Conrady et al., 2013). As a result, many cost-effective efficiency improvements have already been implemented, and further emission reductions — such as through alternative aircraft designs or energy carriers — require substantial technological advancements. Secondly, the deployment of innovative technologies like hydrogen propulsion demands significant global infrastructure investments by both aircraft operators and airports. Thirdly, alternative aircraft designs, such as electric or hydrogen-powered aircraft, currently face limitations in range and payload capacity, which constrain their ability to replace existing aircraft models. Moreover, the certification process in commercial aviation typically spans several years, delaying the entry of new technologies into service and requiring considerable upfront investments from operators. Since SAFs as drop-in solutions are compatible with existing engines to a certain extent, they present a notable abatement potential in the medium term despite facing significant cost barriers.

5. Economic Implications for Aviation in Current Carbon Markets

In principle, carbon markets allow for an efficient reduction of carbon emissions from an economic point of view as explained in section 1. However, will carbon markets lead to significant emission reductions in the air transport sector itself? Both Vesperman and Wald (2011) and Winchester (2019) argue that the aviation sector has a strong interest in investing in carbon offset options in other sectors, as abatement options within the air transport sector are relatively expensive. Due to the fact that MACs are lower in most other sectors, as described above, current carbon markets are not expected to lead to emission reductions per passenger kilometer beyond the historical reduction rate (Larsson et. al, 2019, Fageda and Teixidó 2022). However, as illustrated in Figure 2, operational measures such as increased load factors, reduced contingency fuel, and an improved air traffic management would lead to MACs lower than those of other sectors, making them viable options with costs below current carbon prices. Carbon offset prices under CORSIA averaged 3.10 USD/t_{CO_2eq} in 2021 and are projected to range between 1.90 USD/t_{CO_2eq} and 32 USD/t_{CO_2eq} by 2026 (ICAO, 2022b). In contrast, EU ETS allowance prices increased from 6 USD/t_{CO_2} in 2013 to an average of 96 USD/t_{CO_2} in 2023 before stabilizing at around 61 USD/t_{CO_2} in 2024 (World Bank Group, 2024). These large price deviations can be explained by the fundamental design differences between both market systems.

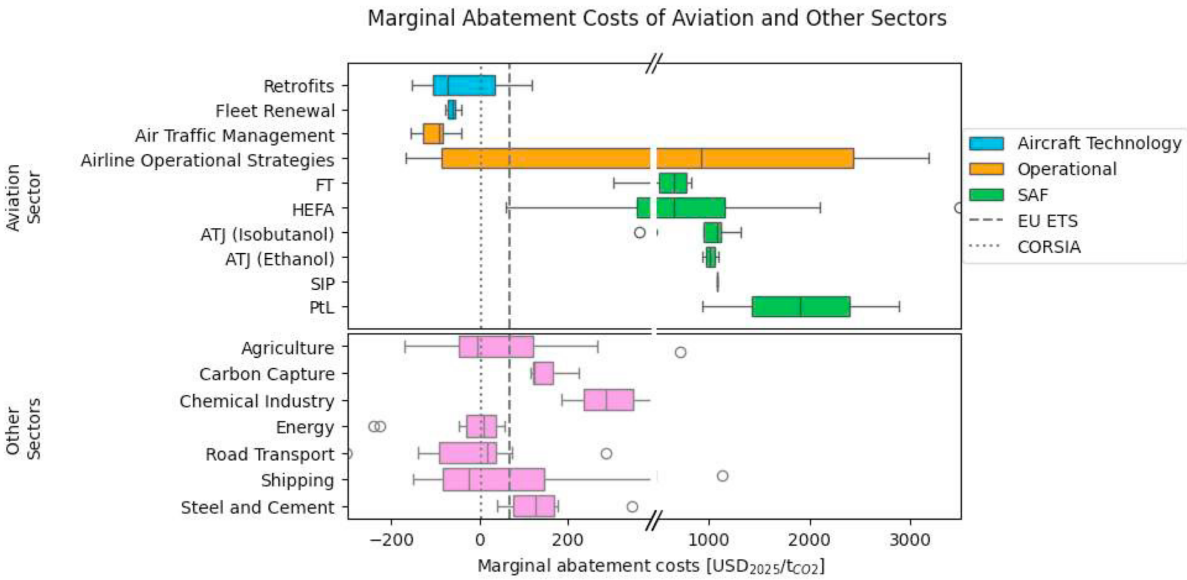

Fig. 2. Marginal Abatement Costs of Aviation Compared to Other Sectors - own compilation based on Bhardwaj et al. (2025), Björnebo et al. (2018), Braun et. al (2024), Bullerdiek et al. (2021), Capaz et al. (2021), Das et al. (2021), De Cara et al. (2001), EWI (2022), Farbes et al. (2021), Fan et al. (2024), IEA (2020), ICAO(2024a), Johnsson et al. (2020), Kajaste et al. (2016), Liu, Jang (2023), Longva et al. (2024), McKinsey (2020), Morris et al. (2009), Nepomuceno de Oliveira et al. (2022), Peng et al. (2018), Rekker et al. (2023), Saygin et al. (2021), Schäfer et al. (2015), Schroten et al. (2012), Schulte et al. (2012), Van den Bergh (2015) Wang et al. (2023)

Operational improvements, according to ICAO (2022a), have the potential to reduce aviation's carbon emissions by up to 11%. Additionally, fleet renewal offers a cost-efficient pathway to emissions reduction, with newer aircraft generations being 15–20% more efficient than their predecessors (Cirium, 2023). However, fleet renewal entails substantial capital investment and long lead times, limiting its accessibility for many aircraft operators. The average costs for in-sector carbon mitigation in aviation mostly remain significantly higher than current carbon prices, particularly for alternative energy carriers like SAF, as shown in Figure 2, and hydrogen. While MACs for HEFA fuel derived from used cooking oil and Brassica Carinata oil aligns approximately with the current EU ETS price level (see Figure 1), investments in these options may be viable depending on local production costs. However, limited feedstock availability for HEFA fuels keeps the overall MACs for SAF in aviation well above current carbon market prices. PtL fuels and hydrogen, while offering substantial carbon reduction potential to meet long-term emissions targets, continue to face prohibitively high costs in the short and medium term, which act as a significant barrier to their widespread adoption.

MACs for SAF in general are expected to decrease gradually as production technologies scale up, feedstock supply chains become more efficient, and policy support reduces cost gaps with fossil jet fuel. However, they will likely remain relatively high compared to other sectors in the near term because SAF production is still constrained by limited feedstock and capital-intensive infrastructure. The planned gradual phase-out of grandfathering free emission allowances within the EU ETS for aviation and other sectors, coupled with the reduction of the total amount of allowances distributed is expected to lead to substantial increases in carbon prices after 2030 (Enerdata, 2023). Figure 3 illustrates the projected development of carbon market prices in the EU ETS up to 2050, shown alongside the corresponding the MACs of hydrogen and PtL fuels for aviation. All values are expressed in USD of the respective year. As illustrated, scaling up the production of advanced technologies such as PtL fuels and hydrogen will be a promising path to mitigate aviation's climate impact. The German Federal Environmental Agency (2022) estimates long-term PtL production costs in 2050 between 1,516 €/t_{fuel} and 2,186 €/t_{fuel}. Given a carbon intensity range of 5–10 g CO_{2eq}/MJ for PtL fuels (German Federal Environmental Agency, 2022) and applying equations 2 and 3, the MACs in central Europe could range from 79 USD/$t_{CO_{2eq}}$ to 342 USD/$t_{CO_{2eq}}$ by 2050. Under certain conditions that lead to an increase in the EU ETS price, PtL fuels could become a viable solution within the next 10–15 years for flights under the EU ETS, potentially competing with abatement options from other sectors. The use of green H_2 currently results in relatively high MACs due to the substantial upfront investments required for infrastructure by both airports and airlines. Other technologies, such as fuel-cell-powered aircraft, are expected to achieve lower MACs and to become competitive in the medium and long term. However, these innovative aircraft are predominantly limited to short- and medium-haul routes, while the majority of aviation's carbon emissions originate from long-haul flights, necessitating costly investments in supporting infrastructure.

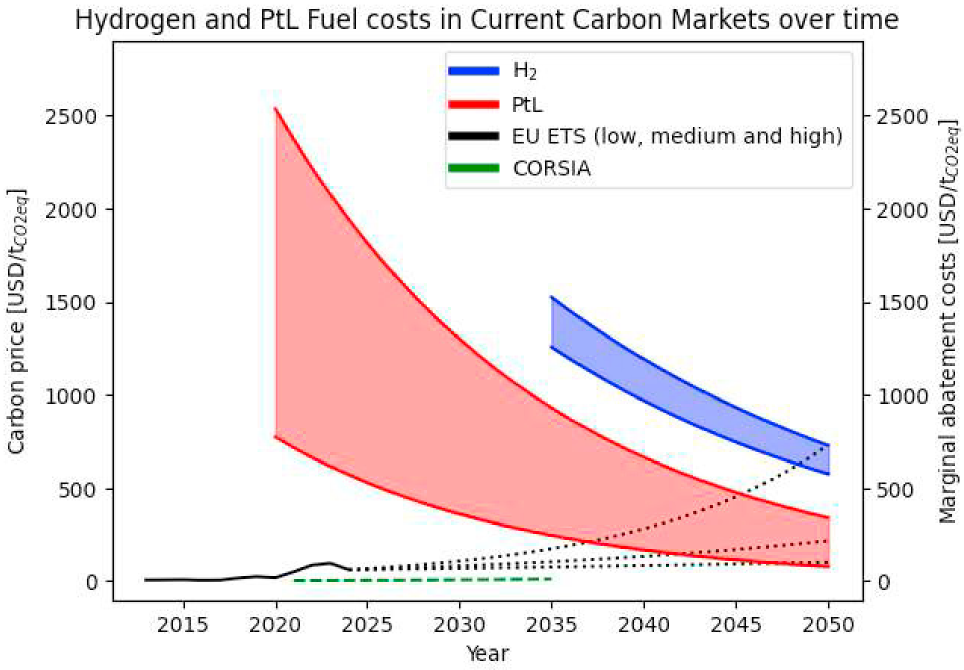

Fig. 3. Future Technologies in the Carbon Market: The Example of H2 and PtL Fuels – own compilation based on Braun et al. (2024), German Federal Environmental Agency (2022), Martin et al. (2023), World Bank Group (2024) and ICAO (2022b) – Note: Projection of EU ETS allowance prices until 2050 in three scenarios with an annual allowance price increase of 2%,5% and 10% – Estimation of jet fuel prices based on oil prices from U.S. Energy Information Administration (2023)

As shown in Figure 3, MACs for H_2 in aviation are projected to also decrease significantly by 2050. Nevertheless, only under optimistic assumptions will the use of hydrogen in aviation be competitive to emission reductions in other sectors under the EU ETS in the long term. Beyond 2050, further reductions in MACs are expected, driven by the assumed increasing availability of renewable energy, positioning H_2 as an economically viable solution in the second half of the century. This long-term potential emphasizes the importance of scaling up renewable energy infrastructure and advancing H_2 technology to enable broader adoption across the aviation industry.

Global initiatives like CORSIA, in their current design, are providing only weak incentives for stakeholders to invest in transformative technologies such as SAF or H_2. This is because of the relatively low market prices for CO_{2eq} offsets which highlights the need for different policy frameworks and targeted investment mechanisms. Overall, with costs of future abatement options expected to decrease substantially only after 2050, current carbon markets provide only limited economic support for scaling up these technologies.

6. Strategies to Reduce In-Sector Emissions and Conclusions

As discussed in the previous section, current carbon markets alone will very likely not lead to a significant reduction of aviation's in-sector emissions. Instead, airlines are most likely to purchase allowances or offsets on the carbon markets. However, in-sector mitigation activities are likely when they will lead to lower operating costs for the airlines. Enhancing operational efficiency or fleet renewal will remain a key focus for aircraft operators as this represents the most cost-effective strategy for reducing aviation's climate relevant emissions. Initiatives like the Single European Sky ATM Research Program, which aims to restructure the European airspace, to create additional capacity and increase the overall efficiency of the air traffic management system (SESAR JU, 2025), could also help to reduce the climate impact cost-effectively. While these initiatives and measures are essential components of a comprehensive strategy to address aviation's climate impact, their limited abatement potential underscores the need for additional mitigation options to achieve in-sector targets.

Considering the significant decarbonization opportunities presented by SAF and H_2 in aviation, additional policy frameworks could accelerate the in-sector decarbonization. Since air transport is a global sector, such measures should be introduced on a global or at least on a supranational, for instance, European level. In this context, the European Union introduced the ReFuelEU Aviation Regulation in 2023 (European Parliament and European Council, 2023). This regulation obliges the fuel suppliers at EU airports to blend jet fuel with SAF starting in 2025 at a blending quota of 2%. This quota will be increasing to 70% by 2050. Further, the European Commission and the US government have defined minimum standards for SAF feedstocks and emissions savings, as outlined in the Renewable Energy Directive II (European Commission, 2018) and the Inflation Reduction Act in the US (H.R.5376 - 117th Congress, 2022). This can significantly support in-sector emission reductions by using SAF. Incorporating measures addressing the total climate impact, including both CO_2 and non-CO_2 emissions (NOx, contrails, e. g.), will further incentivize in-sector emission reductions. In 2025, the EU has introduced a mandatory scheme to monitor, report, and verify non-CO_2 emissions under the EU ETS. However, as of August 2025, aircraft operators are not required to surrender allowances for these emissions.

Together, these measures can accelerate the reduction of climate relevant emissions in aviation as compared to relying on current carbon markets alone. From an economic point of view, however, this could result in emissions being abated at higher costs, leading to increased costs for airlines under these schemes. However, as only European air transport is subject to these regulations currently, competitive disadvantages and welfare losses are a likely result for European aviation.

In general, it is debatable whether a sector's MACs alone should be the decisive criterion for the choice of policy measure. If policymakers were to adopt this approach, purchasing offsets or EU allowances from cost-effective technologies would be the best option for air transport. However, a key challenge is that carbon markets either do not globally include the air transport sector or lack sufficiently stringent environmental targets to lead to meaningful change.

If policymakers would not agree to solely follow the economic efficiency rationale, additional policy measures will become necessary. These policy measures should on the one hand support the introduction of innovative technologies such as SAF or H_2 in aviation. On the other hand, foreseeable competitive disadvantages for the aviation industry subject to these enforced regulations should be actively cushioned by governmental subsidies or other supportive measures. As current carbon markets, such as CORSIA in its present-day design, are insufficient to meet ambitious environmental targets and given that globally coordinated policies to reach these targets are not very likely, additional global or supranational measures, as described above, remain essential to effectively reduce in-sector emissions. This approach could also support the social acceptance of air transport in relation to its environmental footprint, which has faced significant challenges in the past, as, for instance, the globally noticed 'flight shame' movement in Sweden in 2018 demonstrated.

Overall, this study provides an overview of the status quo of abatement options and costs in aviation and how they compare to other relevant sectors. We limited the scope to compare costs, whereas some measures provide very little carbon abatement. Further research should be conducted to examine the concrete abatement potential of specific measures or a sector as a whole to help policy makers decide which industries to prioritize. Another point would be taking into account the degree of correlation between sectors, as sectors like the energy sector for example supply to all the other sectors we discussed. While the cost of abatement measures is central to their evaluation, other macroeconomic factors such as resource availability or impacts on land use or employment need to be considered in order to provide a more comprehensive assessment.

References

Bhardwaj, N., Seethamraju, S., Bandyopadhyay, S., 2025. Carbon abatement options for large iron and steel plants in India. Journal of Cleaner Production 486, 144505

Bicer, Yusuf; Dincer, Ibrahim (2017): Life cycle evaluation of hydrogen and other potential fuels for aircrafts. International Journal of Hydrogen Energy 42 (16), S. 10722–10738. DOI: 10.1016/j.ijhydene.2016.12.119.

Björnebo, L., Spatari, S., Gurian, P., 2018. A greenhouse gas abatement framework for investment in district heating. Applied Energy 211, 1095-1105

Braun, M., Grimme, W., Oesingmann, K., 2024. Pathway to net zero: Reviewing sustainable aviation fuels, environmental impacts and pricing. Journal of Air Transport Management, 117, 102580

Brynolf, S., Hansson, J., Anderson, J. E., Skov, I. R., Wallington, T. J., Grahn, M., Korberg, A.D., Malmgren, E., Taljegård, M., 2022. Review of electrofuel feasibility – prospects for road, ocean, and air transport. Progress in Energy, 4, 042007

Bullerdiek, N., Neuling, U., Kaltschmitt, M., 2021. A GHG reduction obligation for sustainable aviation fuels (SAF) in the EU and in Germany. Journal of Air Transport Management, 92, 102020

Capaz, R. S., Guida, E., Seabra, J. E. A., Osseweijer, P., Posada, J., 2021. Mitigating carbon emissions through sustainable aviation fuels: costs and potential. Biofuels, Bioproducts & Biorefining, 15, 502-524, DOI: 10.1002/bbb.2168

Cirium, 2023. Ascend Consultancy Weekly Team Perspective: Fuel efficiency comparison between old generation and new generation aircraft. https://www.cirium.com/thoughtcloud/ascend-consultancy-weekly-team-perspective-fuel-efficiency-comparison-between-old-generation-and-new-generation-aircraft/ (retrieved December 15, 2024).

Conrady, R., Fichert, F., Sterzenbach, R., 2013. Luftverkehr. Betriebswirtschaftliches Lehr- und Handbuch, 5. Edition, Munich

Das, S., Wilson, E., Williams, E., 2021. The impact of behavioral and geographic heterogeneity on residential-sector carbon abatement costs. Energy & Buildings 231, 110661

De Cara, S., Jayet, P., 2001. Agriculture and Climate Change in the European Union: Greenhouse Gas Emissions and Abatement Costs. AAEA Annual Meeting 2001

Enerdata, 2023. Carbon price forecast under the EU ETS. https://www.enerdata.net/publications/executive-briefing/carbon-price-projections-eu-ets.html (retrieved December 01, 2024)

European Central Bank, 2025. US dollar (USD). https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html (retrieved January 16, 2025)

European Commission, 2018. DIRECTIVE (EU) 2018/2001 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 11 December 2018 on the promotion of the use of energy from renewable sources. Official Journal of the European Union. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2001 (retrieved December 19, 2024)

European Parliament and European Council, 2023. Regulation (EU) 2023/2405 of the European Parliament and of the Council of 18 October 2023 on ensuring a level playing field for sustainable air transport (ReFuelEU Aviation)

EWI, 2022. Low-carbon steel – A global cost comparison. Institute of Energy Economics at the University of Cologne gGmbH (EWI)

Fageda, X., Teixidó, J. (2022): Pricing carbon in the aviation sector: Evidence from the European emissions trading system. Journal of Environmental Economics and Management 111, S. 102591. DOI: 10.1016/j.jeem.2021.102591.

Fan, X., Khanna, M., Lee, Y., Kent, J., Shi, R., Guest, J.S., Lee, D.K., 2024. Spatially Varying Costs of GHG Abatement with Alternative Cellulosic Feedstocks for Sustainable Aviation Fuels. Environmental Science & Technology, 58, 26, 11352-11362

Farbes, J., Haley, B., Jones, R., 2021. Marginal Abatement Cost Curves for U.S. Net-Zero Energy Systems – A Systems Approach. Evolved Energy Research, prepared for Environmental Defense Fund

Friedmann, J., Fan, Z., Ochu, E.K., Sheerazi, H., Byrum, Z., Bhardwaj, A., 2020. Levelized cost of carbon abatement: An improved cost-assessment methodology for a net-zero emissions world. Tech. Rep. New York, NY: Columbia Center on Global Energy Policy

Ge, M., Friedrich, J., Vigna, L., 2024. Where Do Emissions Come From? 4 Charts Explain Greenhouse Gas Emissions by Sector. World Resources Institute, https://www.wri.org/insights/4-charts-explain-greenhouse-gas-emissions-countries-and-sectors (retrieved January 3, 2025)

German Federal Environmental Agency, 2022. Power-to-Liquids: A scalable and sustainable fuel supply perspective for aviation. https://www.umweltbundesamt.de/sites/default/files/medien/376/publikationen/background_paper_power-to-liquids_aviation_2022.pdf (retrieved January 6, 2025)

H. R. 5376 -117th Congress, 2022. Inflation Reduction Act of 2022 - PUBLIC LAW 117–169. https://www.congress.gov/117/plaws/publ169/PLAW-117publ169.pdf (retrieved December 18, 2024)

Hernandez, A., Ng, Max T.M., Siddique, C., Durango-Cohen, P., Mahmassani, H., Elgowainy, A., Wang, M., Zhou, Y. (2024): Abatement cost curve analysis of freight rail decarbonization alternatives. Transportation Research Part D: Transport and Environment 134, S. 104341. DOI: 10.1016/j.trd.2024.104341.

Huang, S., Kuo, L., Chou, K., 2016. The applicability of marginal abatement cost approach: A comprehensive review. Journal of Cleaner Production 127, 59-71

ICAO, 2018. Session 5: CORSIA Calculation of CO2 Offsetting Requirements. https://www.icao.int/Meetings/CORSIAHQ18/Documents/5_CORSIA_Calculation_of_Offsetting_Requirements.pdf (retrieved December 15, 2024)

ICAO,2022a. Innovation for a green transition. 2022 environmental report. https://www.icao.int/environmental-protection/Documents/EnvironmentalReports/2022/ICAO%20ENV%20Report%202022%20F4.pdf (retrieved December 19, 2024)

ICAO, 2022b. Analyses in Support of the 2022 CORSIA Periodic Review: Focus on costs to States and operators. https://www.icao.int/environmental-protection/CORSIA/Documents/2_CAEP_CORSIA%20Periodic%20Review%20(C225)_Focus%20on%20Costs.pdf (retrieved December 21, 2024)

ICAO, 2024a. CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA_Eligible_Fuels/ICAO%20document%2006%20-%20Default%20Life%20Cycle%20Emissions%20-%20October%202024.pdf (retrieved January 6, 2025)

ICAO, 2024b. https://data.icao.int/TrafficForecast/ (retrieved December 17, 2024).

IEA, 2020. Abatement costs for road vehicles. International Energy Agency, Paris. https://www.iea.org/data-and-statistics/charts/abatement-costs-for-road-vehicles (retrieved January 14, 2025)

IEA, 2024. Carbon Capture, Utilisation and Storage. International Energy Agency, Paris. https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage (retrieved January 3, 2025)

IRENA, 2024. Renewable Power Generation Costs in 2023. International Renewable Energy Agency, Abu Dhabi.

Johnsson, F., Normann, F., Svensson, E., 2020. Marginal Abatement Cost Curve of Industrial CO2 Capture and Storage – A Swedish Case Study. Frontiers in Energy Research, 8:175

Karami, O., Dwivedi, P., Lamb, M., Field, J., 2022. Economics of Crop Rotations With and Without Carinata for Sustainable Aviation Fuel Production in the SE United States. Front. Energy Res., 10, 830227

Kajaste, R., Hurme, M., 2016. Cement industry greenhouse gas emissions – management options and abatement cost. Journal of Cleaner Production 112, 4041-4052

Klöwer, M.; Allen, M. R.; Lee, D. S.; Proud, S. R.; Gallagher, L.; Skowron, A. (2021): Quantifying aviation's contribution to global warming. Environ. Res. Lett. 16 (10), S. 104027. DOI: 10.1088/1748-9326/ac286e.

Larsson, J., Elofsson, A., Sterner, T. and Åkerman, J., 2019. International and national climate policies for aviation: a review. Climate Policy, 19:6, 787-799, DOI: 10.1080/14693062.2018.1562871

Lee D. S. Lee, D. W. Fahey, A. Skowron, M. R. Allen, U. Burkhardt, Q. Chen, S.J. Doherty, S. Freeman, P.M. Forster, J. Fuglestvedt, A. Gettelman, R.R. De Leon, L.L. Lim, M. T. Lund, R.J. Millar, B. Owen, J.E. Penner, G. Pitari, M.J. Prather, R. Sausen, L. J. Wilcox, 2021. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. Atmospheric Environment 244, pp 1-29

Lee, D.S., D.W. Fahey, P.M. Forster, P.J. Newton, R.C.N. Wit, L.L. Lim, B. Owen, and R. Sausen, 2009. Aviation and global climate change in the 21st century. Atmospheric Environment 43, pp 3520–3537

Liu, X. and Jiang, P., 2023. How does civil aviation achieve sustainable low-carbon development? — An abatement–cost perspective. Heliyon, 9, e20821

Longva, T., Eide, M., Endresen, Ø., Sekkesæter, Ø., Helgesen, H., Rivedal, N. (2024): Marginal abatement cost curves for CO2 emission reduction from shipping to 2050. Maritime Transport Research 6, S. 100112. DOI: 10.1016/j.martra.2024.100112.

Martin, J., Dimanchev, E., Neumann, A., 2023. Carbon abatement costs for renewable fuels in hard-to-abate transport sectors. Advances in Applied Energy, 12, 100156

McKitrick, R., 1999. A Derivation of the Marginal Abatement Cost Curve. Journal of Environmental Economics and Management 37, 306-314

McKinsey & Company, 2020. Hydrogen-powered aviation: A fact-based study of hydrogen technology, economics, and climate impact by 2050. https://www.euractiv.com/wp-content/uploads/sites/2/2020/06/20200507_Hydrogen-Powered-Aviation-report_FINAL-web-ID-8706035.pdf (retrieved December 19, 2024)

McKinsey & Company, 2023. Decarbonizing aviation: Executing on net-zero goals. https://www.mckinsey.com/industries/aerospace-and-defense/our-insights/decarbonizing-aviation-executing-on-net-zero-goals (retrieved January 6, 2025)

Morris, J., Rowbotham, A., Angus, A., Mann, M., Poll, I., 2009. A Framework for Estimating the Marginal Costs of Environmental Abatement for the Aviation Sector. OMEGA Project 14 – Draft Final Report. Cranfield University, Bedford

Nepomuceno de Oliveira, M., Szklo, A., Castelo Branco, D.(2022): Implementation of Maritime Transport Mitigation Measures according to their marginal abatement costs and their mitigation potentials. Energy Policy 160, S. 112699. DOI: 10.1016/j.enpol.2021.112699.

Peng, J., Yu, B., Liao, H., Wei, J., 2018. Marginal abatement costs of CO2 emissions in the thermal power sector: A regional empirical analysis from China. Journal of Cleaner Production 171, 163-174

Rekker, L., Kesina, M., Mulder, M., 2023. Carbon abatement in the European chemical industry: assessing the feasibility of abatement technologies by estimating firm-level marginal abatement costs. Energy Economics 126, 106889

Saygin, D., Gielen, D., 2021. Zero-Emission Pathway for the Global Chemical and Petrochemical Sector. Energies 14, 3772

Schäfer, A., Evans, A., Reynolds, T., Dray, L., 2015. Costs of mitigating CO2 emissions from passenger aircraft. Nature Climate Change 6, 412–417. https://doi.org/10.1038/nclimate2865

Scheelhaase, J., Maertens, S. and Grimme, W., 2021. Options for improving the EU Emissions Trading Scheme (EU ETS) for aviation. Transportation Research Procedia, 59 (2021), 193–202.

Schroten, A., Warringa, G., Bles, M., 2012. Marginal abatement cost curves for Heavy Duty Vehicles. Background report, Delft 2012

Schulte, R., Crosson, P., Donnellan, T., Farrelly, N., Finnan, J., Lalor, S., Lanigan, G., O'Brien, D., Shalloo, L., Thorne, F., 2012. A Marginal Abatement Cost Curve for Irish Agriculture. Teagasc – Agriculture and Food Development Authority

SESAR JU, 2025. Single European Sky: About. https://www.sesarju.eu/background-ses (retrieved January 13, 2025)

U.S. Energy Information Administration, 2023. Annual Energy Outlook 2023 – Brent Spot Prices. https://www.eia.gov/outlooks/aeo/data/browser/#/?id=1-AEO2023&region=0-0&cases=ref2023&start=2021&end=2050&f=A&linechart=~ref2023-d020623a.52-1-AEO2023~ref2023-d020623a.41-1-AEO2023&ctype=linechart&sourcekey=0 (retrieved January, 20 2025)

Van den Bergh, K., Delarue, E., 2015. Quantifying CO2 abatement costs in the power sector. Energy Policy 80, 88-97

Vesperman, J. and 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, 45, 1066-1076

Wang, K., Zhang, Y., Wie, Y., 2023. China's aviation passenger transport can reduce CO2 emissions by 2.9 billion tons by 2050 if certain abatement options are implemented. One Earth, 6, 1050-1065

Winchester, N., 2019. A win-win solution to abate aviation CO2 emissions. Journal of Air Transport Management, 80, 101692

World Bank Group, 2024. State and Trends of Carbon Pricing Dashboard. https://carbonpricingdashboard.worldbank.org/compliance/price (retrieved January 6, 2025)