



Sustainable aviation fuels in Europe: An agent-based simulation of market dynamics in a regulated competitive landscape

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ABSTRACT

While many of the European Union's (EU) economic sectors successfully reduced emissions before the COVID-19 pandemic, transport and aviation in particular showed the opposite trend. With the Fit for 55 package, the EU initiated a political push to drive the sustainable transition in aviation. Taking into account the policy drive of the Fit for 55 package, we investigate the political market intervention in intra-European aviation, considering the potential role of sustainable aviation fuels (SAFs). For this purpose, an agent-based simulation modeling approach coupled with a system dynamics environment was developed to analyze market developments through both economic and ecological lenses. Two key stakeholders, customers (both passengers and freight companies) and airlines, are considered to capture the impacts of their behaviors and decision-making preferences in the adoption of SAFs. Several scenarios, based on different policy interventions, were considered in the analysis in order to comprehensively explore the impacts of further political developments. The results indicate that policy intervention can lead to a transition driven by sustainable sector performance and demand effects in response to price changes. Furthermore, as intended by the regulations, the results suggest that achieving the sustainable transition requires a shared responsibility amongst customers, industry players, and policymakers. While the sector will reduce its relative and absolute emissions, achieving a 90% reduction compared to 1990 levels seems unlikely with current regulatory instruments.

1. Introduction

The European aviation sector has followed a complex path that has been expanded through recent decades. The aviation sector plays a crucial role in the European and global economies by facilitating international trade and tourism, contributing significantly to economic growth via job creation, increased trade volume, and making up a notable share of GDP (Winchester et al., 2013; Su et al., 2023; Avogadro and Redondi, 2024). Nevertheless it accounts for more than 2% of global greenhouse gas (GHG) emissions, over 3% of European Union (EU)'s GHG emissions in 2022, and over 14% of EU transport emissions (Bergero et al., 2023; European Environment Agency, 2024a; Yirgu and Kim, 2023).

Fossil jet fuel (kerosene) is the main contributor to the high level of emissions in the sector (ten Cate et al., 2025; Martin et al., 2023; Staples et al., 2018). Despite the efforts of the International Civil Aviation Organization (ICAO) on fuel efficiency, the primary sources of aviation emissions have not been adequately addressed (Bergero et al., 2023; ICAO, 2022). Along with the ICAO and Air Traffic Management (ATM) program (systems and services that manage aircraft movements), the

Commission Council of the EU has intensified its efforts to mitigate the emissions in all sectors through the EU Green Deal and Fit for 55 package (European Commission, 2021a; Wei and Kallbekken, 2024). The EU Green Deal has set the ambitious target of a 90% reduction in emissions in the transport sector against 1990 levels by 2050. In October 2023, the ReFuelEU aviation was adopted as part of the Fit for 55 package to regulate the defossilization of aviation by mandating the adoption of sustainable aviation fuels (SAFs) (European Commission, 2023a).

Aviation has numerous technical prerequisites that make it difficult to electrify. SAFs with high energy density are considered a promising solution for transitioning the sector into a sustainable state (Gonzalez-Garay et al., 2022; Moncada et al., 2019; Schmidt et al., 2018; Jiang and Liu, 2025). Across different pathways, SAFs are produced from renewable resources and can significantly decrease GHG emissions compared to fossil jet fuel (Schmidt et al., 2018; Trinh et al., 2021; Hu et al., 2022; Thonemann et al., 2024). Therefore, the development and deployment of SAFs are essential for meeting the GHG reduction

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targets in European aviation (Schmidt et al., 2018; Hu et al., 2022; Xu et al., 2025).

Despite the potential of SAFs for sustainable aviation, their adoption faces several major challenges (Ueckerdt et al., 2021; Van Tol et al., 2021; Pescarini et al., 2025). High production and infrastructure costs for hydrogen electrolysis and carbon synthesis, as well as the lack of competitive pricing for SAFs compared to kerosene are common economic barriers (Grim et al., 2022; Singh et al., 2022; Montlaur et al., 2024). In technical terms, complex production processes, low fuel efficiency and scalability have been identified as the main challenges (Rojas-Michaga et al., 2023; Seymour et al., 2024). Most importantly, policy and regulatory frameworks play a critical role in the market uptake of SAFs (Trinh et al., 2021; Yirgu and Kim, 2023; Prussi et al., 2025). The lack of effective policy instruments, such as feed-in tariffs and investment subsidies, create an unfavorable market environment for SAFs, leading to higher production costs, reduced investor confidence, and slower market adoption, ultimately hindering the competitiveness of SAFs against conventional fossil-based alternatives (Dodd and Yengin, 2021; Zheng et al., 2025). Subsidies play a crucial role in accelerating the adoption of SAFs, reducing financial risks for producers, making large-scale production more viable and enhancing price competitiveness by narrowing the cost gap.

Considering the EU's long-term targets to defossilize the sector by 2050, addressing these challenges will require innovative and systematic approaches to investigate and predict the complex dynamics of different SAFs (Martinez-Valencia et al., 2021; Pérez-Calderón et al., 2021). Although initial post-pandemic predictions are available, the shifting political landscape in Europe makes the study of aviation's transition to SAFs a largely unexplored area. In this context, system modeling approaches, such as Agent-based Modeling (ABM) and System Dynamics (SD) can offer valuable insights for understanding and navigating the multi-dimensional landscape of European aviation. In particular, existing studies often struggle to account for how heterogeneous actor behavior and interacting policy instruments jointly influence SAF adoption over time.

In this context, system modeling approaches such as SD and ABM offer complementary strengths for analyzing the multi-dimensional dynamics of European aviation. ABM enables the explicit representation of heterogeneous stakeholders, such as airlines and passengers, and their adaptive decision-making under changing economic and policy conditions (Gurtner et al., 2021; Liu and Madlener, 2021). This is particularly relevant in aviation, where individual procurement and travel decisions can substantially influence aggregate fuel demand and emissions outcomes (Moncada et al., 2019). However, ABM alone is limited in capturing long-term system feedbacks and accumulative effects. SD, by contrast, is well suited to representing feedback loops, time delays, and stock–flow relationships that govern the long-term evolution of fuel demand, emissions, and policy-induced cost dynamics (Tascón and Olariaga, 2021). Yet, purely aggregate SD models typically abstract from heterogeneous actor behavior, which is critical for understanding SAF diffusion in practice.

To address these limitations, this study develops a coupled ABM–SD framework to analyze the energy transition in European aviation under recently introduced regulatory frameworks. The model integrates heterogeneous airline and passenger behavior with system-level dynamics of fuel demand, emissions, and policy-induced costs, while explicitly considering multiple SAF pathways, carbon and fuel pricing, and alternative SAF supply scenarios. By jointly evaluating the effects of Emissions Trading System (ETS), Energy Taxation Directive (ETD), and ReFuelEU Aviation, the proposed approach provides a dynamic and integrated assessment of SAF adoption and diffusion that extends beyond single-policy or static analyses. In summary, this study presents the following methodological, analytical, and policy-relevant contributions:

- **Methodological contribution:** We develop a coupled ABM–SD framework that combines heterogeneous actor behavior with system-level feedbacks to analyze SAF adoption in European aviation.
- **Analytical contribution:** We provide a dynamic and integrated assessment of how multiple EU policy instruments, e.g., ETS, ETD, and ReFuelEU Aviation, jointly influence fuel costs, demand responses, emissions, and SAF diffusion, moving beyond single-policy or static analyses.
- **Sectoral and empirical contribution:** We apply the proposed framework to the EU aviation sector, explicitly considering multiple SAF pathways, airline procurement behavior, passenger demand responses, and alternative SAF supply scenarios under the current EU regulatory context.
- **Policy-relevant insight:** We offer insights into the interactions and trade-offs between climate, energy, and transport policies, highlighting conditions under which policy mixes may accelerate or constrain SAF uptake over time.

This paper is structured as follows: Section 2 presents a detailed literature review of legislation, SAF pathways, and ABM for sustainable aviation. Section 3 details the developed approach by identifying the components for the ABM and SD. Section 4 discusses the case study and introduces the proposed scenarios. Later, economic and environmental results as well as the findings under different scenarios are reported. Section 5 presents a discussion of the findings and limitations of the study. Finally, concluding remarks with a summary of the study's contributions and suggestions for future research are presented in Section 6.

2. Literature review

2.1. Regulations

The aviation sector has been subject to significant political changes over the past decade, with further shifts impending. Major future shifts are planned as part of the EU Green Deal, which serves as a comprehensive framework for achieving sustainability goals, aiming for a 90% reduction in transport emissions by 2050 compared to 1990 levels. Further support is provided by the Fit for 55 package, introduced in 2021, which sets interim targets for reducing emissions in aviation (European Commission, 2021a). Meeting the emissions reduction targets in aviation is challenging (European Environment Agency, 2024a). Emissions peaked at more than double the 1990 levels in 2019 and rose again in 2022 after the decline caused by the COVID-19 pandemic (European Environment Agency, 2024a; European Commission, 2023b). To address GHG (both CO₂ and non-CO₂) emissions challenges in European aviation, a set of revised policies, alongside new policies are considered within the EU Green Deal and Fit for 55 package.

The policy context considered in this study focuses on regulatory instruments that directly shape cost structures, efficiency trends, and fuel demand dynamics in European aviation, which are explicitly represented in the modeling framework. In particular, the EU ETS (European Commission, 2023c) and the ETD (European Commission, 2021b) affect aviation through fuel- and emission-related cost signals, thereby influencing airline operating costs and ticket prices. Policies targeting SAFs, including blending mandates and SAF-specific allowance mechanisms, are reflected through minimum demand constraints and cost relief channels that alter the relative competitiveness of SAF pathways (European Commission, 2023d,a). In addition, operational efficiency policies such as SES2+ are represented through gradual improvements in fuel efficiency, affecting total fuel demand and emissions over time (European Commission, 2011, 2020). Rather than providing a comprehensive policy review, this study operationalizes these instruments as economic and technical drivers within the SD–ABM framework, allowing their combined effects on SAF uptake, emissions, and market dynamics to

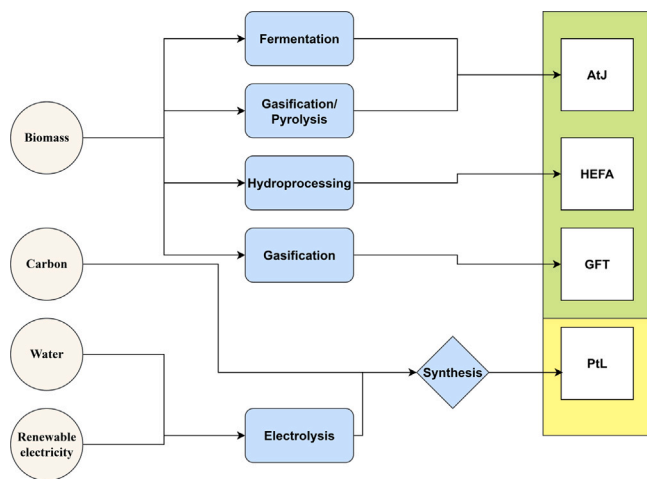


Fig. 1. SAF production pathways (Detsios et al., 2023).

be assessed in a consistent and transparent manner. Table A.1 presents an overview of recent policies for EU aviation and their future targets for becoming sustainable.

Having reviewed the legislative framework, it is essential to understand the various pathways for SAFs that these policies aim to promote and support. This helps clarifying technical characteristics and the effects of policy measures on the adoption and diffusion of SAFs.

2.2. SAF pathways

Drop-in and non-drop-in fuels represent two distinct pathways for SAFs. Drop-in fuels such as Alcohol-to-Jet (AtJ), Hydroprocessed Esters and Fatty Acids (HEFA), Gasification Fischer Tropsch (GFT) and power-to-liquid (PtL) fuels are chemically identical to conventional jet fuels, allowing them to be used in existing aircraft engines and infrastructure without modifications (Drünert et al., 2020; Gyandoh and Gomez, 2025; Bell et al., 2025; Xu et al., 2025). This compatibility ensures their seamless integration into current aviation systems, providing an immediate reduction in GHG emissions (Wandelt et al., 2025; Braun et al., 2024; Yan et al., 2025). However, they face several challenges, including high production costs and limited sustainable feedstock (He et al., 2025; Cui et al., 2024).

In contrast, non-drop-in fuels differ chemically from conventional jet fuels and may require modifications to aircraft engines or fuel infrastructure. These fuels have the potential for higher efficiency and lower emissions and can utilize a broader range of feedstocks. Despite their benefits, non-drop-in fuels demand significant investment in new technologies and infrastructures, face regulatory obstacles, and present compatibility issues with the existing fleet and propulsion systems.

Fig. 1 illustrates both pathways and potential SAF alternatives. For drop-in fuels, AtJ, HEFA, GFT, and PtL are considered in this study. With an understanding of the SAF pathways, it is essential to review and clarify the previous applications of ABM in investigating their adoption and diffusion.

2.3. ABM for sustainable aviation

Considering the high complexity of the adoption and diffusion of SAFs with several stakeholders in its value chain, systems modeling tools such as ABM have shown promising performance in addressing the impacts of potential system components. However, there exist a limited number of studies that directly address the uptake of SAFs for sustainable aviation using system modeling techniques (Cao et al., 2026).

Horio et al. (2015) investigated the development of the U.S. aviation sector, focusing on airline and customer decision-making in a political environment, using an ABM. Mosca and Hoffenson (2017) analyzed the effects of the “Next Generation Air Transportation System” initiative by the U.S. Federal Aviation Administration. Kapeller et al. (2019) focused their ABM on Austrian tourism and a green transition through customer (traveler) choices for modes of transport until 2030.

Moncada et al. (2019) extended a spatially explicit ABM approach to explore the transition from the existing sugarcane-ethanol supply chain to a bio-jet fuel one in Brazil. The study incorporated new policies into the model, such as a feed-in tariff and a capital investment subsidy, to analyze their impacts on production and investment decisions. The study underscores the importance of tailored policy instruments in fostering the development of bio-jet fuel supply chains and suggests further research into market mechanisms for greenhouse gas emissions. An important limitation of this study is its focus on bio-jet fuels only. Schnuelle et al. (2020) used an ABM to simulate the potential uptake of power-to-fuel technologies in Germany from 2016 to 2035. The model incorporated various actors and stakeholders emphasizing the importance of agile regulation through a participatory process to reflect real-world dynamics and regulatory impacts. Key findings indicate that regulatory adjustments, such as CO₂ certificate pricing, start-up subsidies, and emission reduction quotas, are crucial for the economic feasibility and large-scale integration of power-to-fuels. Ullah and Dwivedi (2022) developed a spatially explicit ABM to analyze the adoption of carinata for SAF production among farmers. The model simulated adoption scenarios under varying initial willingness rates and contract prices. The results indicated that the adoption could occupy up to 85% of row cropland by 2050 in high willingness scenarios, demonstrating the importance of contract pricing and neighborhood influences in promoting bioenergy crop adoption.

In one of the latest studies published in 2026, Liang et al. (2025) analyzed the economic performance of SAF blending in airlines using an SD framework, with a focus on China’s SAF pilot policies and carbon market mechanisms. An SD model was developed, which captures interactions between fuel costs, subsidies, demand elasticity, and airline profitability under alternative blending mandates and carbon pricing schemes. The conceptual model spans across not only airlines’ economic, but also their environmental and energy systems. However, the SD structure aggregates decision-making at the sector level and does not explicitly model behavioral responses of individual market actors. In particular, airline fuel choice was represented through exogenously defined blending trajectories rather than endogenous procurement decisions, and demand responses are captured through aggregate elasticities without distinguishing between passenger and freight transport or accounting for modal substitution effects. Moreover, the analysis considered a limited policy configuration tailored to China’s pilot context, without exploring the interaction of multiple overlapping regulatory instruments or heterogeneous SAF pathways that characterize more complex regulatory environments. Table A.2 presents an in-depth analysis of previous studies on SAFs market uptake with ABM.

Synthesizing insights from existing ABM and SD-based studies, three key gaps remain in the literature. First, most analyses rely on aggregate or static representations that are not well suited to capture the heterogeneous and adaptive behavior of market actors, such as airlines and passengers, whose decisions critically shape SAF uptake under evolving cost and policy conditions. Second, the European aviation sector remains underexplored in this regard, particularly in terms of how multiple SAF pathways compete and diffuse under current EU-specific regulatory developments. Third, recent policy instruments introduced under the EU Green Deal and the Fit for 55 package, most notably the EU ETS, the ETD, and ReFuelEU Aviation, are typically assessed in isolation, despite their simultaneous and potentially interacting effects on fuel costs, demand, and investment incentives.

To address these gaps, this study adopts a coupled ABM–SD framework. The ABM component captures heterogeneous decision-making

by key actors, including airline procurement choices and passenger demand responses, while the SD component represents system-wide feedbacks related to fuel demand, emissions, and policy-induced cost dynamics. This integrated approach enables a consistent assessment of how ETS, ETD, and ReFuelEU Aviation jointly influence SAF adoption and diffusion in the EU aviation sector, thereby providing insights that cannot be obtained from single-policy or purely aggregate modeling frameworks.

3. Problem definition

In order to define the required components in reflecting a realistic vision of the sector into an ABM model, it is necessary to understand the current status quo of aviation in the EU in order to identify the technical, environmental, and socio-economic aspects.

3.1. Aviation in the EU

In 2018, both domestic and international flights together emitted around 905 million tons of CO₂, accounting for over 2% of the world's CO₂ emissions (IATA, 2019). Before the decrease in emissions caused by the COVID-19 pandemic, flights within and between EU member states emitted around 65 million tons of CO₂, whereas international flights to non-EU countries contributed approximately 120 million tons of CO₂ in 2019 (European Environment Agency, 2021). The aviation sector saw substantial growth of about 140% over the past three decades before the COVID-19 pandemic (OECD, 2023). Despite the pandemic-induced industry shock, aviation has recovered to former performances. In 2022, commercial aviation in Europe reached over 80% of pre-COVID-19 levels (Eurostat, 2024a,b).

Fig. 2 presents an overview of emissions in the EU from 1990 to 2022 in the aviation sector. The graph highlights emissions from international aviation with a consistent upward trend from 1990, reaching a peak around 2019, reflecting the growth of global air travel over the years.

According to the most recent annual report of the European Organization for the Safety of Air Navigation (EUROCONTROL), 10.2 million flights were recorded in Europe in 2023, which was 10% higher than the previous year, producing nine million tonnes more CO₂ compared to the same year (accounting for 92% of flights in 2019) (Eurocontrol, 2024). The UK, with 5,290; Spain, with 4,616; Germany, with 4,532; France, with 3,999; and Italy, with 3,500, had the highest daily flights, respectively. The European aviation network

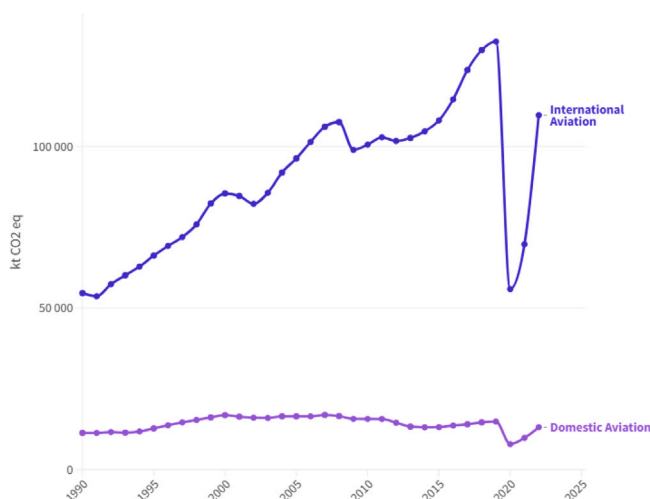


Fig. 2. Overview of GHG emissions in the EU27 aviation (European Environment Agency, 2024a).

experienced a 10% increase in traffic compared to 2022, resulting from positive traffic variation in member states, except for Estonia and Bosnia and Herzegovina. Eastern European countries such as Albania (+30%), Armenia (+26%) and Georgia (24%) had the highest traffic growth in 2023.

Given the sector's recovery and the rising trends in travel frequency, passenger numbers, mileage, and fuel consumption, the urgency to reduce emissions has become increasingly pressing. Therefore, understanding the dynamics of the sector and the potential roles of stakeholders is necessary to transition from fossil jet fuel to SAFs. ABM enables the exploration of individual decision-making processes and their collective impact on the system, offering valuable insights into pathways for achieving defossilization in the aviation sector. The following section outlines the key components of the ABM developed for this purpose, detailing the agents, their behaviors, and the interactions that shape the system dynamics.

3.2. Model conceptualization: Assumptions and components

In order to capture a multi-perspective view of sustainable aviation in Europe, this study aims to highlight the potential political, environmental, and economic impacts within the SAF supply chain. In this regard, the identification and integration of key performance indicators (KPIs) are necessary to reflect the real-world circumstances within an ABM model. With the split of SAFs into the HEFA, ATJ, GFT and PtL, respectively, price development and ecological impacts are essential for building a model (Tables A.3 and A.4).

Fig. 3 presents an overview of the SD environment and the integration of agents in the model. Further details on the model components and its structure, including parameters, variables, stocks, flows, and agents are provided in the supplementary materials. Key assumptions, KPIs, agents and other components of the model are explained below. A detailed overview of the SD model is also presented in Figure S1 in the supplementary materials.

3.2.1. Assumptions

Assumptions are incorporated to provide a nearly realistic projection of future developments within the model. In the following sections, where applicable and relevant, these assumptions will be translated into scenarios to allow for the observation of variations in the assumed factors. A complete description of the assumptions is presented below:

- I. The ICAO aims for 2% annual fuel efficiency gains by 2050, but recent models suggest a more conservative 1% improvement (Oesingmann, 2022). This study bases its computations on the conservative annual 1% efficiency improvement.
- II. The ETS plans to allocate 20 million allowances for the use of SAFs by 2030 (Wissner and Graichen, 2024). However, there is no clarification on how these will be distributed over the years. As a result, the allowances will be distributed based on the assumption of an increasing supply, aligned with the expected SAFs adoption driven by the ReFuelEU Aviation. The allocation will follow a gradual increase, starting with 0.25 million in 2024, 0.5 million in 2025, 1 million in 2026, 1.75 million in 2027, 3.25 million in 2028, 5 million in 2029, and reaching 8.25 million in 2030. Recital 154 of the ETS outlines the possibility of extending free allowances for SAFs until 2035. This measure will be implemented in a scenario that focuses on the effects of SAF adoption.
- III. Emissions (CO₂ eq.) from aviation are calculated on the basis of the well-to-wake GHG emissions. It is assumed that there will be no inherent emission changes from any fuel type.
- IV. Current blending limits for SAFs do not exceed 50%, which is assumed not being a restricting factor for mid-century SAFs adoption developments over 50%.

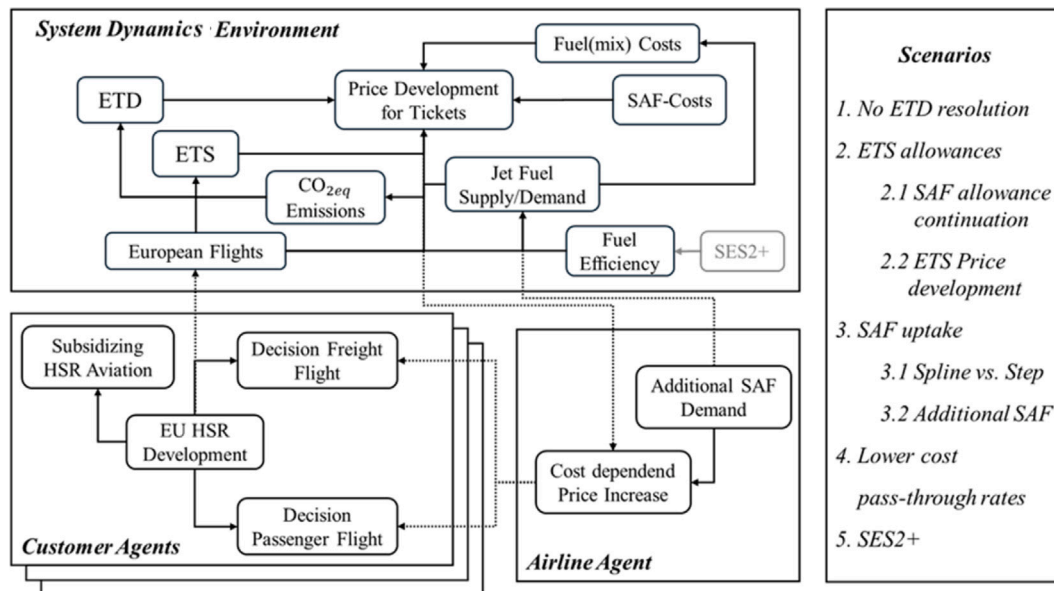


Fig. 3. Schematic of the developed model.

- Scenarios**
1. No ETD resolution
 2. ETS allowances
 - 2.1 SAF allowance continuation
 - 2.2 ETS Price development
 3. SAF uptake
 - 3.1 Spline vs. Step
 - 3.2 Additional SAF
 4. Lower cost pass-through rates
 5. SES2+

- V. This study focuses on economic developments related to regulatory changes, excluding factors affecting aviation's cost structure. Regulatory changes will affect airline costs and pricing strategies, requiring them to decide whether to pass these costs on to customers. Therefore, the model will assume a 100% pass-through rate for cost changes.
- VI. Although the ReFuelEU Aviation has determined the quotas for SAFs, the development of the supply for each SAF is highly uncertain, particularly in long-term considering the 2050 perspective. This is due to uncertainties e.g., in demand, price developments, R&D progress, and feedstock availability. In this study, the supply capacities are modeled using a pathway forecasted by the European Union Aviation Safety Agency (EASA) (EASA, 2023), assuming that half of the capacity will be allocated to intra-European flights, whereas the other half will be designated for extra-European flights, which fall beyond the scope of this study.
- VII. Calculating the reference value for aviation emissions in ETS certificates is challenging due to the need for certificate purchases based on emission factors. Fossil jet fuel has an emission factor of 3.16 tons CO₂ per ton, whereas synthetic fuels and biomass meeting RED III sustainability criteria are calculated with an emission factor of zero if produced using renewable energy. An assumption for the calculation of the required allowances is made by modeling the obligation to surrender allowances from 2027 for SAFs based on individual CO₂ equivalent emissions less a discount rate of approximately 17%. The subtrahend rate is determined by the discrepancy between the ETS relevant emission factor and the actual CO₂ equivalent emission from fossil jet fuel. The year 2027 was selected as the introductory year because the ETS (Article 14, paragraph 5) stipulates that a proposal for the inclusion of non-CO₂ emissions will be published then.
- VIII. The model distinguishes between business and leisure trips. Auclair (2021) claimed that 30% of European aviation emissions originate from business travel. Hence, a 30% share in total flights is attributed to business travel.

- IX. This study assumes no major decline in demand amongst European aviation customers due to pro-environmental attitudes.

Based on the collected data, the ABM model is formulated accordingly. A complete list of the parameters for the SD model and corresponding sources is provided in the supplementary materials. Assumptions were mainly derived where no data was available. After obtaining primary results, carefully designed scenarios are considered to measure the robustness of the results considering the impacts of the assumptions.

Following the definition of the assumptions, subsequent sections present further information regarding the political, technical, ecological, and economic aspects.

3.2.2. Political dimension in aviation system dynamics

The EU has introduced policies that will impact aviation emissions in two main ways (Table A.1). First, policies such as the SAF quota in the ReFuelEU Aviation that will directly reduce emissions by replacing fossil fuels with renewable or less emission-intensive alternatives; second, policies that indirectly influence price changes and related cross-price elasticities (European Commission, 2023a; Efthymiou and Ryley, 2022).

A key regulatory framework is the ETS, which is responsible for the ETS price and EUAs for aviation (Fig. A.1) (Airlines for Europe, 2021; Cui et al., 2017). In addition to the EUAs, allowances related to aviation emissions are also included. These allowances are categorized into auctioned allowances, a special reserve, free allowances for SAFs use, and an allowance gap, which is the difference between granted allowances and those required.

The cost calculation for the ETD is based on a 10-year transition period, eventually reaching a minimum rate of 330€/1,000 liters. This equates to 264.66 €/ton, using a conversion rate of 0.802 kg/l for kerosene, which is assumed to be constant for all eligible jet fuels (Hileman et al., 2010). The revised ETD will apply to domestic and international flights starting in 2025. Lower costs for SAFs are assumed,

but how the ETD will apply to SAFs after the ten-year exemption remains unclear. A reduced tax rate is considered to reflect the lower GHG emission factors of SAFs. The ETD tax for each SAF pathway is calculated by dividing the GHG emissions (in g CO₂ equivalent MJ⁻¹) by the fossil reference value of 89 g CO₂ equivalent MJ⁻¹ (IATA, 2019). The policy-imposed costs are summarized with dynamic variables to show total regulatory costs per flight. Additionally, selective and cumulative costs will be gathered for scenario-specific comparisons.

The ReFuelEU Aviation mandates SAFs use through fixed fuel share quotas until 2050, with no deviations allowed in the default model. In subsequent sections, a scenario analysis will briefly explore the ongoing academic debate and modeling possibilities related to SAF supply scenarios and potential deviations. Further information regarding this directive can be found in previous sections.

The Green Deal and Flightpath 2050 set overarching EU goals, which are pursued through regulations such as the ETD, ETS, RED III, and SES2+. Rather than modeling these targets directly, the model assesses whether their objectives can be met with current and future legislation. Double counting is assumed to be avoided by applying the ETS only to intra-EEA flights, and SES2+ is expected to deliver rapid efficiency improvements. This approach highlights the significance of the objectives for European aviation's development through 2050.

A full list of relevant parameters, variables, stocks, and flows are provided in the supplementary materials.

3.2.3. Ecological dimension in aviation system dynamics

For the ecological aspects, the model highlights the CO₂ equivalent emission within the sector. The CO₂ equivalent emission values for HEFA, ATJ, GFT, and PtL pathways are given as 89 for fossil fuels, 47.4 for HEFA, 39.7 for ATJ, 12.2 for GFT and 5 for PtL in g CO₂ equivalent MJ⁻¹ (Batteiger et al., 2022; IATA, 2019; Okolie et al., 2023). To calculate the overall climate impact, it is necessary to track the dynamic development of the sector-wide fuel mix. The mix is computed by comparing the supply of each fuel to the overall fuel demand (Eq. (1)).

$$E_{mix} = \sum_i S_i \gamma_i \quad (1)$$

where E_{mix} is the total emissions per unit of energy, S_i is the share of each fuel in the fuel mix, and γ_i denotes the emission factor of each fuel.

By utilizing the fuel mix emissions and energy content of jet fuel (43 MJ/kg), it is possible to dynamically model the fuel emissions until 2050 by $E_{total} = E_{mix} \times 0.043$. In order to determine the total CO₂ equivalent emissions from EU27 flights, additional variables such as flight data and fuel consumption per flight were included.

Fuel efficiency in airlines is closely related to the environmental aspects of the model. According to EUROCONTROL (Eurocontrol, 2020), this study assumes an initial value for the average fuel burn of 4.176 t per flight for flights within Europe. The average fuel burn for domestic passenger and freight flights in 2019 is calculated as 3.8513 tons (Eurostat, 2023, 2024a,b). This results in a reduction factor of 0.3247 tons per domestic flight, compared to the overall average fuel consumption of 4.176 tons per flight. While for international flights, burned fuel is calculated as 4.364 tons.

Fuel efficiency improvements of 1% will lower average fuel consumption for both domestic and international flights (Oesingmann, 2022; World Economic Forum, 2020). The expected rise in passengers per flight is modeled separately from fuel efficiencies and factored into price calculations. Pre-2022 passenger growth rates for domestic and international flights were around 2% and 3%, and are expected to gradually decline.

A full list of relevant parameters, variables, stocks, and flows are provided in the supplementary materials.

3.2.4. Economic dimension in aviation system dynamics

For the economic aspect, the model highlights the role of baseline prices for SAFs as a key indicator affecting their market adoption and diffusion (Table A.3) (World Economic Forum, 2020; Braun et al., 2024). The five-year data intervals are considered using a spline function to estimate price developments. Production costs are assumed to match the selling prices, which may lead to an underestimation of the actual market price. It is important to emphasize that long-term SAFs price projections, especially those extending to 2050, are highly uncertain (Detsios et al., 2023).

According to EASA (2023), the price of fossil jet fuel will be around €600 per ton or even higher (IATA, 2024). At the same time, technical studies suggest that the production costs of SAFs will decrease over time, particularly for fuels with a low TRL such as PtL and GFT. The base price for fossil jet fuel is set at €750 per ton, higher than in previous studies but still lower than SAF prices. Price developments for SAFs and fossil jet fuel are modeled to reflect the impact of the ETD and ETS, representing the actual costs aircraft operators incur when using each fuel type. The ETD is planned for implementation in 2025, indicating a three-year delay from the model's 2022 start. As of 2025, the revisions are still underway for the implementation of ETD.

The supply scenario provided by EASA (2023) is used and adjusted by a 0.5 multiplier to fit the reduced scope of inter-European aviation (Fig. 4). In addition to the outlined SAFs, the available fuels include imports that are not specified by the EASA report. The values between the time stamps in Fig. 4 are interpolated using a spline function. Fossil jet fuel supply is assumed to be unlimited and is not modeled as a constraint. An equilibrium between SAF demand and supply is established, allowing the theoretical option to purchase additional SAFs if supply exceeds demand.

The 2022 starting ticket prices are based on Greenpeace EU price analysis, using data from three booking intervals (April to July 2023) for flights between April and November 2023 (Greenpeace, 2023). Prices were averaged across intervals, distinguishing between domestic and international flights. The starting prices were €62.77 ($P_{dom,2022}$) for domestic and €91.71 ($P_{int,2022}$) for international flights (Table A.5). Additionally, as baggage costs are significant, an extra €30 per ticket is added for luggage on some flights. It is assumed that 50% of international and 25% of domestic travelers book additional baggage, resulting in €116.71 and €70.27 ticket prices. Further ticket price developments, influenced by the aforementioned cost factors and the relative increase from the 2022 base value, are measured by dynamic variables (Eqs. (2)–(6)). The default pass-through rate is set at 100%, meaning all cost changes are directly reflected in ticket price changes.

$$\Delta P(t) = (C_{ETD}(t) + C_{ETS}(t) - C_{ETS, start}(t) + C_{SAF}(t)) \times \pi_{pass} \quad (2)$$

where $C_{ETD}(t)$, $C_{ETS}(t)$, $C_{SAF}(t)$ represents the costs related to the ETD, ETS, and the total cost of using SAFs, and π_{pass} shows pass-through rate.

$$P_{dom}(t) = P_{dom, 2022} + \frac{\Delta P_{dom}(t)}{N_{pass, dom}(t)} \quad (3)$$

$$P_{int}(t) = P_{int, 2022} + \frac{\Delta P_{int}(t)}{N_{pass, int}(t)} \quad (4)$$

where $\Delta P_{dom}(t)$ and $\Delta P_{int}(t)$ denote additional price increase due to policies, and $N_{pass, dom}(t)$ and $N_{pass, int}(t)$ indicate the number of domestic and international passengers at time t . Accordingly, price increase ratios can be determined as follows:

$$R_{dom}(t) = \frac{P_{dom}(t)}{P_{dom, 2022}} \quad (5)$$

$$R_{int}(t) = \frac{P_{int}(t)}{P_{int, 2022}} \quad (6)$$

To calculate the price change, historical policy-induced costs are subtracted from the price calculation. As the ETD and SAFs have not impacted costs in the past, only ETS costs are accounted for. From 2022

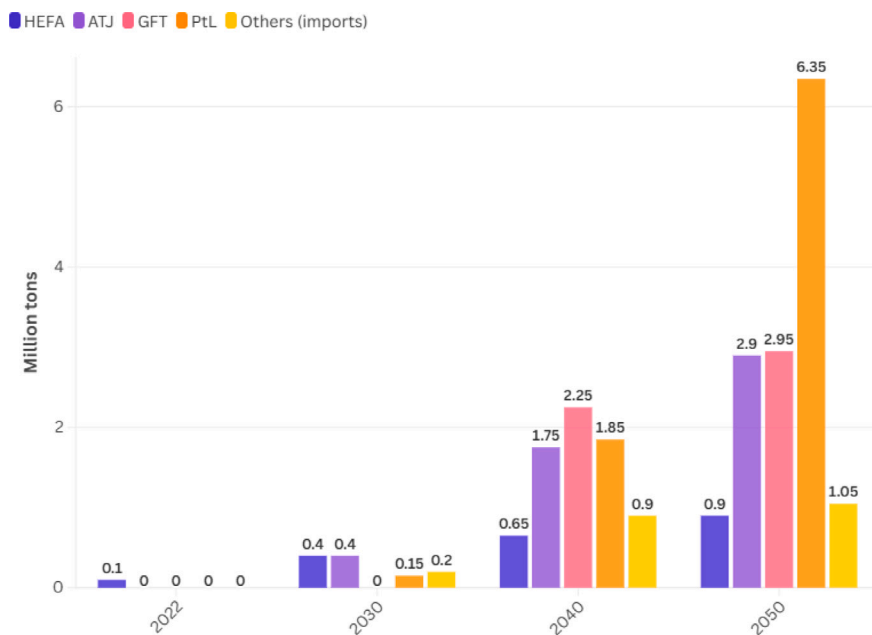


Fig. 4. Customized SAF supply scenario (EASA, 2023).

onward, the model considers emissions per flight, the cost-effective EUAA share, and ETS prices (Table A.6).

Based on the calculated ETS starting costs, the change in policy costs for national and international flights can be determined. The price split is not further divided between freight and passenger flights, as the model assumes that customers drive demand for both. Additional agent specifications will be detailed in the following sections. Additionally, a full list of relevant parameters, variables, stocks, and flows are provided in the supplementary materials.

3.2.5. Technical dimension in aviation system dynamics

Aviation operations are categorized into domestic and international, and further divided between freight and passenger flights. Future trends are modeled using four factors, namely: historical trends, a COVID-19 recovery factor, price sensitivity, and shifts towards high-speed rail (HSR). As freight flights remained stable during the pandemic, the recovery factor only applies to passenger flights. This aligns with the post-pandemic analysis on a return to pre-pandemic levels by 2024–2025 (Eurocontrol, 2023).

After a short recovery period, the model is set to reflect the pre-pandemic development of the sector for passenger flights and the overall quantitative development for freight flights. The first two factors affecting the development of the sector are therefore based on historical data. The third and fourth factors are modeled in the form of price trends and transport alternatives. In this context, for passenger flights, domestic operations show a historical average decrease of over -1% , while intra-EU flights increased by average roughly 2% . The average recovery factors for passenger flights are 19% for domestic and 21% for international ones. Freight flights experienced a historical decline in both domestic (average -5.52%) and intra-EU (average -0.46%) operations, with no recovery factors listed for freight flights (Eurocontrol, 2024).

A full list of relevant parameters, variables, stocks, and flows are provided in the supplementary materials.

3.3. Agents

Considering agents in this study is crucial as the transition from fossil jet fuels to SAFs is inherently a multi-stakeholder process influenced by the decisions, behaviors, and interactions of diverse actors. Two key agents are considered in this study, which are explained in the subsequent sections.

3.3.1. Customers: Passengers & freight companies

This study considers customer agents to improve understanding of aviation transformation. The SD model quantitatively evaluates flight and passenger developments, whereas agents visualize customer decisions over time. Agents respond to economic impacts and inter-modal transport elasticities. Demand elasticities are introduced to allow agents to react to price changes (see Figure S2 in the supplementary materials).

To calculate the development of flights, customer behavior is modeled by dynamic variables and also as agents. The system dynamic customer engagement effectively determines the development of flights in the EU. To reflect the customer behavior in terms of flight selection and ticket prices, price elasticities for international, domestic, leisure, and business passenger flights, as well as domestic and international freight flights are considered in this model (Table 1).

Furthermore, the customers in this model react to the development of airfares and the expansion of the European HSR network. This is modeled by considering the cross-price elasticity between the HSR and aviation of 0.0002 (Gama, 2017). The cross-price elasticity is included to develop over time by $0.0002e^{0.1x}$ to account for the political push towards HSR transport.

In international transport, customers exhibit lower sensitivity to price changes. To account for this, cross-price elasticities are adjusted by multiplying by 0.5 for international transport and by 1.5 for domestic transport. Reductions in airfares are structured to prevent additional customer shifts from HSR to aviation by setting a zero lower bound on the modeled HSR effect. As freight transport prioritizes efficiency

Table 1
Price elasticities for different flight types.

Flight type	Price elasticity (ϵ)	Sources
Domestic leisure	-1.23	European Commission (2024), InterVISTAS Consulting Inc (2007)
Domestic business	-0.68	
International leisure	-1.12	
International business	-0.57	Lo et al. (2015)
Freight	[-0.74, -0.29]	

over comfort, a higher cross-price elasticity of 1.5 is assumed between air and rail freight transport. The price elasticities are combined with airline agents' reported price increases and the proportion of business and leisure flights. To align with rail transport's long-term trends, the rail program uses air transport's cumulative price development from 2022. The roles and modeling approach of customers and airline agents will be detailed in the following sections.

Despite the neglect of climate-related behavioral change (assumption X), several studies have identified general willingness to change modes of transport if sufficient alternatives are available (Alcock et al., 2017; Cocolas et al., 2020). EUROCONTROL (Eurocontrol, 2022) identifies HSR alternatives as a viable option for future developments, thus implemented as a viable alternative to air transport for intra-European routes. Thus, agents in this model may choose the European HSR network by taking the increasing cross-price elasticities into account.

Based on the price elasticities, the agent aims to take the travel or drop it based on Eq. (7).

$$K_{price} = \epsilon \cdot \Delta P \quad (7)$$

where K_{price} indicates price sensitivity transition based on scale of the travel (domestic or international) and type of travel (business or leisure). If the K_{price} is larger than the threshold, the agent drops out of travel.

In summary, passenger behavior is modeled using a rule-based decision process that captures travel realization, trip type selection, modal substitution, and price sensitivity. At each time step, a potential traveler first decides whether to travel, then selects between domestic and international trips based on exogenous shares. For domestic travel, the agent evaluates substitution to high-speed rail using cross-price elasticities before choosing between business and leisure purposes. In both domestic and international cases, realized trips are subject to price sensitivity, with drop-out occurring when ticket price increases exceed purpose-specific tolerance levels. This formulation enables endogenous feedback between ticket prices, passenger demand, and aviation activity while preserving behavioral heterogeneity across trip purposes.

Similarly, freight transport behavior is also modeled using a rule-based decision process that distinguishes between domestic and international freight movements and accounts for both price sensitivity and modal substitution. At each decision step, cargo agents select a trip type based on exogenous shares and evaluate whether aviation remains economically viable given price changes. For domestic cargo, potential substitution to rail freight is assessed using cross-price elasticities reflecting improved rail logistics. If price increases exceed tolerance thresholds or rail becomes sufficiently attractive, aviation cargo is not realized. This formulation enables endogenous adjustment of cargo flight activity in response to policy-induced cost changes while preserving structural consistency with passenger demand modeling.

A detailed description of the parameters, variables, states, and transitions is provided in the supplementary materials.

3.3.2. Airlines

The airline agent performs various tasks in the model, including decisions on SAFs coverage and ticket prices, which influence customer behavior (see Figure S3 in the supplementary materials).

Airlines are subject to several regulations, making them passive in terms of implementing regulations, such as surrendering emission certificates. Regarding the minimum SAF quotas, airlines' demand is constrained by the possible supply or by the SAFs quotas. In this model, the airline agent indicates increased demand for SAFs if they become cheaper than fossil jet fuel. Economic developments are compared to assess SAF attractiveness as an alternative. If agents signal rising demand, it could significantly impact both European policymakers and the aviation sector. Airline agents procure SAFs using an iterative decision rule that increases SAF uptake subject to economic attractiveness and physical availability. First, quota-induced SAF demand is computed as a fixed share of total fuel demand. If an additional-procurement scenario is active, the airline then evaluates SAF pathways with positive available supply and ranks them by relative cost competitiveness. For each pathway, additional SAF demand is increased in incremental steps until either total fuel demand is satisfied, the respective SAF stock is depleted, or the remaining unmet demand falls to zero. This step-wise structure prevents unrealistic instantaneous switching, ensures that adoption is explicitly constrained by supply, and enables feedback to the SD layer through updated SAF demand, fuel mix composition, and emissions accounting.

Relative price increases are important factors for aviation development, as they interact with the given (cross-) price elasticities. In this case, airline agents also compare price increases, providing data on year-to-year relative price changes. This establishes communication between airline and customer agents as well as the SD environment based on the following cost calculation (Eq. (8)).

$$C_i(t) = C_{baseline,i} + C_{ETS}(t) + C_{ETD}(t) \quad (8)$$

In other words, airline agents adjust ticket prices using a rule-based pass-through mechanism that compares current policy-induced cost changes with prices from the previous year. At each time step, airlines observe the net change in regulatory costs affecting international and domestic flights and determine whether prices should increase or decrease relative to the prior period. Cost increases are passed through to ticket prices according to a fixed pass-through rate, while cost reductions are reflected symmetrically. This formulation ensures stable price adjustment over time and enables consistent feedback between regulatory costs, ticket prices, and passenger demand within the framework.

A detailed description of parameters, variables, states and transitions is provided in the supplementary materials.

3.4. Overview of the model structure

The modeling framework combines SD and ABM to capture both system-level feedbacks and heterogeneous actor behavior relevant to

Table 2
Coupling between agents and SD components.

Agent	Passenger agent	Airline agent
Inputs from SD model	Domestic and international ticket prices; rail attractiveness/HSR development index.	Fuel costs (fossil and SAF pathways); policy-induced costs (ETS, ETD, SAF allowances); SAF availability (stocks).
Decision logic (ABM)	Evaluates price changes using segment-specific elasticity and cross-price elasticity with rail; decides on travel demand reduction or modal shift.	Compares SAF pathway costs with fossil fuel; procures additional SAF if cost-competitive and physically available.
Outputs to SD model	Passenger and cargo demand adjustment rates.	Additional SAF demand by pathway.
Affected SD components	Aviation activity (passenger and cargo flights); total flight volumes.	SAF demand and fuel mix; emission intensity; ETS-relevant emissions.

SAF adoption in European aviation. The SD component represents the physical, economic, and policy-related structure of the aviation system, while the ABM component captures decision-making by key actors, whose behavior influences demand and fuel choice.

At the system level, the SD model is organized around five core modules: (i) aviation activity, (ii) fuel efficiency and fuel demand, (iii) SAF supply and fuel mix composition, (iv) emissions accounting, and (v) policy-induced cost and price dynamics. Aviation activity is represented through stock variables for passenger and cargo flights, differentiated by domestic and intra-EU operations. These activity levels determine total fuel demand, which evolves over time in response to changes in flight volumes and fuel efficiency improvements. Fuel efficiency is modeled dynamically to reflect gradual technological and operational changes, including efficiency-oriented policy measures.

SAF availability is represented through separate stock–flow structures for major SAF pathways, allowing total SAF supply and demand to evolve endogenously. The resulting fuel mix determines the emission intensity of aviation fuel use, which feeds into emissions accounting and policy cost calculations. Emissions and allowance requirements under the EU ETS, together with energy taxation under the ETD, translate into cost components that affect airline operating costs and, through a pass-through mechanism, passenger ticket prices. These prices constitute a key feedback channel linking system-level outcomes back to demand behavior. Fig. 5 presents an overview of the conceptual SD-ABM model, interactions between key components, as well as agents.

The ABM layer interfaces with the SD structure by representing two types of agents: airlines and passengers. Airline agents respond to changes in fuel-related costs and SAF availability by adjusting their SAF procurement decisions, subject to cost competitiveness and physical supply constraints. Passenger agents respond to ticket price changes and modal alternatives by adjusting travel demand. The aggregated outcomes of these agent decisions are passed to the SD model as demand adjustment rates and additional SAF demand, ensuring consistency between micro-level behavior and macro-level system dynamics. Table 2 summarizes the information exchange between the agent-based and system dynamics components of the model, highlighting how agent decisions are integrated into system-level dynamics.

4. Results

Based on the initial results, and aligned with the projections of EASA (2023), air traffic in Europe, including both passenger and freight flights, is expected to increase by over 33% by 2050 compared to 2022, and by over 11% compared to 2019. Fig. 6 illustrates the complete development of flights in Europe as well as the projection of the total number of passengers. In contrast to these results, domestic flights are expected to continue their decade-long decline, following a brief recovery phase after COVID-19, until 2026. Domestic aviation is expected to be more easily replaced by HSR networks due to shorter travel distances and higher price sensitivity (Li et al., 2019; Wang et al., 2019). The decline is expected to gradually slow down by the early 2040s.

The growth of the sector through 2050 is attributed entirely to the projected rise in international intra-European aviation. However,

it is important to note that even this growth is expected to level off after the COVID-19 recovery period, around the mid-2030s. In this context, the initial peak in flight numbers during the mid-2020s is expected to coincide with a steady rise in passengers per flight. As a result, if total passenger numbers are used as the sector's performance measure instead of flight numbers, the earlier decline will transit into an expected period of stagnation between 2025 and 2042, after which the growth trend will continue.

The behavior of customer agents confirms that the most significant reductions among domestic and international leisure travelers is expected to start in 2027 (Fig. A.2), aligning with the above-mentioned decline in domestic flight numbers. Price reductions for domestic flights are expected to taper off in the early 2040s. However, the price sensitivity in international leisure travel contrasts with the trend observed between 2026 and 2043. Based on trends in international passengers and flights, this price sensitivity is likely to be offset by other factors driving industry growth. Business travelers show little sensitivity to price changes, which is consistent with their inelastic price behavior. Finally, there is a growing interest among customer agents in HSR transport, starting in the late 2020s.

Intra-European freight flights are expected to decline over time, with domestic freight flights nearly phasing out by 2050. A key difference between passenger and freight flights is the higher popularity of the HSR among freight transport agents compared to passenger agents. Between 2026 and 2043, freight transport actors display similar price-sensitive decision-making behavior as seen in passenger transport, apart from HSR's popularity. However, this pattern occurs at a lower level, reflecting the lower price elasticity in freight transport.

4.1. Ecological results

A key ecological result is that emissions from intra European aviation could decrease by 69% compared to 2012, making a 90% reduction from 1990 levels, which is unlikely under the current policies and SAF demand.

Fig. 7 presents the model's projections for the share of fossil fuels and SAFs, along with the fuel mix emission reduction rate. Considering the role of the ReFuelEU Aviation, fuel mix emissions is expected to become less GHG emission-intensive based on the gradual increase in SAF uptake rate. The share of SAFs is expected to equal that of fossil jet fuel by 2046, given the model's hard constraint on preventing changes in SAF consumption patterns. Fuel mix emissions, in g CO₂ equivalent MJ⁻¹, begin at 89 in 2022 and are projected to drop to 85.98 by 2030, 66.1 by 2040, and 38.93 by 2050. Compared to the 2019 ETS-verified emissions for the EU27 (64.89 million tons), this represents roughly 66% reduction.

Given SAFs' crucial role in reducing emissions by roughly 66%, understanding the SAF share by fuel types is important to assess the contributions of different SAFs with varying emission rates (Table A.3). According to Fig. 8, HEFA is initially the dominant fuel, but its share decreases sharply over the years, nearly phasing out by 2050. ATJ starts with a smaller share but gradually increases over time until 2031 and then eventually decreases in competition with FT and PtL

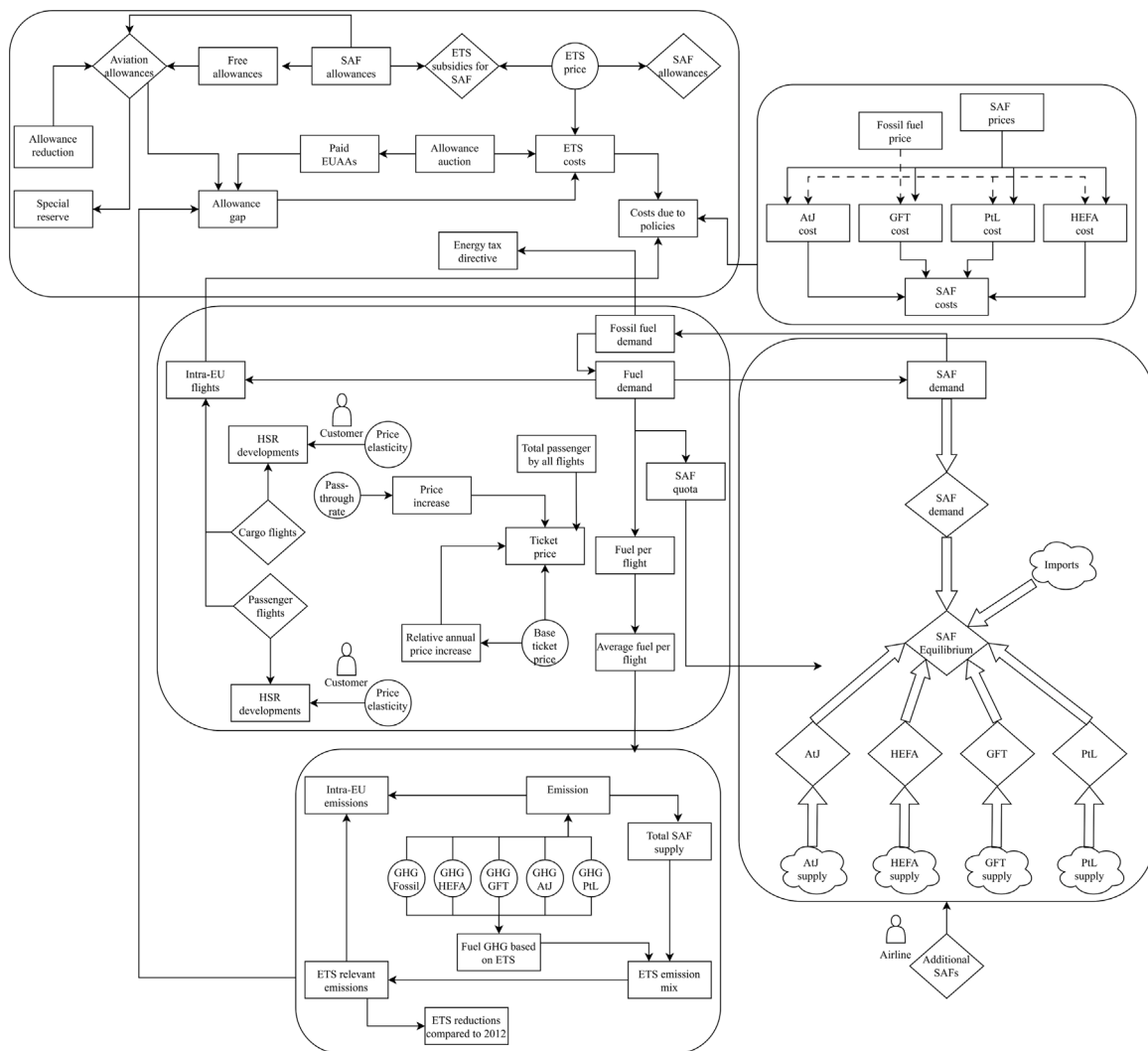


Fig. 5. Overview of the structure of SD-ABM model.

fuels. Similarly, FT fuels are also expected to grow steadily after 2031, gaining a significant share by 2050. PtL fuels, though starting with a smaller portion, will almost be less than 3% by 2026, eventually becoming the most significant contributor, at 46% by 2050, reflecting their key role in future defossilization efforts.

4.2. Economic results

Based on the earlier discussion of fuel price comparisons, the SAF quota is expected to bring notable economic challenges to aviation. However, SAFs could become more cost-effective than fossil jet fuel in the medium- to long-term, considering taxation under the ETD and the benefits of ETS allowances. In this context, Fig. 9 illustrates the projected price changes for various SAFs up to 2050. For a clearer understanding of prices, Table 3 provides a summary of prices in specific milestone years, showing the cheapest and most expensive fuels in green and orange.

According to the results, HEFA is projected to become the most affordable alternative to fossil jet fuel by 2030. This advantage is

mainly driven by the increasing costs of EUAAs, from which SAFs are expected to remain exempt until 2027. However, after this exemption period, the relatively higher GHG emission value of HEFA, compared to other SAFs, could reduce its cost-competitiveness. At the same time, the ETD will emerge as a significant cost factor for fossil fuels between 2025 and 2035. With the introduction of the ETD costs for SAFs by 2035 and the continued rise in EUAA costs, HEFA is expected to lose its cost advantage, making way for PtL fuel to become the most affordable option. On the other hand, due to policy cost advantages tied to lower GHG emissions and reductions in baseline costs, GFT is projected to reach cost parity with HEFA between 2035 and 2040, while PtL will continue to hold its position as the most cost-effective alternative.

Fig. 10 presents a detailed breakdown of cost developments for each policy, including the expenses tied to an average flight. An important implication of this is that SAF quotas are projected to be less economically burdensome than taxation through the ETD and ETS. The phase-out of the casual free EUAAs, along with the specific SAFs EUAAs, leads to several noticeable cost spikes. The most notable leaps in Fig. 10 are those from 2025 to 2026, when casual free EUAAs are

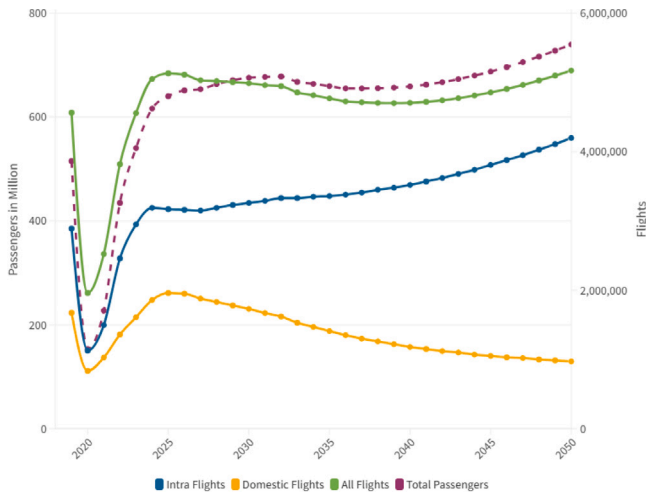


Fig. 6. European flights development through 2050.

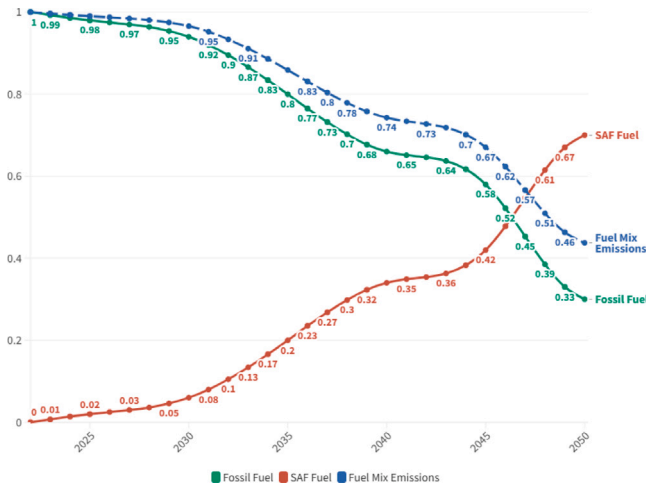


Fig. 7. Fuel share in the aviation sector and corresponding emissions (in percentage).

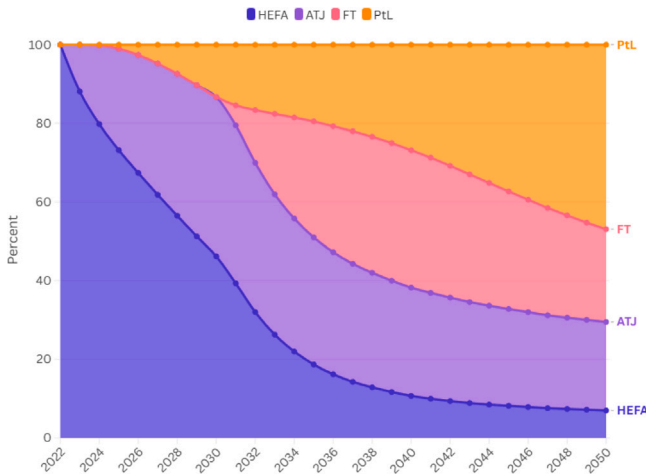


Fig. 8. SAF share in the aviation sector and corresponding emissions.

phased out, and that from 2030 to 2031, as free SAFs EUAs are phased out.

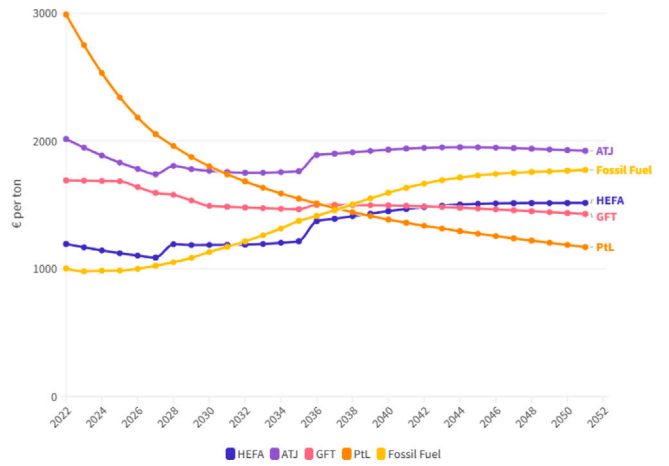


Fig. 9. Jet fuel price development.

Table 3
Price development of SAFs vs. fossil kerosene.

Year	HEFA	ATJ	GFT	PtL	Fossil Fuel
2022	1195.40	2016.25	1693.32	2989.97	1003.81
2025	1122.94	1831.83	1686.23	2343.25	987.632
2030	1187.64	1767.55	1492.95	1803.99	1131.97
2035	1217.02	1764.53	1467.29	1550.00	1375.84
2040	1452.35	1933.37	1497.31	1386.72	1595.78
2045	1509.25	1952.12	1472.26	1276.06	1731.66
2050	1516.37	1929.62	1437.33	1188.06	1768.95

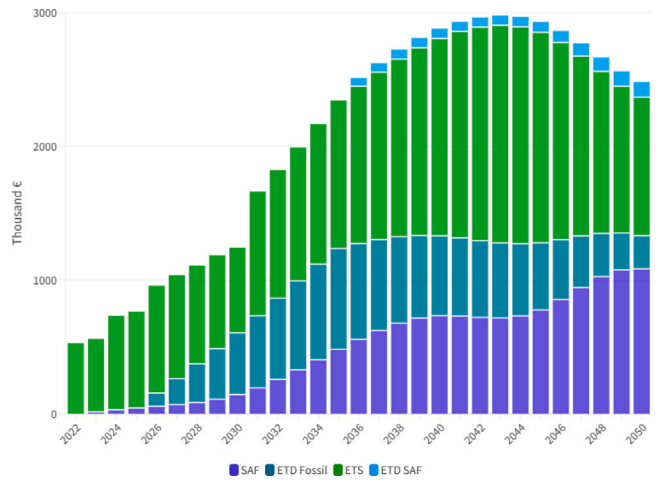


Fig. 10. Fuel policy cost development.

The ETD costs are distributed between SAFs and fossil jet fuel. It is anticipated that the implementation of the ETD will be concluded by 2035, coinciding with its projected maximum cost (Fig. 10). Consequently, as the proportion of SAFs rises, overall ETD costs decline. SAFs, which are subject to a reduced taxation rate, will account for approximately 10% of the total cumulative tax burden. The estimated cost of the ETD for SAFs is €6.098 billion, calculated from their introduction in 2035 until 2050. A breakdown of the costs for the sector at the level of the average flight, assuming strict adherence to the SAF quotas set by the ReFuelEU Aviation, reveals a range of €61 to €114 for the respective period. An analysis of the scenario in which the EU does not implement a revised ETD could enhance understanding of the impact of policy decisions on flight operations, policy costs, and environmental developments.

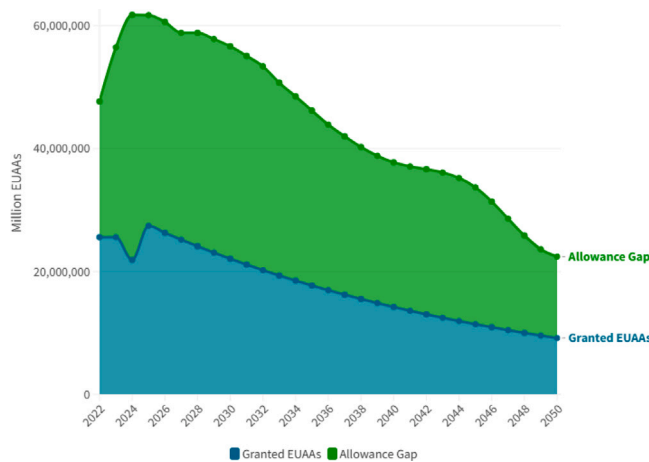


Fig. 11. Allocated and required EUAs over the modeling period.

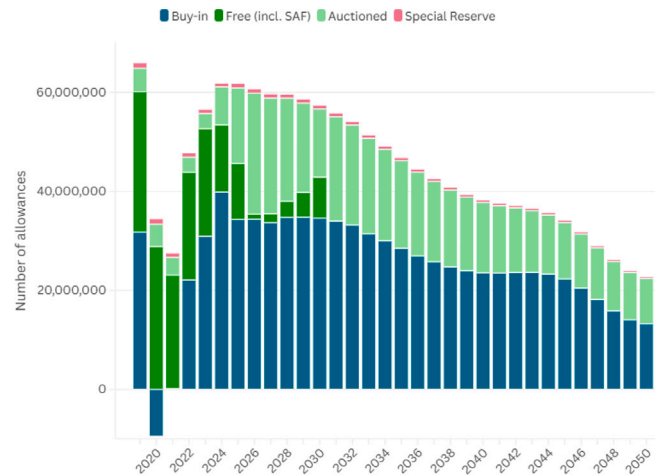


Fig. 12. ETS allocation over the modeling period.

On the other hand, the ETS is anticipated to be the primary policy cost driver for future aviation operations due to three key factors. First, EUAA prices are estimated to rise to €315 per ton of CO₂, a nearly 400% increase compared to 2022 prices. Secondly, the phase-out of free allowances and the general reduction rate in allocated allowances are projected to further elevate costs. The rapid decline of casual free allowances from 82% to zero by 2026 presents a significant challenge for adaptation. However, the introduction of allowances for SAF usage provides a positive incentive for a shift towards cleaner alternatives. The ETS poses a third challenge regarding the acquisition of Emission Allowances (EUAs) from other sectors, considering the phase-out combined with the increased reduction factor for allowances.

In 2019, verified aviation emissions exceeded the allocated emissions by approximately 96%. Free allowances thus accounted for over 43% of the total verified aviation emissions. Not only will free allowances be phased out by 2026, but the trend of exceeding the allocated allowances is modeled to continuously be present in future aviation developments as well. Despite the decreasing need for aviation allowances in the medium- to long-term, the emission reductions are not keeping up with the reduced allowances. To address the allowance gap, which is the difference between the granted and needed allowances for aviation, the sector is expected to heavily rely on certificates from other sectors, as shown in Fig. 11.

In light of the challenges posed by the ETS, Fig. 12 presents a detailed overview of ETS allocation based on the free allowances for SAFs, buy-in and auctioned from other sectors, as well as special reserve (European Environment Agency, 2024b). In general, however, aviation allowances are modeled to decline, free allowances are phased out, and finally, the future of allowances for the use of SAFs after 2030 is uncertain. While SAF allowances are discussed in the scenario-specific results, new insights emerge from the main findings. Based on the projected ETS price and allowance allocation, subsidies for the aviation sector could reach approximately €2.524 billion by 2030, offering a significant incentive for SAFs given the price difference between fossil jet fuel and SAFs.

4.3. Scenario analysis

Based on the framework developed within the EU’s regulatory context, there are several key areas where scenario analysis can offer valuable insights into potential challenges under varying conditions. This analysis will help to better anticipate and address obstacles as regulatory and market factors evolve. To do so, several scenarios are considered, and corresponding results are discussed below. All scenarios are designed as exploratory policy experiments rather than forecasts, aiming to test system responses under alternative regulatory designs and implementation pathways.

4.3.1. No ETD

The ETD and ETS are expected to impose costs that may directly affect customers. However, the former has not yet been implemented by the EU, and aviation’s exemption from fuel taxation has been justified by the emission levies imposed under the ETS. However, achieving emission reductions conflicts with current energy taxation laws (the revised ETD). This scenario represents a counterfactual baseline reflecting continued political delay or failure to implement the revised ETD, which has been repeatedly postponed despite alignment with the EU Green Deal. According to the results, failing to implement the revised ETD will have serious consequences. As the ETD is a significant lever of policy-induced costs, the price increases for aviation are much lower in this scenario. Based on Fig. 13, price differentials are expected to reach their maximum in the mid-2030s. This is due to the steady increase in SAF shares, while the scope of the ETD costs fully develops by the tipping point in 2035, leading to lower costs that stimulate aviation growth. As a result, the previously observed decline in flights is slightly mitigated. However, the increase in flights is projected to lead to higher emissions from European aviation, with an estimated 65 million tons of GHG emissions either being saved by the ETD revision or emitted in its absence.

Focusing on SAFs’ appeal to market players, simulation results indicate that most SAFs remain economically disadvantaged compared to fossil jet fuel until the late 2030s. The ETD helps to equalize fuel costs based on emissions. Without ETD, HEFA is expected to break even with fossil fuel in 2036, followed by PtL in 2038 and GFT in 2039. Therefore, it is concluded that the revised ETD should be implemented to reinforce the EU’s commitment to transforming aviation.

4.3.2. ETS allowances

The second scenario addresses the implementation of the EU ETS under two sub-scenarios. The ETS offers 20 million free allowances for SAF use until 2030. Despite this subsidy, the price gap between fossil jet fuel and SAFs may still challenge European airlines, especially after subsidies ending in 2030. To measure the impact of additional ETS allowances, in the first sub-scenario, 8 million free SAFs allowances were distributed over four years (2031–2035), with two million annually. The post-2030 allocation of additional SAF allowances is not intended as a forecast but as a policy stress test, reflecting a potential extension of transitional support mechanisms discussed in the context of long-term SAF market stabilization.

In the second sub-scenario, a deviation in price projections is based on the S&P Global Inc. studies, predicting lower ETS prices compared to the pathway suggested by the Aerospace & Defence Industries Association of Europe (Airlines for Europe, 2021; Evans et al., 2023).

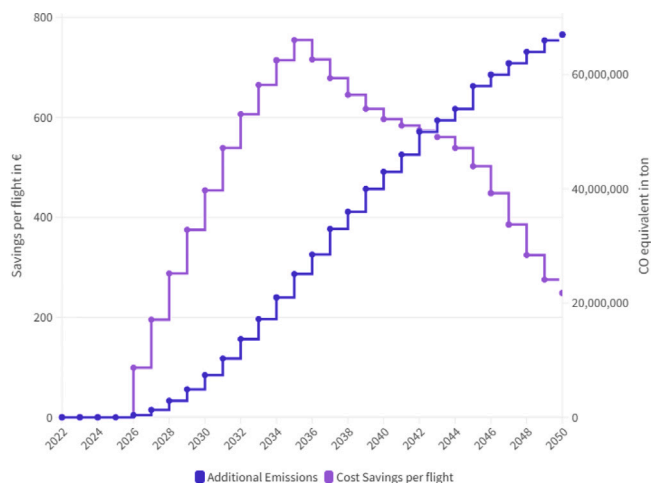


Fig. 13. Cost and emission effects in the ETD scenario.

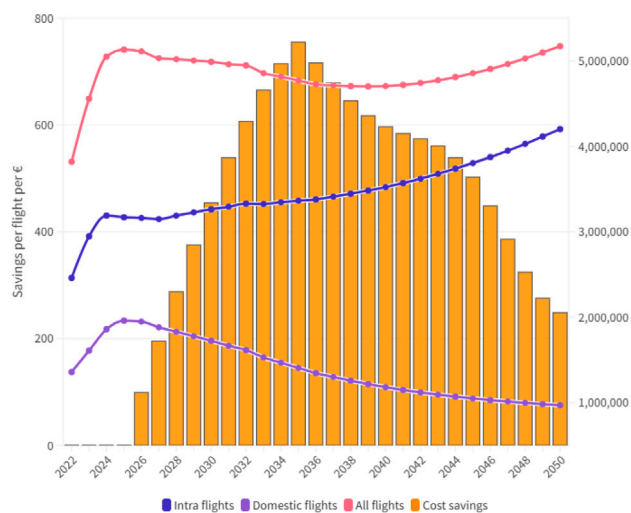


Fig. 14. Flight development with alternative ETS price forecast.

The choice to use S&P Global’s forecast as an alternative scenario is supported by BloombergNEF’s latest forecast for ETS prices until 2030, which aligns with the pathway in the Destination 2050 study (Coker, 2023).

The economic results from the previous section support additional subsidies to close the SAF and fossil jet fuel price gap in the 2030s. From 2031 to 2035, two million annual allowances will be allocated to airlines, with a cumulative subsidy of €1.256 billion. This brings total SAF EUAA subsidies to €3.78 billion by 2035. While these subsidies may not significantly boost aviation activity in Europe, they will enhance SAF economics and improve supply chain planning security.

As discussed earlier, the ETS price development can be considered a key component in SAF adoption. According to Fig. 14, at a 100% cost pass-through rate, lower costs lead to reduced prices for customers, significantly boosting aviation. This pattern follows cost savings passed on to customers, with a delayed response as cost effects become decision-relevant after a two-year trend from 2022 to 2023. The results highlight the cost decrease from 2029 to 2030, reflecting the phase-out of free SAF allowances. After the implementation of the ETD, the global peak in 2042 and the delayed market response in 2043 mark the tipping point, with total costs leading to fewer additional flights and reduced cost savings. Moreover, with lower tax rates, HEFA undercuts fossil jet fuel from 2032, whereas GFT and PtL break even by 2038. Meanwhile, ATJ fuel does not reach price parity with fossil fuel.

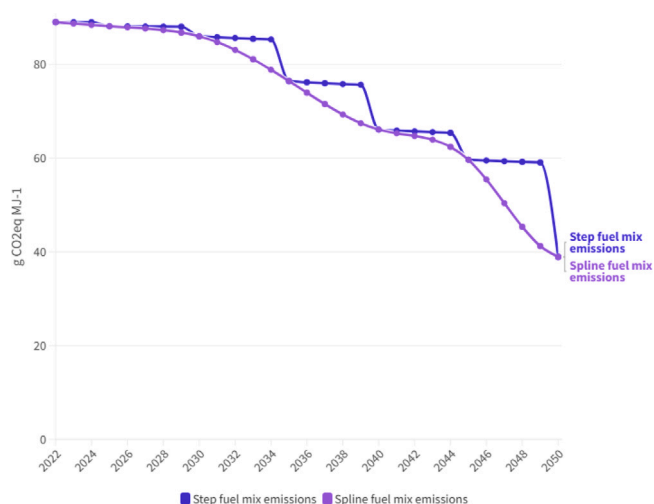


Fig. 15. Fuel mix emissions based on the step and spline functions.

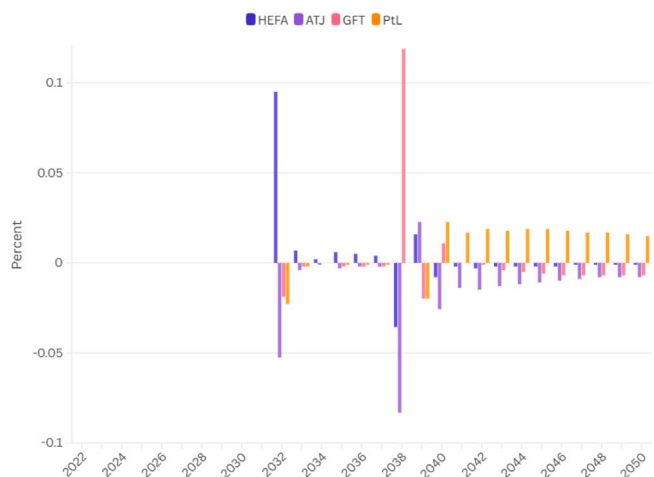


Fig. 16. Difference of SAF share by fuel types.

4.3.3. SAF uptake

This scenario is divided into two sub-scenarios. The first one examines the difference between spline and step interpolation for SAF quotas. For instance, the SAF quota is set at 20% in 2035, rising to 34% by 2040. Airlines could maintain a 20% rate until 2039 and then increase it by 14% in 2040, representing the step approach. The primary model uses the spline approach, which gradually increases SAF adoption to 34% by 2040. In this scenario, the step approach is implemented. Therefore, this scenario reflects regulatory uncertainty regarding the temporal enforcement of SAF quotas, as current legislation specifies target levels but does not define whether compliance will be enforced continuously or discretely.

As shown in Fig. 15, the stepwise approach leads to unfavorable results in economic and environmental terms. Thus, airlines would probably face additional costs due to the change in fossil and SAF price ratios from the 2030s (Fig. A.3). From an environmental perspective, the cumulative emissions under the step approach are always higher than under the spline one (Fig. A.4). This is a result of the difference in fuel mix emissions, which is consistent with the step function of the SAF quotas. Theoretically, airlines could change from a spline to a step approach, as soon as SAFs become economically favorable. The decreased emission reductions would then be limited to when airlines take the step approach.

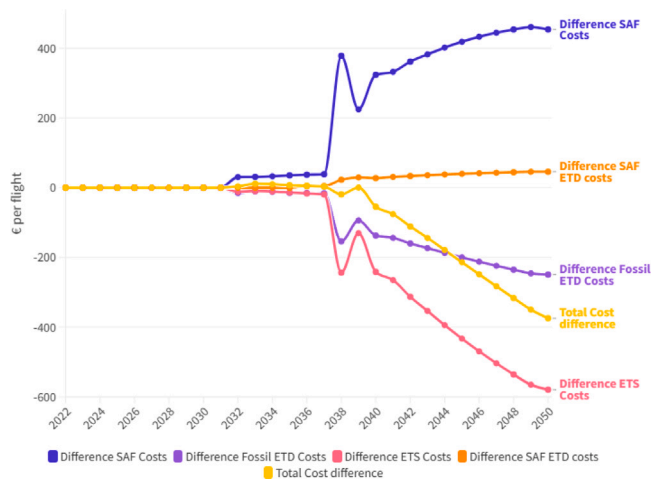


Fig. 17. Scenario cost difference for an average flight.

The second sub-scenario examines the demand limitation for the SAF uptake. The SAFs quotas set by the ReFuelEU Aviation are assumed to represent both a maximum and minimum demand in the primary model. This scenario allows airlines to purchase additional SAFs if they are economically attractive compared to fossil jet fuel. The additional demand is limited by the supply of SAFs and fuel demand. Limiting the purchase prevents fuel stockpiling and accounts for supply capacities. In other words, allowing additional SAF uptake represents an upper-bound behavioral response, capturing conditions under which airlines voluntarily exceed mandated quotas when SAFs become cost-competitive.

In this sub-scenario, the differences in SAF shares start to diverge strongly from the base case by 2034 (Fig. 16). The divergence is driven by two factors: SAF price and availability (the fuel stock). Airline decision-makers assess whether SAFs are more economical than fossil jet fuel, considering all political costs. If prices are equal, SAFs are preferred for their climate benefits. As fossil fuel prices are not expected to undercut PtL, GFT, and HEFA after 2035, the trend of increasing SAF shares continues until 2050. Two key years stand out: in 2045, SAFs reach over 66% market diffusion (compared to 42% in the primary model), and in 2050, SAFs exceed the mandatory 70% quota by 30%, achieving 100% diffusion. The market share of PtL is expected to grow steadily from 2037, surpassing 25% in 2045 and 54% in 2050. On the other hand, ATJ will be consumed at a minimum due to unfavorable price trends.

Fig. 17 presents a complete overview of changes in prices under the ETD and ETS. With the increased use of less GHG-intensive fuels, fuel mix and cumulative emissions are significantly lower than in the primary case. Additionally, as SAFs are chosen for economic reasons, the average flight cost drops by over €550 by 2050, mainly due to the reduced ETS and ETD costs, which outweigh the added SAFs expenses.

From an environmental perspective, the ETS-relevant emissions is projected to decrease by approximately 86% compared to 2012. The final total emissions account for 12.05 million tons of emissions in this scenario. This decrease in the ETS costs leads to the observation that the allowance gap, which is the difference between granted and needed ETS allowances for the aviation sector, is projected to decrease from 12.94 million in the primary case to just under 800,000 allowances by 2050. Given the limitations of fuel supply capacities and total fuel demand, this sub-scenario presents a potential market diffusion of SAFs that surpasses the ambitious goals of ReFuelEU Aviation. The current policies offer enough incentives for a technical shift towards sustainable fuel solutions, reinforced by economic benefits.

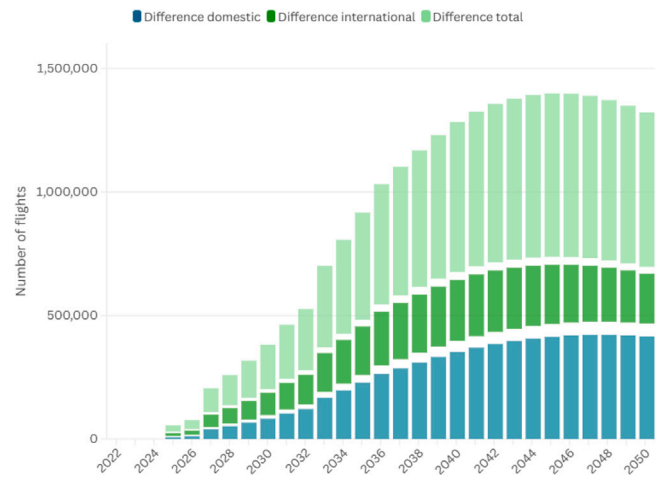


Fig. 18. Difference in number of flights under the pass-through scenario.

4.3.4. Lower cost pass-through rates

The fourth scenario examines the pass-through rates of airline costs to customers. While some studies assume a 100% pass-through, others suggest lower rates. Thus, this scenario explores a deviation with a 50% pass-through rate. The 50% pass-through rate is selected as a mid-range sensitivity case, reflecting empirical evidence that airlines partially absorb regulatory costs to remain competitive.

Controlling for a 50% cost pass-through rate was expected to increase customers, flights, and GHG emissions. Passing only half the costs amplifies the ETS scenario's effect but does not alter SAFs' economic competitiveness. According to Fig. 18, flights do not decline as seen in the primary case, stabilizing at 5.12–5.2 million per year between 2025 and the mid-2030s, already surpassing the primary case's air traffic growth. By 2050, this leads to a cumulative surplus of 749,000 flights, with an additional 886,000 in 2043. While domestic flights still decline, international air traffic remains the main driver of the sector's growth.

The additional flights result in an expected cumulative surplus emissions of 152 million tons of CO₂ equivalent until 2050 (Fig. A.5). Moreover, airline margins are reduced due to the shared costs. The effect of airline profits is unclear, as the additional number of flights could still increase profits after all (Fig. A.6). Therefore, effective communication between airlines and policymakers is expected to be crucial in shaping a pathway that enables a robust industry recovery, long-term perspectives, and the achievement of the climate-related targets set by the EU.

4.3.5. SES+2

Implementing SES-related efficiencies in Europe's ATM network has been widely discussed as a key lever for reducing aviation emissions. Existing arrangements suggest that eliminating current en-route inefficiencies could yield emission reductions of approximately 6%, while more comprehensive reforms under a fully implemented SES could enable reductions of up to 10% (EASA, 2023; Debyser, 2023). Against this background, this study assumes a gradual ATM efficiency improvement of up to 5% by 2035 under the SES2+ scenario, which represents a conservative deviation from the upper range of reported estimates. This assumption allows us to assess whether even moderate efficiency gains, consistent with delayed or partial implementation of SES2+, are sufficient to generate meaningful emission reductions within the modeled policy framework.

The increased efficiencies will reduce policy costs, resulting in more flights. However, the efficiency gains outweigh the additional traffic load, enabling a reduction of 15 million tons of CO₂ equivalent until 2035 and 37 million tons until 2050. The relative annual

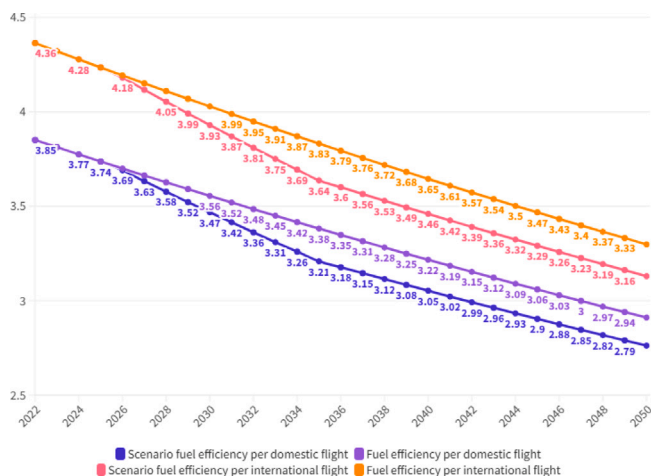


Fig. 19. Fuel efficiency gains in percentage under SES+2 program.

emission reduction compared to the primary model peaks at 4.1% in 2035 and decreases to 3.89% by 2050. Therefore, the cumulative and annual emission savings are not within the range of the previously believed 10% emission reduction. Fig. 19 illustrates an overview of fuel efficiency gains under the scenario.

Despite these results, the implementation is not seen as a major technical challenge with low temporal and economic costs (Fig. A.7). The efficiency gains are still significant, especially given the urgency to meet the EU's Fit for 55 targets. Improving en-route efficiencies could also reduce the risk of SAFs shortages. Therefore, the SES2+ program is viewed as essential in aviation, offering a viable solution to support SAF uptake.

5. Discussion

The discussion section is structured to interpret the results in terms of their policy implications, to position the proposed ABM-SD framework within the literature, and to outline avenues for future research, which are addressed in the subsequent subsections.

To begin, the results indicate that domestic European aviation emissions could be reduced by over 69% compared to 2012. This reduction rate is also expected to increase to 86% if additional SAFs become competitive. Given the higher emissions in 2012 than in 1990, achieving a 90% reduction from 1990 levels would require other transport modes to achieve greater reductions. In addition, further emission reductions could be achieved through fleet renewal and future technologies, such as green hydrogen. Moreover, aviation emissions is expected to generate levies, providing funds for R&D and climate projects, ensuring that the sector still contributes to the net-zero target.

The EU will subsidize the aviation transformation, partly via free ETS allowances for SAFs. However, costs are projected to rise, leading to higher ticket prices and a likely decrease in demand. The sector must decide whether declining customer numbers or reduced margins are preferable. Based on the model results, aviation is supposed to require support from national or European funds to ensure a stable and consistent industry, protecting both customers and industry representatives against excessive cost or price increases. The EU has opted to enhance the technology direction for e-fuels and enable market-based development through the sub-mandate outlined in the ReFuelEU Aviation. It is yet to be determined whether further guarantees are needed to ensure SAF supply chain growth and R&D for market-ready SAFs.

Passenger transport is more challenging due to higher comfort demands. However, rising public awareness of aviation's climate impact may drive a shift to HSR. While studies suggest limited reductions in

air travel from climate concerns, the lack of competitive alternatives may explain this. Improved HSR networks could have a greater impact than expected.

A balanced framework will induce necessary political interference and allow for market-driven development under overarching political objectives. To further understand the dynamics of SAFs uptake, it is essential to consider customer and industrial perspectives in future policymaking.

5.1. Customer perspective

HSR produces less emissions than aviation, making the growth of international aviation before the COVID-19 seem contradictory with environmental movements. Low-cost airlines, by offering time advantages on long trips and undercutting less GHG-intensive options on short routes, reverse ecological incentives for customers and create conflicts of interest.

Customers can support the aviation transformation by purchasing carbon offsets or paying for SAF use, although the acceptance of voluntary compensation remains low. While most customers support environmental charges, few are willing to compensate for their own emissions, indicating a preference for airlines to manage emission reduction. This raises questions regarding shared responsibilities in mitigating emissions. In this case, political efforts to promote low-emission HSR travel in Europe could also address customer acceptance, which is key to achieving low-emission travel.

This study examined policies and industry behavior driving technological transitions in GHG-intensive aviation, highlighting costs and prices as critical factors. The findings emphasize that pricing strategies seem to be essential for promoting greener transport modes, such as HSR. Both aviation and policymaking rely on a population motivated to align actions with environmental values, stressing the shared responsibility amongst all stakeholders.

5.2. Industrial perspective

Industrial reports conclude that using SAFs in aviation will result in higher fuel prices globally (Danicourt et al., 2023). However, it is crucial to critically assess such comparisons. Comparing future SAF prices in 2030 and 2050 with historical fossil jet fuel prices may distort future price projections. While historical data offers limited insight, it suggests that flying will likely become more expensive in the coming decades.

From an economic perspective, production costs are often mentioned as a barrier to SAF adoption. While producing only the cheapest alternative, currently HEFA, might seem practical, this mono-strategy fails in two ways. First, it hinders other SAFs from achieving cost efficiency, as it discourages R&D and economies of scale and progress across multiple SAF processes for reducing emissions and meeting SAF quotas above 50%. Second, a mono-strategy conflicts with the future SAF needs outlined by the ReFuelEU, as feedstock supply, regulated by RED III, is limited and subject to competition with other industries. Therefore, relying solely on one pathway is not recommended for meeting EU SAF targets.

Aviation is predicted to face rising costs until the early 2040s to enable transformation. Sector players will either pass these costs on to customers, bear them, or find a middle ground, each of which pose socio-economic risks. If costs are not passed on, companies may face higher expenses, forcing them to cut costs elsewhere or accept lower margins. Passing costs to customers would raise ticket prices, making flying a luxury, with potential effects on demand. Differing airline strategies are projected to likely result in price variations, highlighting social equity concerns in climate policies. However, it is argued that policy cost increases could be balanced by developing an affordable HSR network as an alternative for price-sensitive customers.

A positive note in the transport sector is the development of Europe's inter-modal network. While HSR and aviation are expected to compete, with political incentives favoring HSR, aviation has not taken a hostile position. Instead, recent inter-modal cooperation between Star Alliance and Deutsche Bahn demonstrates collaboration (Deutsche Lufthansa AG, 2022). Partnerships like these could reduce intra-European stopover flights, significantly cutting GHG emissions by promoting HSR.

The aviation upheaval necessitates an examination of the strategic alignment among industry players. This study assumes homogeneous airlines that follow a cost-focused strategy while industry players follow heterogeneous strategies in the real-world. Airline business strategies fall into cost leadership, differentiation, and focus approaches. Low-cost carriers, such as Ryanair and EasyJet focus on low prices, whereas airlines like Lufthansa prioritize comfort, leading to higher prices (differentiation strategy). Freight airlines such as DHL Aviation serve niche markets with a focus approach. As policies affect all operators, some strategies may be more impacted by industry changes. It is suggested that differentiated airlines will fare better, as low-cost carriers are more vulnerable to price increases. Further research is needed to examine the viability of sustainable business strategies in aviation.

5.3. Policy implications

According to the results, three main recommendations can be derived for future sustainable aviation.

One recommendation relates to the regulatory challenges that European policy faces criticism for inconsistent regulation consultations, as seen with the delayed ETD and SES2+ revisions. These policies are able to drive industry transformation and support defossilization, as our results suggest. Exempting aviation from the ETD taxation contradicts the EU's Green Deal and Fit for 55 goals. Similarly, the SES2+ could deliver rapid efficiency gains, aiding in meeting the Fit for 55 transport targets. In addition, extending the EU ETS to all flights departing in the EEA as well as strengthening international and intercontinental cooperation on in-sector emission reduction could also play significant role in decreasing emissions.

Second, the inconsistency in the regulatory framework stems from failure to implement well-designed aviation policies and progress made through the ReFuelEU Aviation and the revised EU ETS. While the EU has restructured aviation, it has yet to implement a true SES or updated ETD, which could significantly reduce CO₂ emissions. Beyond regulatory updates, the EU must monitor the ReFuelEU and ensure that SAF supply does not hinder sector transformation.

Third, CO₂ equivalent emissions highlight the need for broader changes in sustainable aviation. EU regulations focus on CO₂ but normally neglect other harmful emissions such as NO_x, soot, sulfate, and water vapor. Including non-CO₂ emissions in the ETS should guide future policies. Additionally, non-CO₂ emissions could be considered in the revised ETD, as after SAF's ten-year ETD exemption, they will be key for determining jet fuel taxation rates.

5.4. Model extensibility

Although this study focuses on the European aviation sector and its specific policy mix, the proposed ABM-SD framework is designed to be modular and transferable to other regional and policy contexts. The core decision rules governing airline fuel procurement, price pass-through, passenger and cargo demand, and modal substitution are generic and policy-agnostic, while region-specific characteristics enter the model through parameters such as fuel costs, demand elasticities, infrastructure availability, and regulatory instruments. As a result, the framework can be adapted to other jurisdictions by replacing EU-specific policy components (e.g., EU ETS, ETD, ReFuelEU Aviation) with alternative carbon pricing schemes, fuel mandates, or subsidy mechanisms, and by recalibrating behavioral parameters to reflect

local travel patterns and market structures. This extensibility enables comparative analysis across regions with different regulatory designs, levels of SAF maturity, and transport alternatives, supporting broader assessments of sustainable aviation transitions beyond the European context.

5.5. Limitations

Although there is a growing body of research on regulatory frameworks aimed at the sustainable transition in aviation, many questions remain unanswered. Despite the broad spectrum of research approaches used to assess the impacts of regulatory frameworks on SAFs, the developed ABM-SD framework enabled the investigation of economic and environmental effects of ongoing European policies while accounting for dynamic interactions between customers and airlines. Nevertheless, several limitations should be acknowledged.

A key limitation of this study lies in data availability. The analysis was conducted in 2024 using the most recent dataset available at the time, covering records up to 2022. Since then, additional data has been released that may provide further insights. Future research could incorporate these updated datasets to enhance the model's accuracy and relevance.

Beyond data availability, the results are influenced by several structural assumptions that introduce uncertainty and may affect the magnitude and timing of the observed effects. Fuel efficiency improvements are modeled using a conservative annual rate of 1%, reflecting recent empirical evidence, which may overestimate long-term fuel demand and emissions compared to more optimistic efficiency trajectories. In addition, the temporal distribution of SAF-related ETS allowances is based on an assumed gradual increase aligned with expected ReFuelEU-driven adoption, as no binding allocation schedule currently exists. Alternative allocation profiles could shift SAF uptake dynamics, particularly in earlier years.

Emissions are calculated using well-to-wake lifecycle factors that are assumed to remain constant over time, thereby excluding potential future reductions in upstream emissions from technological learning or decarbonization of energy inputs. Similarly, current blending limits are assumed not to constrain long-term SAF adoption, which may overestimate mid-term penetration if certification or technical barriers persist longer than expected. On the supply side, SAF availability follows exogenous pathway projections based on EASA forecasts, with a fixed share allocated to intra-European aviation, abstracting from strategic reallocation or competition across regions.

Several economic and behavioral assumptions further shape the results. The model assumes full pass-through of policy-induced cost increases to ticket prices, representing an upper-bound estimate of price effects, as airlines may partially absorb costs to maintain competitiveness. Moreover, the model does not account for autonomous demand reductions driven by pro-environmental attitudes or psychological factors, despite growing empirical evidence of environmentally motivated flight avoidance. Excluding such behavioral responses may lead to conservative estimates of demand reduction and emissions mitigation, particularly in the long term.

An additional source of uncertainty relates to future SAF cost projections. While this study relies on the best available cost estimates at the time of analysis, future SAF cost trajectories remain uncertain due to factors such as technological learning rates, feedstock availability, electricity prices, scale-up dynamics, and policy-induced market responses. Variations in these cost curves may influence the relative competitiveness of SAF pathways and the timing and magnitude of adoption.

Another limitation of this study relates to the representation of trade-offs between economic, ecological, and social dimensions of aviation defossilization. While the scenario analysis captures system-level interactions between costs, demand, fuel choice, and emissions, it does not explicitly model broader supply-chain constraints or cross-sectoral

competition for low-carbon resources, such as renewable electricity or sustainable feedstocks required for large-scale SAF production. Consequently, high SAF penetration scenarios should be interpreted as indicative of upper-bound outcomes under favorable conditions rather than as unconstrained deployment pathways. Moreover, the analysis does not assess distributional or social equity effects associated with changes in ticket prices or travel demand, such as potential differences in accessibility across income groups. Investigating how environmental effectiveness, economic viability, and social welfare interact under alternative policy designs remains an important avenue for future research and would require the explicit integration of social indicators and heterogeneous consumer groups beyond the scope of the present framework.

Finally, the study focuses on drop-in fuels and models airlines as homogeneous, cost-oriented actors. This abstraction neglects heterogeneous business models, strategic pricing behavior, and differentiated network structures observed in real-world aviation. Furthermore, the model includes only two agent types. Future research could extend the framework by incorporating additional agents such as fuel producers, policymakers, and financial institutions, as well as by explicitly modeling behavioral heterogeneity and environmental awareness among consumers.

6. Conclusions

In a complex and competitive regulatory landscape, aviation could become more sustainable but also more expensive (economically, environmentally and socially) by 2050. The EU can significantly support this transition by enforcing a stronger GHG reduction strategy. To recover, when geopolitical challenges, the aviation sector should adopt sustainable pathways to meet regulations, including SAFs. The shift to SAFs is complex and not solely dependent on the industry; customers, both passengers and freight, play a key role in balancing environmental transport with social challenges.

To investigate the complex aviation system under the European regulatory landscape, this study presents an ABM-based approach to reflect real-world dynamics in the sector. The success of such a complex system in adopting SAFs heavily depends on customer choices. While aviation can lower emissions, customers, alongside industry and policy, should choose transport modes that achieve emission reductions. Therefore, two agents: customers and airlines, as main body of the aviation sector are considered in the ABM approach. The system is then mainly investigated in terms of economic and ecological aspects under the impacts of European legislation.

With the primary results of SAF uptake under different fuel shares, achieving the EU Green Deal’s goal of a 90% GHG reduction is unlikely via aviation alone. On the other hand, stricter aviation regulations would not solve the issue, as overregulation could harm competitiveness. While EU measures are necessary, additional burdens should be avoided. Economically, projected SAF prices indicate eventual price parity with fossil jet fuel, with PtL fuels becoming the most cost-effective option from 2040 onward.

While this study tackles the significant challenge of reducing emissions in EU aviation, there are several directions for further, more in-depth analyses of this complex system. Expanding the developed approach to include additional regions beyond Europe would provide a more comprehensive analysis of the global impacts of European legislation. In addition, focusing on different geographical areas would allow for comparisons of regional strategies. Additionally, while the empirical calibration of this study reflects European conditions, the underlying model structure is intentionally formulated to support reparameterization for other regions and policy environments in future studies. Moreover, incorporating a wider range of transport modes into the analysis would offer a more comprehensive perspective on the overall emissions trajectory. This study focuses solely on drop-in fuels; however, a new perspective on the issue could be achieved

by also examining non-drop-in fuels. This study focuses on a specific level of complexity in the aviation sector by considering only customer and airline agents. Future research could incorporate additional agents, such as fuel suppliers, policymakers, airports, NGOs, and aircraft manufacturers, to tackle climate challenges with a more realistic and comprehensive framework. Moreover, global SAFs supply chains, along with potential disruptions and risks, could be incorporated to assess the impact of resilience factors.

CRediT authorship contribution statement

Ali Ebadi Torkayesh: Writing – review & editing, Writing – original draft, Methodology, Visualization, Validation, Supervision, Resources, Investigation, Conceptualization. **Jakob Joachim Rohner:** Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sandra Venghaus:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used DeepL and Chat-GPT in order to improve language and readability. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Appendix A

See Figs. A.1–A.7 and Tables A.1–A.5.

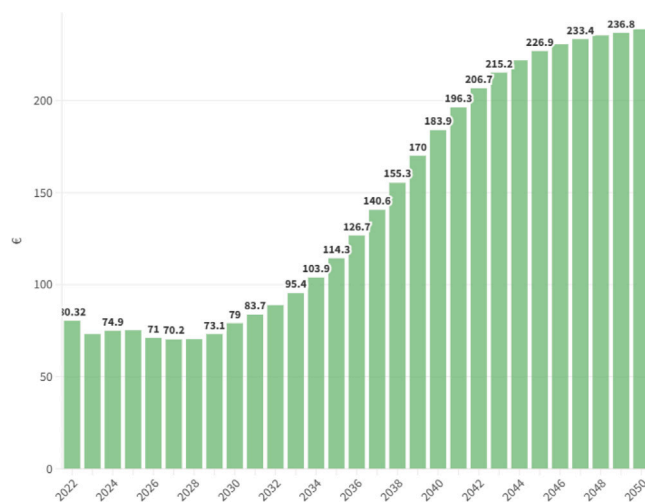


Fig. A.1. EUAA price development (Airlines for Europe, 2021).



Fig. A.2. Customer drop in different flight types and switch to HSR (in percentage).

Table A.1

A summary of regulatory policies and strategies with corresponding targets for aviation.

Policy	Implications	Reference
Flightpath 2050	<ul style="list-style-type: none"> - Aviation growth and sustainability, - Reducing CO₂ emissions by 75% and NOx emissions by 90%. 	European Commission (2011)
Single European Sky (SES) & SES+2	<ul style="list-style-type: none"> - Optimizing the use of airspace, - Reducing air traffic control costs, -Enhancing safety and environmental performance. 	European Commission (2020)
Energy Taxation Directive (ETD)	<ul style="list-style-type: none"> - Imposing the minimum levels of taxation applicable to motor fuels, of €330 per 1000 liters of kerosene for intra-EU flights, - Considering zero-tax rate on SAFs with a ten-year introductory phase. 	European Commission (2021b)
EU Emissions Trading System (EU ETS)	<ul style="list-style-type: none"> - Regulating European Aviation Allowances (EUAs), - Allocating free EUA certificates, auctioning, and keeping reserves, - The latest figures indicate that there will be 28,866,578 EUAs for 2024, - From 2024 to 2026, the free certificates will decrease: 75% in 2024, 50% in 2025, and 0% from 2026 onward, - The ETS mandates a continuous reduction in certificates, with the annual reduction factor increasing from 2.2% in 2021 to 4.3% (2024–2027) and 4.4% from 2028 onward. 	European Commission (2023c)
Renewable Energy Directive (RED III)	<ul style="list-style-type: none"> - For aviation, RED III sets a goal: member states can choose between a 14.5% reduction in GHG emissions or achieving a 29% share of renewable energy in transport by 2030, - The requirement for a 5.5% share of advanced biofuels and renewable fuels of non-biological origin (RFNBOs) in transport, with 1% specifically allocated to e-fuels. - Annex 9 of RED II/III outlines the potential feedstocks to be used for SAF in the EU. 	European Commission (2023d)
ReFuelEU Aviation	<ul style="list-style-type: none"> - Enforcing 2%, 6%, 20%, 34%, 42% and 79% quotas for SAFs by 2025, 2030, 2035, 2040, 2045 and 2050, - Enforcing 1.2%–2%, 5%, 10%, 15% and 35% quotas for synthetic fuels in the EU aviation for the same periods, - Preventing carbon leakage by mandating a tanking quota of 90% of the yearly fuel demand for aircraft operators. 	European Commission (2023a)

Table A.2
Summary of recent studies on ABM for sustainable aviation.

Author(s)	Geographic focus	Agent 1	Agent 2	Agent 3	Agent 4	Agent 5
Horio et al. (2015)	US	Customers	Airlines	–	–	–
Mosca and Hoffenson (2017)	US	Airports	Airlines	Passengers	Congress	FAA
Kapeller et al. (2019)	Austria	Customers	Travel Partners	–	–	–
Moncada et al. (2019)	Brazil	Mill Operators	Farmers	Drivers	Airport Managers	–
Schnuelle et al. (2020)	Germany	Operators	Customers	Subsidizer	–	–
Ullah and Dwivedi (2022)	US	Farmers	–	–	–	–
Khanra and Prabhu (2022)	Germany	Airlines	–	–	–	–

FAA: Federal Aviation Administration.

Table A.3
Literature review on SAF costs (€/t).

Source	Year	HEFA	ATJ	GFT	PtL
World Economic Forum (2020) (PC)	2020	1251	2157	1698	3501
	2025	1123	1832	1686	2343
	2030	1055	1656	1459	1790
	2035	1025	1603	1418	1530
	2040	1002	1556	1381	1334
	2045	986	1514	1351	1238
	2050	974	1475	1298	1146
Detsios et al. (2023) (MJSP)	2020	1509	2257	2382	3728
	2030	1272	1721	2045	3127
	2040	1209	1621	1933	1421
	2050	1172	1534	1808	1234
Danicourt et al. (2023) (LCoSAF)	2023	1820	2457	3185	3003
	2035	1729	1911	2548	2002
	2050	1638	1729	2002	1456
Shehab et al. (2023) (PC)	–	1001–1411	1911–2639	1698–2047	–
Pavlenko et al. (2019) (LPC)	–	1097–1359	2319–3454	1670–2332	2805–3117

PC = Production Costs, LPC = Levelized Production Costs, LCoSAF = Levelized Costs of SAF, MJSP = Minimum Jet fuel Selling Price, Exchange rate (Dollar/Euro) = 0.91 & kg/l = 0.802.

Table A.4
Literature review on GHG emissions of SAF (g CO₂ equivalent MJ⁻¹).

Source	HEFA	ATJ	GFT	PtL
ICAO (2022)	13.9–71.5	12.4–85.5	11.6–22.5	–
Okolie et al. (2023)	47.4	39.7	12.2	–
Shehab et al. (2023)	13.9–60	23.8–65.7	7.7–12.2	–
Prussi et al. (2021)	13.9–60	23.8–55.8	5.2–12.2 (73.4)	–
Batteiger et al. (2022)	–	–	–	05–10

Table A.5
Ticket prices for European flights (Greenpeace, 2023).

ZFlight	Short-term Booking	Mid-term Booking	Long-term Booking	Total
Type	(max 7 days)	(1 Month)	(4 Months)	Average
Domestic average	€ 77.01	€ 60.12	€ 51.18	€ 62.77
International average	€ 119.24	€ 86.09	€ 69.81	€ 91.71

Currency conversion: HUF/EUR = 0.0026; GBP/EUR = 1.15; CHF/EUR = 1.04; NOK/EUR = 0.085, retrieved from the European Central Bank (2023), on November 24 2023.

Table A.6
ETS starting prices in 2022.

Variable	Characteristic	Source
ETS price 2022	€ 80.32	German Environment Agency (2023a,b)
Fuel for international (domestic) flights	4.364 (3.8513) t/flight	Eurocontrol (2022)
Emission Factor fossil fuel	3.16 t CO ₂ equivalent/t of fuel	European Commission (2023c) (Annex IV Part B)
Share of cost-effective EUAs	(Auctioned + Buy in)/ Total verified emissions	Calculations based on European Environment Agency (2024a)

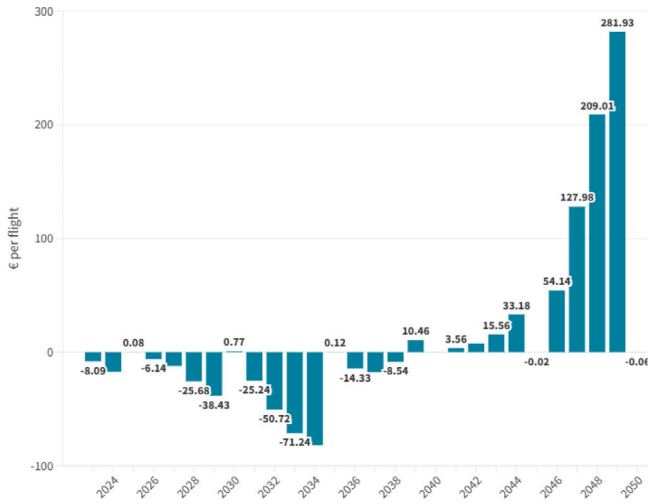


Fig. A.3. Total flight price difference based on the scenario costs compared to the primary results.

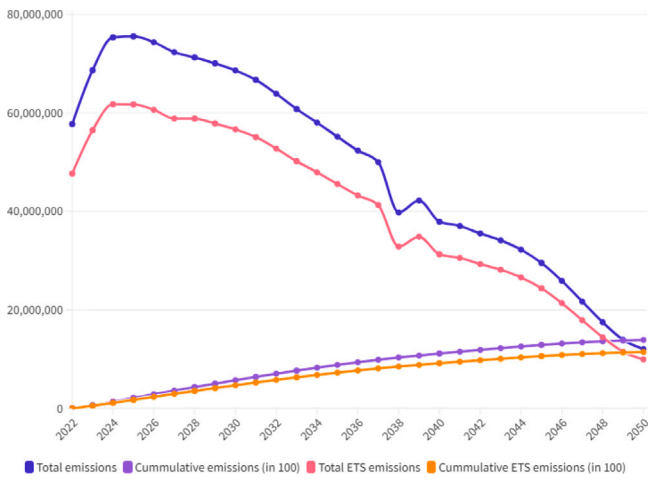


Fig. A.4. Emissions under the SAF uptake scenario (in CO₂ eq.).

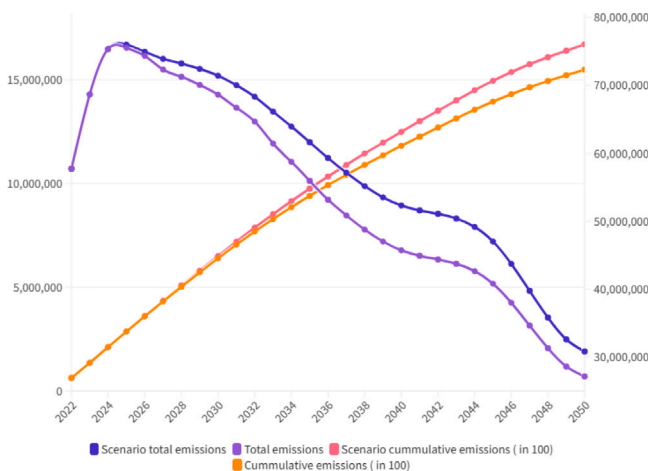


Fig. A.5. Emissions under the pass-through scenario (in CO₂ eq.).

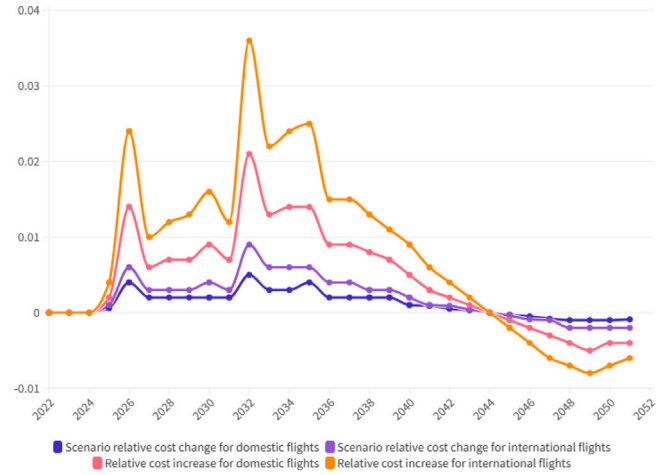


Fig. A.6. Cost changes under the pass-through scenario (in percentage).

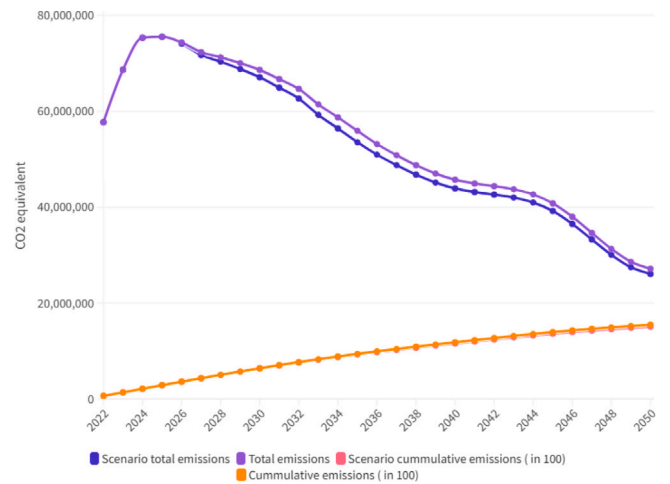


Fig. A.7. Emissions under the SES+2 program.

Appendix B. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.tranpol.2026.104158>.

Data availability

Data will be made available on request.

References

Airlines for Europe, 2021. Destination 2050: A route to net zero European aviation. <https://www.destination2050.eu>.
 Alcock, I., White, M.P., Taylor, T., Coldwell, D.F., Gribble, M.O., Evans, K.L., Corner, A., Vardoulakis, S., Fleming, L.E., 2017. ‘Green’on the ground but not in the air: Pro-environmental attitudes are related to household behaviours but not discretionary air travel. *Glob. Environ. Chang.* 42, 136–147.
 Auclair, D., 2021. Travel chaos: can your business stay immune?. <https://www.transportenvironment.org/discover/travel-chaos-can-your-business-stay-immune>.

- Avogadro, N., Redondi, R., 2024. Pathways toward sustainable aviation: Analyzing emissions from air operations in Europe to support policy initiatives. *Transp. Res. Part A: Policy Pr.* 186, 104121.
- Batteiger, V., Ebner, K., Schmidt, P., Weindorf, W., Raksha, T., 2022. Power-to-liquids: A scalable and sustainable fuel supply perspective for aviation. <https://www.umweltbundesamt.de/en/publikationen/power-to-liquids>.
- Bell, A., Mannion, L.A., Kelly, M., Ghaani, M.R., Dooley, S., 2025. Life cycle CO₂e intensity of commercial aviation with specific sustainable aviation fuels. *Appl. Energy* 382, 125075.
- Bergero, C., Gosnell, G., Gielen, D., Kang, S., Bazilian, M., Davis, S.J., 2023. Pathways to net-zero emissions from aviation. *Nat. Sustain.* 6 (4), 404–414.
- Braun, M., Grimme, W., Oesingmann, K., 2024. Pathway to net zero: Reviewing sustainable aviation fuels, environmental impacts and pricing. *J. Air Transp. Manag.* 117, 102580.
- Cao, F., Wang, C., Chen, S., 2026. Mapping the green aviation: A bibliometric analysis of green aviation research (1900–2025). *Transp. Policy* 104014.
- Coccolas, N., Walters, G., Ruhanen, L., Higham, J., 2020. Consumer attitudes towards flying amidst growing climate concern. *J. Sustain. Tour.* 29 (6), 944–963.
- Coker, E., 2023. EU ETS market outlook 2H 2023: Cleared for the ascent. <https://about.bnef.com/blog/eu-ets-market-outlook-2h-2023-cleared-for-the-ascent>.
- Cui, Q., Lei, Y., Li, Y., 2024. Co-benefit scenario analysis on replacing aviation kerosene with sustainable aviation fuels in Africa. *Environ. Impact Assess. Rev.* 104, 107318.
- Cui, Q., Li, Y., Wei, Y.-M., 2017. Exploring the impacts of EU ETS on the pollution abatement costs of European airlines: An application of network environmental production function. *Transp. Policy* 60, 131–142.
- Danicourt, J., Harris, J., Papania, A., Kim, A., 2023. Realistic path to net-zero emissions for commercial aviation: The quest to decarbonize the industry by 2050 will sharply increase costs and depress air traffic growth. <https://www.bain.com/insights/a-realistic-path-to-net-zero-emissions-for-commercial-aviation/>.
- Debysers, A., 2023. Air transport: single European sky. https://www.europarl.europa.eu/factsheets/en/sheet/133/air-transport-single-europeansky#_ftn3.
- Detsios, N., Theodoraki, S., Maragoudaki, L., Atsonios, K., Grammelis, P., Orfanoudakis, N.G., 2023. Recent advances on alternative aviation fuels/pathways: A critical review. *Energies* 16 (4), 1904.
- Deutsche Lufthansa AG, 2022. DB wird erster intermodaler partner der star alliance [press release]. <https://newsroom.lufthansagroup.com/db-wird-erster-intermodaler-partner-der-star-alliance>.
- Dodd, T., Yengin, D., 2021. Deadlock in sustainable aviation fuels: A multi-case analysis of agency. *Transp. Res. Part D: Transp. Environ.* 94, 102799.
- Drünert, S., Neuling, U., Zitscher, T., Kaltschmitt, M., 2020. Power-to-liquid fuels for aviation—processes, resources and supply potential under german conditions. *Appl. Energy* 277, 115578.
- EASA, 2023. European aviation environmental report 2022. <http://dx.doi.org/10.2822/04357>.
- Efthymiou, M., Ryley, T., 2022. Governance and policy developments for sustainable aviation fuels. In: *Sustainable Alternatives for Aviation Fuels*. Elsevier, pp. 201–214.
- Eurocontrol, 2020. Environmental assessment. European ATM network fuel-inefficiency study. <https://www.eurocontrol.int/sites/default/files/2020-12/eurocontrol-european-atm-network-fuel-inefficiency-study.pdf>.
- Eurocontrol, 2022. Eurocontrol aviation outlook 2050. <https://www.eurocontrol.int/publication/eurocontrol-aviation-outlook-2050>.
- Eurocontrol, 2023. Eurocontrol forecast update 2023–2029. <https://www.eurocontrol.int/publication/eurocontrol-forecast-update-2023-2029>.
- Eurocontrol, 2024. Eurocontrol European aviation overview - archive 2023. <https://www.eurocontrol.int/publication/eurocontrol-european-aviation-overview-archive-2023>.
- European Commission, 2011. Flightpath 2050. Europe's vision for aviation; maintaining global leadership and serving society's needs; report of the high-level group on aviation research.
- European Commission, 2020. Single European sky. https://transport.ec.europa.eu/transport-modes/air/single-european-sky_en.
- European Commission, 2021a. Fit for 55. <https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55/>.
- European Commission, 2021b. Energy taxation directive. https://energy.ec.europa.eu/topics/markets-and-consumers/energy-taxation_en.
- European Commission, 2023a. Refueled aviation. https://transport.ec.europa.eu/transport-modes/air/environment/refueled-aviation_en.
- European Commission, 2023b. EU transport in figures – statistical pocketbook 2023.
- European Commission, 2023c. Commission decision (EU) 2023/2440 of 27 October 2023 on the union-wide total quantity of allowances to be allocated in respect of aircraft operators under the EU emissions trading system for 2024. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L_202302440.
- European Commission, 2023d. Renewable energy directive III. https://transport.ec.europa.eu/transport-modes/air/environment/refueled-aviation_en.
- European Commission, 2024. Taxes in the field of aviation and their impact – final report. <https://www.eurocontrol.int/publication/eurocontrol-european-aviation-overview-archive-2023>.
- European Environment Agency, 2021. Annual European union greenhouse gas inventory 1990–2019 and inventory report 2021, submission to the UNFCCC secretariat. https://transport.ec.europa.eu/transport-modes/air/environment/refueled-aviation_en.
- European Environment Agency, 2024a. EEA greenhouse gases — data viewer. https://transport.ec.europa.eu/transport-modes/air/environment/refueled-aviation_en.
- European Environment Agency, 2024b. EU emissions trading system (ETS) data viewer. <https://www.eea.europa.eu/en/analysis/maps-and-charts/emissions-trading-viewer-1-dashboards>.
- Eurostat, 2023. Air passenger transport by aircraft model, distance bands and transport coverage. http://dx.doi.org/10.2908/AVIA_PAODIS.
- Eurostat, 2024a. Air passenger transport by reporting country. http://dx.doi.org/10.2908/AVIA_PAOC.
- Eurostat, 2024b. Freight and mail air transport by reporting country. http://dx.doi.org/10.2908/AVIA_GOOC.
- Evans, M., Kramarchuk, R., Dörner, J., Williams, M., Giordano, S., Feng, X., Peng, Y., 2023. EU carbon border adjustment mechanism to raise 80b per year by 2040. S&P global. <https://www.spglobal.com/esg/insights/featured/special-editorial/eu-carbon-border-adjustment-mechanism-to-raise-80b-per-year-by-2040>.
- Gama, A., 2017. Own and cross-price elasticities of demand for domestic flights and intercity trains in the US. *Transp. Res. Part D: Transp. Environ.* 54, 360–371.
- German Environment Agency, 2023a. Aviation in the EU ETS and CORSIA in the 'fit for 55' package. <https://www.umweltbundesamt.de/publikationen/aviation-in-the-eu-ets-corsia-in-the-fit-for-55>.
- German Environment Agency, 2023b. Emissions trading rings up record revenues: More than 13 billion euros for climate protection. <https://www.umweltbundesamt.de/en/press/pressinformation/emissions-trading-rings-up-record-revenues-more>.
- Gonzalez-Garay, A., Heuberger-Austin, C., Fu, X., Klokkenburg, M., Zhang, D., van der Made, A., Shah, N., 2022. Unravelling the potential of sustainable aviation fuels to decarbonise the aviation sector. *Energy Environ. Sci.* 15 (8), 3291–3309.
- Greenpeace, 2023. Ticket prices of planes vs trains - A Europe-wide analysis. How low-cost carriers destroy the climate while their unfair and aggressive pricing strategies go unchecked. <https://www.greenpeace.de/publikationen/ticket-prices-planes-vs-trains-europe-wide-analysis>.
- Grim, R.G., Ravikumar, D., Tan, E.C., Huang, Z., Ferrell, J.R., Resch, M., Li, Z., Mevawala, C., Phillips, S.D., Snowden-Swan, L., et al., 2022. Electrifying the production of sustainable aviation fuel: the risks, economics, and environmental benefits of emerging pathways including CO₂. *Energy Environ. Sci.* 15 (11), 4798–4812.
- Gurtner, G., Delgado, L., Valput, D., 2021. An agent-based model for air transportation to capture network effects in assessing delay management mechanisms. *Transp. Res. Part C: Emerg. Technol.* 133, 103358.
- Gyandoh, E., Gomez, J., 2025. Techno-economic analysis (TEA) of civilian sustainable aviation fuel (SAF)—A systematic review of hydrotreated esters and fatty acids (HEFA) and lignocellulosic biomass conversion (LCBC) strategies. *Appl. Energy* 399, 126421.
- He, S., Dong, K., Hou, M., Song, H., Zhu, T., Li, A., Jiang, C., 2025. Fueling the future: A comparative analysis of sustainable aviation fuel pathways. *Transp. Policy* 103843.
- Hileman, J.L., Stratton, R.W., Donohoo, P.E., 2010. Energy content and alternative jet fuel viability. *J. Propuls. Power* 26 (6), 1184–1196.
- Horio, B.M., Kumar, V., DeCicco, A.H., 2015. An agent-based approach to modeling airlines, customers, and policy in the US air transportation system. In: 2015 Winter Simulation Conference. WSC, IEEE, pp. 336–347.
- Hu, Y.-J., Yang, L., Cui, H., Wang, H., Li, C., Tang, B.-J., 2022. Strategies to mitigate carbon emissions for sustainable aviation: A critical review from a life-cycle perspective. *Sustain. Prod. Consum.* 33, 788–808.
- IATA, 2019. Economic performance of the airline industry.
- IATA, 2024. IATA jet fuel price monitor, suggest a higher price level for fossil jet fuel in Europe. <https://www.iata.org/en/publications/economics/fuel-monitor>.
- ICAO, 2022. CORSIA default life cycle emissions values for CORSIA eligible fuels. <https://www.icao.int/environmental-protection/CORSIA/Pages/CORSIA-Eligible-Fuels.aspx>.
- InterVISTAS Consulting Inc, 2007. Estimating air travel demand elasticities: Final report. <https://www.iata.org/en/iata-repository/publications/economic-reports/estimating-air-travel-demand-elasticities-by-intervistas>.
- Jiang, C., Liu, Y., 2025. The role of sustainable aviation fuel in CORSIA: An economic analysis. *Energy Econ.* 143, 108238.
- Kapeller, M.L., Füllsack, M., Jäger, G., 2019. Holiday travel behaviour and correlated CO₂ emissions—modelling trend and future scenarios for Austrian tourists. *Sustainability* 11 (22), 6418.
- Khanra, M., Prabhu, S., 2022. Assessment of the additional electricity demand to decarbonise the aviation sector in Germany until 2050 based on technology diffusion method. *Fraunhofer Publ.*
- Li, H., Strauss, J., Lu, L., 2019. The impact of high-speed rail on civil aviation in China. *Transp. Policy* 74, 187–200.
- Liang, L., Chen, P., Ma, M., 2025. Dynamic analysis and simulation of the economic viability of sustainable aviation fuel blending in airlines: Emphasizing China's pilot policy and future development potential. *Transp. Policy* 103944.
- Liu, X., Madlener, R., 2021. The sky is the limit: Assessing aircraft market diffusion with agent-based modeling. *J. Air Transp. Manag.* 96, 102104.
- Lo, W.W.L., Wan, Y., Zhang, A., 2015. Empirical estimation of price and income elasticities of air cargo demand: The case of Hong Kong. *Transp. Res. Part A: Policy Pr.* 78, 309–324.

- Martin, J., Neumann, A., Ødegård, A., 2023. Renewable hydrogen and synthetic fuels versus fossil fuels for trucking, shipping and aviation: A holistic cost model. *Renew. Sustain. Energy Rev.* 186, 113637.
- Martinez-Valencia, L., Garcia-Perez, M., Wolcott, M.P., 2021. Supply chain configuration of sustainable aviation fuel: Review, challenges, and pathways for including environmental and social benefits. *Renew. Sustain. Energy Rev.* 152, 111680.
- Moncada, J.A., Versteegen, J.A., Posada, J.A., Junginger, M., Lukszo, Z., Faaij, A., Weijnen, M., 2019. Exploring the emergence of a biojet fuel supply chain in Brazil: An agent-based modeling approach. *GCB Bioenergy* 11 (6), 773–790.
- Montlaur, A., Kuljanin, J., Ganić, E., 2024. The pathway to net-zero emission in aviation—how much can we rely on sustainable aviation fuel? *Transp. Res. Procedia* 80, 3–10.
- Mosca, M., Hoffenson, S., 2017. Using agent-based modeling to understand stakeholder interactions in the rollout of nextgen by the federal aviation administration. In: 2017 Annual IEEE International Systems Conference (SysCon). IEEE, pp. 1–8.
- Oesingmann, K., 2022. The effect of the European emissions trading system (EU ETS) on aviation demand: An empirical comparison with the impact of ticket taxes. *Energy Policy* 160, 112657.
- Okolie, J.A., Awotoye, D., Tabat, M.E., Okoye, P.U., Epelle, E.I., Ogbaga, C.C., Güleç, F., Oboirin, B., 2023. Multi-criteria decision analysis for the evaluation and screening of sustainable aviation fuel production pathways. *Iscience* 26 (6).
- Pavlenko, N., Searle, S., Christensen, A., 2019. The cost of supporting alternative jet fuels in the European union. *Int. Counc. Clean Transp. (ICCT)*, Wash. DC, USA.
- Pérez-Calderón, E., Milanés-Montero, P., Gutiérrez-Pérez, C., 2021. Climate change, where do we come from and where are we going? *European aviation sector behaviour*. *Transp. Policy* 114, 40–48.
- Pescarini, H.B., da Silva, C.R.U., Petrielli, G.P., Chagas, M.F., Guimarães, H.R., Bressanin, J.M., da Silva, C., de Souza Henzler, D., Simões, D.A., Bonomi, A., et al., 2025. Strategic productive arrangements to leverage greenhouse gas emissions mitigation in the production of sustainable aviation fuels in Brazil. *Sustain. Prod. Consum.*
- Prussi, M., Noussan, M., Laveneziana, L., Chiamonti, D., 2025. The risk of increasing energy demand while pursuing decarbonisation: the case of the e-fuels for the EU aviation sector. *Transp. Policy* 160, 154–158.
- Prussi, M., Scarlat, N., Acciaro, M., Kosmas, V., 2021. Potential and limiting factors in the use of alternative fuels in the European maritime sector. *J. Clean. Prod.* 291, 125849.
- Rojas-Michaga, M.F., Michailos, S., Cardozo, E., Akram, M., Hughes, K.J., Ingham, D., Pourkashanian, M., 2023. Sustainable aviation fuel (SAF) production through power-to-liquid (PtL): A combined techno-economic and life cycle assessment. *Energy Convers. Manage.* 292, 117427.
- Schmidt, P., Batteiger, V., Roth, A., Weindorf, W., Raksha, T., 2018. Power-to-liquids as renewable fuel option for aviation: a review. *Chem. Ing. Tech.* 90 (1–2), 127–140.
- Schnuelle, C., Kijes, K., Stuehrmann, T., Thier, P., Nikolic, I., Von Gleich, A., Goessling-Reisemann, S., 2020. From niche to market—An agent-based modeling approach for the economic uptake of electro-fuels (power-to-fuel) in the german energy system. *Energies* 13 (20), 5522.
- Seymour, K., Held, M., Stolz, B., Georges, G., Boulouchos, K., 2024. Future costs of power-to-liquid sustainable aviation fuels produced from hybrid solar PV-wind plants in Europe. *Sustain. Energy Fuels* 8 (4), 811–825.
- Shehab, M., Moshammer, K., Franke, M., Zondervan, E., 2023. Analysis of the potential of meeting the eu's sustainable aviation fuel targets in 2030 and 2050. *Sustainability* 15 (12), 9266.
- Singh, H., Li, C., Cheng, P., Wang, X., Liu, Q., 2022. A critical review of technologies, costs, and projects for production of carbon-neutral liquid e-fuels from hydrogen and captured CO₂. *Energy Adv.* 1 (9), 580–605.
- Staples, M.D., Malina, R., Suresh, P., Hileman, J.I., Barrett, S.R., 2018. Aviation CO₂ emissions reductions from the use of alternative jet fuels. *Energy Policy* 114, 342–354.
- Su, J., Wu, H., Tsui, K.W.H., Fu, X., Lei, Z., 2023. Aviation resilience during the COVID-19 pandemic: A case study of the European aviation market. *Transp. Res. Part A: Policy Pr.* 177, 103835.
- Tascón, D.C., Olariaga, O.D., 2021. Air traffic forecast and its impact on runway capacity: a system dynamics approach. *J. Air Transp. Manag.* 90, 101946.
- ten Cate, M., Dienstknecht, M., Ursavas, E., Zang, G., Zhu, S.X., 2025. From CO₂ emissions to jet fuel: Analysis of potential sustainable aviation fuel supply chains in Europe. *Appl. Energy* 396, 126131.
- Thonemann, N., Pierrat, E., Dudka, K.M., Saavedra-Rubio, K., Dragsdahl, A.L.S.T., Laurent, A., 2024. Towards sustainable regional aviation: Environmental potential of hybrid-electric aircraft and alternative fuels. *Sustain. Prod. Consum.* 45, 371–385.
- Trinh, J., Harahap, F., Fagerström, A., Hansson, J., 2021. What are the policy impacts on renewable jet fuel in Sweden? *Energies* 14 (21), 7194.
- Ueckerdt, F., Bauer, C., Dirnmaier, A., Everall, J., Sacchi, R., Luderer, G., 2021. Potential and risks of hydrogen-based e-fuels in climate change mitigation. *Nat. Clim. Chang.* 11 (5), 384–393.
- Ullah, K.M., Dwivedi, P., 2022. Ascertain land allocation decisions of farmers about the adoption of carinata as a potential crop for sustainable aviation fuel production in the southern United States. *GCB Bioenergy* 14 (7), 824–839.
- Van Tol, M., Moncada, J., Lukszo, Z., Weijnen, M., 2021. Modelling the interaction between policies and international trade flows for liquid biofuels: an agent-based modelling approach. *Energy Policy* 149, 112021.
- Wandelt, S., Zhang, Y., Sun, X., 2025. Sustainable aviation fuels: A meta-review of surveys and key challenges. *J. Air Transp. Res. Soc.* 100056.
- Wang, B., O'Sullivan, A., Schäfer, A.W., 2019. Assessing the impact of high-speed rail on domestic aviation CO₂ emissions in China. *Transp. Res. Rec.* 2673 (3), 176–188.
- Wei, T., Kallbekken, S., 2024. Carbon leakage from aviation under the European union fit for 55 policies. *Transp. Res. Part D: Transp. Environ.* 132, 104269.
- Winchester, N., McConnachie, D., Wollersheim, C., Waitz, I.A., 2013. Economic and emissions impacts of renewable fuel goals for aviation in the US. *Transp. Res. Part A: Policy Pr.* 58, 116–128.
- Wissner, N., Graichen, V., 2024. Aviation in the EU climate policy: Key issues for the EU 2040 and 2050 target. <https://www.oeko.de/fileadmin/oekodoc/2024-briefing-aviation-in-EU-policy.pdf>.
- World Economic Forum, 2020. Clean skies for tomorrow: Sustainable aviation fuels as a pathway to net-zero aviation. <https://www.weforum.org/publications/clean-skies-for-tomorrow-sustainable-aviation-fuels-as-a-pathway-to-net-zero-aviation>.
- Xu, Y., Zhang, Y., Deng, X., Lee, S.-Y., Wang, K., Li, L., 2025. Bibliometric analysis and literature review on sustainable aviation fuel (SAF): Economic and management perspective. *Transp. Policy* 162, 296–312.
- Yan, R., Tang, B.-J., Hu, Y.-J., Ji, C.-J., Lin, K.-B., Shen, M., 2025. Sustainable aviation fuel and next-generation aircraft: Low-carbon pathway for China's civil aviation industry. *J. Environ. Manag.* 391, 126493.
- Yirgu, K.W., Kim, A.M., 2023. Estimating the effects of price-based environmental policies on aviation emissions at neighboring airports. *J. Clean. Prod.* 425, 138928.
- Zheng, S., Jiang, C., Li, A., 2025. Aviation e-fuel mandates: balancing average and minimum requirements for emission reduction. *Transp. Res. Part A: Policy Pr.* 202, 104726.