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Scenario Generation for Strategic Decision-Making towards Net-Zero Aviation

Ranya Almarzooqi [*], Haoyuan Chen[*], Burak Bagdatli [†], Holger Pfaender [‡] and Dimitri Mavris [§]
Aerospace Systems Design Laboratory, Georgia Institute of Technology
School of Aerospace Engineering, Atlanta, Georgia, 30332

Being a major contributor to both global economics and global greenhouse gas emissions, the aviation industry is experiencing a great transition to a greener future. Recognizing the transition needs the collaborative efforts of all relevant industries, transcending the aviation sector alone. This is compounded by the pressing time constraint aimed at reducing emissions by 2050. All pose significant challenges to successfully identify the consequences of certain actions and their contribution towards the 2050 emission goals. In the context of multilateral decisions and their corresponding timing, this paper introduces a simulation model that captures the interconnected decision-making process of various stakeholders. This model is essential for effectively realizing the transition to a more sustainable aviation industry. The tool offers an innovative approach to simulate the decision-making process of stakeholders involved in the aviation industry, addressing the value and timing of their decisions. By utilizing this tool, stakeholders can explore and analyze decisions, enabling them to navigate the aviation industry's transition to net-zero emissions.

I. Introduction

The aviation industry is crucial to the global economy, providing essential connectivity and contributing significantly to economic growth. In 2023 alone, the global airline industry conducted 34.4 million flights, generating approximately \$3.5 trillion in economic activity and supporting 11.3 million jobs [1, 2]. This economic output emphasizes the importance of aviation as a driver of global commerce and connectivity, making it essential to sustain the sector's economic vitality.

As of July 2023, the industry has nearly recovered to pre-pandemic activity levels, with global air traffic at 95.6% of pre-COVID levels and domestic Revenue Passenger Kilometers (RPK) reaching record highs [3]. Forecasts predict continued growth, expecting global air travel to reach 10 billion passengers and 22 trillion RPKs by 2050[4]. The anticipated increase in traffic, if met with current technology and efficiency standards, would require over 620 Mega tonnes (Mt) of traditional fossil fuel and produce around 2000 Mt of CO_2 emissions [4]. Therefore, achieving a reduction of greenhouse gas (GHG) emissions while accommodating aviation's growth demands significant transformations within the industry.

Aviation currently accounts for approximately 2.5% of global GHG emissions, which does not include all emissions from well-to-wake [5]. *Well-to-wake* refers to the entire life-cycle of fuel production and consumption; including emissions from raw material extraction and cultivation, processing refining, transportation and shipping, and finally, combustion in aircraft engines [6]. Within the transport sector, aviation is responsible for 13.9% of total emissions, of which 90% is attributed to petroleum-based fuels [7].

The projected growth in air traffic means aviation emissions will continue to rise unless effective mitigation measures are taken. The aviation industry will require a multifaceted strategy and significant transformations to the way it operates that balance achieving net-zero emissions while maintaining its economic growth.

A. Net-Zero Efforts in Aviation

The term *Net-zero aviation emissions* refers to achieving an overall balance between GHG emissions produced and emissions removed from the atmosphere [8]. The International Air Transport Association (IATA) has committed to achieving net-zero carbon emissions in aviation by 2050 through its Fly Net Zero initiative, which emphasizes the need

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[*] Graduate Research Associate, Aerospace Systems Design Laboratory, AIAA Student Member.
[†] Research Engineer II, Aerospace Systems Design Laboratory, AIAA Senior Member.
[‡] Senior Research Engineer, Branch Chief System-of-Systems, Aerospace Systems Design Laboratory, AIAA Senior Member.
[§] S.P. Langley Distinguished Regents Professor, Aerospace Systems Design Laboratory, School of Aerospace Engineering, AIAA Fellow.

for coordinated efforts within the aviation industry and substantial government support [9]. Achieving net-zero emissions will require significant investments and efforts in technology development, infrastructure adaptation, and regulatory frameworks. Furthermore, the transition to net-zero will require holistic approaches, combining advancements in aircraft and engine technology to enhance fuel efficiency, the adoption of alternative fuels and energy sources, and improvements in operational practices to cut emissions while preserving the industry's economic impact.

The Long-Term Aspirational Goals (LTAG) and Waypoint 2050 frameworks propose strategies aimed at achieving net-zero emissions in aviation by 2050 [4, 10]. While these frameworks offer *scenarios* or *pathways* for the transition toward net-zero, their practical application is hindered by a series of assumptions regarding real-world complexities and constraints. Realizing the scenarios highlighted in both reports would require concerted actions from aircraft manufacturers, technology developers, airports, airlines, fuel producers, and regulatory bodies.

For instance, the LTAG framework, developed by the International Civil Aviation Organization (ICAO), broadly assumes that all necessary policies are already in place, operational infrastructure is immediately available, and that airline operations can continue to expand without limit[10]. These assumptions overlook the staggered nature of policy implementation across different regions and the significant lead times required for infrastructure development. Furthermore, the expectation of unlimited airline operations does not take into account potential regulations that may restrict growth.

Similarly, Waypoint 2050, developed by the Air Transport Action Group (ATAG), assumes that essential policies, infrastructure, and technological developments are already aligned with the aspirational goals depicted by the developed scenarios [4]. Achieving the ambitious fleet compositions described in these scenarios would require rapid advancements and the widespread adoption of Sustainable Aviation Fuels (SAFs) and new propulsion technologies such as hydrogen combusting propulsion systems.

B. Key Players and Enablers in Achieving Net-Zero Aviation

The aviation industry is a true system of systems, consisting of a close-knit collection of entities ranging from airlines and energy producers to governmental agencies. These entities are responsible for making crucial decisions that shape the industry's future. Each decision may impact these entities differently and to varying degrees. Thus, a stakeholder, or key player, is defined as any party that is directly impacted by or who must act to achieve a net-zero aviation scenario.

1. Airlines

Airlines are vital to achieving a net-zero aviation reality, serving as the backbone of the aviation industry. An airline's functions include purchasing, operating, and maintaining aircraft, providing air travel services to customers, running flight operations, and reporting aircraft environmental impact to authorities. To expedite net-zero emissions, airlines have a crucial role in decision-making. They are responsible for determining which aircraft to purchase and operate from aircraft models offered by OEMs, facilitating the retirement and replacement of the current fleet, and running flight operations.

To achieve net-zero emissions, airlines must invest in and adopt innovative aircraft designs that reduce fuel burn [11]. Technological advancements such as more efficient engines, improved aerodynamics, and lightweight materials can significantly reduce fuel burn per passenger mile, contributing to a 15–20% reduction in emissions in the short term and up to 34% if aggressive technology acceleration and adoption (such as the introduction of hydrogen aircraft) are enforced [4, 12].

To realize 2050 goals, airlines and OEMs must work together to prioritize emissions reduction for the whole fleet, not individual aircraft [9, 13]. This means not only buying new advanced aircraft but also an accelerated replacement of legacy fleet resulting in additional stress on their industrial system and manufacturing rates. Additionally, airlines should adopt Sustainable Aviation Fuels (SAFs) and non-drop-in fuels such as hydrogen and electric power [11]. While SAFs can be used in existing fleets, infrastructure upgrades are necessary to accommodate hydrogen and electric propulsion. The purchased aircraft should facilitate the transition to net-zero through developing variants and families or replacing the current fleet. Aircraft should not cause unmanageable changes to current operations or aircraft maintenance. Ultimately, airlines must prioritize emission reduction while ensuring economic viability.

2. Airports

Airports provide the supporting infrastructure for airlines to operate and for passengers to access their services. They will also be significantly impacted by the decisions taken to realize net-zero emissions in the aviation sector and will make decisions to reach the end goal, such as investing in and developing new infrastructure to accommodate necessary changes, providing alternative energy sources to airlines, and facilitating flight operations.

Airports must invest in infrastructure to store, handle, and distribute SAFs, cryogenic or gaseous hydrogen, and electrical power. They will play a vital role in ramping up SAF usage by ensuring refueling facilities and systems are in place and implementing hydrogen infrastructure [14]. In addition, airports should implement sustainable taxi operations, ground vehicle electrification, and energy-efficient infrastructure upgrades [15]. These operational improvements can help airports meet sustainability goals while maintaining flight efficiency.

The decisions taken by airports must not cause unmanageable changes to airport operation procedures and infrastructure. This requirement will be a significant consideration moving forward, as investment decisions directly impact the developed concepts and vice versa [16, 17]. Airport decisions should also not significantly reduce flights to and from that airport for prolonged periods, referring to grounding aircraft for retrofitting novel technologies, which ties into airline decisions [18]. Ultimately, the decisions made by airports should reduce emissions without imposing excessive costs [19]. The transition from current operations to future operations must be carefully managed as substantial disruptions can cause long-lasting effects on air travel in general [20].

3. Government Research and Development Entities

Government research agencies such as NASA, referred to as technology developers within this paper, are the catalyst for progress in technological development in the aviation industry. Collaborating with universities and OEMs, they perform the preliminary research and using benchmarks before any cutting-edge technology makes its way to commercial aviation. These agencies' decision-making could be the flag-bearer of change [21, 22]. Their decisions involve sponsoring and supervising technological developments and facilitating research and development of these novel technologies. The technology developers are responsible for demonstrating the feasibility and profitability of these technologies. To achieve net-zero aviation emissions, technology developers can de-risk and demonstrate the feasibility of new technologies like blended-wing bodies, truss-braced wings, and hydrogen or electric propulsion [12]. Their research sponsorship and supervision accelerate technological development [23].

Furthermore, technology developers can work with policymakers to create standards and certifications for emerging technologies, ensuring consistent guidelines for OEMs and airlines [24]. One of the most noteworthy constraints on decisions made by technology developers is the necessity for de-risking and reducing the uncertainty of the demonstrated technologies. This effort is necessary for implementing these technologies on a wide scale as they need to meet safety standards and acquire certification. Ultimately, their decisions must result in significant technological progress to decrease aviation emissions [22, 25].

4. Original Equipment Manufacturers

OEMs in the commercial aviation industry are companies that design, manufacture, and sell aircraft, engines, and related aviation products. This includes aircraft manufacturing companies such as Boeing and Airbus and engine manufacturing companies such as General Electric, Rolls-Royce, and Pratt & Whitney. The decisions that OEMs make pertaining to net-zero are broadly defined as determining which concepts to manufacture and implement, scoping the market demand for the product and setting the purchasing price, and the ultimate decision of reiterating past designs or manufacturing totally new concepts [26].

To achieve net-zero emissions, OEMs must lead in developing revolutionary designs like hydrogen or electric propulsion systems, blended-wing bodies, and ultra-high bypass engines [12]. They must also prioritize lightweight composite materials and aerodynamically optimized designs, with the overall goal of reducing the fuel consumption of the fleet [4, 12]. OEMs should ensure their aircraft designs are compatible with various alternative energy sources such as SAFs, hydrogen, and liquefied natural gas.

The overarching objective of the decisions made by OEMs is that they must increase efficiency and subsequently reduce fuel burn and emissions without producing a cost too large to bear by themselves. The decisions made by OEMs must result in a net profit or gain for the OEMs [11, 26]. An overlooked, but equally pertinent, objective is the requirement for the decisions made to follow a sustainable manufacturing process given that the primary goal is to reduce aviation emissions [27].

5. Energy Producers

Energy producers and fuel companies hold the responsibility of producing sustainable alternative energy carriers, including SAFs, hydrogen, and electric power. They hold the financial and infrastructural burden of ramping up production of these fuels to drive down the cost of their uptake by airports.

To meet the growing demands of the aviation industry, energy producers must make decisions on scaling up SAF production, hydrogen infrastructure, and renewable electric power. For instance, SAFs, which can reduce lifecycle emissions by up to 80%, are relatively advanced due to mature fuel conversion technologies and certifications [28]. However, current SAF production in the U.S. accounts for only 0.1% of the total fuel used by major airlines, reflecting significant limitations in feedstock availability and production capacity [29]. Expanding SAF production requires energy producers to invest in sourcing from sustainable energy sources such as sustainable feedstocks and advanced technologies like Power-to-Liquid (PtL), which combines green hydrogen and CO_2 [12, 30].

Thus, energy producers' decisions pertain to the energy production scale to meet the demand for the entire fleet, methods of this production, and the implementation of the infrastructure required for production and transportation. Due to the criticality of these decisions, their constraints are more stringent. The decisions made by energy producers must first and foremost prioritize production from a sustainable source. The aircraft must also be capable of running the energy produced. Finally, the decisions made must prove some profit incentive for energy producers to encourage them to prioritize the reduction of well-to-wake emissions.

6. Policymakers and Government Entities

Policymakers play a crucial role in shaping the strategies and regulations necessary to transition the aviation sector toward more sustainable practices. Entities such as the Federal Aviation Authority (FAA), ICAO, and IATA fall under this category. Policymakers can drive change through comprehensive regulations, certifications, and subsidies. The 2021 U.S. Aviation Climate Action Plan [13], for example, exemplifies the significant commitment required by policymakers to reach net-zero emissions. Government entities, on the other hand, have the highest financial burden amongst all the stakeholders, as they have to provide funds to many of the other stakeholders to adopt sustainable solutions.

Decisions by policymakers and government entities could help guide the industry towards a net-zero emissions reality, including offering tax breaks and government subsidies for the uptake and production of alternative energies, developing net-zero guidelines and roadmaps, and setting criteria and mandates for new energy carriers through certifications and regulations. Policymakers and government entities must facilitate investments by offering incentives, subsidies, and tax breaks to airlines, airports, energy producers, technology developers, and OEMs [12]. Broadly, the decisions made by policymakers and financiers must result in an economic benefit as well as a benefit to public safety within the scope of aviation. Ultimately, their decisions should provide a pathway—and facilitate the transition—to net zero.

C. Decision-Making Scenario Generation

The decision-making process within the aviation industry resembles a complex network of interconnected pathways. Each decision by a stakeholder influences subsequent choices by others, forming a web of cause and effect that guides the industry's trajectory toward achieving net-zero emissions. The potential trajectories the industry can take before 2050 as well as the impacts of the decisions, creates uncertainties whether the industry will reach the 2050 goals. The trajectories can be visualized through a tree diagram, where each decision point represents a fork in the road, leading the industry down various potential paths. A conceptual visualization is provided in Fig. 1 showing the many-worlds-like representation of aviation's state in 2050.

The interconnected nature of decisions in the aviation industry means that each choice not only has direct consequences, but also shapes the decision-making landscape for other stakeholders. The choice of fuel production strategies by energy producers, for example, can dictate the design priorities of OEMs. If energy producers allocate significant resources toward SAFs, OEMs might prioritize compatibility with SAFs in their new designs. Similarly, the development of new aircraft technologies by OEMs is heavily influenced by the operational needs and environmental targets of airlines. Commitments by airlines to reduce their carbon footprint provide a market for OEMs to fill by developing more efficient and less polluting aircraft. While the decisions by key players in the industry unlocks advancements for others, they simultaneously could restrict the pursuit of other decisions. For example, if policymakers and financiers do not encourage or provide incentives for the development of hydrogen infrastructure at airports, airlines would be unable to purchase and operate hydrogen aircraft within their fleet.

Navigating this complex decision landscape to identify and pursue pathways within the many-worlds model that lead to feasible and sustainable states of net-zero emissions is the primary objective. Each decision pathway is generated and

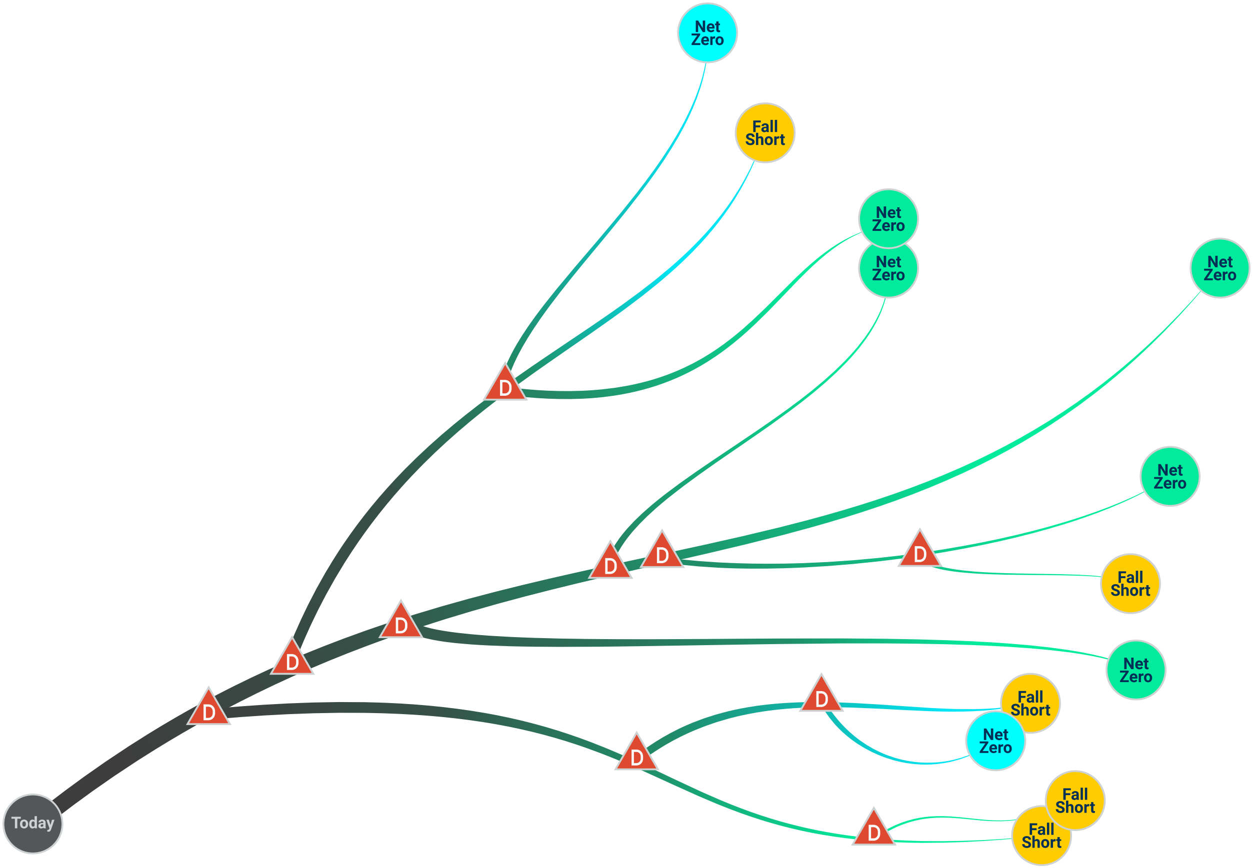


Fig. 1 Conceptual graphic for the many alternative future worlds possible for the aviation industry based on stakeholder decisions and their impacts

assessed based on impact metrics such as return on investment for airlines and OEMs, operational costs for airports, and the broader environmental impact.

Thus, the overarching goal of this paper is to develop a method that outlines numerous detailed pathways toward achieving net-zero emissions in the aviation industry. This goal includes specifying the necessary decisions and collaborative efforts by key industry players, along with the timeline of such actions.

II. Methodology

The developed scenario-generation framework is designed to forecast the future of the aviation industry from 2024 to 2050 by employing a comprehensive approach, which methodically integrates the complex lattice of decisions made by the key players within aviation. The process in which this framework is developed is informed by the multi-lateral interests of the industry's stakeholders. This approach is outlined in four phases detailed in Sec.s II.A– II.D.

A. Define the Decisions

This framework draws directly from the strategies outlined in the IATA Net-Zero Roadmaps to define the enabling decisions for achieving a net-zero aviation reality [12]. The IATA Net Zero roadmaps outline several enabling solutions for addressing life-cycle emissions from well-to-wake. The enablers include (1) the development and deployment of novel aircraft technologies, (2) the use and expansion of sustainable fuels and energy carriers, (3) improvements in the operational efficiency of the fleet, (4) support through globally aligned policies, and (5) adequate regulatory and investment backing for transitioning to net-zero operations. Furthermore, the IATA Net-Zero Roadmaps emphasize significant milestones the industry needs to meet to successfully transition to this net-zero reality. For instance, the aircraft technology IATA roadmap highlights a relevant milestone in which a decision point around the 2023–2030 period must occur on whether the clean-sheet hydrogen aircraft sized and defined for the future of sustainable aviation is a regional or narrow-body aircraft. This is a critical action or decision the industry must make as it attempts to transition to net-zero.

The decision definition process starts by pinpointing critical actions necessary to realize the strategies. For each category listed in IATA's Net Zero roadmaps—ranging from technology implementation to policy formulation—decisions are identified and mapped to the relevant stakeholders based on their capabilities and responsibilities within the industry. The mapping ensures that each stakeholder is engaged with actions that are both impactful and within their scope of influence regarding the transition to clean aviation.

For instance, the decisions involving SAF are distributed among all six key players mentioned in Sec. I.B and summarized in Table 3. Energy producers are tasked with decisions that increase the production of biofuels and expand hydrogen production for SAF, which are crucial for ensuring that the supply of alternative fuels meets the growing demand for aviation fuel. Airlines, on the other hand, face decisions that influence the demand for SAF through fleet operations of concepts that utilize SAF. Meanwhile, OEMs and technology developers are responsible for technological decisions aimed at developing aircraft concepts optimized for fuel use reduction and improving SAF production and blending processes, which affects the speed at which these new technologies can be implemented and their efficiency.

Electrification of the aviation fleet requires enabling decisions from stakeholders such as policymakers, energy producers, and technology developers as given in Table 3. For example, policymakers bear the burden of enabling electrification of the fleet through research and development (R&D) funding, operational incentives, and infrastructure developments to boost the efficiency and adoption rates of electric aircraft. Energy producers need to ensure that the infrastructure and production capabilities for electricity are scaled to meet the demand for electrifying the fleet, and technology developers and OEMs are tasked with advancing battery technology and electric propulsion systems to ensure that the developed electric aircraft concepts are operationally efficient.

Hydrogen as an energy carrier for aviation requires many decisions ranging from increasing hydrogen production and infrastructure development at airports to technological advancements in hydrogen storage and hydrogen aircraft design. For instance, the production and supply of hydrogen must be expanded by energy producers and supported by policymakers to encourage airport and production infrastructure investment. Simultaneously, OEMs and technology developers must research and develop aircraft technologies to use hydrogen efficiently, and then airports and airlines must develop the necessary infrastructure and facilitate hydrogen fueling operations respectively. Along with the other decisions, hydrogen-related decisions are listed in Table 3.

A detailed list of the relevant decisions for enabling this transition was collected via literature review. The decisions are categorized by the stakeholder responsible for realizing them; policymaker decisions are denoted by the prefix **P**, energy producer decisions are denoted by the prefix **E**, technology developer decisions are denoted by the prefix **N**, OEMs decisions are denoted by the prefix **O**, airline decisions are denoted by the prefix **AL**, and airport decisions are denoted by the prefix **AP**.

The complete decision list is given in Table 3 in the Appendix. It is important to note that due to the ever-changing nature of aviation, each decision must be revisited and refined periodically to reflect shifts in industry dynamics. Furthermore, while there are a total of 37 decisions in this study's decision list, there are numerous other decisions that were not accounted for, such as the decision by policymakers to implement tax exemptions and carbon tax, that could be added in a future study to help increase relevancy and accuracy of the generated scenarios.

B. Determine the Impacts

Once the decisions have been defined and fleshed out, the next step of the process is to ascertain whether they influence certain impact parameters of interest and by how much. These parameters have been chosen according to their pertinence to the aviation industry and their utility within the analysis tool utilized in this study.

For instance, *Relative fuel price* will provide insight into alternative fuels' competitiveness compared to conventional jet fuel. *Operational Improvements* and *Efficiency Improvements* are vital for determining the enhancements each decision can pose regarding aircraft performance and cost-effectiveness. Availability metrics such as *H_2, SAF, and Electric Power Available* assess the readiness of infrastructure to support widespread adoption. Additionally, the shares of electric, SAF, and hydrogen operations (*electric operations share*, *SAF operations share*, *H_2 operations share*) indicate the extent of integration into the aviation fleet. Price-related parameters (*H_2 price*, *SAF price*, *Electricity price*) alongside demand indicators (*SAF Demand*, *H_2 Demand*, *Electricity Demand*) reflect market dynamics. Lastly, technological assessments such as *Battery Specific Energy Density* and *Gravimetric Index* are essential for evaluating the progress in battery technology and hydrogen storage. The comprehensive impact matrix that illustrates how each decision was mapped to these impact parameters is visualized in Fig. 11in the Appendix.

The decisions surrounding electric, SAF, and hydrogen operations in aviation can be effectively categorized into three key impact domains: Demand, Supply, and Technologies. Each category plays a pivotal role in steering the trajectory of aircraft integration of these novel fuels and energy carriers into the global aviation fleet. Electric decisions are utilized as a proof of concept to illustrate how the decisions are mapped to the impacts with percentage ranges of how much the decisions increase or decrease the impact parameters.

Within the category of electricity demand, decisions by policymakers for R&D funding, operations incentives, and electric infrastructure funding for electric aircraft arise. *P1*, “funding for R&D for electric aircraft”, directly impacts efficiency improvements and battery technology. Current propulsive efficiency stands at 77%, while electric motors achieve an impressive 90%, promising a substantial improvement in overall performance [31, 32]. Simultaneously, advancements in battery technology result in a predicted increase to 250–300 W h/kg by 2035 [33]. Thus, this decision is predicted to result in a 15–20% improvement in efficiency. In contrast, *P2*, “funding for operations of electric aircraft”, results in direct impacts on operational improvements, reduced operating cost, and increased electric operations share. With the assumption of a global fleet operating on batteries, the energy cost is estimated at $1.9 billion, leading to a potential 10–20% reduction in operating costs [34]. Similarly, based on incentives, the adoption rate is expected to increase, resulting in a proportional rise in electric operations share, potentially ranging between 10–20%. Finally, *P3*, “the decision to fund electric infrastructure at airports”, directly impacts operational efficiency improvements, reduced operating costs, and increased electric operations share. Improved infrastructure is expected to decrease turnaround time by 15–25%, positively impacting operational costs. Furthermore, inverse proportionality with operation costs suggests a 15–25% increase in electric operations share.

Electric power supply decisions, exemplified by *P4* and *E1*, which are decisions for “certification of wide-scale electrification” and “increase in electricity production”, hold sway over the aviation industry’s ability to alter their fleet composition. *P4*, “certification for electrification of aircraft”, directly impacts the entry into service. This results in a slight decrease in entry into service (EIS) due to fast-tracking the certification of the aircraft. *E1*, the decision to “increase electricity production for electrification of the fleet”, directly impacts changes in electricity availability and price. Electricity availability is directly proportional to the increase in production, estimated at 50–100%, impacting the overall electrification of the fleet. In terms of electricity price, market competition may lead to slightly low prices, thus we assign a conservative estimate of −5% to +5% impact.

In the electric technology domain, decisions such as *N1* and *N2* drive decisions to improve battery technology and de-risk technologies respectively. Such decisions have direct implications on efficiency improvements, resulting in a 10–20% improvement in overall efficiency and a slight decrease in EIS by approximately 5–15% for *N2*. The “development of retrofitted hybrid electric concepts” for both short and long-haul flights, *O5* and *O6*, directly impacts efficiency, entry into service, and replacement rates due to the increased efficiency of electric motors. A less significant change is depicted in long-haul electric concepts compared to short-haul due to the substantial difficulties with battery charge life that still need to be overcome.

Furthermore, investment decisions in “electric infrastructure by airports” (*AP1*) and “operations of electric or hybrid concepts by airlines” (*AL1*) depict the significance of changes within the system of systems. *AP1* directly influences replacement rate and electric operations share due to improvements in efficiency, turnaround time, and electrical energy supply, increasing to 10–25% in replacement rate and 15–30% in electric operations share. *AL1* directly influences replacement rate, electricity demand, and electric operations share as it allows for a gradual phase-out of older aircraft and anticipates the transition rate from traditional jet fuel to electric power.

These impacts vary yearly within this range due to technological evolution, market dynamics such as fluctuating fuel prices and regulations, and operational variability due to resource availability and implementation strategies [35–37]. Before a decision is fully adopted, its potential impact fluctuates similarly to the predicted performance of a technology during the R&D phase. During the R&D phase, impacts vary yearly in a stochastic manner due to various external factors such as funding availability, market conditions, and regulatory changes [38, 39]. To illustrate this variability, consider historical fluctuations in R&D performance. For example, an investigation of the growth rate of China’s R&D investment, technological innovation, and economic growth development levels between 1996 to 2016 shows the fluctuating nature of such investments [40].

Thus, to mimic how the impacts of a decision fluctuate from year to year before the decision is made, this study uses a uniform distribution to randomly select impact values within a specified range for each year, assuming equal likelihood of all values within this range. It is important to note that this method could be further developed for more accuracy to how real-world decision impacts fluctuate.

C. Define Relationships between Decisions

With the decisions and their respective impacts determined, the groundwork to model the decision-making process for key aviation stakeholders is established. However, the dynamic relationships between decisions and the evaluation of a decisions value must still be addressed. Some decisions exhibit hierarchical dependencies, while others are inherently incompatible. To capture these dynamics, a compatibility matrix has been created for all decisions. The matrix is given in full with all 37 decisions considered in Fig. 12.

In the analysis process, incompatible decisions are only allowed if no prior incompatible decisions have been made. Additionally, the order of decisions can influence compatibility. Some decisions may be incompatible in one sequence but compatible in another, meaning the matrix is asymmetric. Furthermore, time-based compatibility must also be considered, as certain decisions can only occur after a specified time interval has passed since the last decision was made.

To systematically capture the relationships described above, all the relationships between the decisions are categorized into three general types. The first type involves fiscally or physically incompatible decisions. These decisions are mutually exclusive due to conflicting objectives, resource constraints, or technological limitations. For example, decisions by energy producers for which method of SAF production to pursue (*E3*, *E4*) cannot be pursued simultaneously due to the significant investment required for either method [29, 30]. This relationship directly impacts the execution of decisions.

The second type of relationship is hierarchical. In these cases, one decision requires a prerequisite decision to be made first before it can be pursued. This poses no restriction on the execution of the following decision itself but imposes timing constraints. The decisions between OEMs and airlines usually have this kind of relationship. Airlines can only operate an aircraft that OEMs have chosen to develop first. Typically, a year or more may separate such prerequisite and dependent decisions.

The last type of relationship describes decisions that are simply compatible with each other. These decisions neither interfere with each other nor impose restrictions on timing or execution. Most decisions belong to this kind of relationship. For example, energy producers investing in SAF production and technology developers adopting more fuel-efficient aircraft technologies may occur independently and concurrently, as both contribute to reducing emissions without interfering with each other's implementation.

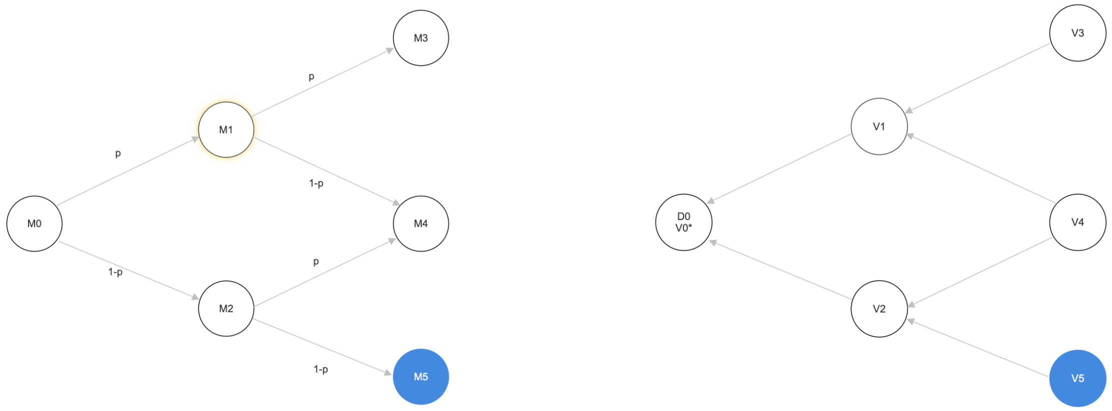
D. Make Decisions

Even with a well-mapped relationship between decisions, real-world decision-making faces significant challenges, particularly when balancing varying stakeholder priorities and navigating uncertainties in future predictions. The Binomial Lattice Option Pricing Model is adapted to address these complexities as a decision-making framework. Originally developed for financial options pricing, this approach systematically evaluates options under uncertainty by constructing a binomial lattice [41, 42]. Each node on the lattice represents a potential future state, characterized by its value and probability, derived from the decision's impact on stakeholder interests and market conditions.

At each step in the lattice, two possible outcomes are considered: an upward or downward movement in market conditions [43]. The model evaluates the potential impacts of decisions over time by performing a forward pass through the lattice. A backward pass then recalculates the value of each decision by optimizing from the most beneficial outcomes at the end of the lattice back to the present. This iterative process, depicted in Fig. 2a, allows for more dynamic decision-making, enabling stakeholders to adapt to evolving market conditions and systematically address uncertainty. As illustrated in Fig.s 2a and 2b, the decision's value is determined through a discretized finite time horizon, comprising a forward pass and a backward pass. In the forward pass, the potential value of pursuing the decision is represented by M# at each node. Each node has a predefined probability p that represents the possibility of environmental change based on the decisions. At the end of the time horizon, the final decision value is evaluated. In Fig. 2a, M5 is the highest decision value among the final nodes. The final decision value is calculated by its best-performing state (V5) depicted in Fig. 2b. The value is then propagated backward to the decision at the starting nodes. This final value, denoted as $V0^*$, serves as the basis for further evaluation to determine its worthiness of execution. This results in a systematic framework for evaluating the feasibility of making specific decisions within a defined timeline.

Stakeholder priorities play a pivotal role in this process, as the metrics of interest differ depending on their objectives. For example, airlines prioritize projected revenues and their expenses, airports prioritize operational revenue and infrastructure costs, and policymakers prioritize metrics such as the social cost of carbon. Table 1 outlines the specific metrics associated with aviation's stakeholders utilized in this study.

The impact of decisions is quantified using the Technology Identification, Evaluation, and Selection (TIES) method,



(a) Forward pass to evaluate the potential impact of decision **(b) Backward pass to calculate the value of the decision**

Fig. 2 Binomial Lattice Option Pricing Model

which introduces k-factors to capture the sensitivity of a stakeholder metric to a particular decision [44]. For instance, an airport investing in hydrogen infrastructure might see an 8% increase in hydrogen operations, with a k-factor of 0.3 for revenue, reflecting a slightly positive impact, and a k-factor of 0.5, indicating a moderate cost increase [45]. These k-factors, or impacts, help map the decisions' effects into quantifiable changes in stakeholder metrics, enabling a structured evaluation of trade-offs. Figure 3 illustrates a schematic of mapping decision impacts to stakeholder metrics.

As mentioned in Sec. II.B, the impacts of a decision can be modeled similarly to the effect of a novel technology. The S-curve model in Fig. 4 illustrated the performance improvement of technology over time and at what point the transition from older to newer technologies occurs. Initially, performance improvements are slow, followed by a period of rapid advancement, and eventually plateauing as the technology matures. This model effectively captures the lifecycle of technological adoption where an older technology is gradually replaced by a newer one as it becomes more efficient and cost-effective.

Once a decision is made, there is a delay before the impacts of that decision become evident, followed by a period of rapid advancement, and eventually plateauing as the impacts of the decision matures. Once we obtain the value of the decisions, the next challenge that needs to be addressed is whether the decisions is being made or not. In reality, this behavior is solely dependent on the stakeholder's choice. For the purpose of this study, the stakeholder's decision-making behavior is simplified to using the decision value calculated from the binomial lattice method, as previously mentioned, passing a threshold. This simplification assumes all stakeholders are purely rational and have comprehensive knowledge when making decisions. Each decision's value is assessed against specific interest thresholds defined as a percentage of the potential projected revenue or benefit of pursuing that decision. As different stakeholders have different interests, different stakeholders' decisions will be evaluated against different threshold values. These thresholds are critical as they determine the viability of pursuing a decision based on whether it meets the minimum expected benefit for the stakeholder. Only decisions that surpass these thresholds and are compatible with previous

Table 1 Stakeholder Interests

Stakeholder	Interest
Airline	Projected Revenue & Projected Expenses (M$)
Airport	Projected Revenue & Projected Expenses (M$)
Energy Producers	Projected Revenue & Projected Expenses (M$)
OEMs	Projected Revenue (M$), Projected Value, and Risk Factor
Technology Developer	Projected Benefits & Costs (M$)
Policymaker	Social Cost of Carbon ($)

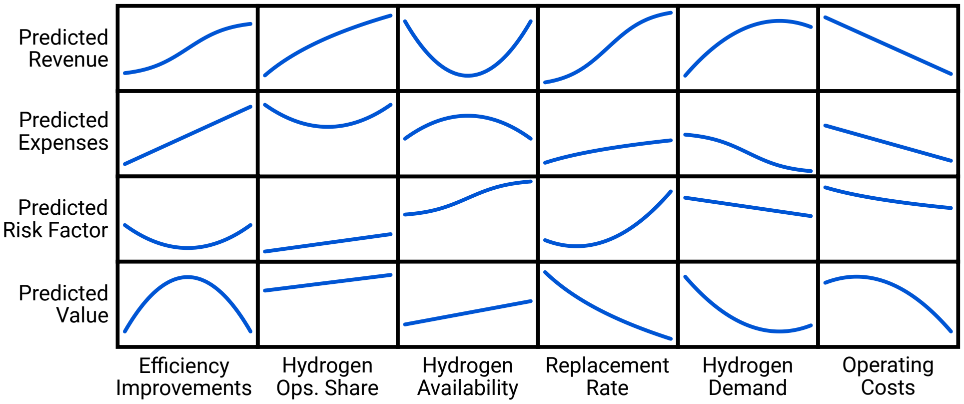


Fig. 3 Conceptual Illustration of Impact Mapping to Stakeholder Metrics of Interest

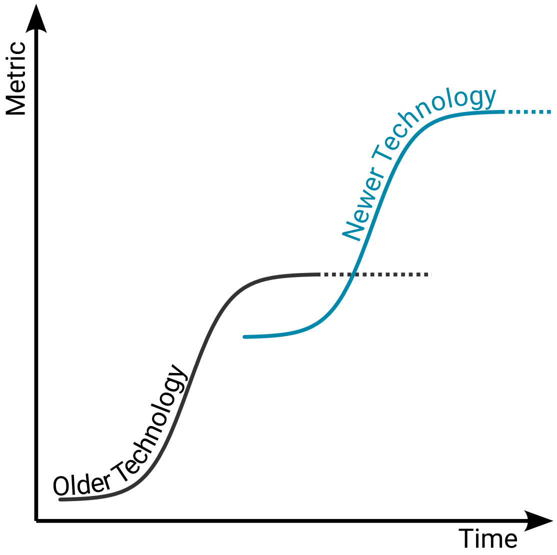


Fig. 4 Idealized S-Curve for Technological Evolution [46]

decisions are considered actionable and included in the scenario. The iterative evaluation of each decision continues annually until the end of the simulation period (chosen to be 2050 for this study). This allows stakeholders to adjust their strategies in response to new information or changing conditions, such that if a decision may not be viable to pursue one year due to its option value, it might be feasible the next year. However, the approach does not allow for stakeholders to pull out or abort pursuing a decision; once a decision has been made, it cannot be reversed or overridden and its effects will remain indefinitely.

As decisions are made within the simulation, the impacts of each decision are aggregated into a cumulative impact matrix, which monitors the state of each impact metric over time. The cumulative impact evolution is calculated through a summation of all the individual impacts. This step is important not only because it will allow for the subsequent fleet-level assessment of each scenario within a modeling and simulation environment, but also because it can illustrate the temporal evolution of different impact parameters. Therefore, the ending output of the scenario generation process will be a time series that presents the compounded effects of all the decisions when they are made, and how they grow over time. Figure 5 is a simple way of visualizing the delayed impacts of the decisions within a scenario. The white lines represent the time delay of the decision's impact, while the green lines indicate the region of growth of the decision's impact as it reaches maturity.

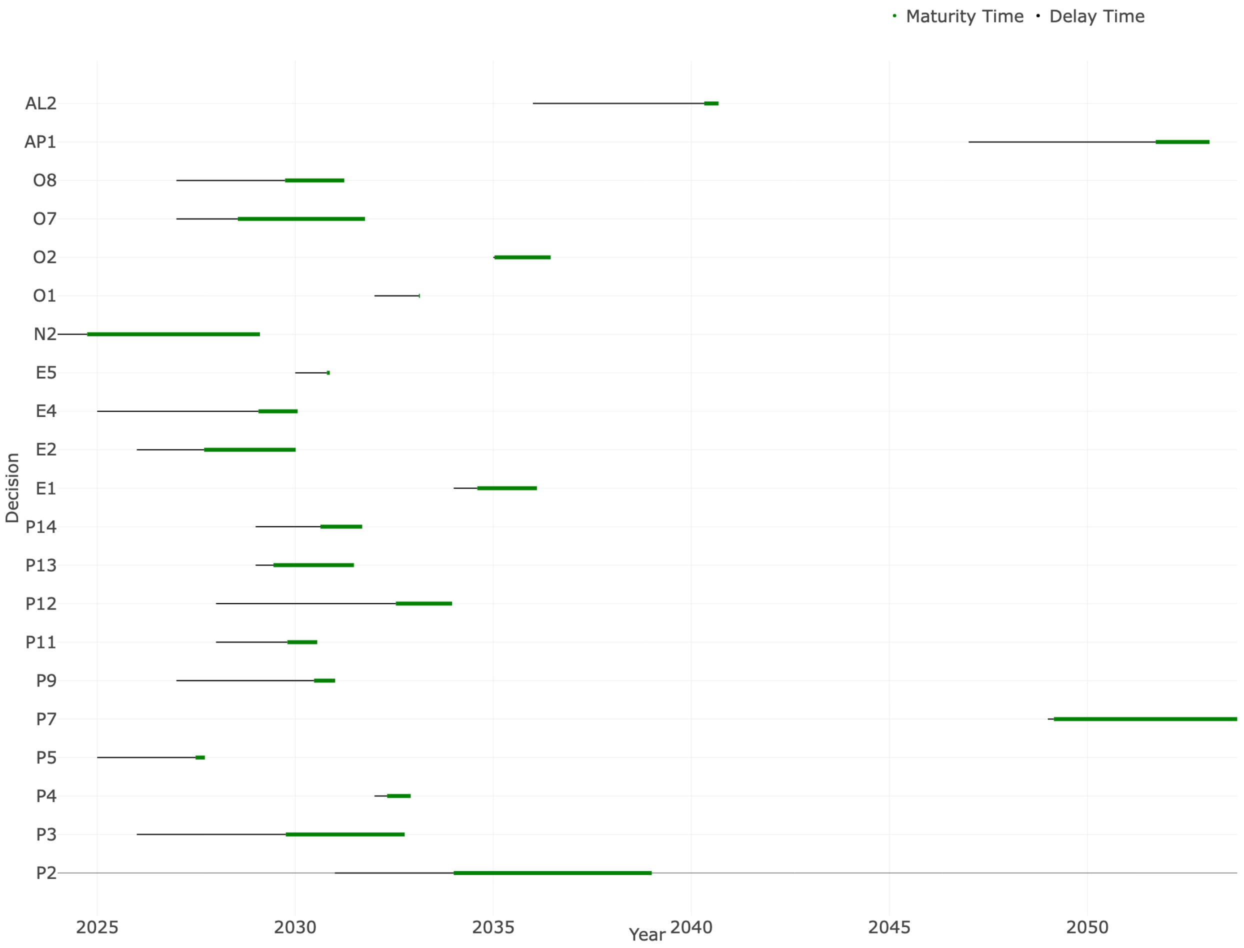


Fig. 5 Delay and maturity time of all decisions within a given generated scenario

III. Modeling

To implement the methodology discussed in Sec. II, a comprehensive model was developed to demonstrate its feasibility. The model integrates the core concepts outlined in Sec. II.A to Sec. II.D and follows the logical sequence described. The process flow is illustrated in Fig. 6, which provides an overview of the general architecture for scenario generation.

This section explains the mechanics of the model, detailing how it creates scenarios from combinations of decisions. It incorporates deterministic impact modeling, compatibility checks, and real options valuation to assess whether stakeholder decisions are pursued within a given scenario.

The model begins by generating a deterministic impact matrix from the impact matrix depicted in Fig. 11, which essentially acts as the foundation of the scenario generation process. This matrix maps the impact parameters to the 37 relevant decisions using impact percentage ranges described in Sec. II.B. The resulting matrix mirrors the structure of the impact matrix, with each entry representing a specific deterministic impact value. These values are then used to evaluate whether the decisions are pursued or not for that year.

However, before evaluating the value of pursuing the decision, its compatibility with previously executed decisions within the scenario must be assessed. As described in Sec. II.C, a decision compatibility matrix categorizes the relationships between decisions into three major types: compatibility, incompatibility, and hierarchy. The full decision compatibility matrix is included in Fig.s 12 in the Appendix. For each pair of decisions (A, B), where A is a decision in the row index and B is a decision in the column index in the compatibility matrix, the value describes that when evaluating B, the condition if A is already executed.

For each decision, the compatibility matrix is referenced to determine if the decision is viable for that scenario. For hierarchical relationships, the matrix guides the directional dependencies between decisions. For example, airlines

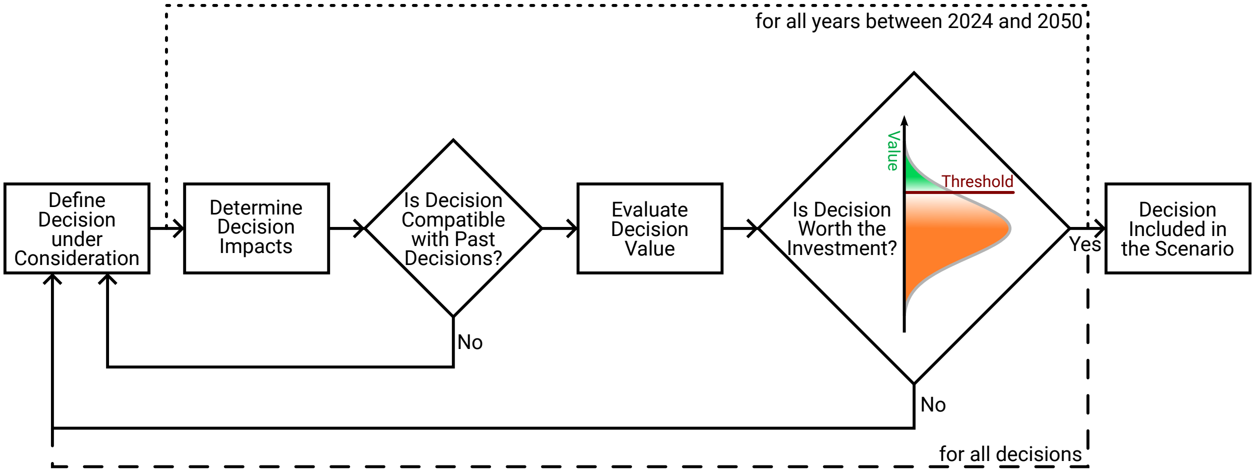


Fig. 6 General Architecture of Scenario Generation Process

can only operate SAF aircraft after OEMs have developed such vehicles not vice versa. In the compatibility matrix, compatible relationships are coded as 0, incompatible relationships as −1, and hierarchical relationships as nonzero values representing how many years since the previous decision that the current decision can be made. For example, the compatibility matrix entry for decision pair (*E3*, *E4*)—representing energy producer decisions for different SAF production methods—is −1. This implies that if *E3* has been executed, *E4* cannot be pursued simultaneously due to resource constraints.

The compatibility matrix also accounts for asymmetry. For hierarchical relationships, the entry for one direction represents the time interval (e.g., 10 years), while the opposite is marked −1, indicating it is not viable in that direction. For example, in the decision pair (*O4*, *AL3*), the matrix specifies a 10 year interval after *O4* before *AL3* can be executed, whereas the reverse (*AL3*, *O4*) is invalid.

Once compatibility is confirmed, the deterministic impact matrix is used to compute the evolution of the decision's impact over time. As discussed in Sec. II.D, a sigmoid function models this evolution, assuming consistent delay and maturation time ranges for simplicity. Ideally, subject matter experts would provide unique delay and maturation time ranges for each decision-impact combination to better reflect real-world dynamics. These refinements to the model could be achieved through stakeholder discussions or tabletop exercises (see Sec. V).

The evolution of the impact value follows Eq. 1, where D is the deterministic impact value, k is the tuning coefficient governing how rapidly the impact value reaches its full potential, and $t_{1/2}$ is the time to reach 50% impact. It is important to realize that several assumptions have been made to model the impact value evolution. Firstly, the time to reach 50% impact is calculated by taking half of the maturation time that is assigned to each decision. Secondly, the constant k is the same value for all decisions and a delay time (t_D) may be needed for the investment to start showing benefit. These assumptions have inherent limitations to the degree that they can mimic real-life dynamics.

$$I(t) = \begin{cases} 0, & t \in [0, t_D] \\ \dfrac{D}{1 + \exp\left[-k\left(t - t_{1/2}\right)\right]}, & t \in [t_D, \infty) \end{cases} \tag{1}$$

Following impact modeling, the binomial lattice option pricing model is then applied to assess whether executing a decision aligns with stakeholder interests. This real options approach utilizes the time evaluation of impact to determine if the decision is in the stakeholders' interest to execute in that year [42]. Each decision evaluated using this real options model incorporates fixed assumptions for simplicity and computational efficiency. For instance, the risk-free rate—the return on investment with zero risk—is assumed to be 11% for the aviation industry. This value is used to discount the future payoffs of the option back to their present value. Furthermore, the volatility—the degree of variation of an asset's prices over time—was determined for each stakeholder by studying fluctuations in daily stock prices from the industry. For example, the volatility for OEMs was set to be 18% after studying fluctuations in stock returns for Airbus.

The real options method used constructs a decision tree to evaluate the evolution of potential outcomes at discrete time intervals. Each node in this lattice represents a possible future state of the decision, calculated using predetermined

Algorithm 1 Scenario generation algorithm

```
procedure SCENARIO GENERATION(Impact matrix,decision list)
    Initialize DecisionList, decisionValues, cumulativeImpact, executionYear
    for year ∈ time horizon do
        ImpactValue ← Volatility from Impact Matrix
        for decision ∈ decisions list do
            if decision is compatible with decisionsList then
                decisionImpact ← $Equations 1$
                decisionValue ← calculated based on correspond stakeholder
                if decisionValue ≥ threshold then
                    cumulativeImpact ← cumulativeImpact + decisionImpact
                    executionYear ← $year$
                    Add year into executionYear
                    Add decisions into decisionList
    return decisionList, cumulativeImpact, executionYear
```

up and down factors derived from the volatility specific to each stakeholder's scenario. In this framework, the asset price at each node S_t can move to either $S_t \times u$ or $S_t \times d$, where u and d are factors calculated as Eqs. 2 and 3 with σ representing the volatility and δt the time step.

$$u = \exp\left(\sigma\sqrt{\Delta t}\right) \tag{2}$$

$$d = \frac{1}{u} \tag{3}$$

The likelihood of each upward or downward movement is determined by the risk-neutral probability p, given in Eq. 4, where r is the risk-free rate. This probability plays a pivotal role in the valuation process, guiding the weighted average of the up and down movements in the model.

$$p = \frac{\exp(r\Delta t) - d}{u - d} \tag{4}$$

Starting from the terminal nodes of the lattice, which correspond to the maturity of the option, the payoff is calculated. For a call option, the payoff at each node is $\max(S - K, 0)$ where K is the strike price. These terminal payoffs are then discounted back to the present value using the risk-free rate, taking into account the calculated probabilities. The value of the option at each node is derived recursively from the end of the lattice to the beginning, as given in Eq. 5.

$$f(t) = \exp(-r\Delta t)\left[(p)\ f(t + \Delta t, \text{up}) + (1 - p)\ f(t + \Delta t, \text{down})\right] \tag{5}$$

The recursive process combines future values and probabilities, bringing them back to the present to support informed decision-making under uncertainty. By integrating this model, the decision-making process accounts for both timing and the likelihood of different outcomes.

As the value of each decision is quantified, the value is sent through a threshold to check if that decision is in the stakeholders' interest and if it is viable to be executed. Because each stakeholder has a unique variable of interest, the threshold is also in their respect variable of interest. For example, for OEM-related decisions, the value of interest is the potential revenue increase that the decisions can generate. Ideally, these thresholds will be determined by each stakeholder to show their actual behavior. However, in this modeling process, the threshold is manually tuned to reflect the general frequency of the decisions in a scenario. The decision is then recorded if the value passes the threshold.

The process repeats annually within the user-defined time horizon, generating a cumulative impact matrix and a list of decisions with their execution timelines. As the time horizon only limits when decisions are pursued, impacts may evolve beyond this period due to maturation and delay times. A pseudo-code for the algorithm is presented in Algorithm 1.

As stakeholders make decisions, these decisions directly shape the aviation industry, altering fleet composition, driving up or down operating costs, adjusting ticket prices, and shifting air traffic patterns. All of this, of course, impacts

CO_2 emissions. To understand how effective these decisions are at reducing emissions, it is necessary to perform a comprehensive fleet-level analysis to map out how the industry evolves under each scenario. The detailed list of decisions, decisions' execution time in each scenario, and decisions' cumulative impact is passed along into a fleet-level simulation model. This kind of analysis is critical for determining the best path forward. An innovative process is developed within the fleet-level simulation model to accommodate emerging new technologies and decisions that will shape the future of aviation. More details of the fleet-level modeling and analysis are highlighted in the parallel paper *Scenario Modeling and Analysis for Strategic Decision-Making towards Net-Zero Aviation* [47].

IV. Results and Discussion

To model the many potential pathways. or decision combinations, from 2024 to 2050, the described algorithm was executed 20,000 times, generating 20,000 unique scenarios to capture and analyze the stochastic effects inherent in the decision-making process. These scenarios then underwent a fleet-level analysis to quantify the effects of pursuing that scenario on relevant fleet-level metrics such as relative CO_2 emissions, operating costs, and ticket prices. These scenarios and their analyses provide valuable insights into the various pathways and critical decisions required to achieve net-zero aviation.

The frequency of each decision within the 20,000 scenario run, as shown in Fig. 7, offers insights into which decisions are most likely to be prioritized as the industry transitions. Some of the most frequently occurring decisions include the decision by policymakers for hydrogen aircraft operations (*P7*), which occurred in about 72% of the 20,000 scenarios, and the decision by OEMs to develop retrofitted SAF concepts for short-haul (*O7*), which occurred in about 79% of the scenarios.

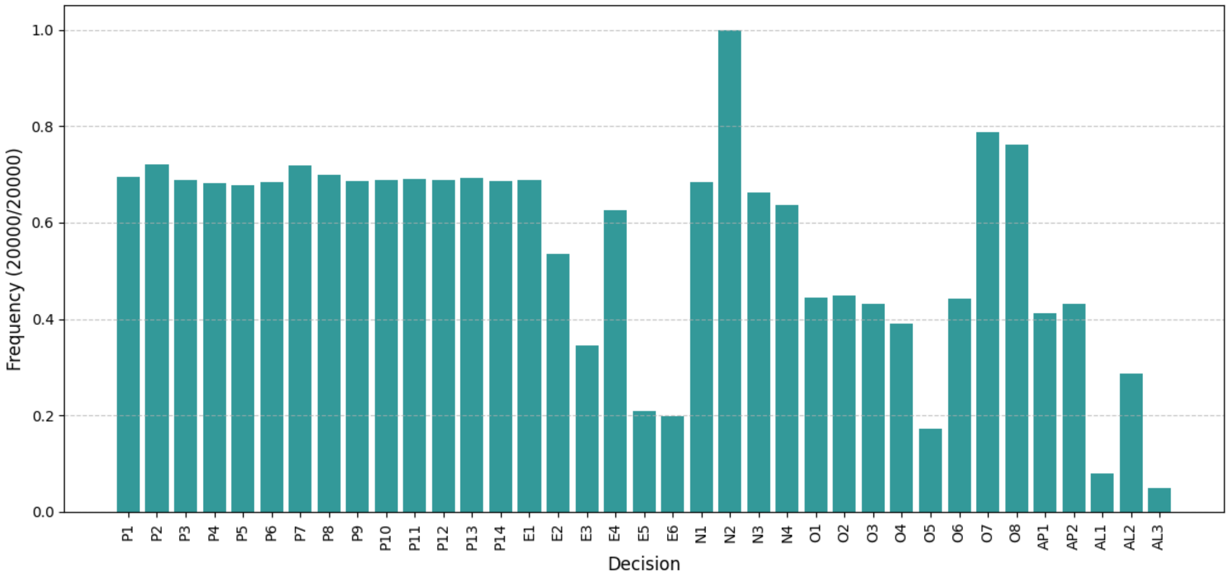


Fig. 7 Frequency of decisions present in 20,000 scenarios, Decision descriptions are included in Table 3

A stakeholder-specific analysis, depicted in Table 2, reveals the varied roles and priorities of industry players. Policymakers frequently opted for investments in hydrogen aircraft operations, energy producers most commonly prioritized scaling up electricity production, airports opted to invest in hydrogen infrastructure and airlines focused on operating SAF concepts.

The results also emphasize the foundational role of policymakers in setting the stage for the industry's transition. Investments in hydrogen aircraft operations (*P7*) are critical for establishing hydrogen as a viable long-term alternative, particularly due to the significant changes required to production capacity and infrastructure. Without these policies, downstream adoption of hydrogen technologies by airports and airlines would remain limited. Similarly, OEMs opting most frequently to develop retrofitted SAF concepts (*O7*) reflects the practicality of SAF as an immediate solution by utilizing existing infrastructure while the industry works toward more transformative technologies like hydrogen and electric propulsion.

Table 2 Most Common Decisions by Stakeholder in 20,000 Generated Scenarios

Stakeholder	Most Common Decision	Frequency
Policymaker	Investments for operations of hydrogen aircraft	72%
Energy Producers	Increase electricity production	69%
Airlines	Operate SAF concepts	29%
Airports	Invest in hydrogen infrastructure development	43%
OEMs	Develop retrofitted SAF aircraft concepts (short haul)	79%
NASA	Derisk technologies/improve readiness level	100%

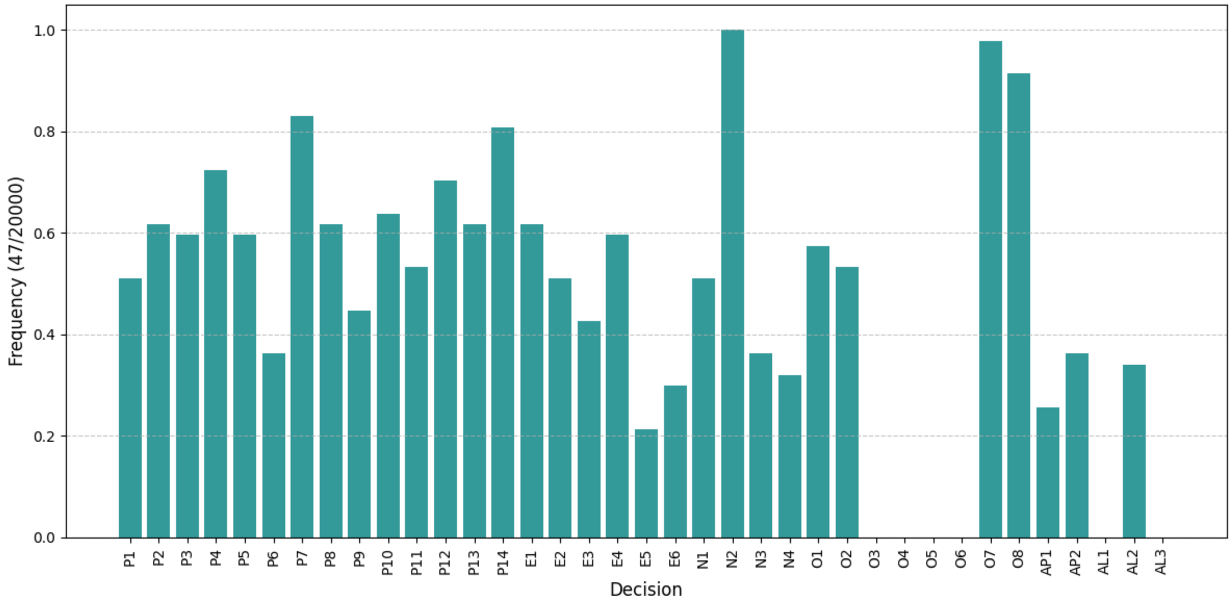
Energy producers' focus on scaling up electricity production shows the necessity of clean electricity production in achieving net-zero. While electric propulsion remains largely limited to short-haul and regional applications, scaling electricity production lays the groundwork for future advances in hybrid-electric systems. This also reflects the broader goal of diversifying energy sources and reducing reliance on one aviation fuel. Airports' investments in hydrogen infrastructure (*AP2*) occurred less frequently which indicates the high costs and logistical challenges associated with hydrogen storage, distribution, and fueling systems. Airlines, however, were most likely to operate SAF concepts (*AL2*), which highlights their reliance on the progress made by policymakers, energy producers, and airports. This distribution of priorities reflects the likely trajectory each stakeholder might pursue as they transition to net-zero and highlights the importance of coordinated efforts as progress in one area depends on actions taken across the entire aviation sector.

The framework developed to generate and analyze thousands of pathways toward net-zero demonstrates significant potential for determining what decisions need to be pursued and when to achieve the scenarios developed by the key initiatives mentioned in Sec. I.A. By taking ICAO's LTAG Integrated Scenario 1 (IS1) as a proof of concept, the simulation environment can filter the thousands of generated pathways to only depict the pathways that align with the characteristics of this scenario. Specifically, IS1 was filtered by two critical categories: (1) the CO_2 emissions reduction achieved by 2050 compared to the business-as-usual scenario and (2) the actions pursued in terms of technologies, operations, and fuels categorized under LTAG's classification.

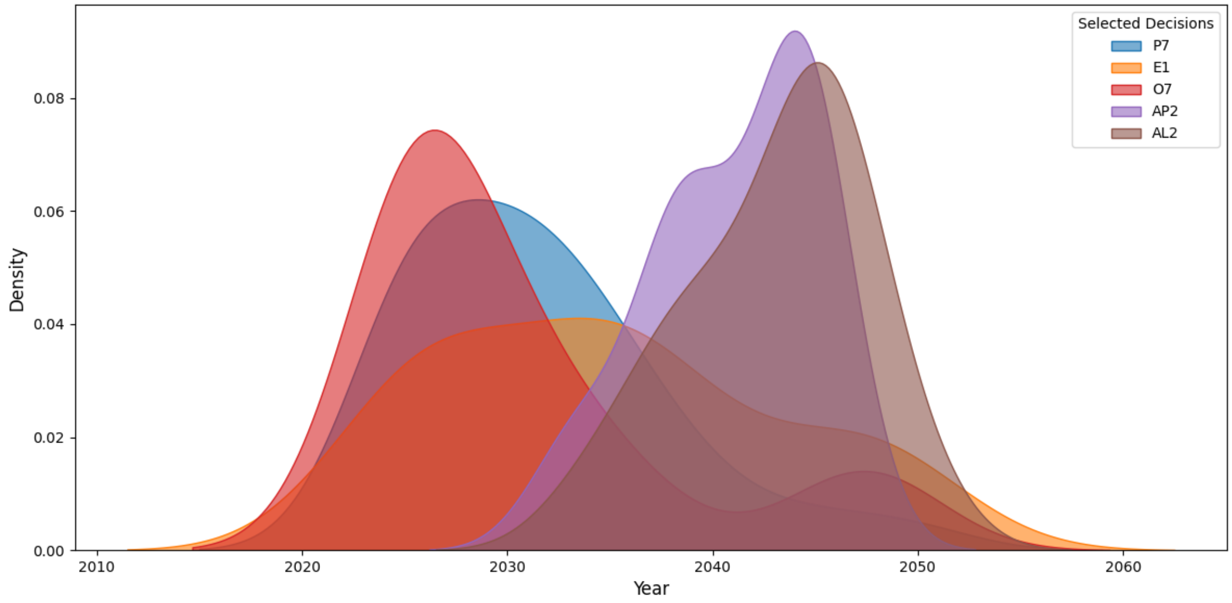
IS1 is classified to represent the current (c. 2021) expectation of future available technologies, operational efficiencies, and fuel availability if no significant infrastructure changes were assumed [48]. This means that only advanced tube & wing aircraft compatible with drop-in fuel are developed and operated. Thus, any decisions for developing advanced concept aircraft (such as electric aircraft) or aircraft compatible with non drop-in fuels (such as hydrogen aircraft) were filtered out. Furthermore, this scenario achieves a 39% reduction in CO_2 emissions by 2050 compared to the baseline, thus, the environment filtered out all scenarios that exceed this goal or fall short [49].

Figure 8a illustrates the frequency of the decisions that were retained after filtering for LTAG IS1 characteristics. Out of 20,000 scenarios, 47 scenarios meet the LTAG IS1 characteristics. The decisions within these remaining scenarios align with IS1's focus on drop-in fuels and advanced tune-and-wing aircraft, excluding electric and hydrogen aircraft development and operation. Among the most frequent decisions, OEM's decision to develop retrofitted SAF aircraft (*O7*) and airline's decision to operate SAF-compatible aircraft (*AL2*) dominate, with these decisions made in 96% and 37% of scenarios respectively. On the other hand, policymaker decisions for investments into hydrogen operations (*P7*) and the energy producer decision for scaling up electricity production remain prominent, with these decisions made in 84% and 63% of scenarios respectively. This implies forward-looking strategies even in scenarios primarily focused on SAF and emphasize their foundational role in achieving long-term emission reduction.

Fig. 8b provides a density plot of the timeline for major decisions for each stakeholder in the scenarios that meet LTAG's IS1 characteristics. The OEM decision for retrofitted SAF aircraft development (*O7*) peaks between 2025 and 2030, indicating that retrofitting tube & wing aircraft for SAF compatibility is prioritized early in the transition. This aligns with the scenario's emphasis on leveraging existing aircraft designs and drop-in fuels as immediate solutions. The policymaker decision to invest in hydrogen operations peaks slightly after, between the 2025 to 2035 range. This distribution suggests that there is consistent early action to ensure long-term readiness for hydrogen technologies despite them not being operated in IS1. Scaling up clean electricity production (*E1*) spans across the timeline from 2025 to 2050, reflecting its importance and sustained role in decreasing emissions. Decisions related to retrofitted SAF aircraft development (*O7*) and operations (*AL2*) peak later, between 2035 to 2045, reflecting the longer lead times and capital requirements necessary for infrastructure development and the gradual adoption curve of these operations due to its



(a) Filtered frequency of decisions that is satisfied with IS1 scenario requirements



(b) Decision Timeline Distribution for Scenarios that meet IS1 Characteristics

Fig. 8 Decisions that are satisfied with LTAG IS1 scenario

dependency on earlier actions by policymakers and energy producers. These distributions highlight the interconnected nature of decisions, where early investments by policymakers and energy producers lay the groundwork for subsequent operational transitions by airlines and airports.

Figure 9a plots the emissions trajectories for all 47 scenarios that meet LTAG's IS1 criteria and compares them to the business-as-usual trajectory. Each IS1 Scenario achieves the required 39% reduction in CO_2 emissions by 2050 relative to the baseline. The variation in trajectories emphasizes that differences in timing and sequencing of decisions may result in reaching the same end state, however, it will drastically vary in its trajectory throughout the time horizon. This reflects the flexibility in decision-making strategies that stakeholders can pursue to achieve the emissions reduction targets characterized by IS1.

To further evaluate the timing and sequencing of decisions for one singular scenario and analyze the CO_2 emission reduction resulting from that, the isolated emissions trajectory for the optimal scenario mimicking IS1 was plotted and depicted in Fig. 9b. Compared to the broader set of 47 scenarios, the optimal scenario achieves a smoother and more linear decline in emissions. The initial rise in emissions before 2035 reflects the aviation sector's growing demand outpacing early emission reduction efforts. Furthermore, the decision timeline for this scenario, depicted in Fig. 10, further illustrates the interconnected and sequential nature of the decisions made by all stakeholders. Key actions by policymakers are made earlier in the time horizon, emphasizing the significance of early implementation of these policies. Key actions like investment in SAF certification (*P14*), hydrogen infrastructure development (*AP2*), and pursuing the biofuel method for SAF production (*E5*) display not only their maturity timelines but also the delays required for their impacts to materialize. The longer delay periods for infrastructure-related decisions emphasize the complexity and scale of these initiatives and how they essentially hinge on early and sustained support from policymakers and energy producers. Decisions by airlines and OEMs occur late in the timeline, reflecting their dependence on earlier technological developments and infrastructure readiness. Furthermore, decisions for developing retrofitted SAF concepts show relatively shorter maturity times, which suggests that they are closer to technological and operational readiness.

The overarching observations of this analysis signify that early decisions have a disproportionate influence over the success of later stages, which means stakeholders must prioritize high-impact but low-risk actions even amid uncertainty. Furthermore, the concentration of impactful changes in the 2035 to 2045 window highlights narra ow window for success, where delayed or poorly executed actions could inhibit the aviation industry from reducing emissions.

V. Conclusions

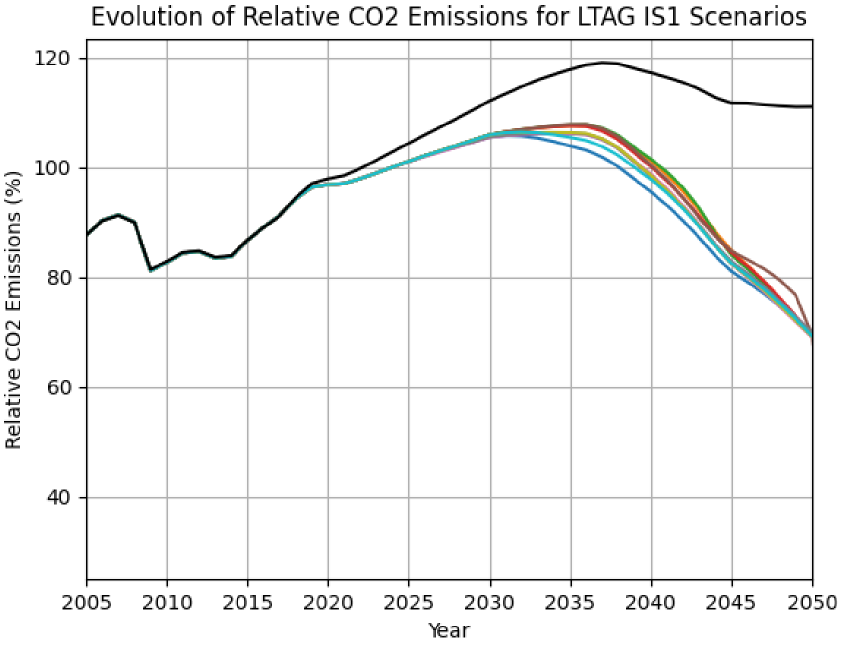
This study aimed to address the problem that there is a lack of a comprehensive, robust framework capable of identifying and evaluating all potential pathways that lead to a net-zero aviation future by 2050. The core challenge lies in mapping these pathways while accounting for the complexity of stakeholder interactions and their decision-making processes. To tackle this, this study focuses on developing a scenario-generation framework that captures the complex, interconnected decision-making processes of airlines, OEMs, airports, energy producers, policymakers, and technology developers.

Due to the impracticality of interviewing a large number of representatives from all industry and government stakeholders, a simulated approach was created to generate realistic future scenarios. The method is capable of identifying six critical industry stakeholders and their primary interests to predict a large set of probable outcomes based on information available in the open literature.

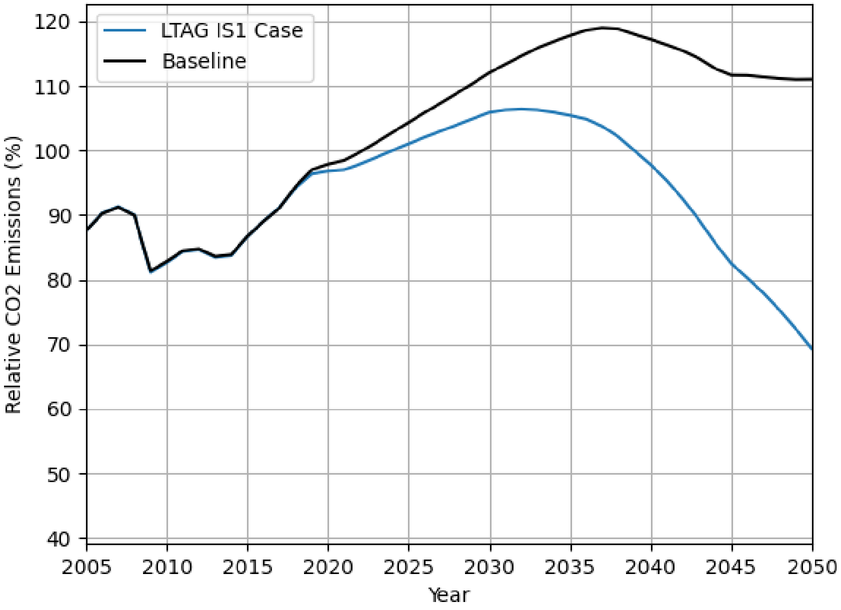
The simulation logic uses real options to predict the value of each decision, which is assessed every year of the simulation. By executing this simulation, 20,000 scenarios, each representing unique sequences of decisions were generated and analyzed. These scenarios provide critical insights into the timing, prioritization, and interdependencies of decisions required to achieve net-zero. By executing the simulation, the team generated 20,000 unique scenarios that can be analyzed based on their merits in terms of emissions reduction and cost.

Key findings of this study emphasize the necessity of early, high-impact actions by policymakers and energy producers to lay the groundwork for subsequent technological and operational transitions. The results also underscore the pivotal role of collaboration across stakeholders to address constraints and align goals to ensure the feasibility of these pathways. While the modeled scenarios highlight flexibility in achieving emissions reduction targets, they also reveal narrow windows for critical actions, signifying the importance of timely and coordinated efforts.

Most importantly, this work offers a valuable tool for strategic decision-making, enabling stakeholders to navigate uncertainties and optimize their actions moving forward as they attempt to achieve net-zero by 2050. Looking ahead, this work can be further refined by incorporating a more comprehensive, realistic set of decisions. More accurate projections and improved methods, specifically for calculating decision value can be integrated into the tool to further



(a) CO_2 evolution for all IS1 scenarios compared to baseline



(b) CO_2 evolution for best-performing IS1 Scenario compared to baseline

Fig. 9 CO_2 trajectory with LTAG IS1 scenario

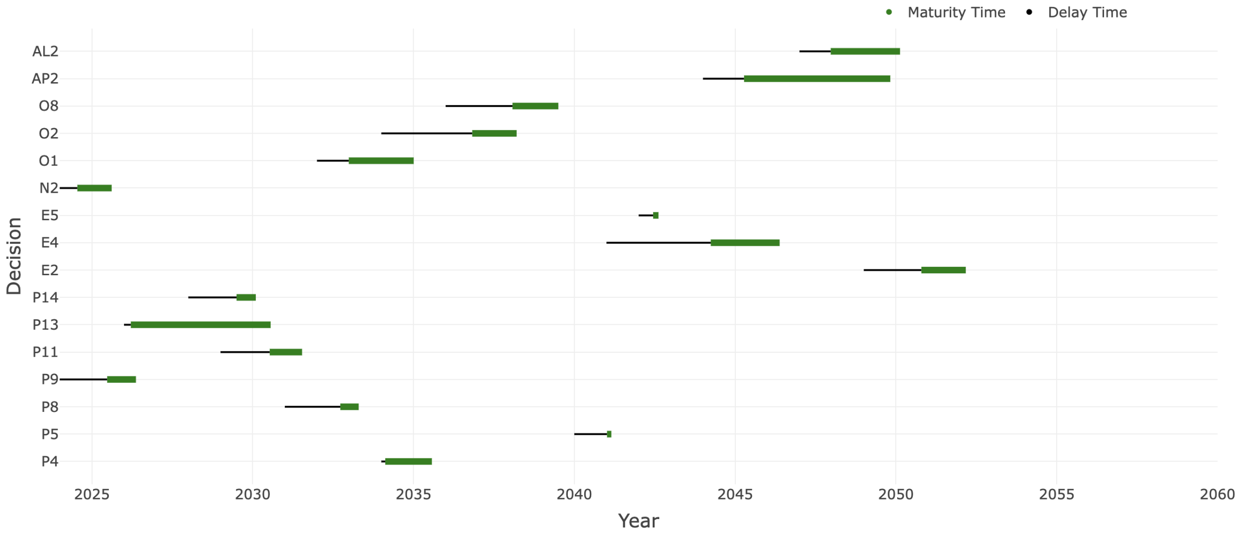


Fig. 10 Decision Timeline Distribution for Scenarios that meet IS1 Characteristics

improve it. By relaxing some of the current assumptions—such as static maturation times for impacts, fixed decision thresholds, or a more dynamic decisions compatibility matrix—the framework could deliver even more actionable insights. For example, integrating real-world data on infrastructure readiness and stakeholder-specific constraints could make the scenarios even closer to reality.

Additionally, the team is actively seeking input from the industry and government stakeholders regarding assumptions, dependencies, or additional decisions and technologies that can be used to expand the study. If there is interest from each stakeholder, one proposed step is to conduct *tabletop* exercises, where stakeholders can simulate their decision-making in real time and collaborate to test the feasibility of various pathways. These exercises would provide significantly valuable feedback and data as well as potentially identify opportunities and bottlenecks that may not be apparent at this time.

Thus, this framework is more than just a theoretical exercise—it is a practical tool for navigating the aviation industry's transition to net-zero. By offering a way to explore, analyze, and prioritize decisions, it provides stakeholders with the necessary insights needed to take meaningful action promptly.

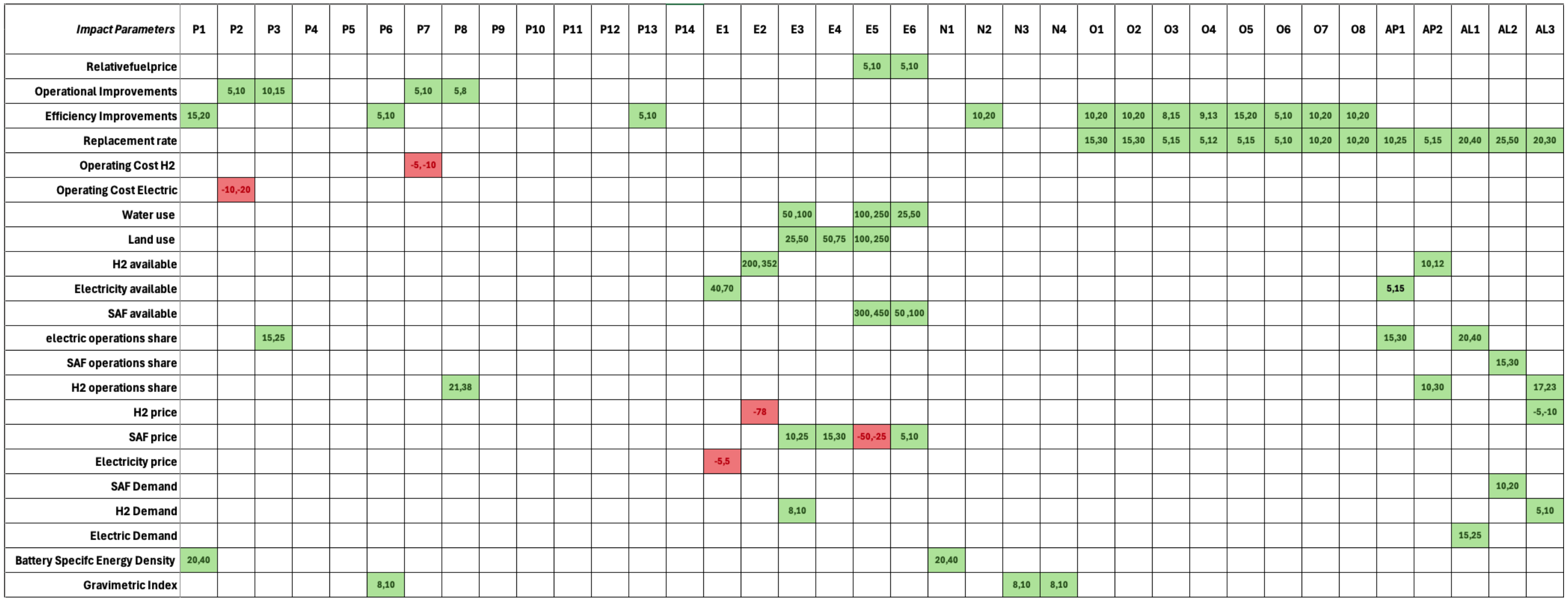
VI. Appendix

A. Decision List

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

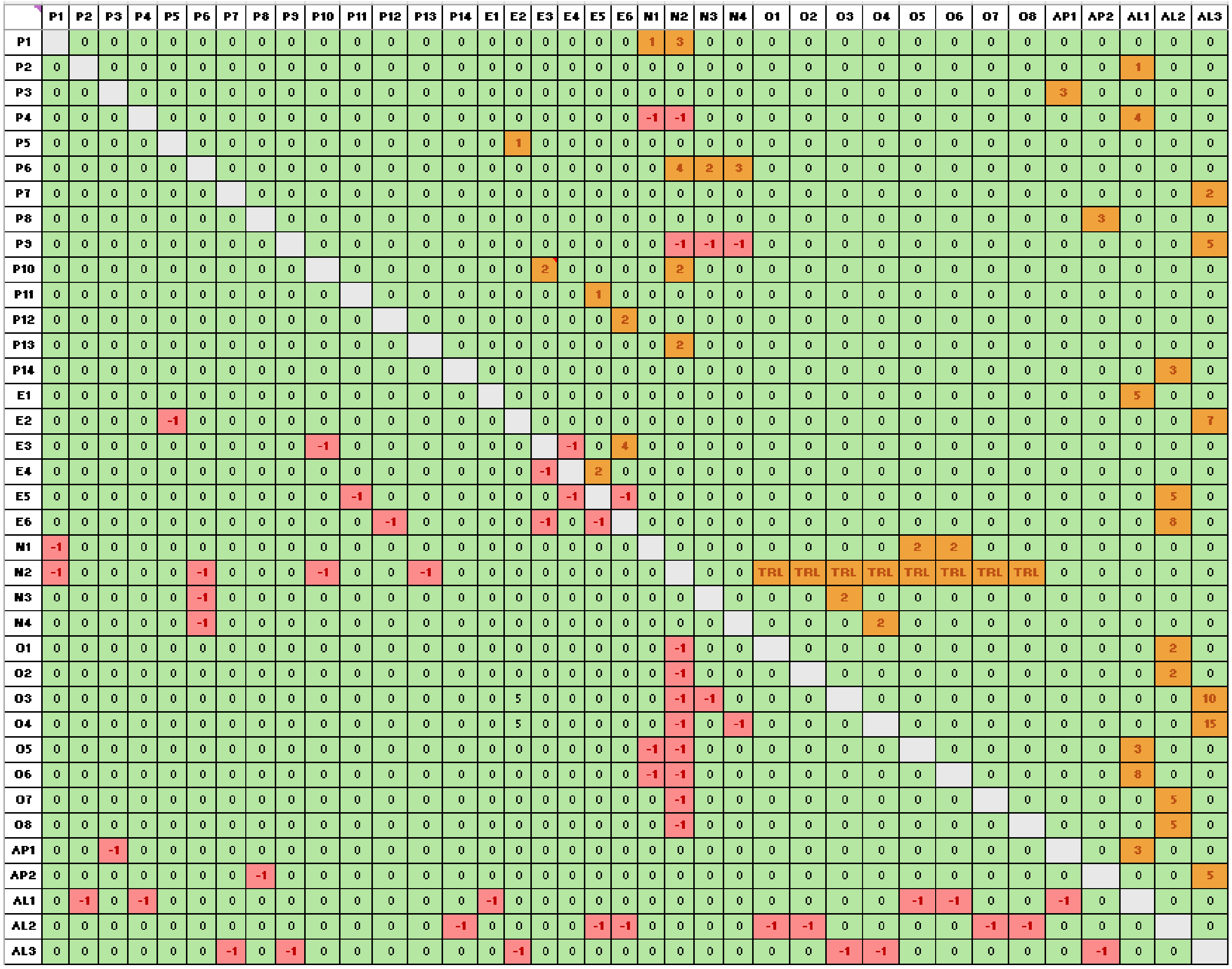
B. Impact Matrix



Impact Parameters	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	E1	E2	E3	E4	E5	E6	N1	N2	N3	N4	O1	O2	O3	O4	O5	O6	O7	O8	AP1	AP2	AL1	AL2	AL3
Relativefuelprice																			5,10	5,10																	
Operational Improvements		5,10	10,15				5,10	5,8																													
Efficiency Improvements	15,20					5,10							5,10									10,20			10,20	10,20	8,15	9,13	15,20	5,10	10,20	10,20					
Replacement rate																									15,30	15,30	5,15	5,12	5,15	5,10	10,20	10,20	10,25	5,15	20,40	25,50	20,30
Operating Cost H2							-5,-10																														
Operating Cost Electric		-10,-20																																			
Water use																	50 ,100		100,250	25,50																	
Land use																	25,50	50,75	100,250																		
H2 available																200,352																		10,12			
Electricity available															40,70																		5,15				
SAF available																			300,450	50 ,100																	
electric operations share			15,25																														15,30		20,40		
SAF operations share																																				15,30	
H2 operations share								21,38																										10,30			17,23
H2 price																-78																					-5,-10
SAF price																	10,25	15,30	-50,-25	5,10																	
Electricity price															-5,5																						
SAF Demand																																				10,20	
H2 Demand																	8,10																				5,10
Electric Demand																																			15,25		
Battery Specifc Energy Density	20,40																				20,40																
Gravimetric Index						8,10																	8,10	8,10													

Fig. 11   Impact Matrix

C. Compatibility matrix



	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	E1	E2	E3	E4	E5	E6	N1	N2	N3	N4	O1	O2	O3	O4	O5	O6	O7	O8	AP1	AP2	AL1	AL2	AL3
P1		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P2	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
P3	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0
P4	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0
P5	0	0	0	0		0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P6	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	2	3	0	0	0	0	0	0	0	0	0	0	0	0	0
P7	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
P8	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0
P9	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	-1	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	5
P10	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	2	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P11	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P12	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P13	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P14	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0
E1	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0
E2	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7
E3	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0		-1	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1		2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E5	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	-1		-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0
E6	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	-1	0	-1		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0
N1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	2	2	0	0	0	0	0	0	0
N2	-1	0	0	0	0	-1	0	0	0	-1	0	0	-1	0	0	0	0	0	0	0	0		0	0	TRL	TRL	TRL	TRL	TRL	TRL	TRL	TRL	0	0	0	0	0
N3	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	2	0	0	0	0	0	0	0	0	0	0
N4	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	2	0	0	0	0	0	0	0	0	0
O1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0		0	0	0	0	0	0	0	0	0	0	2	0
O2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0		0	0	0	0	0	0	0	0	0	2	0
O3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	-1	-1	0	0	0		0	0	0	0	0	0	0	0	0	10
O4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	-1	0	-1	0	0	0		0	0	0	0	0	0	0	0	15
O5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	-1	0	0	0	0	0	0		0	0	0	0	0	3	0	0
O6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	-1	0	0	0	0	0	0	0		0	0	0	0	8	0	0
O7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0		0	0	0	0	5	0
O8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0		0	0	0	5	0
AP1	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	3	0	0
AP2	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	5
AL1	0	-1	0	-1	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	-1	0	0	-1	0		0	0
AL2	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	-1	-1	0	0	0	0	-1	-1	0	0	0	0	-1	-1	0	0	0		0
AL3	0	0	0	0	0	0	-1	0	-1	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	-1	-1	0	0	0	0	0	-1	0	0	

Fig. 12 Compatibility matrix

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