Scenario Modeling and Analysis for Strategic Decision-Making towards Net-Zero Aviation

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With the commercial aviation industry being a major contributor to global emissions, there is a growing sense of urgency among stakeholders to reduce carbon emissions generated by the industry. Industry stakeholders must collaborate and execute decisions at crucial moments in time and realize a scenario to achieve the goal of net-zero emissions by 2050. This work integrates a methodology for generating emissions-reducing scenarios for the aviation industry with an approach to simulate the fleet-level impacts for these scenarios and assess them in terms of pertinent metrics, such as CO_2 emissions, airline operating costs, and flight ticket prices. The simulation approach is integrated into an environment called Sustainable Aviation Visualization Environment (SAVE) to allow users to compare the generated scenarios, analyze them, and aid aviation's stakeholders in making informed decisions for enabling net-zero by 2050.

I. Nomenclature

ASM = Available Seat Miles
ATAG = Air Transport Action Group
CO_2 = Carbon Dioxide
FAA = Federal Aviation Administration
GHG = Greenhouse Gas
IATA = International Air Transport Association
ICAO = International Civil Aviation Organization
LH_2 = Liquid Hydrogen
LTAG = Long Term Aspirational Goal
OEM = Original Equipment Manufacturer
PtL = Power to Liquid
RJ = Regional Jet
SAF = Sustainable Aviation Fuel
SAVE = Sustainable Aviation Visualization Environment
SSA = Small Single Aisle
TIES = Technology Identification, Evaluation, and Selection
TP = Turboprop

II. Introduction

As the world moves towards sustainability, industries are ramping up emissions reduction efforts. A Capgemini report shows 84% of executives claim their companies are on track to meet carbon goals [1]. However, balancing emissions reduction with economic performance may be a challenging exercise for all industries. While some, like light road transport, agriculture, and aluminum production, are considered to be easier to decarbonize as they have lower abatement costs and complexities [2], the aviation industry requires meticulous coordination among its key stakeholders, such as airlines, manufacturers, fuel suppliers, and regulators, to reduce its carbon emissions [3]. Achieving net-zero CO_2

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emissions in aviation by 2050 requires coordinated efforts among aviation's key players and significant advancements in aircraft technology, sustainable fuels, and more efficient operations [4]. This complexity makes the aviation industry one of the hardest industries to decarbonize.

Aviation's economic impact further complicates emissions reductions. In 2019, aviation created more than 87 million jobs worldwide and generated $3.5 trillion in economic impact, including direct, indirect, induced, and tourism-related effects [5]. Furthermore, air transport carries over 35% of global trade by value, amounting to approximately $6.8 trillion in goods, although it represents less than 1% by volume [6].

Despite aviation playing a vital role in economic growth and global connectivity, aviation also contributed 2.5% of global CO_2 emissions in 2019, a share that has steadily increased since the 1990s as passenger and freight demand more than quadrupled, growing from 1.03 billion in 1990 to approximately 4.54 billion in 2019 [7, 8]. Though technological advancements improved fuel efficiency by 1.1% annually between 2009 and 2013 [9], rapid growth in flight activity has outpaced these gains. Air travel demand has increased by 5.1% per year over this period and is expected to double by 2040, with emissions potentially rising 300% over 2005 levels by 2050 if these trends continue [10, 11].

Driven by the anticipated rise in passenger air demand, the global aviation fleet is projected to nearly double by 2042, increasing from approximately 24,500 aircraft today to around 48,600, according to Boeing's 2023 Commercial Market Outlook [12]. The global fleet is expected to grow by 3.5% annually, requiring about 40,000 new aircraft over the next two decades for replacement and growth of the fleet. This poses a chance to develop new, more sustainable aircraft designs to replace and expand the fleet. Replacing the current commercial aircraft fleet with the most fuel-efficient aircraft in service today would reduce fuel consumption by about 20%, which is not sufficient for reducing the projected increase in aviation emissions due to the increase in air travel demand [13]. IATA notes that, despite these improvements, the pace of efficiency gains is not keeping up with the rapid growth in air travel, which requires additional measures to effectively reduce emissions.

III. Background

Several key initiatives and reports provide structured scenarios or pathways for achieving net-zero emissions. For example, the International Air Transport Association (IATA) has developed detailed roadmaps that outline pathways to net-zero emissions by 2050. These roadmaps are based on extensive data, incorporating current and projected advancements in fuel efficiency, adoption rates of sustainable aviation fuels (SAFs), advancements in aircraft technology, and operational improvements [14]. However, these roadmaps are built on assumptions about technological readiness and market uptake and do not outline possible outcomes if the roadmaps are not strictly followed. Similarly, the Long-Term Aspirational Goals (LTAG) report, published by the International Civil Aviation Organization, and the Waypoint 2050 report, published by the Air Transport Action Group (ATAG), use detailed scenario modeling to evaluate the impact of various technological and operational strategies. Each report models just three scenarios, limiting their ability to capture the full range of potential outcomes and challenges [15, 16].

Despite the comprehensive scenarios generated by IATA, ICAO, and ATAG, the challenge lies in realizing these scenarios. The LTAG and Waypoint 2050 reports assume that the necessary policies, regulatory frameworks, and infrastructure will be in place, which may not be uniformly implemented across different regions [17, 18]. Additionally, these scenarios often anticipate the development of operational infrastructure, such as SAF production facilities and hydrogen refueling stations at airports, underestimating the substantial investment and time required to develop and scale these technologies[19]. Moreover, these strategies do not adequately consider the collaborative efforts required from key aviation players, including airlines, airports, energy producers, policymakers, and technology developers, to realize these scenarios effectively [3].

Thus, realizing the aviation sector's goal of achieving net-zero CO_2 emissions will require a well-rounded approach. This means carefully considering every major decision required by aviation's key stakeholders that could lower emissions and combining them into comprehensive, actionable scenarios. Furthermore, to effectively aid decision-makers and stakeholders in the industry in making informed decisions, these scenarios must also be assessed for their broader impacts–not just on the environment but on the aviation sector as a whole.

This work introduces a practical method for addressing this challenge by developing a simulation tool to assess and compare different net-zero scenarios, enabling scenarios to understand their effects at the fleet level and helping identify the most effective path forward.

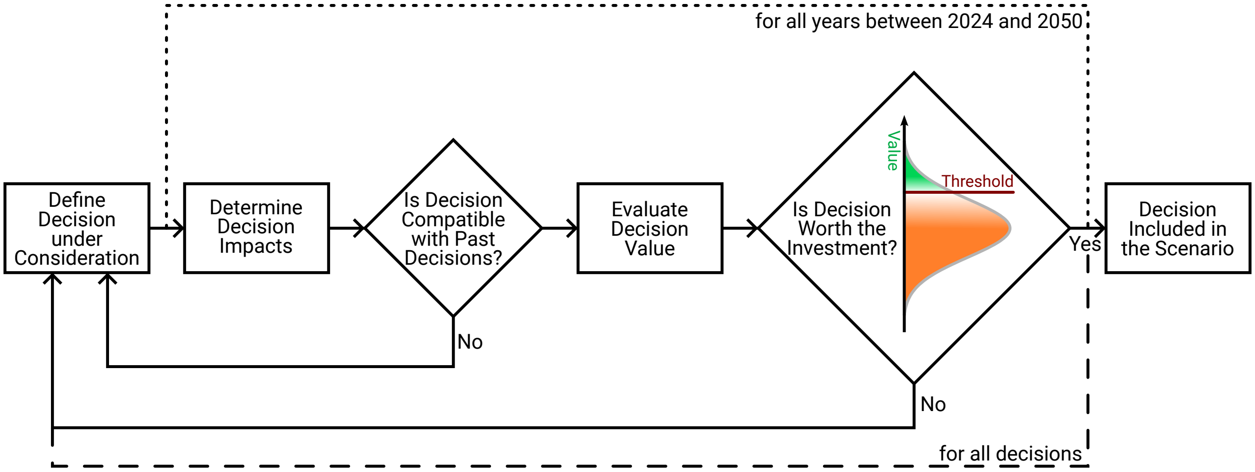


Fig. 1 General Architecture of Scenario Generation Process

A. Generation of Scenarios

To address this challenge, Almarzooqi et al. [20] focus on tackling this issue by developing a simulation tool to generate thousands of decision-making scenarios for achieving net-zero emissions in aviation by 2050. Almarzooqi et al. achieved this by creating a four-phase structured framework depicted in the flowchart in Fig. 1 and described below.

Defining Decisions Key enabling solutions from the IATA Net-Zero roadmaps were mapped to six primary aviation stakeholders: policymakers, energy producers, technology developers, OEMs, airports, and airlines. Decisions were defined based on these stakeholders' responsibilities, specifically within areas regarding alternative fuels, aircraft technology, operational efficiency, and policy frameworks. Drawing from Waypoint2050, IATA's Commercial Passenger Market Analysis, and other literature, 37 decisions were identified and grouped by stakeholder [16, 21]. A comprehensive list of all these decisions can be found in the Appendix of this work.

Mapping Impacts to Decisions Each decision is then mapped to various impact parameters, which quantify the effects of each decision on various parameters. For example, decisions related to electric aviation infrastructure funding are mapped to parameters such as operational efficiency and electric operations share. Improved infrastructure decreases turnaround time (by 15 to 25%) and increases electric operations share (by 10 to 25%) [20]. For every given year, the simulation randomly generates a deterministic impact value within this pre-defined range. The impacts are time-dependent, meaning they have a delay period (no immediate effect after decision execution) and a maturation period (the time for impacts to reach full effect). A logistic function models this maturation, allowing impacts to grow over time. This method ensures stochasticity, meaning that in two different scenarios, the same decision taken at the same point in time could have a different impact on the timeline altogether as well as a different delay period and maturation period.

Making Decisions To capture the interconnected nature of the stakeholders, a compatibility matrix maps relationships between the 37 decisions, categorizing them as compatible, incompatible, or hierarchical (dependent on the timing of the previously made decisions). The decision impacts are mapped to each stakeholder's primary interest (for example, airlines' primary interest is projected revenue and expenses). using the Technology Identification, Evaluation, and Selection (TIES) method [22]. A real options approach, adapted from economics, then uses these stakeholder interests to evaluate each decision annually, considering its compatibility and impact evolution to determine if it meets the criteria for making that decision that year. Decisions that have not been executed yet are re-evaluated every year in the timeline, ensuring flexible and adaptable decision-making throughout the time horizon.

Aggregating Impacts The impacts of executed decisions every year are aggregated into a cumulative impact matrix, which tracks the time evolution of each impact metric. The cumulative impacts are derived by summing all the individual

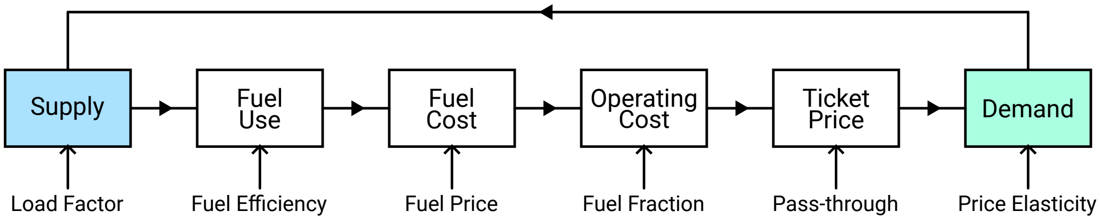


Fig. 2 Block diagram representation of the aviation system [23]

decision impact parameters. The final output is a time series capturing the combined effect of all decisions on each impact metric, forming the basis for fleet-level scenario assessments, which are detailed in this work.

Almarzooqi et al. provide further information on the stakeholders and their decisions, a detailed breakdown of the approach, and a discussion of results.

B. Need for Fleet-Level Analysis

Simply proposing scenarios that could possibly result in a net-zero aviation industry may not suffice as there are some key metrics that stakeholders, particularly airlines, would be interested in inspecting closely before considering or committing to certain decisions required for a scenario. As such, the scenario generation methodology proposed by Almarzooqi et al. does not include a simulation or analysis of how scenarios would impact the industry with respect to those key metrics. Thus, to get more insight into which decisions help the transition to net-zero, a way to analyze the performance of these scenarios is needed.

As decisions are executed by key stakeholders, these decisions impact the evolution of the industry, altering the fleet composition, operating costs, ticket prices, and other metrics, eventually affecting the air traffic and the corresponding CO_2 emissions. Therefore, it is necessary to perform a fleet-level analysis for each one of the scenarios generated to determine the actual evolution of the industry and assess their effectiveness in reducing carbon emissions. For that purpose, this study based its work on the simulation framework, the Interactive Dynamic Environment Analysis tool, developed by Hassan et al. [23]. This method uses FAA forecast data along with various scaling factors for the different variables (e.g., fuel price) to estimate the evolution of the air traffic for a predetermined time frame before performing an optimization to match the evolution of the supply and the demand. For each year, the growth of the fleet and the aircraft replacements required in order to reach the supply are calculated, and the resulting fleet composition is used to compute the total CO_2 emissions. For more details on the assumptions made in these simulations, refer to the original paper detailing the development of the tool [23]. A schematic view of the optimization loop is presented in Fig. 2.

IV. Modeling

In the original work by Hassan et al., the fleet-level analysis only accounted for conventional jet fuel operations. However, as the industry slowly transitions towards a net-zero future, new energy sources are being considered to power aviation in a more sustainable way. Specifically, hydrogen and electric aircraft are generally accepted as the most promising options for reducing aviation emissions, in addition to the large-scale adoption of Sustainable Aviation Fuels. Therefore, most of the decisions implemented in the scenario generation revolved around these three pillars, requiring modifications to the fleet-level analysis to account for such operations.

Compared to the initial analysis depicted in Fig. 2, the adoption of hydrogen or electric power as a replacement for conventional fuel affects the calculations of the fuel use, fuel cost, and operating cost. The modified analysis determines these three variables independently for each fuel type, resulting in fuel-specific operating costs. These costs are then averaged across operations to determine an average operating cost, which is subsequently used to modify ticket prices. Finally, variations in these prices affect the overall demand through price elasticity. The underlying assumption in this approach is that the cost increase associated with the operation of hydrogen and electric aircraft is distributed across all operations. The new process is described by the modified block diagram representation shown in Fig. 3. Subsections IV.A to IV.D describe the different steps involved in calculating the operating costs associated with alternative fuels.

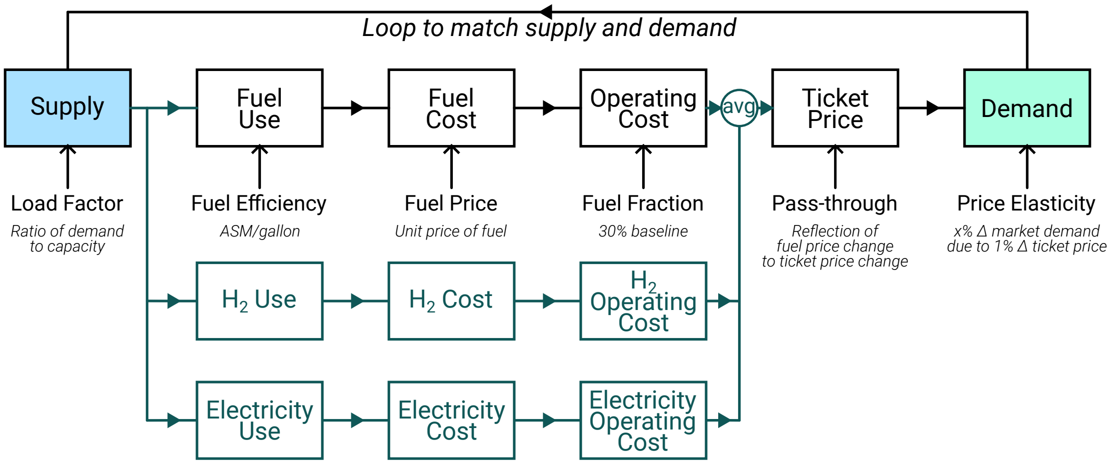


Fig. 3 Modified block diagram representation of the modeled aviation system

A. Hydrogen Aircraft

Given the current readiness level of hydrogen aircraft and the time horizon of this study, it was assumed that hydrogen-powered aircraft would only replace aircraft from the small single-aisle (SSA), regional jet (RJ), and turboprop (TP) categories in scenarios where airlines decided to incorporate such concepts into their fleet. For these scenarios, introducing hydrogen aircraft into the fleet modifies the efficiency of flight operations in terms of fuel consumed per Available Seat Miles (ASM). In the conventional-fuel case, aircraft efficiency is expressed relative to the forecasted fuel efficiency, calculated using the FAA forecast data, as shown in Eq. 1. Here, F represents the fuel consumed, η_{conv} denotes the relative efficiency, $E_{forecast}$ stands for the forecast fleet efficiency in gallons per available seat mile (gal/ASM), and ASM represents the available seat miles.

$$F = \eta_{conv} E_{forecast} \text{ASM} \tag{1}$$

Then, the relative jet fuel efficiency η_{conv} can be used to define a relative jet fuel price π_{conv} following Eq. 2, where C_{fuel} represents the Fuel Costs (\$/ASM), P_{fuel} stands for the Fuel Price (\$/gal), E_f is the Fuel Efficiency (gal/ASM), and $C_{forecast}$ stands for the Forecast Fuel Costs (\$/ASM).

$$\begin{aligned} C_{fuel} &= P_{fuel} E_f \\ &= \left(\pi_{conv} P_{forecast}\right)\left(\eta_{conv} E_{forecast}\right) \\ &= \pi_{conv} \eta_{conv} C_{forecast} \end{aligned} \tag{2}$$

Assuming that the fuel costs represent 30% of the operating cost initially [23], the relative operating costs κ_{conv} are calculated using Eq. 3.

$$\kappa_{conv} = 0.7 + 0.3 \pi_{conv} \eta_{conv} \tag{3}$$

The actual operating costs can finally be recovered from κ_{conv} and the forecast data, following Eq. 4.

$$TOC_{conv} = \kappa_{conv} TOC_{forecast} \tag{4}$$

To maintain consistency in the different formulations, a similar model was used to define a hydrogen-powered aircraft's relative efficiency η_{H_2}. It is expressed in kgH$_2$/gallons of jet fuel, as defined in Eq. 5, where F_{H_2} (kgH$_2$) is the amount of hydrogen consumed at the fleet level.

$$F_{H_2} = \eta_{H_2} E_{forecast} \text{ASM} \tag{5}$$

In order to determine the value of the hydrogen efficiency η_{H_2}, it was assumed that the overall propulsive efficiency of hydrogen aircraft will remain unchanged compared to conventional aircraft, which implies that the same amount of

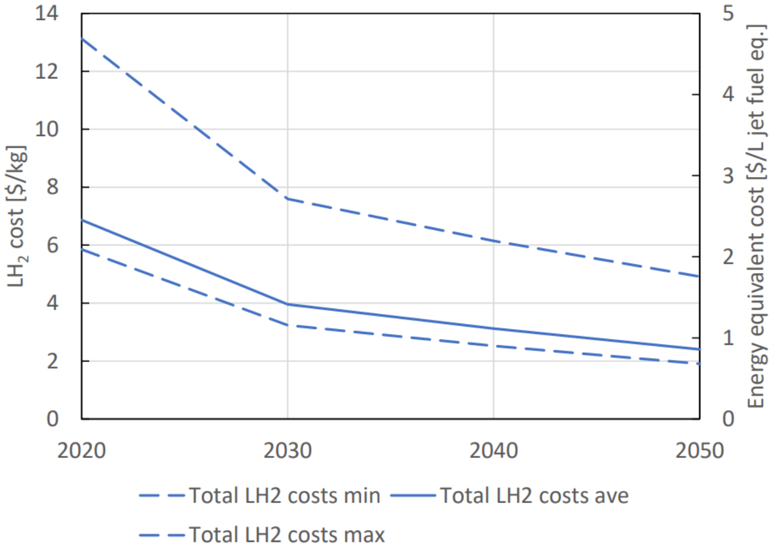


Fig. 4 LH_2 cost trajectory baseline [24]

energy is required per ASM for both types of operations. Under this assumption, the relative efficiency for hydrogen aircraft is given by Eq. 6, in which η_{H_2} represents the Relative H_2 Efficiency in (kgH_2/gal), LHV_{conv} is the Lower Heating Value of conventional fuel, LHV_{H_2} is the Lower Heating Value of hydrogen fuel, ρ_{conv} stands for the density of conventional fuel, and η_{conv} represents the Relative Conventional Fuel Efficiency. This assumption could be relaxed in future work by adding a conversion factor to Eq. 6, to account for different propulsion architectures.

$$\eta_{H_2} = \frac{LHV_{conv}}{LHV_{H_2}} \rho_{conv} \eta_{conv} \tag{6}$$

The next step in determining the evolution of the operating costs is to estimate the evolution of hydrogen prices, which are not included in the FAA forecast data. For that purpose, the average LH_2 cost trajectory featured in the LTAG report fuel appendix [24] was chosen in the analysis and reproduced in Fig. 4 for convenience to the reader. These costs are then rescaled depending on the specific decisions in the scenario being analyzed.

Using the LH_2 cost trajectory, a relative hydrogen fuel price π_{H_2} can be defined similarly to the jet fuel case, as shown in Eq. 7 where P_{H_2} represents the H_2 Price ($/kg). From there, hydrogen costs C_{H_2} ($/ASM) can be calculated using Eq. 8.

$$\pi_{H_2} = \frac{P_{H_2}}{P_{forecast}} \tag{7}$$

$$\begin{aligned} C_{H_2} &= P_{H_2} E_{H_2} \\ &= \pi_{H_2} \eta_{H_2} C_{forecast} \end{aligned} \tag{8}$$

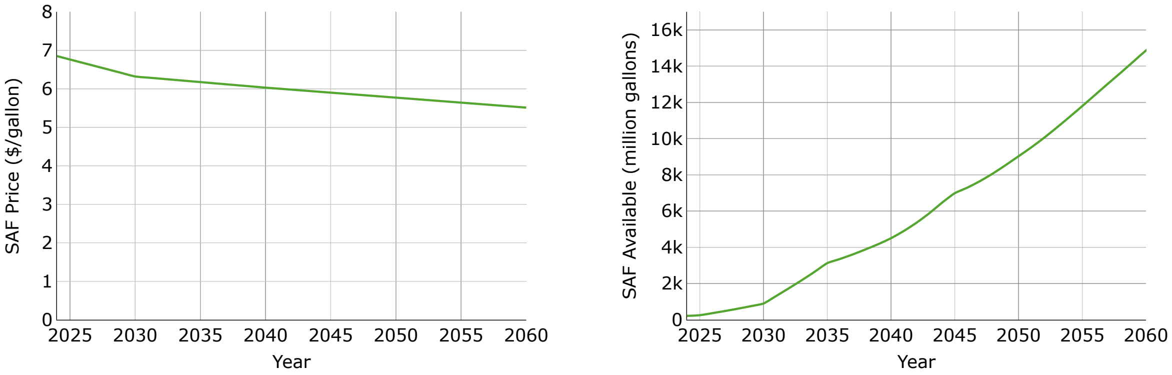
Assuming a 5% extra in hydrogen operating costs due to airport fees and aircraft ownership [25], the relative operating costs for hydrogen aircraft are given by Eq. 9, where κ_{H_2} represents the Relative H_2 Operating Costs. Finally, the actual hydrogen operating costs are recovered using Eq. 10, with TOC_{H_2} representing the H_2 Operating Costs ($/ASM).

$$\kappa_{H_2} = 0.7 + 0.05 + 0.3 \pi_{H_2} \eta_{H_2} \tag{9}$$

$$TOC_{H_2} = \kappa_{H_2} TOC_{forecast} \tag{10}$$

B. Electric Aircraft

The same approach is followed to determine the relative operating costs of electric aircraft. With the same assumptions as for hydrogen aircraft (same propulsive efficiency as conventional aircraft and 5% increase in fixed



(a) Evolution of SAF price

(b) Evolution of SAF availability

Fig. 5 Sustainable Aviation Fuel: baseline evolution

operating costs), an electric efficiency η_{elec} (MJ/ASM) is determined using Eq. 11.

$$\eta_{elec} = LHV_{conv}\rho_{conv}\eta_{conv} \tag{11}$$

The baseline evolution of the electricity price was estimated based on the data from the U.S. Energy Information Administration's Annual Energy Outlook [26] for transportation. This data, scaled with the impacts of the decisions in the scenario to analyze, defines the evolution of a relative electricity price π_{elec} that verifies Eq. 12.

$$C_{elec} = \pi_{elec}\eta_{elec}C_{forecast} \tag{12}$$

The evolution of the relative operating costs for electric aircraft κ_{elec} is determined similarly to the hydrogen relative operating costs, as shown in Eqs. 13 and 14.

$$\kappa_{H_2} = 0.7 + 0.05 + 0.3\pi_{H_2}\eta_{H_2} \tag{13}$$

$$TOC_{elec} = \kappa_{elec}C_{forecast} \tag{14}$$

C. Sustainable Aviation Fuel

The last key enabler to reduce emissions through fuel technologies is Sustainable Aviation Fuels (SAF). In the original analysis [23], the authors used biomass availability to estimate the amount of biofuels available and correct CO_2 emissions accordingly. However, this approach assumes that the use of biofuels does not affect the operating costs, the ticket prices, and therefore, the evolution of the air traffic supply. Moreover, comparing the results obtained with this methodology with recent studies like LTAG [15] reveals an overestimation of biofuel production and SAF adoption. Therefore, the modeling approach to Sustainable Aviation Fuels was revised. First, a baseline evolution of SAF prices and available quantities is defined from LTAG's fuel scenario 1 [24]. This scenario only considers fuel technologies with high readiness and attainability levels that are likely to be implemented in the near future. It also assumes low incentives for SAF production. The evolution of the SAF prices and the amount of SAF available under this scenario can be found in Fig. 5.

For this study, it is assumed that all the SAF available for a specific year would be used as part of the fleet operations. Therefore, the ratio of SAF operations is calculated using the total amount of fuel required to provide a specific supply (total ASM), which depends on the average fuel efficiency of the fleet and the amount of SAF available that year, as shown in Eq. 15. This proportion is used to modify the average fuel price for jet fuel operations and account for the economic consequences of using SAF. It is important to note that no limits to the SAF blend were implemented in the simulations, meaning that some scenarios could potentially lead to a higher blending ratio than the currently certified ratio of 50% (as of 2024) [27]. However, due to the relatively low availability of SAF compared to the amount of fuel required to meet the fleet-level demand, exceeding the current 50% limit is not likely to occur in the early years of the

Table 1 Electricity demand for LH2 production and transportation [MJ (electricity) / MJ (LH2)] [24]

	2020	**2030**	**2040**	**2050**	**2060**	**2070**
Electrolysis	1.43	1.43	1.43	1.43	1.43	1.43
Liquefaction	.30	.25	.20	.15	.15	.15
Transport	.02	.02	.02	.02	.02	.02
Total	**1.75**	**1.70**	**1.65**	**1.60**	**1.60**	**1.60**

simulations. Moreover, since the industry is already preparing to adopt SAF blends of up to 100% in the coming years [28], the impact of this assumption is expected to remain limited in later years.

$$\text{SAF proportion} = \min\left(\frac{\text{SAF available}}{\text{Total fuel needed}}, 1\right) \tag{15}$$

D. CO_2 emissions

Once the evolution of the air traffic supply and the fleet composition have been determined for a specific scenario, corresponding fuel quantities are estimated using each year's average fleet efficiency. The different fuel amounts are then linked to fleet-level CO_2 emissions using the appropriate carbon intensity, which represents the amount of emissions released during the production and consumption process of a unit of fuel. This property is highly dependent on the method of production and the characteristics of the fuel. As such, different CO_2 intensities were implemented for hydrogen, SAF, and electricity. The SAF carbon intensity used as a baseline for the simulation corresponds to the F1 scenario in the LTAG Fuel Appendix M5 [24], and the electric grid intensity baseline is based on the integrated scenario IS1. This low-aspiration scenario assumes minimal systemic changes and represents the expected trajectory of the industry. Assuming electrolysis as the main method of hydrogen production, the CO_2 intensity of hydrogen is directly linked to the electricity grid's intensity, as producing and consuming liquid hydrogen does not generate direct CO_2 emissions. The electricity required to produce and transport 1 MJ of liquid hydrogen is summarized in Table 1, extracted from the LTAG report.

V. Analyzing Scenarios

A. Baseline Scenario

As suggested in Sec. IV, the evaluation of decision scenarios is done around a "business as usual" baseline. This baseline reflects the projected evolution of the industry, as forecasted by previous studies [15, 29], and does not consider any major shift of the industry apart from than standard efficiency improvements. Specifically, hydrogen and electric aircraft are not used in the baseline case. However, unlike previous studies, this baseline includes the use of sustainable aviation fuels due to the rapid increase in SAF production observed in recent years (Fig. 6). This assumption is in accordance with the expectations of SAF adoption presented in LTAG's Fuel Appendix M5 [24].

This baseline scenario was evaluated using the modeling approach presented in Sec. IV. Fig. 7 displays the expected evolution of CO_2 emissions relative to 2024 (in orange) and total air traffic (in blue) for the United States fleet. As can be seen, even though air traffic keeps increasing exponentially, the inclusion of sustainable aviation fuels outweighs the increase in operations and prevents CO_2 emissions from increasing proportionally to the traffic. Because of that, the baseline scenario used in this study differs from the "business as usual" case that can be found in other studies, which often feature an exponential growth in CO_2 emissions.

B. Evaluating Decision Scenarios

1. Rescaling the baseline

Once the baseline is defined, the scenarios generated using the methodology presented by Almarzooqi et al. [20] can be analyzed.

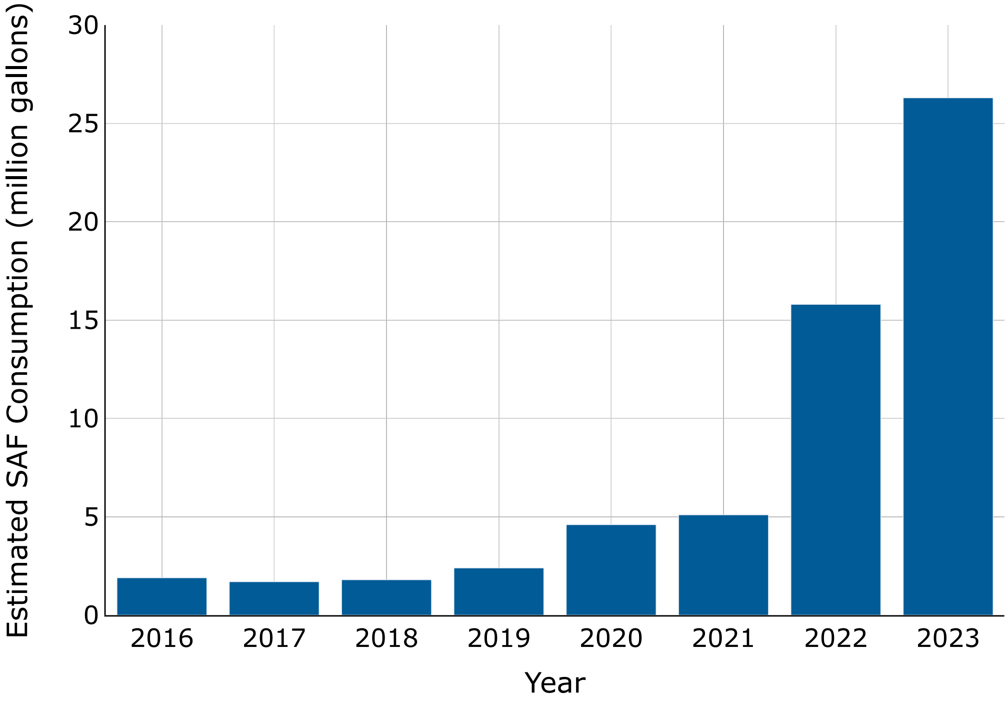


Fig. 6 Estimated consumption of SAF in the U.S. [30]

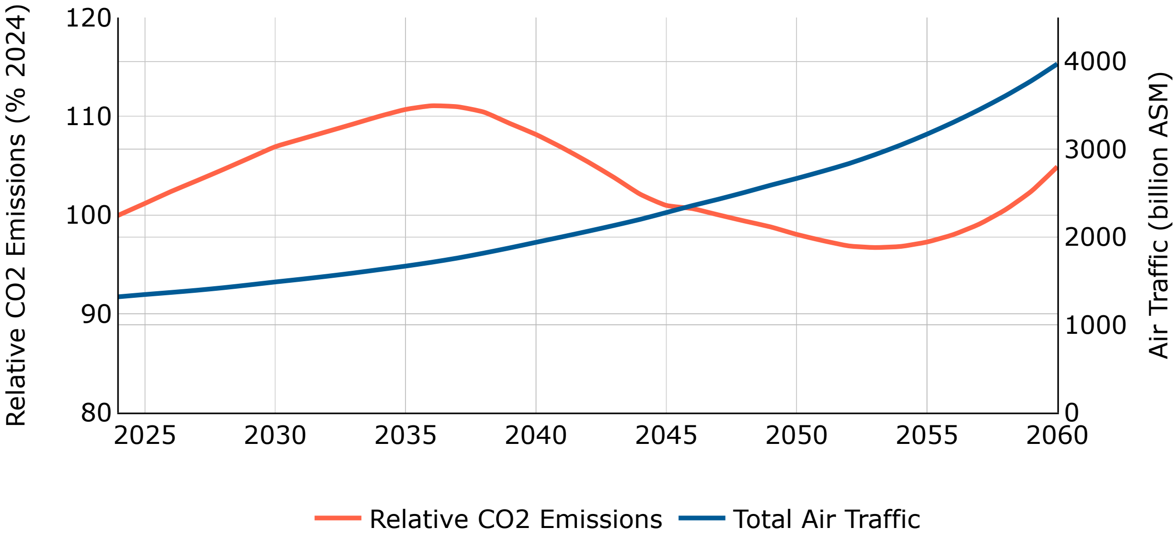


Fig. 7 Computed time-evolution results for the baseline scenario.

Table 2 Decision Impacts

Impact	Description
Jet Fuel Price	Scales the jet fuel price evolution.
Operational Efficiency	Accounts for fuel savings due to improved operations (e.g., continuous descent).
Fleet Replacement Rates	Modifies the rate at which airlines replace the oldest aircraft in their fleet.
Fixed Operating Costs (Electric)	Scales the increase in non-fuel related operating costs caused by additional costs (e.g., fees) of electric aircraft.
Fixed Operating Costs (Hydrogen)	Scales the increase in non-fuel related operating costs caused by additional costs (e.g., fees) of hydrogen aircraft.
Electricity Price	Scales the electricity price evolution.
Hydrogen Price	Scales the hydrogen price evolution.
SAF Price	Scales the SAF price evolution.
SAF Quantities	Scales the SAF quantities available.
Aircraft efficiency	Scales the fuel efficiency of new aircraft in the specified class.

As mentioned in Sec. III, a scenario represents a timeline of decisions made by the stakeholders. Each one of those decisions affects the evolution of several impact variables, resulting in cumulative impact time series that are associated with each scenario. Specifically, some of these impacts are directly linked to elements used to evaluate fleet-level emissions, like the evolution of the fuel price. Therefore, such impacts can be used to rescale the forecast evolution of the industry and evaluate the fleet-level impact of the scenario using the approach in Sec. IV. The impact variables used as scaling factors for the fleet-level analysis are summarized in Table 2.

2. Introducing alternative fuels into the fleet

In the baseline scenario, conventional aircraft are replaced with other conventional aircraft, potentially with improved efficiencies. In order to introduce hydrogen or electric aircraft in the simulations, the scenario must include the airlines' decision to incorporate these aircraft into their fleet. In that case, aircraft in the SSA, TP, and RJ categories start being partially replaced with hydrogen and/or electric aircraft from the year the corresponding decision is made. For the specific implementation used in this study, it is assumed that the share of replacements made using hydrogen or electric aircraft would follow a logistic function growing from 0% the year the decision is made, to 100% six years later.

Thus, a methodology has been devised to model scenarios and analyze them for their fleet-level impacts. Now, a platform is required that packages this methodology with tools to inspect the far-reaching effects of scenarios and to compare individual scenarios to each other. Some key findings noted by the team after analyzing the generated scenarios through one such platform are described in Sec. VI.

VI. Results

The modeling and simulation approach detailed in this study was integrated into an environment developed by the team called the Sustainable Aviation Visualization Environment (SAVE). In addition to the ability to analyze the thousands of generated scenarios using the approach discussed by Almarzooqi et al. [20], the environment was developed to assess the fleet-level impacts of these scenarios and compare different scenarios based on those impacts.

For this study, all metrics are analyzed relative to the baseline case. This means the metric for a certain scenario is denoted as a percentage of the same metric for the baseline case as it was in 2024. For instance, CO_2 emissions will be analyzed using the metric “Relative CO_2 Emissions”.

Some interesting trends and observations can be seen when analyzing the fleet-level impacts of the generated scenarios. First, the overall CO_2 emissions behavior of all 20,000 scenarios is inspected. The distribution of reduction in relative CO_2 emissions achieved by 2050 for all scenarios can be plotted to know how they perform overall. Figure 8 shows a probability density function (PDF) plot depicting the same. The horizontal axis denotes the percent of emissions

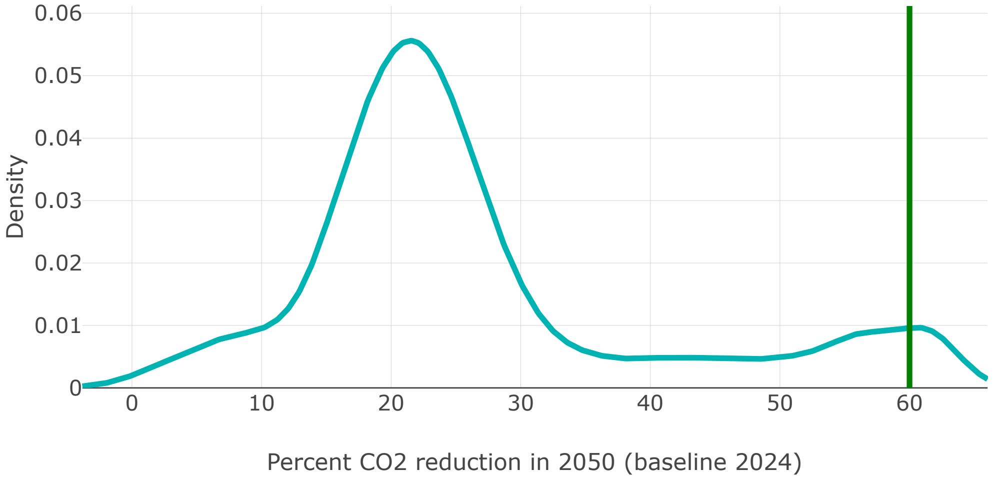


Fig. 8 PDF plot of CO_2 emissions reductions for all 20,000 scenarios. Scenarios achieving more than 60% relative emissions reduction are towards the right of the green vertical line.

reduced by 2050 (relative to the baseline case in 2024), and the vertical axis denotes the probability density of scenarios. The first observation is that, interestingly, none of the 20,000 scenarios manage to achieve a 100% reduction in emissions. In a majority of cases, the decisions made by the stakeholders were able to reduce their 2050 emissions by 10–30% from their 2024 levels, as seen in the substantial peak of the curve between 10–30% emissions reduction.

Another notable aspect in Fig. 8 is a secondary peak toward the 60% emissions reduction mark. It indicates that some scenarios were able to outperform others, reaching a 60% reduction in relative emissions or more. It was found that 867 of the 20,000 total scenarios, a mere 4.3%, achieved this figure. Although these scenarios achieve a significant reduction compared to the baseline case, for which an 8% increase in equivalent CO_2 emissions is expected in 2050, they still fall short of achieving the goal of net-zero emissions.

By filtering out the scenarios to focus on just the ones that have a higher reduction in relative emissions, it can be possible to learn further about why they performed better than all the other scenarios. To do this, the ten best scenarios in terms of CO_2 reductions by 2050 are looked at. Figure 9 depicts a time-evolution of the relative CO_2 emissions for these ten scenarios.

It can be seen that all ten scenarios achieve a comparable reduction of relative emissions by 2060, with a difference of only around 2% between them. Thus, it could seem that all ten scenarios may be feasible to consider. However, evaluating the time evolution of other metrics may hold the key to differentiating between them and choosing a certain scenario over others. For example, two scenarios among the top ten are selected: Scenario 1 and Scenario 4, the first and fourth best-performing scenarios, respectively. The details of the specific decisions considered for these scenarios, along with their timelines, can be found in the Appendix.

Comparing the relative CO_2 emissions over time for these two scenarios in Fig. 9, it is evident that while Scenario 1 leads to an earlier drop in emissions than Scenario 4, the end result is the same: both achieve comparable reductions by 2050. Thus, it may prove difficult for stakeholders to differentiate between these two scenarios merely through emissions reductions.

However, when inspecting the time evolution of relative operating costs, as shown in Fig. 10, it is seen that Scenario 1 has a significant spike in operating costs after 2040, while Scenario 4 shows a lower rise in operating costs around that same time. In addition, Scenario 1 ends with slightly higher relative operating costs by 2050 than Scenario 4.

This indicates that Scenario 4 could be a more feasible alternative to Scenario 1, citing lower operating costs and comparable emissions reductions. In essence, the interests and priorities of stakeholders will be paramount in deciding the pathway to take towards reducing CO_2 emissions in the aviation industry. Akin to this comparison, multiple metrics will require analysis in parallel in order to decide the best way forward.

Another important exercise is understanding which decisions enable the highest reductions in emissions. Some unique information can be gathered when analyzing the best-performing scenarios further—specifically, the decisions that they are composed of and the years in which those decisions are executed.

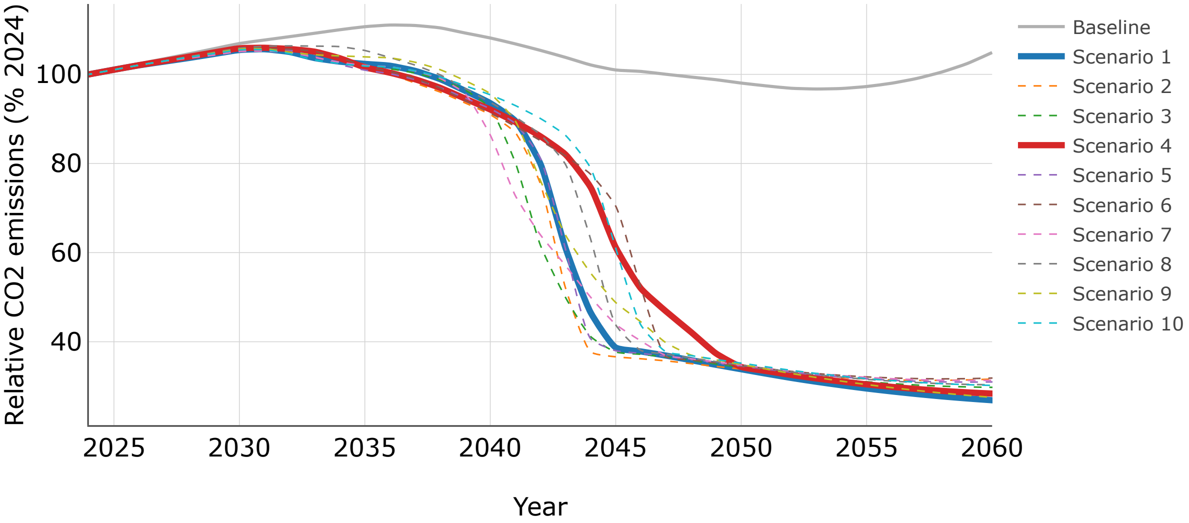


Fig. 9 **Comparison of the time evolution of relative CO_2 emissions for the top ten scenarios. The first and fourth best-performing scenarios are highlighted in blue and red, respectively.**

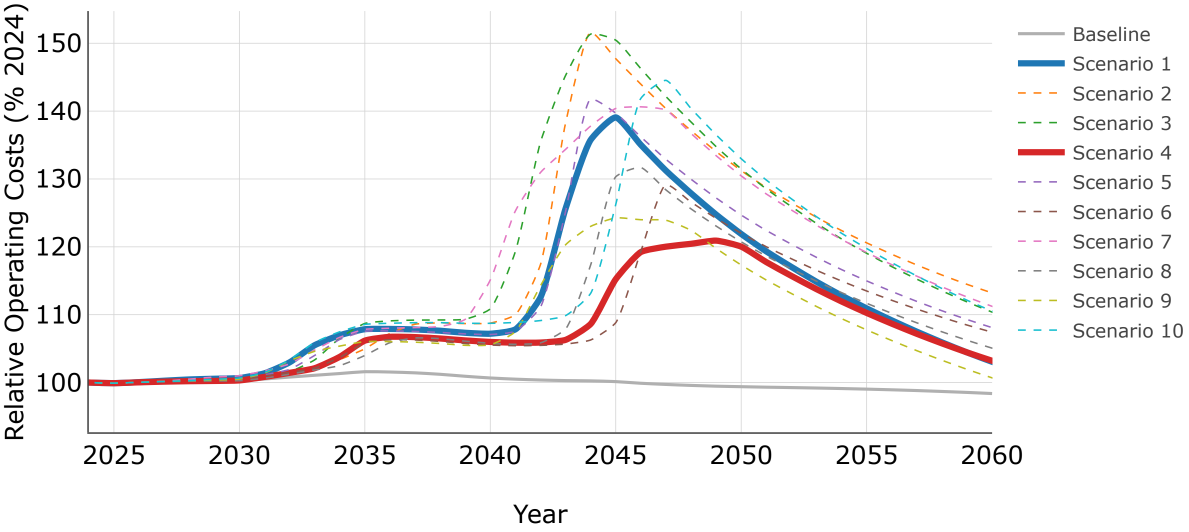


Fig. 10 **Comparison of the time evolution of operating costs for the top ten scenarios. The first and fourth best-performing scenarios are highlighted in blue and red, respectively.**

(a) All scenarios (20,000/20,000)

(b) Best-performing scenarios (867/20,000)

Fig. 11 Frequency of all decisions occurring in scenarios

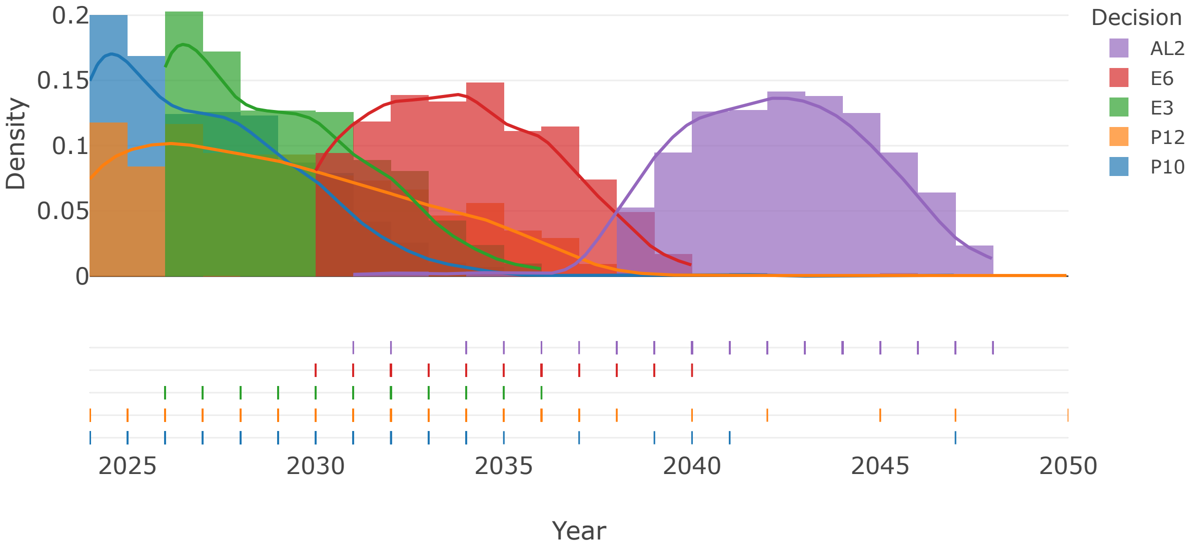


Fig. 12 Time distribution of the critical decisions to reach higher CO_2 reduction by 2050.

Figure 11, a pair of decision vs. frequency plots, highlights a few such observations.N2, a technology developer's decision, occurs in all of the 20,000 scenarios—evident from the decision's frequency of 1.0. Also, almost all of the 867 scenarios that achieved higher CO_2 reductions prominently feature certain "critical decisions" that were otherwise uncommon in the 20,000 scenarios overall. In particular, the energy producers' decisions E3 and E6, and the airlines' decision AL2, which are present in less than 40% of all scenarios, play a role in a vast majority of the best-performing scenarios. Other critical decisions identified are the policymakers' decisions P10 and P12. A description of these decisions can be found in Table 3 in the Appendix.

These observations are particularly interesting as they give an indication as to what decisions may form a part of the "critical path", that is, the scenario that would enable the highest possible CO_2 emissions reductions.

Looking at when these critical decisions occur within the best-performing scenarios can provide further insight into the timing that stakeholders might consider for these decisions to have optimal impact. In order to analyze this, a distribution of the year the critical decisions were made is shown in Fig. 12.

In Fig. 12, each critical decision is represented by a unique color. One thing that stands out at first glance is that each decision has its own critical timeline, that is, the range of years in which a higher proportion of scenarios have the decision executed. For instance, the policymaker decision P10 (blue) is generally executed as early as possible in the scenarios, with a majority of scenarios executing it between 2024–2028 and only a few choosing to execute the decision after 2035. This is also true for P12 (yellow); in fact, policymakers' decisions create the highest impact when they are executed earlier in the timeline overall, as they are the prerequisites for the decisions of other stakeholders, which is consistent with their effect in the real-world aviation industry. In contrast, the airline decision AL2 (purple) features much later in the timeline than the other critical decisions; many scenarios execute it as late as 2040–2045. This indicates that airline decisions are among the last to take place, which is consistent with industry behavior. Yet, airlines are responsible for realizing the highest impact, as they choose to actually operate developed alternative technologies and initiate fleet replacement, which the other stakeholders' decisions build up to.

Executing the decisions in a scenario at the right time may be crucial to achieving the desired reduction in emissions. It could happen that a slight delay in realizing a scenario may result in a significant impact on how much emissions the scenario can enable, in addition to hurting other metrics stakeholders could be interested in optimizing.

In order to analyze this, a single scenario that focuses exclusively on the eventual fleet-wide operations of hydrogen-powered aircraft is considered. The decisions that are executed in this scenario are all pertinent to the end goal of realizing a hydrogen-dominant fleet composition; the composition of specific decisions in this scenario can be found in the Appendix.

Two cases of this hydrogen-focused scenario were considered—one where the scenario plays out in its original timeline, and the other where it is shifted 4 years ahead in time. A comparison is made between these two scenarios in terms of the time evolution of their relative CO_2 reductions and relative operating costs. These can be seen in Figs. 13 and 14.

It is evident that delaying a scenario leads to a lower reduction in relative CO_2 emissions. The delayed scenario proceeds in an identical fashion to the baseline case until its impacts start to show, which are themselves delayed as compared to the original scenario. This is a consequence of how the impacts of decisions are modeled in this work—there is a 'delay period' and a 'maturation period' associated with each decision. So, the actual effects of a decision only get activated some years after it is executed and mature over a period of time after the activation. For the two scenarios under consideration, this means that the effects of the delayed scenario show up at a later time than the original one, even though both are composed of the same decisions. Consequently, while the original scenario achieves a 31% reduction in relative emissions by 2050, the delayed one only manages up to an 18% reduction.

In order to corroborate this observation, the two scenarios are compared using another metric: the relative operating costs. Figure 14 shows a comparison of the time evolution of this metric.

Clearly, the delayed scenario results in higher relative operating costs compared to the original scenario. While both see a drop in relative operating costs over time, the decision impacts only become activated at a later stage for the delayed scenario as a result of its delayed start. So, the original scenario reaches 91% relative operating costs in 2050, while the delayed one ends up with marginally higher relative operating costs, at 93%.

Thus, it is crucial for a scenario to be realized at the right time. Any delays in decisions may result in a butterfly effect, thereby increasing the potential environmental impact of that scenario, and also increasing the economic burden of stakeholders.

While this notional study was performed using a few metrics such as CO_2 emissions and airline operating costs, it can be expanded to include deeper analysis and stakeholder-specific metrics in order to create a more accurate analysis encompassing all stakeholders in the aviation industry. Stakeholders could eventually use the environment developed for this study to conduct trade-off studies between reducing environmental impact and preserving their own economic interests.

VII. Conclusions

This work has established a method of simulating fleet-level impacts of emissions-reducing scenarios in the commercial aviation industry by modeling and quantifying the effects of decisions taken by various stakeholders in the industry. The ultimate goal is to aid decision-makers in gaining further insight into the crucial decisions that must be executed, and the timeline of those decisions, in order to realize and transition to the industry-wide goal of achieving net-zero emissions.

For the purposes of the study presented in this work, a novel methodology to generate scenarios, as developed by Almarzooqi et al. [20], was used. This methodology was then combined with a modified version of the fleet-level analysis approach originally discussed by Hassan et al. [23]. The original analysis approach, which only considered conventional aviation fuels, was built upon in order to account for and accurately model the implementation of alternative fuels, such as hydrogen and electric power, and aircraft powered by those fuels.

After a total of 20,000 scenarios were generated using the scenario generation methodology, these were analyzed for their fleet-level impacts. None of these scenarios achieved a 100% reduction in CO_2 emissions; however, the few scenarios that achieved higher than 60% reductions helped unravel the crucial decisions that factor into the highest possible emissions reductions within a scenario and their most impactful time of execution. Moreover, while some scenarios may perform similarly in terms of their emissions, it was necessary to analyze them using other metrics, such as airline operating costs and ticket prices, in order to form a more informed opinion. Another key observation gleaned from this analysis is the importance of timing in making decisions—delays at any point in time may result in missed emissions reduction targets or hurting other stakeholder interests, such as operating costs.

As such, the framework developed within this work acts as a proof-of-concept. It was performed using a notional list of decisions and associated impacts that were then sequenced into thousands of emissions-reducing scenarios. Researchers undertaking future work may consider collaborating directly with industry partners to refine and expand upon this list and adjust the impact values and time dynamics of these decisions for more accuracy. Additionally, the assumptions incorporated into the modeling approach can be modified to reflect the behavior of the commercial aviation industry more reliably. These can ensure a holistic modeling of future aviation scenarios and assist stakeholders in making informed decisions to realize the industry-wide goal of achieving net-zero emissions.

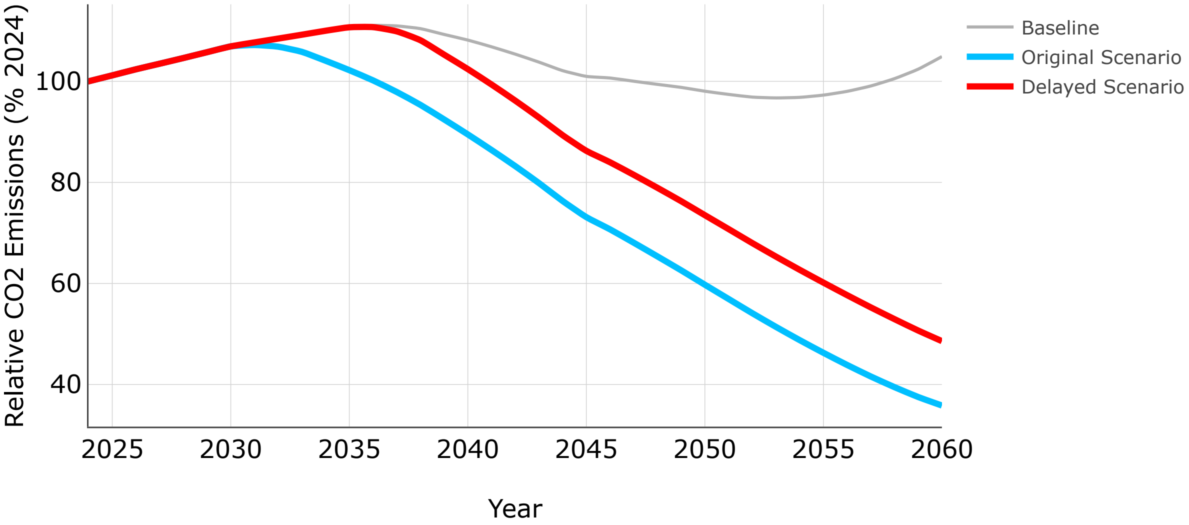


Fig. 13 Comparison of the time evolution of relative CO_2 emissions reductions for the baseline case, the original hydrogen-focused scenario, and the same scenario delayed by 4 years.

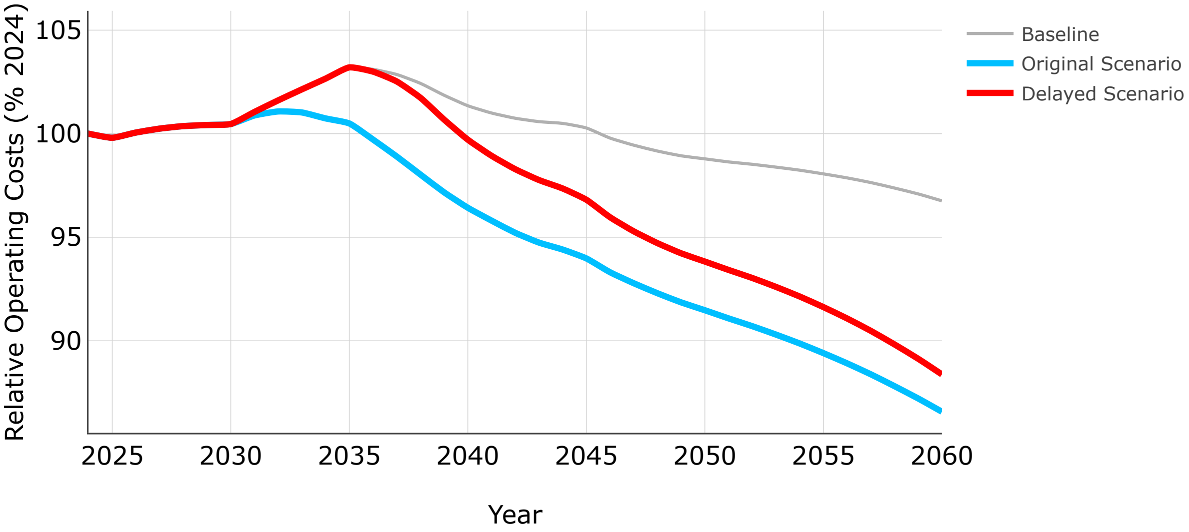


Fig. 14 Comparison of the time evolution of relative operating costs for the baseline case, the original scenario, and the delayed scenario.

VIII. Appendix

A. List of Decisions

For the purposes of this study, the team decided on a total of 37 decisions, spanning across 6 stakeholders. This list is discussed in more detail by Almarzooqi et al. [20].

Table 3 List of considered decisions for aviation industry stakeholders

Stakeholder	#	Decision
Policymaker	P1	R&D funding for electric a/c
	P2	Operations incentives for electric a/c
	P3	Electric infrastructure funding
	P4	Certification electrification on wide scale
	P5	Green hydrogen production incentives for hydrogen a/c
	P6	R&D funding for H_2 aircraft
	P7	Operations incentives for hydrogen a/c
	P8	Hydrogen infrastructure funding
	P9	Certification for hydrogen a/c on a wide scale
	P10	R&D funding for PtL production
	P11	Novel feedstock production incentives
	P12	Green hydrogen incentives specifically for SAF production
	P13	R&D funding for 100% drop-in SAF, new processes, and their approval
	P14	Certification for SAF fuel uptake on a wide scale
Energy Producer	E1	Increase electricity production
	E2	Increase green H_2 production specifically for a/c
	E3	Use PtL as method for SAF production
	E4	Use biofuel as method for SAF production
	E5	Increase biofuel production
	E6	Increase green H_2 production specifically for SAF
Tech. Developer	N1	Improve battery technology
	N2	Derisk technologies/improve readiness level
	N3	Improve gravimetric index of hydrogen tanks for regional a/c
	N4	Improve gravimetric index of hydrogen tanks for commercial
OEM	O1	Develop clean sheet SAF concepts (short haul)
	O2	Develop clean sheet SAF concepts (long haul)
	O3	Develop clean sheet H_2 concepts (short haul)
	O4	Develop clean sheet H_2 concepts (long haul)
	O5	Develop retrofitted hybrid electric concepts (short haul)
	O6	Develop retrofitted hybrid electric concepts (long haul)
	O7	Develop retrofitted SAF concepts (short haul)
	O8	Develop retrofitted SAF concepts (long haul)
Airport	AP1	Invest in electric infrastructure development
	AP2	Invest in hydrogen infrastructure development
Airline	AL1	Invest in electric/hybrid electric concepts
	AL2	Invest in SAF
	AL3	Invest in hydrogen concepts

B. Scenarios used for Comparison

As seen in Sec. VI, two scenarios, Scenarios 1 and 4, were picked for comparing results. The decisions considered within these scenarios and the year those decisions were executed are specified in Tables 4 and 5.

Table 4 Decision composition of Scenario 1

Year	#	Decision
2024	P10	R&D funding for PtL production
	N2	Derisk technologies/Improve readiness level
2025	P8	Hydrogen infrastructure funding
2026	P1	R&D funding for electric aircraft
	E3	Use PtL as method for SAF production
	O7	Develop retrofitted SAF concepts (short haul)
2027	P7	Operations incentives for hydrogen aircraft
	P9	Certification for hydrogen aircraft on a wide scale
	N1	Improve battery technology
	O8	Develop retrofitted SAF concepts (long haul)
2028	P6	R&D funding for H_2 aircraft
	P14	Certification for SAF fuel uptake on a wide scale
2029	P12	Green hydrogen incentives specifically for SAF production
2030	N3	Improve gravimetric index of hydrogen tanks for regional aircraft
2031	P3	Funding for electric infrastructure
	P13	R&D funding for 100% drop-in SAF, new processes, and approval
	E6	Increase green H_2 production specifically for production of SAF
2032	N4	Improve gravimetric index of hydrogen tanks for commercial aircraft
	O3	Develop clean sheet H_2 concepts (short haul)
2033	O1	Develop clean sheet SAF concepts (short haul)
	O2	Develop clean sheet SAF concepts (long haul)
	AP1	Invest in electric infrastructure development
2034	E1	Increase electricity production
	AP2	Invest in hydrogen infrastructure development
2036	O4	Develop clean sheet H_2 concepts (long haul)
2040	E2	Increase green H_2 production specifically for aircraft
	AL2	Invest in SAF
2042	P11	Novel feedstock production incentives
	AL3	Invest in hydrogen concepts
2043	P2	Operations incentives for electric aircraft

Table 5 Decision composition of Scenario 4

Year	#	Decision
2024	P6	R&D funding for H_2 production
	N2	Derisk technologies/Improve readiness level
	N2	Derisk technologies/Improve readiness level
2025	P4	Certification for electrification on a wide scale
	P9	Certification for hydrogen aircraft on a wide scale
	O7	Develop retrofitted SAF concepts (short haul)
2026	P8	Hydrogen infrastructure funding
	P10	R&D funding for PtL production
	N3	Improve gravimetric index of hydrogen tanks for regional aircraft
2027	P5	Green hydrogen production incentives for hydrogen aircraft
	E2	Increase green hydrogen production specifically for aircraft
2028	E3	Use PtL as method for SAF production
	N4	Improve gravimetric index of hydrogen tanks for commercial aircraft
2029	P7	Operations incentives for hydrogen aircraft
	P12	Green hydrogen incentives specifically for SAF production
2030	P2	Operations incentives for electric aircraft
	O3	Develop clean sheet H_2 concepts (short haul)
2032	P1	R&D funding for electric aircraft
	P14	Certification for SAF fuel uptake on a wide scale
	E6	Increase green H_2 production specifically for production of SAF
	O4	Develop clean sheet H_2 concepts (long haul)
2033	N1	Improve battery technology
	O2	Develop clean sheet SAF concepts (long haul)
2035	P11	Novel feedstock production incentives
2037	O6	Develop retrofitted hybrid electric concepts (long haul)
	AP2	Invest in hydrogen infrastructure development
2038	AL3	Invest in hydrogen concepts
2040	AL2	Invest in SAF
2043	E1	Increase electricity production
2048	O5	Develop retrofitted hybrid electric concepts (short haul)

C. Hydrogen-Focused Scenario

Also analyzed in Sec. VI is a scenario that emphasizes on enabling and increasing production of hydrogen and allowing hydrogen-powered aircraft to enter commercial airline fleets. The decisions that form this scenario are given in the Table 6.

Table 6 Decision composition of the hydrogen-focused scenario

Year	#	Decision
2025	P6	R&D funding for H_2 production
	N3	Improve gravimetric index of hydrogen tanks for regional aircraft
2026	N2	Derisk technologies/Improve readiness level
2028	O3	Develop clean sheet H_2 concepts (short haul)
	O4	Develop clean sheet H_2 concepts (long haul)
2030	P8	Hydrogen infrastructure funding
2033	P5	Green hydrogen production incentives for hydrogen aircraft
	AP2	Invest in hydrogen infrastructure development
2034	E2	Increase green hydrogen production specifically for aircraft
2035	P9	Certification for hydrogen aircraft on a wide scale
2037	AL3	Invest in hydrogen concepts

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