A techno-economic assessment for net-zero aviation

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A techno-economic assessment for net-zero aviation

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The finalisation of this thesis also marks the end of an 7,5 year journey to obtain my Master's degree. Looking back on these years, I realise that my time as a student has been far more then just following lectures, finishing assignments and taking exams. Of course, I would not be there today if I did not complete those milestones. However, I think that a big part of my learning also happened outside of the university. By taking more time for my studies, gave me the opportunity to develop myself in ways I could never have imagined once I commenced on this journey. Besides, I made friends for life which I am sure I will keep in touch with for long after my studies.

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Contents

Introduction

The aviation sector has committed to achieving net-zero CO_2 emissions by 2050, while passenger demand is expected to continue growing. This combination creates a strategic challenge: aviation must decarbonise at system level without undermining connectivity, affordability, and its wider economic value. Several mitigation pillars are being pursued, most prominently Sustainable Aviation Fuels (SAF) as a near-term drop-in option, and hydrogen and electric propulsion as longer-term solutions. However, these options differ strongly in cost, maturity, infrastructure requirements, and upstream clean energy needs, and their large-scale deployment remains uncertain.

This thesis responds to this challenge by developing an integrated techno-economic modelling framework for European aviation transition pathways from 2025 to 2050. The framework links fleet evolution, technology adoption, energy-carrier supply, and infrastructure implications within one consistent system view. Rather than producing a single "best" pathway, it is designed to quantify trade-offs between system costs, well-to-wake CO_2 emissions, and upstream clean energy demand across a predefined set of scenarios. The work was developed at Delft University of Technology in collaboration with the Skyfinity Foundation (Amsterdam), which provided practical context and helped steer the project toward policy- and investment-relevant questions. From a societal perspective, the main contribution is a transparent basis to discuss what aviation decarbonisation could realistically require, what it may cost, and which potential bottlenecks, particularly clean energy availability, could constrain progress.

This thesis report is organised as follows. In Part I, the scientific paper is presented. Part II contains the research proposal, including the literature study that supports the work and the preliminary research plan.

Part I

Scientific Paper

A Techno-Economic Assessment for Net-Zero Aviation

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Abstract

This paper develops a system-level techno-economic optimisation framework to assess European aviation transition pathways from 2025 to 2050. The model jointly determines fleet evolution, technology adoption, energy-carrier supply, and infrastructure in a mixed-integer linear programming formulation. A three-objective optimisation over discounted system costs, cumulative well-to-wake CO_2 emissions, and upstream clean energy demand is solved using the AUGMECON2 ϵ-constraint method to construct Pareto frontiers, after which a representative compromise is selected via a normalised closest-to-utopia metric. Results show pronounced and asymmetric trade-offs. Cost minimisation yields the lowest expenditures but produces CO_2 emissions around six times higher than the emissions-optimal benchmark. Emissions minimisation delivers deep abatement, yet increases both costs and clean energy demand by roughly a factor four due to deployment of capital-intensive and upstream-energy-intensive technologies. Clean-energy minimisation reduces upstream demand but still results in emissions about seven times higher than the emissions-optimal solution. Across scenarios, the relationship between costs and sustainability objectives remains strongly conflicting, while emissions and clean energy demand exhibit a non-monotonic relationship. Closest-to-utopia solutions consistently originate from cost-optimal primary runs, indicating that cost-efficient baselines provide the most flexible starting point for improving emissions and clean energy performance via ϵ-constraints. Sensitivity analysis further shows that emissions outcomes are dominated by well-to-wake assumptions, whereas costs and clean energy demand are mainly driven by market growth and SAF ambition, highlighting clean energy availability as a potential binding constraint.

1 Introduction

The aviation sector has committed to achieving net-zero CO_2 emissions by 2050 [NLR SEO Amsterdam, 2021]. This ambition coincides with sustained growth in passenger demand, which fundamentally challenges the sector to decarbonise while maintaining and expanding capacity. Historical efficiency improvements in aircraft and operations have reduced emissions intensity per passenger-kilometre, but these gains have been outweighed by demand growth. As a result, meeting long-term climate targets requires structural changes in energy carriers, aircraft technologies, and fleet composition rather than incremental efficiency improvements alone.

Multiple mitigation pathways are currently being pursued. Sustainable Aviation Fuels (SAFs), here defined as drop-in fuels for conventional aircraft, enable near-term emissions reductions using existing infrastructure. In contrast, hydrogen- and electricity-based propulsion concepts require new aircraft and infrastructure but offer the potential for deeper long-term decarbonisation. However, these options differ substantially in technological maturity, cost structure, infrastructure requirements, and upstream energy demand. In particular, hydrogen and electric aircraft face long development and certification timelines, high capital requirements, and significant uncertainty regarding large-scale deployment. At the same time, SAF availability, production pathways, and life-cycle emissions remain uncertain and strongly policy dependent.

These challenges are amplified by the capital-intensive nature of aviation and its stringent safety and certification regimes, which increase financial risk and discourage rapid adoption of unproven technologies [Dialogic, 2021]. Consequently, decision-makers face complex trade-offs between system costs, emissions reductions and available resources under deep uncertainty. Addressing these trade-offs requires quantitative modelling frameworks that integrate fleet evolution, technology availability, fuel pathways, and policy constraints within a consistent system-level perspective.

Against this background, this study develops a techno-economic optimisation framework to assess system-level trade-offs between economic performance, climate impact, and clean energy requirements in European

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aviation up to 2050. The framework integrates fleet evolution, energy carrier choices, and infrastructure requirements under operational, technological, and policy constraints, while explicitly accounting for uncertainty through scenario-based sensitivity analysis. A multi-objective optimisation approach is used to analyse trade-offs between costs, emissions, and clean energy demand, enabling identification of balanced transition outcomes and assessment of their robustness.

The central research question addressed in this thesis is therefore:

> *What are the key techno-economic drivers and uncertainties influencing an effective transition to a cost-competitive and sustainable European aviation sector by 2050 based on scenario-based sensitivity analysis?*

Beyond its technical contribution, this research addresses a broader societal challenge. Aviation plays a critical role in mobility, trade and economic development, yet its climate impact must be reduced substantially within the coming decades. By providing a transparent and integrated modelling framework that quantifies key trade-offs between cost, emissions and energy use, this study supports more informed policy design and strategic decision-making for the transition to net-zero aviation. Accordingly, the framework is intended for long-horizon strategic assessment and does not optimise operational decisions such as flight scheduling, dispatch, or airport peak-capacity management, nor the short-term operational dynamics of fuel production, storage, and distribution.

This paper is structured as follows. Chapter 2 reviews the relevant literature on aviation decarbonisation pathways and modelling approaches. Chapter 3 presents the methodological framework and optimisation model. The results are discussed in Chapter 4, followed by conclusions and recommendations for future work in Chapter 5.

2 Literature Review

This chapter reviews the current state of knowledge on aviation emissions, decarbonisation technologies, and modelling approaches for the transition to net-zero aviation. Section 2.1 outlines the sector's climate impact and mitigation options, including sustainable fuels and novel propulsion systems. Next, Section 2.2 discusses global decarbonisation roadmaps and transition models that assess the feasibility of these solutions. Lastly, Section 2.3 will review the strategies for Multi Objective Optimisation techniques. This review provides the basis for the integrated techno-economic model that will be explained in Chapter 3.

2.1 Aviation emissions and mitigation pathways

The aviation industry contributes significantly to global greenhouse gas (GHG) emissions. The combustion of fossil hydrocarbons leads to the emissions of carbon dioxide (CO_2) and water vapor. However, due to inconsistencies in fuel quality and imperfect combustion, also other products are emitted. These byproducts include Nitrogen oxides NO_x, Sulfur oxides SO_x, soot and other aerosols. The climate effects of aviation can thus be categorised by CO_2-effects and non-CO_2 effects. The emitted CO_2 traps heat in the atmosphere which enhances the greenhouse effect. This emitted CO_2 is a long-lived climate forcer. As around 20% of the emitted CO_2 stays in the atmosphere for more than 1,000 years, the effects of these emissions are accumulative. The byproducts contribute to global warming via complex mechanisms such as contrail-induced cloud formation and chemical reactions that alter atmospheric composition. Even though these non-CO_2 effects have durations of hours to decades, their effect on short term global warming can be significant. ([Lee et al., 2021] ;[Delbecq et al., 2023])

Emissions from the combustion of aviation fuels are typically quantified using metrics such as the emission index (EI), which expresses the amount of a given pollutant emitted per kilogram of fuel burned. The median CO_2 emission index for Jet-A1 fuel is widely cited as 3.16 kg CO_2/kg fuel [Grewe et al., 2021]. It should be noted that this value is the value for the Tank-to-Wake (TTW) emissions. These are the emissions that are produced when the fuel is burned in flight. To gain a more representative view of the actual emissions, the Well-to-Wake (Well-to-Wake) emissions can be used. These emissions include the emissions produced by the entire value chain of the fuel. This includes the emissions emitted during the extraction of the feedstock, transport, refining, distribution and burning of the fuel. [ATAG, 2023]. This WTW emission index has a global volume weighted average of approximately 3.82 kg CO_2/kg fuel [Jing et al., 2022].

Just the Emission Index alone is not enough to quantify the entirety of aviation emissions. Therefore, the total size of the aviation market should also be accounted for. This can be done by the Kaya identity introduced by Yoichi Kaya. This identity states that the total CO_2 emissions can be calculated by the product of the following factors: Energy intensity, population, carbon intensity and GDP per capita [Kaya and Yokobori, 1997]. In the context of aviation, this identity is often rewritten as the product of the fuel carbon intensity

(CO_2 released per unit of energy), the aircraft energy intensity (amount of energy used for 1 RPK) and the total distance traveled by the passengers (RPK). See Equation 1([Delbecq et al., 2023];[Bergero et al., 2023]).

$$CO_2 = \underbrace{\frac{CO_2}{MJ}}_{\text{fuel carbon intensity}} \cdot \underbrace{\frac{MJ}{RPK}}_{\text{Aircraft energy intensity}} \cdot \underbrace{RPK}_{\text{Flown distance}} \tag{1}$$

[Ritchie, 2024] studied how these three metrics evolved from 1990 until 2021 and concluded the following:

- The total RPK has grown exponentially. Between 1990 and 2021 the demand has almost quadrupled. According to forecasts, the sector will continue to grow. Eurocontrol expects an average annual growth rate of 1.2% [Eurocontrol, 2022]. Whereas Airbus and Boeing expect way higher growth rates of 3.6% and 4.2% annual growth respectively ([Airbus, 2025];[Boeing, 2025]). The discrepancy arises because Eurocontrol provides a conservative, Europe-focused forecast that explicitly accounts for capacity and policy constraints, whereas Airbus and Boeing present global, unconstrained RPK growth projections driven by emerging markets and optimistic long-term demand assumptions.
- The aircraft energy intensity has decreased over 50% between 1990 and 2021. This is explained by the efficiency gains in fleet renewals and increase in passenger load factors [Gössling and Humpe, 2023].
- The carbon intensity of the used fuels today is still the same as in 1990. This is because the same fuel is being used as back in 1990 and has not become any 'cleaner' in the meantime.

According to the study of [Ritchie, 2024], it becomes clear that gains in energy intensity alone are not enough to counteract the growth in demand in order to reduce aviation emissions and these emissions will thus continue to grow if no action is taken. In 2023, the total aviation emissions were 2.5% of global CO_2 emissions [IEA, 2025]. Even though this percentage seems low, it is important to realise that this percentage is caused by only a small part of the worlds population. In 2018, no more than 4% of the world's population flew internationally [Gössling and Humpe, 2020].

The analysis in [Ritchie, 2024] indicates that reductions in energy carriers carbon intensity remain a key driver for aviation decarbonisation. This can be done by either using drop in fuels such as Sustainable Aviation Fuels (SAFs) or whole new propulsion techniques such as hydrogen powered and electric flight. SAF, or Sustainable Aviation Fuel, is an aviation fuel made from non-petroleum feedstock. SAF blends in with conventional jet fuels in percentages of 10 to 50%. In the future, this percentage might grow to 100% if the right chemicals are added to the SAF to ensure lubricity and other engineering requirements [ACI, 2021]. The properties of SAFs depend on their production pathway. The most mature pathways are Hydroprocessed Esters and Fatty Acids (HEFA), Alcohol to Jet (AtJ), Biomass gasification and Fischer Tropsch (FT-SPK) and Electrofuel. Each of them varies in the feedstock that is being used and their emission reduction potential. The first three of the pathways are so called biofuels, their feedstocks are organic materials. The Electrofuel captures CO_2 directly from the atmosphere and with a reaction with green hydrogen, new hydrocarbons can be created. The main advantage of drop-in fuels is that there would be no to little adjustments necessary to existing infrastructure or combustion techniques in aircraft engines.

The contrary is true for the non-drop-in fuels. Aircraft that would use non-drop-in fuels like hydrogen or electricity are not compatible with existing aircraft designs and infrastructure. In order to introduce these aircraft, entirely new aircraft designs and infrastructures will be required in order to be able to use them [Neiva et al., 2022]. In line with this, several manufacturers are already developing aircraft tailored to these alternative propulsion systems. IATA has provided an overview of what aircraft with non-drop-in propulsion techniques are currently being developed and their expected Entry-Into-Service (EIS) year. This overview can be found in Figure 1. A total of 44 individual aircraft concepts from 23 different companies has been identified, including legacy OEMs (Original Equipment Manufacturer) but also start-ups. It reveals a clear technology trajectory: short-range, low-capacity battery and hybrid-electric aircraft dominate early entries (2025–2030), while larger, longer-range hydrogen aircraft are projected for post-2030 introduction [IATA, 2024]. Table 1 shows a summary of the different pathways and their feedstock.

2.2 Aviation transition models and roadmaps

The preceding analysis has shown that while improvements in energy efficiency have helped reduce emissions intensity per passenger-kilometer, the overall growth in air traffic continues to drive up total emissions. In response to the growing climate impact of the aviation sector, several organisations have developed long-term decarbonisation roadmaps. Among the most influential are those by the European Union, the International Air Transport Association (IATA), the Air Transport Action Group (ATAG) and the Federal Aviation Administration (FAA). These roadmaps outline multi-decade strategies to achieve net-zero CO_2 emissions by 2050. These roadmaps can be found in Figure 2

Table 1: Overview of different propulsion pathways. Values obtained from [Neiva et al., 2022]. DAC = Direct Air Capture

Technology	Type	Feedstock	TTW reduction	WTW reduction
HEFA	Drop-in	Waste oils and fats	0%	63-90%
AtJ	Drop-in	Biomass derived alcohols	0%	45-60%
FT-SPK	Drop-in	Organic waste material	0%	Up to 90%
Electrofuel	Drop-in	CO_2 from DAC and green H_2	0%	Up to 97%
Hydrogen	Non-drop-in	Water and green electricity	100%	64%(2030) up to 100%(2050)
Electricity	Non-drop-in	Green electricity	100%	64%(2030) up to 100%(2050)

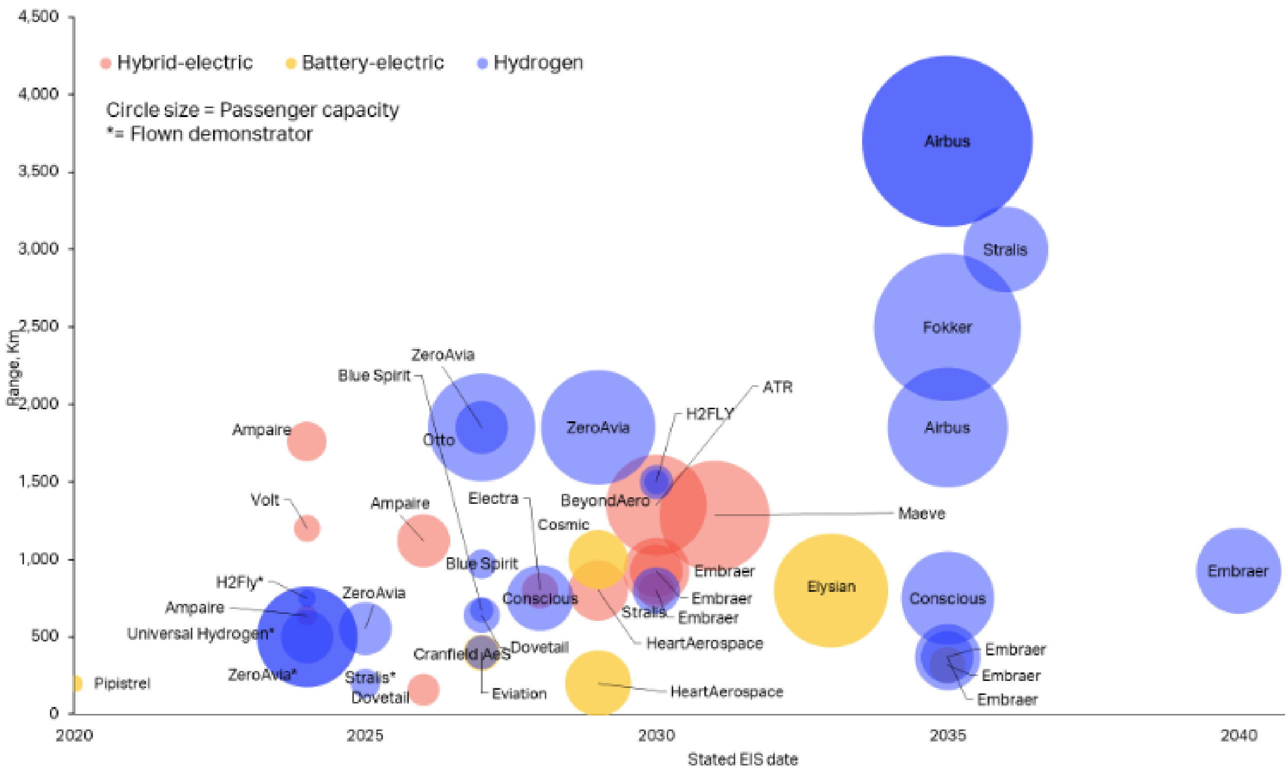
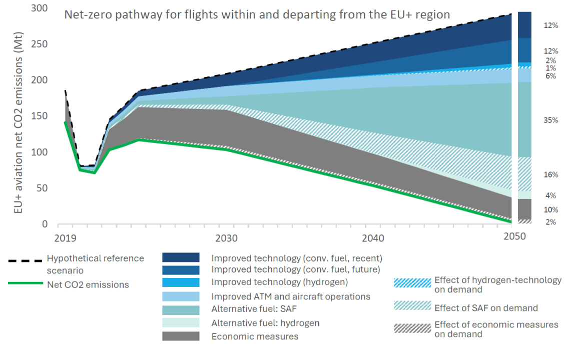
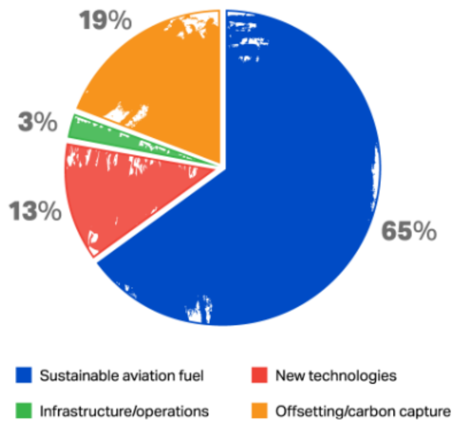


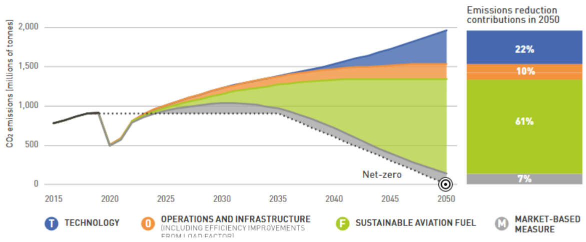
Figure 1: Announced hydrogen, battery, and battery-hybrid aircraft by range, passenger capacity, and date of expected entry into service (EIS). Retrieved from [IATA, 2024].



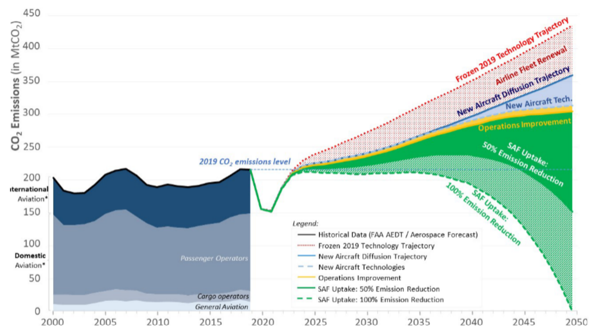
(a) EU Roadmap [NLR SEO Amsterdam, 2021]



(b) IATA Roadmap for 2050 [IATA, 2021]



(c) ATAG Roadmap [ATAG, 2021]



(d) FAA Roadmap [FAA, 2021]

Figure 2: Overview of aviation decarbonisation roadmaps

Common pillars across these strategies include improvements in operational efficiency, increased use of Sustainable Aviation Fuels (SAFs), deployment of zero-emission aircraft (hydrogen and electric), and carbon offsetting mechanisms. While the end goal is consistent across initiatives, the effect of each pillar differs throughout the roadmaps. For example, the ATAG roadmaps expects that new technologies such as hydrogen and electricity can reduce the CO_2 emissions by 22% as the IATA roadmaps account a share of 13% for this pillar. The differing shares of decarbonisation pillars across aviation roadmaps primarily reflect variations in institutional perspective, policy context, system boundaries, and assumptions regarding technology readiness. For example, IATA, representing airlines, emphasises fleet-compatible measures such as Sustainable Aviation Fuel, whereas ATAG, representing the broader aviation value chain, adopts a more diversified strategy that also assigns greater importance to aircraft technology and operational measures. These strategic visions help coordinate industry efforts, inform regulatory frameworks, and provide input parameters for transition modelling approaches.

However, the pathways outlined are not forecasts, but rather normative scenarios that assume a high level of technological and policy alignment. In order to assess the effectiveness of these roadmaps, a techno-economic assessment (TEA) could be used. This is a method to analyze the economic impact on an industrial process when new technologies are introduced. This tool is mostly used in chemical engineering processes. [Zimmerman et al., 2018] describes a methodology on how to perform a TEA in this industry.

When a TEA is performed in an aviation application, this is often combined with a fleet assignment optimisation model. A fleet optimisation model deals with assigning the available aircraft fleet to routes that have to be flown while it takes into account the equipments availabilities and capabilities [Sherali et al., 2006]. This can be done for a single airline as described by Sherali, but it can also be done by modeling a global air transportation system [Kühlen et al., 2022]. For example, [Rau et al., 2024] models the impact of the introduction of first generation hydrogen aircraft on the air transport system. Similar kind of studies on the impact of electric flights do not seem to exist in literature. However, to be able to assess the effectiveness of an entire transition, a holistic model should be used to take into account the introduction of drop-in and non-drop-in propulsion techniques, policy measures and technical limitations.

Such a holistic model has not been identified in the existing literature. This research addresses this gap by developing a system-level optimisation framework that jointly represents sustainable aviation fuel pathways and novel propulsion technologies, while explicitly trading off discounted system costs, well-to-wake emissions, and clean energy demand. The model integrates fleet evolution dynamics, technology-specific constraints, and policy scenarios within a unified mathematical formulation, enabling systematic exploration of feasible transition pathways and quantification of trade-offs under alternative strategic assumptions.

2.3 Multi objective optimisation

Many engineering and policy problems involve multiple performance metrics that often conflict with one another. An improvement in one metric may cause a compromise for the other metrics. This also occurs in long-term transition modelling where costs, emissions and clean energy resources have to be evaluated simultaneously. For example, reducing emissions may lead to high system costs and high clean energy resources. This means that only evaluating one of these metrics will lead to a suboptimal transition strategy. Therefore all the different objectives should be taken into account. As emphasised by [Miettinen, 1999], multi-objective optimisation (MOO) enables a systematic exploration of trade-offs between competing goals.

A central concept in multi-objective optimisation is Pareto Optimality. A solution is defined to be Pareto Optimal when an improvement in one objective worsens of at least one of the other objectives. Such solutions cannot be dominated by any other feasible solutions. The set of the non-dominated solutions forms the Pareto frontier. This frontier thus shows what solutions are possible for the decision makers and at what costs a certain solution comes for the other objectives. To compute the Pareto frontier, numerous approaches exist, as reviewed by [Marler and Arora, 2004]. One commonly used method is the ϵ-constraint technique, which optimises one objective while imposing bounds on the others. Its performance, however, depends strongly on the chosen bounds: poorly selected ϵ-values can lead to infeasible problems or to *weakly efficient* solutions. Weakly efficient solutions satisfy all constraints but do not lie on the true Pareto frontier; that is, another feasible solution may exist that improves at least one objective without worsening the others.

To address these limitations, [Mavrotas and Florios, 2013] introduced the AUGMECON2 method. AUGMECON2 improves the classical ϵ-constraint formulation by introducing two key enhancements: *priority ordering* and *slack (helper) variables*. Priority ordering ensures that the solver first fully optimises the primary objective before checking whether the secondary objectives meet their ϵ-bounds. This prevents solutions in which the primary objective is not fully minimised. The slack variables act as small, controlled buffers in the secondary-objective constraints. They force the solver to expose any unused margin in these constraints and to minimise this margin. As a result, weakly efficient solutions are automatically eliminated, and all solutions generated lie on the true Pareto frontier. A comparison of the classical ϵ-constraint and AUGMECON2 formulations is shown below.

Classical ε-constraint formulation [Marler and Arora, 2004]

$$\begin{aligned} \min_{x} \quad & f_1(x) \\ \text{s.t.} \quad & f_2(x) \le \varepsilon_2, \\ & f_3(x) \le \varepsilon_3, \\ & x \in X. \end{aligned}$$

AUGMECON2 formulation [Mavrotas and Florios, 2013]

$$\begin{aligned} \min_{x,\, s_2,\, s_3} \quad & f_1(x) + \rho(s_2 + s_3) \\ \text{s.t.} \quad & f_2(x) + s_2 = \varepsilon_2, \\ & f_3(x) + s_3 = \varepsilon_3, \\ & s_2 \ge 0, \quad s_3 \ge 0, \\ & x \in X. \end{aligned}$$

Comparison between the classical ε-constraint formulation and the AUGMECON2 formulation for multi-objective optimisation.

In the AUGMECON2 formulation, the slack variables s_i and the parameter ρ ensure that only strictly Pareto-optimal solutions are obtained. The slack variables quantify the deviation between the achieved value of a secondary objective $f_i(x)$ and its prescribed ε_i-bound. A positive slack therefore indicates that the corresponding constraint is not binding and that further improvement of the secondary objective would be possible without violating feasibility.

The parameter ρ introduces a small penalty on the slack variables in the objective function. Its value is chosen sufficiently small to preserve strict priority of the primary objective $f_1(x)$, while ensuring that any remaining slack is minimised once the primary optimum has been attained. Consequently, among all solutions that are optimal with respect to the primary objective, the formulation selects those for which the secondary-objective constraints are as tight as possible. This mechanism eliminates weakly efficient solutions and guarantees that all generated solutions lie on the true Pareto frontier.

In practice, the AUGMECON2 procedure begins by solving the optimisation problem independently for each objective to determine the minimum and maximum values. These ranges are then divided into a grid, and each grid point becomes an ϵ-value for the secondary objectives. By solving the problem for each combination of ϵ-values, the complete Pareto frontier can be reconstructed.

After constructing the Pareto frontier, additional decision-support techniques can be used to identify a balanced compromise solution. One common approach is the distance-to-utopia method, which measures the (typically Euclidean) distance between each solution and the *utopia point*, where all objectives attain their minimum value. Because the objectives differ in scale, normalisation is applied to prevent any single objective from dominating the distance measure. The solution with the smallest normalised distance to the utopia point is interpreted as the most balanced trade-off.

3 Methodology

This chapter presents a system-level techno-economic optimisation framework for the European aviation sector over the period 2025–2050. The framework is used to quantify trade-offs between discounted system costs, well-to-wake CO_2 emissions and clean energy demand. The overarching objective is to assess the system-level impact of the combined introduction of multiple decarbonisation technologies by analysing their interactions within a unified transition model.

Section 3.1 describes the mathematical optimisation model. It defines the sets, decision variables, objective functions, and constraints governing fleet evolution, aircraft acquisition and retirement, route-level flight activity, energy carrier choice, fuel production pathways, and infrastructure requirements. The model is formulated as a Mixed Integer Linear Program.

Section 3.2 describes the acquisition, filtering, and processing of the numerical input data used in the model. This includes the construction of the route network, aircraft datasets, fuel pathways, infrastructure cost parameters, policy inputs, and other exogenous parameters required to parameterise the optimisation model within the defined system boundaries.

Uncertainty in future developments is incorporated through a scenario-based approach along three axes: well-to-wake emissions assumptions, SAF deployment trajectories and passenger demand growth. The definition of these uncertainty axes, the construction of the scenario set, and the associated sensitivity analysis are described in Section 3.3. For each scenario, the optimisation problem is solved using the AUGMECON2 ϵ-constraint method to construct Pareto frontiers spanning the three objectives. A representative compromise solution is identified for each scenario using a distance-to-utopia approach. Section 3.3 further describes the post-processing steps used to extract system-level performance indicators, reconstruct trade-off spaces, and assess the robustness of results across scenarios.

3.1 Mathematical model

This section describes the mathematical linear programming model that has been used in this research. This is done by defining the Sets, Decision Variables and Parameters first. After that, the different objectives will be defined. Finally, the constraints of the model are explained.

Sets, decision variables and parameters

The sets, decision variables and parameters of the model can be found in Tables 2 - 4 respectively. The sets are described in Table 2. It is important to note that set **A** consists of three subsets:

- $\mathbf{A_{conv}}$: Subset of conventional aircraft that are already on the market. These aircraft can fly on conventional fuels and SAFs.
- $\mathbf{A_H}$: Subset of hydrogen aircraft.
- $\mathbf{A_E}$: Subset of electric and hybrid electric aircraft.

The decision variables can be found in Table 3. The decision variables $x_{a,y}$ and $e_{a,k,y}$ are integer decision variables.whereas $\text{freq}_{a,f,r,y}$ is defined as continuous variable. Realistically, the frequency would also be an integer value. However, the problem does not require the frequency to be an integer as this is a multi-year strategic planning model. The variable $\text{freq}_{a,f,r,y}$ thus does not represent an exact count of flights but an annual average frequency. This assumption allows the model to solve more efficiently in the Gurobi optimiser. This assumption is also supported in literature by [Kühlen et al., 2022].

The model parameters are listed in Table 4. The data sources and methods used to assign values to these parameters are discussed in Section 3.2. While all parameters are presented explicitly for clarity, several of them are derived from other model parameters, namely the annual route-specific demand, the required energy per flight, and the weight factor for R&D costs.

The demand on route r in year y is calculated using Equation 2, which scales the baseline demand in the initial year by the assumed market growth rate:

$$D_{r,y} = D_{r,2025} \cdot (1 + g_m)^{y-2025}. \tag{2}$$

The energy required per flight for aircraft a using energy carrier f on route r is computed according to Equation 3. A distinction is made between combustion and electric aircraft. For combustion aircraft, the energy requirement is obtained by multiplying the flight time, given by the route distance divided by the aircraft cruise speed, by the fuel flow rate and the lower heating value of the energy carrier. For electric aircraft, where no fuel flow exists, the energy requirement is calculated by multiplying the specific energy consumption in Wh per passenger-kilometre by the aircraft seat capacity and the route distance. Conversion factors of 0.0036 and 1.852 are applied to convert Wh to MJ and nautical miles to kilometres, respectively.

$$epf_{a,f,r} = \begin{cases} \dfrac{\text{dist}_r}{v_a} \cdot \phi_a \cdot \text{LHV}_f, & \text{if } f \text{ is not electric,} \\ \text{seat}_a \cdot 1.852 \cdot \text{dist}_r \cdot 0.0036 \cdot \Phi_a, & \text{if } f = \text{electric.} \end{cases} \tag{3}$$

Total R&D costs RDC_{td} for each technology td are taken from [Neiva et al., 2022] and distributed over the development period $[y_{td}^{\text{start}}, y_{td}^{\text{EIS}})$ using an increasing expenditure profile. The weight factor $w_{td,y}$ represents the share of total R&D costs allocated to year y, with lower values at early development stages and higher values approaching entry into service. This factor depends on the discount rate r and the technology-specific R&D growth rate g_{td}, and is defined as

$$w_{td,y} = \begin{cases} \dfrac{(r - g_{td})(1 + g_{td})^{k_{td}(y)}}{1 - \left(\dfrac{1 + g_{td}}{1 + r}\right)^{N_{td}}}, & y_{td}^{\text{start}} \leq y < y_{td}^{\text{EIS}}, \\ 0, & \text{otherwise,} \end{cases} \tag{4}$$

where

$$N_{td} = \frac{y_{td}^{\text{EIS}} - y_{td}^{\text{start}}}{\text{step}}, \quad k_{td}(y) = \frac{y - y_{td}^{\text{start}}}{\text{step}},$$

denote the number of time steps in the development period.

Table 2: Sets for the model

Set	Description	Indexed by
A	Aircraft types	a
$\mathbf{T_{dev}}$	Technologies considered under R&D	t_d
$\mathbf{T_{ac}}$	Technologies requiring aircraft structure modifications	t_{ac}
F	Energy carriers	f
Y	Years	y
R	Routes	r
K	Aircraft age	k
$\mathbf{P_f}$	Production pathways for energy carrier f	p

Table 3: Decision variables for the model

Variable	Description	Unit
$x_{a,y}$	Number of new aircraft type a entering in year y	[#AC]
$e_{a,k,y}$	Number of aircraft type a, age k, retired in year y	[#AC]
$\text{freq}_{a,f,r,y}$	Number of flights of aircraft type a, flying with energy carrier f, route r, year y	[#flight]

Objectives

This section defines the objective functions of the multi-objective linear program. The model considers three objectives: transition costs, CO_2 emissions and clean energy demand. After introducing each objective individually, the combined multi-objective formulation based on the AUGMECON2 method is presented.

Costs of Transition
To determine the Costs of transition, the methodology presented in [Neiva et al., 2022] is used with additional costs for retiring aircraft early as described by [Repko and Santos, 2017]. Neiva describes the costs of transition as the sum of R&D costs, aircraft acquisition costs and fuel production costs. Additionally, the penalty for retiring aircraft early, required infrastructure investments and the costs for still emitting CO_2 are also considered for the total cost of transition in this research.

The yearly R&D investments are calculated by splitting the total R&D investments over different periods with a weight that can be calculated as explained in previous section. This way, it can be modeled that the R&D costs increase during the ramp-up phase and it increases until the entry into service year of the technology. The aircraft acquisition costs can be calculated by adding an aircraft reference list price and a purchase cost

Table 4: Parameters for the model. Process for the aqcuisition of these variables will be explained in Section 3.2.

Symbol	Description	Unit
ABT_a	Annual block time of aircraft a	[hr]
$\alpha_{f,p,y}$	Unit cost of energy carrier f produced via pathway p in year y	[€/MJ]
$c^{infra}_{f,p,size\_origin(r)}$	Infrastructure costs per MJ for carrier f with pathway p at the origin airport of route r	[€/MJ]
$D_{r,y}$	Passenger demand on route r in year y	[# pax]
$\delta_{t_{ac}}$	Incremental Capex for fitting technology t_{ac} on aircraft a	[€]
dist_r	Distance of route r	[nm]
$\text{EF}_{\text{kerosene}}$	Well-to-wake emissions factor of kerosene	[kg CO_2/MJ]
EIS_a	Entry into service year of aircraft a	[-]
$\text{epf}_{a,f,r}$	Energy per flight flown by aircraft a using carrier f on route r	[MJ/flight]
$F_{a,k,y}$	Fleet size of aircraft type a, age k, in year y	[#AC]
Φ_a	Energy consumption of electric aircraft a	[Wh/pax-km]
ϕ_a	Fuel flow of combustion aircraft a	[kg/hr]
g_m	Annual aviation market growth factor	[%/a]
g_{t_d}	Annual growth rate of R&D spending for technology t_d	[%/a]
$\text{IF}_{a,k}$	Initial fleet size of aircraft type a with age k	[# AC]
L_a	Economic lifetime of aircraft a	[yr]
LF	Average passenger load factor	[%]
LHV_f	Lower heating value of energy carrier f	[MJ/kg]
minSAF_y	Minimum required SAF uptake in year y	[%]
minSYN_y	Minimum required synthetic SAF uptake in year y	[%]
minUSE_a	Minimum annual block time required to avoid retirement of aircraft a	[-]
$\mu_{f,p}$	MJ of clean energy required to produce 1 MJ of carrier f via pathway p	[MJ/MJ]
p^{ETS}_y	ETS price per kg CO_2 emitted in year y	[€/kg CO_2]
p^{offset}_y	Offset price per kg CO_2 in year y	[€/kg CO_2]
P_a	List price of aircraft a	[€]
$\text{PR}_{a,y}$	Production rate of aircraft a in year y	[# AC]
RDC_{t_d}	Total undiscounted R&D costs for technology t_d	[€]
r	Discount rate	[%/a]
range_a	Maximum range of aircraft a	[nm]
seat_a	Seat capacity of aircraft a	[# pax]
step	Time interval between years	[yr]
v_a	Cruise speed of aircraft a	[kts]
$w_{t_d,y}$	Weight factor for distributed R&D costs of technology t_d in year y	[-]
$\text{WTW}_{f,p}$	Well-to-wake emissions reduction of carrier f via pathway p	[%]
$y^{start}_{t_d}$	First R&D year for technology t_d	[-]
$y^{EIS}_{t_d}$	Entry-into-service year for technology t_d	[-]
$z_{a,f,r,y}$	Energy consumed by aircraft a, flying with energy carrier f on route r in year y	[MJ]
$z_{a,f,p,r,y}$	Energy consumed by aircraft a, flying with energy carrier f, produced via pathway p on route r in year y	[MJ]

increment incurred due to the introduction of the new technology. The values for the total R&D costs and increment in purchase costs can be found in [Neiva et al., 2022]. The costs for retiring an aircraft can be calculated by multiplying its remaining book value, assuming linear depreciation, by the number of aircraft that will be depreciated.

The fuel costs can be calculated by multiplying the fuel price by the quantity of fuel consumed. Infrastructure costs can be approximated by multiplying the required infrastructure investment per MJ of energy carrier by the amount of MJ that is produced. The emissions costs can be calculated by multiplying the WTW emissions with the corresponding costs per emmitted tonne of CO_2. After aggregation, all annual cost components are converted to present values by discounting them to the base year y_0 using a constant discount rate r. The exponent $y - y_0$ represents the number of years between the year in which the cost is incurred and the base year of the analysis. The final cost objective function can be found in OF_{costs}.

$$\min \sum_{y\in Y} \frac{1}{(1+r)^{y-y_0}} \Bigg[\underbrace{\sum_{td\in T_d} w_{td,y}\cdot \mathrm{RDC}_{td}}_{\text{R\&D}} + \underbrace{\sum_{a\in A}(P_a+\delta_{tac})\cdot x_{a,y}}_{\text{Acquisition}} + \underbrace{\sum_{\substack{a\in A\\ k\in K}} \left(1-\tfrac{k}{L_a}\right) P_a\cdot e_{a,k,y}}_{\text{Early retirement}}$$

$$+ \underbrace{\sum_{\substack{a\in A,\, f\in F,\\ r\in R,\, p\in P_f}} \alpha_{f,p,y}\cdot z_{a,f,p,r,y}}_{\text{Fuel production}} + \underbrace{\sum_{\substack{a\in A,\, f\in F,\\ r\in R,\, p\in P_f}} c^{infra}_{f,p,\text{size origin (r)}}\cdot z_{a,f,p,r,y}}_{\text{Infrastructure}} \tag{OF$_{\text{costs}}$}$$

$$+ \underbrace{\sum_{\substack{a\in A,\, f\in F,\\ r\in R,\, p\in P_f}} \left(p^{ETS}_y + p^{offset}_y\right)\cdot(1-\mathrm{WTW}_{f,p})\cdot \mathrm{EF}_{kerosene}\cdot z_{a,f,p,r,y}}_{\text{ETS + offset costs}} \Bigg]$$

CO_2 emissions

As described in Section 2.1, the total CO_2 emissions of aviation can be calculated by the Kaya identity adaptation for aviation. The carbon intensity can be calculated by multiplying the complement of the Well to Wake reduction factor by the Emissions factor of conventional kerosene. The multiplication of the aircraft energy consumption (MJ/RPK) and the demand (RPK) can be represented by the decision variable $z_{a,f,r,y}$. Therefore, the total CO_2 emissions can be defined as the summation of this multiplication over all the aircraft, energy carriers, routes and years. The corresponding objective function can be found in $\mathrm{OF}_{\text{emissions}}$.

$$\min \sum_{\substack{a\in\mathbf{A}\\ f\in\mathbf{F}\\ r\in\mathbf{R}\\ y\in\mathbf{Y}\\ p\in\mathbf{P_f}}} \underbrace{(1-\mathrm{WTW}_{f,p})\cdot \mathrm{EF}_{kerosene}}_{\text{Fuel carbon intensity}} \cdot \underbrace{z_{a,f,p,r,y}}_{\text{aircraft energy consumption}\,\cdot\,\text{demand}} \tag{OF$_{\text{emissions}}$}$$

Clean energy required

The third objective minimises the total upstream clean energy required to supply aviation energy demand. Here, clean energy refers to renewable electricity used directly by electric aircraft and indirectly in the production of Sustainable Aviation Fuels and hydrogen. This objective does not aim to minimise the deployment of clean energy carriers themselves, but rather the cumulative renewable energy input required to produce them.

Similar to the CO_2 emissions, the required clean energy to produce the required fuels can be calculated by summing the required energy multiplied with the required amount of clean energy to produce 1 MJ of energy carrier f produced via production pathway p $\mu_{f,p}$. Because fossil fuels are produced without renewable energy, $\mu_{fossil,p}=0$ and thus only summation over the set consisting of {SAF, H_2, electric} has to be summed in the objective. Therefore, the corresponding objective function, $\mathrm{OF}_{\text{energy}}$, can be defined as:

$$\min \sum_{\substack{a\in\mathbf{A}\\ f\in\{SAF,H_2,Electric\}\\ r\in\mathbf{R}\\ y\in\mathbf{Y}\\ p\in\mathbf{P_f}}} \mu_{f,p}\cdot z_{a,f,p,r,y} \tag{OF$_{\text{energy}}$}$$

Multi Objective formulation

After defining the three objective functions individually, they are combined within a multi-objective optimisation framework using the AUGMECON2 method. This approach reformulates the original multi-objective linear program into a sequence of augmented single-objective problems, in which one objective is treated as the primary objective while the remaining objectives are imposed as ϵ-constraints. To ensure that only Pareto-efficient solutions are obtained, non-negative slack variables are introduced for the ϵ-constraints and penalised in the objective function. By alternating the choice of the primary objective between costs, CO_2 emissions and clean energy demand, the formulations shown below avoid implicit prioritisation and enable a systematic exploration of trade-offs across all three dimensions. Collectively, these formulations generate the Pareto frontier that characterises feasible transition pathways for the aviation sector.

Costs as primary

$$\min_{\mathbf{x},\mathbf{s}} \quad \mathrm{OF}_{\text{costs}} + \rho\big(s_{\text{emissions}} + s_{\text{energy}}\big)$$
$$\text{s.t.} \quad \mathrm{OF}_{\text{emissions}} + s_{\text{emissions}} = \varepsilon_{\text{emissions}},\quad \mathrm{OF}_{\text{energy}} + s_{\text{energy}} = \varepsilon_{\text{energy}},\quad \mathbf{x} \in \mathcal{X},\quad s_{\text{emissions}}, s_{\text{energy}} \geq 0$$

Emissions as primary

$$\min_{\mathbf{x},\mathbf{s}} \quad \mathrm{OF}_{\text{emissions}} + \rho\big(s_{\text{costs}} + s_{\text{energy}}\big)$$
$$\text{s.t.} \quad \mathrm{OF}_{\text{costs}} + s_{\text{costs}} = \varepsilon_{\text{costs}},\quad \mathrm{OF}_{\text{energy}} + s_{\text{energy}} = \varepsilon_{\text{energy}},\quad \mathbf{x} \in \mathcal{X},\quad s_{\text{costs}}, s_{\text{energy}} \geq 0$$

Clean energy as primary

$$\min_{\mathbf{x},\mathbf{s}} \quad \mathrm{OF}_{\text{energy}} + \rho\big(s_{\text{costs}} + s_{\text{emissions}}\big)$$
$$\text{s.t.} \quad \mathrm{OF}_{\text{costs}} + s_{\text{costs}} = \varepsilon_{\text{costs}},\quad \mathrm{OF}_{\text{emissions}} + s_{\text{emissions}} = \varepsilon_{\text{emissions}},\quad \mathbf{x} \in \mathcal{X},\quad s_{\text{costs}}, s_{\text{emissions}} \geq 0$$

AUGMECON2 formulations with alternative primary objectives.

Constraints

The constraints restrict the decision variables such that the resulting fleet evolution, flight activity, and fuel use remain physically feasible, operationally meaningful, and compliant with relevant policy mandates. The constraints in C1–C11 can be grouped into five logical categories.

First, C1–C3 define the evolution of the aircraft fleet over time. C1 fixes the initial fleet in the base year, C2 prevents retiring more aircraft than present in each age category, and C3 updates the age-structured fleet over time. New aircraft enter with age zero, existing aircraft age according to the time step, and all aircraft older than the economic life are grouped into the last age bucket to ensure that the early-retirement term in the cost objective cannot become negative.

Second, C4–C7 govern flight activity and energy use. Constraint C4 links flight frequencies to total energy consumption on each route. Constraint C5 enforces energy balance by disaggregating this total energy demand across the admissible production pathways for each energy carrier, ensuring that all required energy is fully supplied. Demand must be met in every route–year pair as enforced by C6. In addition, C7 introduces an upper bound on total frequency per route-year based on the minimum seat capacity on that route, which tightens the formulation without altering the feasible region.

Third, C8–C11 guarantee that aircraft operations respect physical and operational limits. C8 ensures that the total block time flown by each fleet type does not exceed the available annual block time, while C9 enforces a minimum utilisation level to prevent unrealistically idle fleets. C10 forbids an aircraft from flying routes beyond its range. C11 provides an additional route-specific utilisation tightening, limiting the frequency on each route by the maximum number of flights possible given the available aircraft and the block time of that route.

Fourth, technology availability is governed by C12, which prevents aircraft from entering the fleet before their entry-into-service year and limits yearly acquisitions by the applicable production rate thereafter.

Finally, C13–C14 implement fuel-policy mandates. C13 enforces a market-level minimum SAF share consistent with the RefuelEU Aviation regulation, while C14 ensures that a minimum fraction of all SAF consumed is supplied by synthetic (e-SAF) pathways. Together, these constraints embed policy-driven decarbonisation requirements into the model.

- Initial fleet

$$F_{a,k,2025} = \mathrm{IF}_{a,k} \qquad \forall\, a \in \mathbf{A},\ k \in \mathbf{K} \tag{C1}$$

- Maximum retirements

$$e_{a,k,y} \leq F_{a,k,y} \qquad \forall\, a \in \mathbf{A},\ k \in \mathbf{K},\ y \in \mathbf{Y} \tag{C2}$$

- Fleet evolution

$$F_{a,k,y} = \begin{cases} x_{a,y}, & \text{if } k = 0, \\ F_{a,k-\text{step},y-\text{step}} - e_{a,k-\text{step},y-\text{step}}, & \text{if } 0 < k < \max(\mathbf{K}), \\ \displaystyle\sum_{k'=\max(\mathbf{K})-\text{step}}^{\max(\mathbf{K})} \big(F_{a,k',y-\text{step}} - e_{a,k',y-\text{step}}\big), & \text{if } k = \max(\mathbf{K}) \end{cases} \qquad \forall\, a \in \mathbf{A},\ k \in \mathbf{K},\ y > 2025 \tag{C3}$$

- Energy calculation

$$z_{a,f,r,y} = epf_{a,f,r} \cdot \mathrm{freq}_{a,f,r,y} \qquad \forall\, a \in \mathbf{A},\ f \in \mathbf{F},\ r \in \mathbf{R},\ y \in \mathbf{Y} \tag{C4}$$

- Pathway split

$$z_{a,f,r,y} = \sum_{p \in \mathbf{P_f}} z_{a,f,p,r,y} \qquad \forall\, a \in \mathbf{A},\ f \in \mathbf{F},\ r \in \mathbf{R},\ y \in \mathbf{Y} \tag{C5}$$

- Demand satisfaction

$$\sum_{a\in\mathbf{A}}\sum_{f\in\mathbf{F}} freq_{a,f,r,y}\cdot \mathrm{LF}\cdot \mathrm{seat}_a \geq D_{r,y} \quad \forall\, r\in\mathbf{R},\ y\in\mathbf{Y} \tag{C6}$$

- Maximum frequency limit

$$\sum_{a\in\mathbf{A}}\sum_{f\in\mathbf{F}} \mathrm{freq}_{a,f,r,y} \leq \left\lceil \frac{D_{r,y}}{\mathrm{minSeats}_r} \right\rceil \quad \forall\, r\in\mathbf{R},\ y\in\mathbf{Y} \tag{C7}$$

- Annual utilisation limit

$$\sum_{r\in\mathbf{R}}\sum_{f\in\mathbf{F}} \frac{\mathrm{dist}_r}{v_a}\cdot \mathrm{freq}_{a,f,r,y} \leq \mathrm{ABT}_a \sum_{k\in\mathbf{K}} F_{a,k,y} \quad \forall\, a\in\mathbf{A},\ y\in\mathbf{Y} \tag{C8}$$

- Minimum utilisation

$$\sum_{r\in\mathbf{R}}\sum_{f\in\mathbf{F}} \frac{\mathrm{dist}_r}{v_a}\cdot \mathrm{freq}_{a,f,r,y} \geq \mathrm{minUSE}_a\cdot \mathrm{ABT}_a \sum_{k\in\mathbf{K}} F_{a,k,y} \quad \forall\, a\in\mathbf{A},\ y\in\mathbf{Y} \tag{C9}$$

- Range feasibility

$$\mathrm{freq}_{a,f,r,y} = \begin{cases} 0, & \text{if } \mathrm{dist}_r \geq \mathrm{range}_a, \\ \geq 0, & \text{otherwise} \end{cases} \quad \forall\, a\in\mathbf{A},\ f\in\mathbf{F},\ r\in\mathbf{R},\ y\in\mathbf{Y} \tag{C10}$$

- Route frequency tightening

$$\mathrm{freq}_{a,f,r,y} \leq \frac{\mathrm{ABT}_a}{\frac{\mathrm{dist}_r}{v_a}} \sum_{k\in\mathbf{K}} F_{a,k,y} \quad \forall\, a\in\mathbf{A},\ f\in\mathbf{F},\ r\in\mathbf{R},\ y\in\mathbf{Y} \tag{C11}$$

- EIS and production rate

$$x_{a,y} \leq \begin{cases} 0, & \text{if } y < \mathrm{EIS}_a, \\ \mathrm{PR}_{a,y}\cdot \mathrm{step}, & \text{if } y \geq \mathrm{EIS}_a \end{cases} \quad \forall\, a\in\mathbf{A},\ y\in\mathbf{Y} \tag{C12}$$

- Market SAF blend

$$\sum_{a\in A_{\mathrm{conv}}}\sum_{r\in\mathbf{R}}\sum_{p\in P^{\mathrm{SAF}}} z_{a,\mathrm{SAF},p,r,y} + \sum_{a\in A_{\mathrm{H2}}}\sum_{r\in\mathbf{R}}\sum_{p\in P^{\mathrm{H2}}} z_{a,\mathrm{H2},p,r,y} \geq \mathrm{minSAF}_y\cdot \left[\sum_{a\in A_{\mathrm{conv}}}\sum_{r\in\mathbf{R}} \Big(\sum_{p\in P^{\mathrm{Conv}}} z_{a,\mathrm{Conv},p,r,y} + \sum_{p\in P^{\mathrm{SAF}}} z_{a,\mathrm{SAF},p,r,y} \Big) + \sum_{a\in A_{\mathrm{H2}}}\sum_{r\in\mathbf{R}}\sum_{p\in P^{\mathrm{H2}}} z_{a,\mathrm{H2},p,r,y} \right] \quad \forall\, y\in\mathbf{Y} \tag{C13}$$

- e-SAF blending mandate

$$\sum_{a\in A_{\mathrm{conv}}}\sum_{r\in\mathbf{R}}\sum_{p\in P^{\mathrm{eSAF}}} z_{a,\mathrm{SAF},p,r,y} \geq \mathrm{minSYN}_y\cdot \left[\sum_{a\in A_{\mathrm{conv}}}\sum_{r\in\mathbf{R}} \Big(\sum_{p\in P^{\mathrm{Conv}}} z_{a,\mathrm{Conv},p,r,y} + \sum_{p\in P^{\mathrm{SAF}}} z_{a,\mathrm{SAF},p,r,y} \Big) + \sum_{a\in A_{\mathrm{H2}}}\sum_{r\in\mathbf{R}}\sum_{p\in P^{\mathrm{H2}}} z_{a,\mathrm{H2},p,r,y} \right] \quad \forall\, y\in\mathbf{Y} \tag{C14}$$

3.2 Data aqcuisition

As became evident from Section 3.1, the model relies on a range of input parameters derived from real-world datasets. The following section outlines how these data were collected, filtered, and processed. Before that is done, it is important to describe the scope of the data that will be used in this study. This scope follows the scope of [NLR SEO Amsterdam, 2021]. The scope is defined as followed:

- Geographical: The countries that will be considered are the members of the European Union, the United Kingdom and the European Free Trade Association. The UK and EFTA countries are added in the scope because they have similar greenhouse gas reduction targets as the EU.

- Emissions: This study considers only CO_2 emissions, primarily due to their cumulative nature. Although aviation also contributes to climate impacts through non-CO_2 effects, such as contrail formation and NO_x emissions, these effects are excluded from the analysis. This exclusion reflects the relatively high uncertainty associated with their quantification and the limited availability of consistent data to robustly represent their impacts [NLR SEO Amsterdam, 2021].
- Flights: The flights that will be considered are all the scheduled commercial passenger flights departing from the countries considered in the geographical scope. This is because the EU greenhouse gas emission inventories assign emissions from international aviation to the country where the fuel is bunkered. Therefore, flights arriving in the countries, are not accounted to the country itself and only departing flights are considered.
- New technologies: The new technologies that are under consideration are Sustainable Aviation Fuels, hydrogen aircraft and electric or hybrid-electric aircraft.

Now that the scope is clear, the following paragraphs will explain how the datasets were acquired.

The route dataset was constructed from the R&D Data Archive of Eurocontrol [Eurocontrol, 2025b], which contains all IFR flights based on filed flight plans. From the extensive set of recorded variables, only the origin, destination, date, aircraft type, and actual distance flown were retained for this study. Since the archive is updated annually with a two-year delay and only provides data for March, June, September, and December, these four months were triplicated to approximate a full year of traffic. The most recent complete dataset (2022) was used as a baseline and subsequently extrapolated to obtain data for 2025. The raw data were filtered to include only scheduled passenger flights departing from airports in EU and EFTA member states, identified through ICAO location indicators. In line with Eurocontrol's market segment definitions, business aviation, cargo operations, and other non-scheduled traffic were excluded using aircraft type, operator, and registration filters. To ensure statistical robustness, only origin–destination pairs with at least 365 annual flights (i.e., an average of one flight per day) were retained. For each valid route, seat capacities were merged from the Eurocontrol Aircraft Performance Database [Eurocontrol, 2025a], and an average European passenger load factor of 82% [EUROCONTROL Business Cases, 2025] was applied to estimate demand. Route distances were calculated as the mean actual distance flown per OD pair. As the size, and thus the runtime, of the optimisation model scales strongly with the number of routes, this data set was scaled down to the 2,000 routes with the highest passenger demand. By retaining routes across the entire spectrum of flight distances, the reduced network remains representative of the operational and technological diversity present in the full European route system. This scaling down still covers 80% of the passenger demand and also 80% of the total passenger-km demand. Finally, this processed route dataset was used as input for the model. To validate the resulting data, the total number of flights at Amsterdam Schiphol (EHAM) was compared with official traffic statistics published by Schiphol Group [Schiphol Group, 2022]. The modelled flight count deviated by 22.1% from reported values, which is considered acceptable given the applied filtering criteria and data availability constraints. The full flights input data set used for the optimisation can be found in Table A.1

In the fuel dataset, the following parameters were gathered: $\{\alpha_{f,p,y}, LHV_f, WTW_{f,p}, \mu_{f,p}\}$. The identified energy carriers and production pathways for this study are:

- Conventional jet A1 fuel: serves as a reference in comparison to the sustainable energy carriers
- SAF: Sustainable Aviation Fuels. The following pathways are considered: {HEFA, FT-SPK, AtJ, eSAF}
- Hydrogen: both liquefied and gaseous
- Electricity

The costs evolution $\alpha_{f,p,y}$ for the different energy carriers and pathway combinations from 2025 until 2050 were obtained from [Neiva et al., 2022]. The lower heating value LHV_f for conventional fuels and the Sustainable Aviation Fuels are set to 43 MJ/kg and hydrogen is assigned a value of 120 MJ/kg. The well-to-wake reduction factor $WTW_{f,p}$ for conventional fuel is set to zero as there is no CO_2 reduction achieved with this energy carrier. For the Sustainable Aviation carriers, the well-to-wake reduction is strongly dependent on the production pathway and feedstock that is being used. Therefore, a best and worst case WTW factor has been acquired. For the drop-in Sustainable Aviation Fuels, this is taken from the ICAO SAF rules of thumb [ICAO, 2023]. For hydrogen and electricity these values have been obtained from [Neiva et al., 2022]. Finally, the clean energy that is required for the production for 1 MJ of energy carrier $\mu_{f,p}$ has been obtained from [Boter, 2023] for the drop-in fuels. For hydrogen, these values have been obtained by [World Nuclear Association, 2024] and [DOE, 2009]. The fuel data set used in the optimisation can be found in Table A.2.

For the technology in development dataset, the following parameters are obtained: $\{RDC_{td}, y_{td}^{start}, y_{td}^{EIS}, g_{td}, \delta_{td}$. These values have been obtained from [Neiva et al., 2022] and can be found in Table A.3.

A time dependent dataset has been constructed to contain the data for every year of the following variables: $\{minSAF_y, minSYN_y, p_y^{ETS}, p_y^{offset}\}$. The values for $minSAF_y$ and $minSYN_y$ have been gathered from Eurocontrols Standard inputs for Economic Analyses [EUROCONTROL Business Cases, 2025]. As it is still uncertain how the adoption of SAF will go into the market, three scenarios has been defined per year to reflect possible outcomes of the adoption. The medium scenario reflects the European Unions RefuelEU mandate. The prices to emit 1 kg of CO_2 ,p_y^{ETS}, has been defined in line with the European Emission Trading System (ETS). The evolution to offset 1kg of CO_2 ,p_y^{offset}, is reflecting CORSIA's offset price range from \$18/tCO_2 today towards \$ 91/tCO_2 in 2050. The dataset can be found in Table A.4

The infrastructure cost dataset was constructed as follows. To incorporate airport-side infrastructure investments into the model, all infrastructure costs were expressed in €/MJ, allowing them to be linearised and included directly in the cost objective. Although real-world infrastructure expenditures do not scale linearly with airport energy carrier use, this proportionality assumption is adopted to maintain tractability within the linear MILP framework. To partially preserve realism, the costs are differentiated by airport size, as infrastructure requirements vary notably between small and large airports. Airport size classification follows the ACI definition [ACI, 2025]:

- Small: $<$ 1 million passengers per year
- Medium: Between 1 million and 10 million passengers per year
- Large: $>$10 million passengers per year

This divides the 166 airports present in the data into 48 small, 89 medium and 29 large airports. For electricity, representative charger-site investments (per airport size) were estimated based on MW-scale charging installations reported in current demonstration projects and industry benchmarks. These CAPEX values were converted to €/MJ by dividing the total investment by the expected lifetime energy throughput of the installation. The numbers for these investments are based upon industry expert consultation. For hydrogen, infrastructure CAPEX per airport category was taken from the FlyZero hydrogen airport infrastructure model [FlyZero, 2022](Scenario 1), which already aggregates tank storage, conditioning, and required bowsers or hydrant systems for a typical airport of each size. These total investments were converted to €/MJ using the projected LH_2 daily demand per airport type together with LH_2 density (70.8 kg/m^3) and its lower heating value (120 MJ/kg). For the infrastructure of SAF, industry expert judgment has been consulted who advised on numbers for investments per Mt of biofuels and synthetic fuels. Based on these numbers, their costs per MJ are calculated by these numbers by their LHV. It is important to note that these numbers are for the fuels specific and thus not airport size dependent. The input data for the optimisation can be found in Table A.5

Finally, the aircraft data set had to be constructed. This dataset is split up in two sub data sets: conventional aircraft and new aircraft. The conventional aircraft data set contains for every aircraft type: How may aircraft are there currently, how many seats, range, maximum annual block hours, list price, economic age, current age, fuel consumption, cruise speed, production rate, fuel weight and maximum take-off weight. The aircraft types and their initial fleet size have been obtained from the same data as the route data set. By checking the aircraft types and the unique tail numbers of all the flight that contain the scope of the route data set, an approximation could be made of how many aircraft there are initially in the fleet. This led to a fleet of 73 conventional aircraft types. Furthermore, the seating capacity, range, cruise speed, fuel capacity and MTOW have been obtained from Eurocontrol aircraft performance database [Eurocontrol, 2025a]. The economic age has been assumed 25 years for each aircraft as this is this average age for which commercial aircraft are retired [ICAO, 2019]. The current age of each aircraft type is approximated as the midpoint between its entry-into-service year and the present model year. This assumption represents an average fleet age under steady-state conditions, where aircraft are continuously delivered and retired over time. For example, for an aircraft type that entered service 18 years prior to the base year, the average in-service age is assumed to be 9 years. Furthermore it is assumed that an aircraft has a maximum amount of 3650 block hours per year. This corresponds with 10 block hours per day which is consistent with the value that Airbus is using in its Global Market Forecast for 2025 [Airbus, 2025]. For the aircraft that are still in production, the production rate is set to reported number of the OEM. The list price for the conventional aircraft has been determined by a regression based on data of [Axion Aviation Group, 2015]. By grouping them based on aircraft size (regional jet, narrow body, wide body) a regression has been done based on the number of seats. The results of this regressions can be found in Table 5.

The fuel consumption of the aircraft can be calculated via the adaptation of equation (1) from [Schäfer et al., 2019]. The adaptation can be found in Equation 5

$$\dot{m} = \frac{V}{(L/D) \cdot \eta_{\text{fuel}} \cdot \text{LHV}} \frac{W_{fuel}}{\ln \frac{W_i}{W_f}} \tag{5}$$

In Equation 5, the parameters lift-to-drag ratio L/D and η_{fuel} had to be estimated. These values were split up per aircraft size. For regional jets, narrow body and wideboy aircraft, the L/D has been set to $\{18, 19, 20\}$

Table 5: Regression formulas for list price for conventional aircraft

Size	List price formula [M€]	R^2
Regional jet	0.1973 · seats + 8.5911	0.9956
Narrow body	0.378 · seats + 26.523	0.914
Wide body	0.9528 · seats - 41.502	0.8682

Table 6: Validation of fuel flow determination. $\dot{m}$ is in kg/hr.

Aircraft	$\dot{m}$ model	$\dot{m}$ online	Difference
E295	2062	2352	12.33%
A20N	2418	2184	-10.71%
B788	5413	6750	19.81%

respectively. For the tank to propulsive efficiency η_{fuel}, this division is {0.3,0.28,0.29}. The mission mass fraction $\frac{W_i}{W_f}$ has been determined by $\frac{MTOW}{MTOW-W_{fuel}}$. To validate this method, the resulting fuel consumptions are compared for a regional jet (Emraer 195 E2) narrow-body (A320neo) and a widebody (Boeing 787-800) in Table 6 with values found from the online consumption calculator tool [ConsumptionCalculator.io, 2025]. Overall, the model-derived fuel flows show reasonable agreement with external reference values, with deviations remaining within a 10–20% band that is acceptable given the simplified aerodynamic and propulsion assumptions used in the method. The input data can be found in Table A.6.

The same data had to be obtained for the upcoming aircraft with the new technologies. The identified set for the new aircraft were the programs from Figure 1 that still exist at the time of writing. This resulted in a set of 24 aircraft consisting of four electric, nine hybrid electric, eight hydrogen fuel cell and three hydrogen combustion aircraft. The seating capacity, range and entry into service year were obtained from the websites of the manufacturer. If it was stated at the website, the cruise speed was also obtained from there. If it was not there, a regression was performed based upon a data set of reference aircraft for which the new aircraft have comparable seating capacity and mission range. The formula and corresponding R^2 value can be found in Table 7. The list price was estimated by using a rule of thumb from an industry expert: €500,000 per seat. The MTOW was also obtained from the website or used a regression was used from the same data set as for the cruise speed. The used regression formula can also be found in Table 7. The MTOW regression shows a high goodness of fit ($R^2 = 0.95$), indicating that seat count and range explain most of the variance in aircraft mass. In contrast, the cruise-speed regression has a lower goodness of fit ($R^2 = 0.543$), reflecting that speed depends on additional design factors not captured by these two variables but still provides a reasonable first-order estimate where data are missing.

Table 7: Regression formulas used for approximation of future aircraft parameters

Parameter	Regression formula	R^2
Cruise speed [kts]	203+0.45· Seats + 0.069 · Range	0.543
MTOW[kg]	$e^{5.3+1.15\cdot\ln Seats+0.016\cdot\ln Range}$	0.95

For the estimation of the production rate, a logistics learning curve has been used. The formula for this curve can be found in Equation 6 Therefore, the production rates at entry into service PR_{EIS} and the maximum production rate after ramp up PR_{max} had to be estimated. Also the rate at which the production rate improved during ramp up had to be estimated. The differentiation of these parameters was done based on the maturity of the manufacturer. The ranges and rationale for these values are explained in Table 8. These production rates are deliberately conservative, as they represent early-market ramp-up conditions for novel aircraft technologies and manufacturers, rather than mature production levels of established legacy aircraft programmes.

$$\text{PR}_{a,y} = \text{PR}_{a,EIS} + \frac{\text{PR}_{max} - \text{PR}_{EIS}}{1 + e^{-k(y-y_{EIS})}} \tag{6}$$

Table 8: Assumed annual production rate ranges for new aircraft

Manufacturer	PR_{EIS}	PR_{max}	k	Rationale
Retrofit	20–40	60–100	0.9–1.0	No new production lines, so higher scale-up
New startup	10–30	40–60	0.8–0.9	Slow beginning due to early adopter demand and gradual supply chain development
Legacy OEM	30–50	80–120	0.8–0.9	High initial production due to experience, but relatively limited scale-up due to new processes

For the aircraft fuel burn, a similar process was used as for the conventional aircraft. However, Equation 5 does not apply for electric aircraft. Therefore, the aircrafts energy consumption per RPK could be calculated with equation (2) from [Schäfer et al., 2019]. This equation can be found in Equation 7

$$\frac{E}{RPK} = \frac{W_{AEA}}{\eta_{\text{total}} \cdot \text{PAX} \cdot \frac{L}{D}} \tag{7}$$

For this equation, the total efficiency in the energy chain η_{total} was in a range of $0.78 - 0.85$ as suggested by [Schäfer et al., 2019]. Furthermore, the L/D was assigned to the aircraft based on the L/D ratio of its assigned reference aircraft. For hybrid aircraft, a linear division was used between the aircraft range with and without the batteries in order to estimate what part of the energy would be used by the fuel flow and what part by the batteries. The input data can be found in Table A.7.

3.3 Post-processing

The size of the optimisation problem depends on the sizes of the sets that are being used. In the configuration presented in this research, the problem consists of roughly 7.5 million decision variables and 6.3 million constraints. The problem is programmed in Python and the Gurobi Optimiser is used in order to find an optimal solution. The runtime of a single AUGMECON2 run varies between 5 minutes and 1.5 hours depending on the set objective. After solving the optimization model for all ϵ-runs and scenarios, several additional steps are required to transform raw model outputs into interpretable performance metrics. These include the reconstruction of the multi-objective trade-off space, the extraction of detailed single-scenario results and the comparison of uncertainty scenarios. This section describes these procedures.

Pareto Frontier Reconstruction and Utopia-Point Evaluation

For each scenario, the model is solved with the AUGMECON2 method, once for each primary objective and for every combination of ϵ-values on a predefined grid (five points per secondary objective in this study). Merging all ϵ-runs yields a three-dimensional objective space from which the Pareto frontier is obtained by retaining only the non-dominated solutions, as described in Section 2.3.

To identify the most balanced trade-off between the three objectives, the distance to the utopia point is evaluated. The utopia point is constructed by taking, for each objective, the minimum value achieved across the corresponding single-objective runs. Conversely, the nadir point represents the worst values observed within the ϵ-grid. Because the objectives differ in scale, the distance must be computed using normalised values. The normalisation of an objective x is given by Equation 8, and the Euclidean distance to the utopia point is defined in Equation 9.

$$\bar{x} = \frac{x - x_{utopia}}{x_{nadir} - x_{utopia}} \tag{8}$$

$$d_{utopia} = \sqrt{\overline{\text{Costs}}^2 + \overline{\text{Emissions}}^2 + \overline{\text{Energy}}^2} \tag{9}$$

The solution with the smallest d_{utopia} is interpreted as the most balanced compromise for the scenario under consideration.

Single scenario results retrieval process

In addition to the objective values, several system-level performance indicators can be derived from the decision variables of a single scenario. These indicators are computed as follows:

- **Fleet evolution:** The parameter $F_{a,k,y}$ specifies the number of aircraft of type a and age k operating in year y. Summing over all age classes and aircraft types per subset yields the total fleet size per technology, enabling visualisation of the fleet transition over time.
- **Energy carrier use:** The variable $z_{a,f,p,r,y}$ defines the energy consumed by aircraft type a using fuel f produced via pathway p on route r. For combustion fuels, dividing by LHV_f yields the associated fuel mass, whereas for electricity-based propulsion $z_{a,f,p,r,y}$ directly represents electrical energy consumption.
- **Market share per technology:** Market shares can be expressed either in flights or in passenger-kilometres. The former is obtained by grouping and summing $\text{freq}_{a,f,r,y}$ over technologies, while the latter follows from $\text{freq}_{a,f,r,y} \cdot \text{seat}_a \cdot \text{dist}_r$, aggregated over all aircraft types and routes.
- **Abatement costs:** To evaluate the cost of avoiding one tonne of CO_2, a Marginal Abatement Cost Curve (MACC) is constructed [Kesicki and Strachan, 2011]. The abatement cost reflects the additional operational expenditure relative to a fossil baseline per unit of CO_2 avoided. Capital-related terms such as R&D costs, aircraft acquisition, and early-retirement penalties are not attributable to individual energy carriers and are therefore excluded. The abatement cost for pathway p of energy carrier f is given by

$$AC_{f,p} = \frac{\sum\limits_{a \in A} \sum\limits_{r \in R} \sum\limits_{y \in Y} (\text{FuelCost}_{a,f,p,r,y} + \text{InfraCost}_{a,f,p,r,y} + \text{EmissionCost}_{a,f,p,r,y})}{\text{Emissions}_{\text{baseline}} - \text{Emissions}_{f,p}}. \tag{10}$$

Sensitivity analysis

To assess the robustness of the system-level performance indicators under uncertainty, three sensitivity axes are embedded directly into the optimisation model:

- **Well-to-Wake (WTW) emissions case:** As the different energy carriers rely on distinct production pathways and feedstocks, their upstream lifecycle emissions vary significantly. A *best* and a *worst* WTW reduction case is therefore specified for each fuel pathway. The SAF values are obtained from [ICAO, 2023], while the values for the hydrogen and electricity pathways follow [Neiva et al., 2022]. The used inputs for both cases can be found in Table A.8.

- **SAF adoption trajectory:** Although the SAF blending mandates of the ReFuelEU Aviation regulation [EU, 2023] are legally defined, their long-term realisation remains uncertain due to future policy, investment pace and supply-chain development. To capture this uncertainty, three cases (*low*, *medium*, *high*) are adopted based on the scenarios in [EUROCONTROL Business Cases, 2025], covering both overall SAF and eSAF-specific mandates. The used input for the three cases can be found in Table A.9.

- **Market growth:** Future passenger demand is uncertain and directly affects total emissions, required fleet size, operational costs and energy demand. Three demand projections (*low*, *medium*, *high*) are taken from the literature reviewed in Section 2.1. The used input for the three cases can be found in Table A.10.

Together, these axes yield $2 \times 3 \times 3 = 18$ distinct scenarios. Each scenario has been given its own number. The specifications for these numbers can be found in Table B.1 in the appendix. For each scenario, the model is solved for all ϵ-combinations under the AUGMECON2 algorithm. This produces a complete multi-objective trade-off space and one closest-to-utopia solution per scenario. After the single-scenario results retrieval process, the set of 18 utopia-closest solutions forms the basis for evaluating the ranges of the key system-level performance indicators.

In addition to the three uncertainty axes embedded in the optimisation, a fourth sensitivity axis is evaluated in post-processing: the learning-curve effects on infrastructure costs. These effects represent cost reductions with cumulative production, typically expressed as a fixed percentage decrease for every doubling of production capacity (Wright's law, [Connor, 2022]). Because production volumes of the new energy carriers are endogenous outputs of the model, incorporating learning directly would make the cost coefficients endogenous and violate the linearity of the optimisation. Therefore, the learning-curve effects are applied in post-processing, allowing the potential impact on system costs to be assessed without altering the optimisation structure.

Together, these post-processing steps provide a complete and internally consistent dataset for the results chapter, including reconstructed Pareto frontiers, utopia-closest solutions, system-level performance indicators, marginal abatement cost components, and cross-scenario uncertainty ranges.

4 Results and discussion

This chapter presents and discusses the results of the optimisation model, structured to progressively build insight from extreme solutions toward balanced transition pathways. Section 4.1 first analyses the single-objective results to illustrate how cost minimisation, emissions minimisation, and upstream clean energy minimisation individually shape fleet composition, energy carrier demand and emissions outcomes. Section 4.2 then introduces the multi-objective formulation, presenting the Pareto frontiers and motivating the selection of a representative closest-to-utopia solution. Building on this, the system-level performance of the closest-to-utopia solutions across all scenarios is examined in Section 4.3, covering fleet evolution, energy carrier production, clean energy demand, and emissions trajectories.

4.1 Single objective optimisation results

This section discusses the behaviour of the model when each objective is optimised individually: system-level discounted costs, CO_2 emissions or clean energy demand. The results are evaluated using system-level performance indicators, including fleet composition, clean energy demand and emissions abatement.

Figure 3 shows the fleet evolution by technology group under single-objective optimisation, revealing clear differences across objectives. When minimising costs, the fleet remains dominated by conventional aircraft throughout the horizon. This outcome is driven by the ability to meet emissions constraints primarily through SAF blending, which allows continued use of the existing fleet while avoiding the high aircraft acquisition costs associated with novel propulsion technologies. Although SAF has higher fuel costs than conventional kerosene, it remains the most cost-effective system-level option under cost minimisation. Electric aircraft are introduced

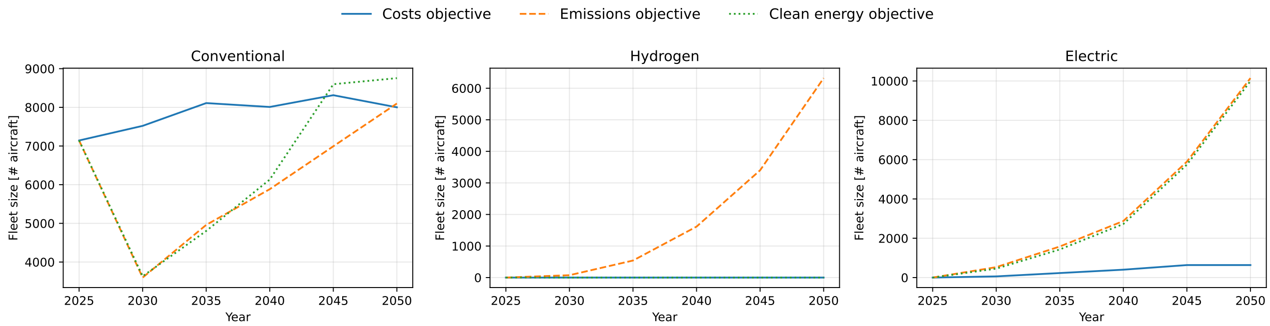


Figure 3: Fleet evolution under single objective optimisation

only gradually and at limited scale, while hydrogen aircraft are not deployed due to their high aircraft and infrastructure costs and limited early availability.

In contrast, the emissions-optimal solution deploys both electric and hydrogen aircraft rapidly and at large scale. Hydrogen propulsion becomes attractive in this case because it achieves large well-to-wake emissions reductions and eliminates tank-to-wake CO_2 emissions, making it highly effective when cost considerations are excluded from the objective. The clean energy–optimal solution also features substantial electrification but excludes hydrogen entirely, reflecting the high upstream energy requirements of hydrogen production relative to direct electrification. While synthetic SAF pathways are also energy intensive, their use is partly enforced through blending mandates and they can be deployed within the existing fleet, whereas hydrogen aircraft remain fully avoidable.

The large electric fleet sizes observed in the emissions and clean energy optimal solutions should be interpreted in the context of aircraft capacity and route structure rather than as a one-to-one replacement of conventional aircraft. The electric aircraft considered are predominantly small, short-range designs with limited seating capacity, requiring higher frequencies and larger fleets to satisfy demand on short-haul routes. The pronounced reduction in the conventional fleet around 2030 in the emissions and clean energy optimal solutions reflects an artefact of single-objective optimisation, in which conventional aircraft are retired aggressively to achieve immediate objective improvements before being reintroduced as demand continues to grow. Overall, these results demonstrate that cost minimisation favours prolonged reliance on conventional aircraft supported by SAF, emissions minimisation drives rapid adoption of hydrogen and electric propulsion, and clean energy minimisation prioritises electrification while avoiding fully energy-intensive hydrogen pathways.

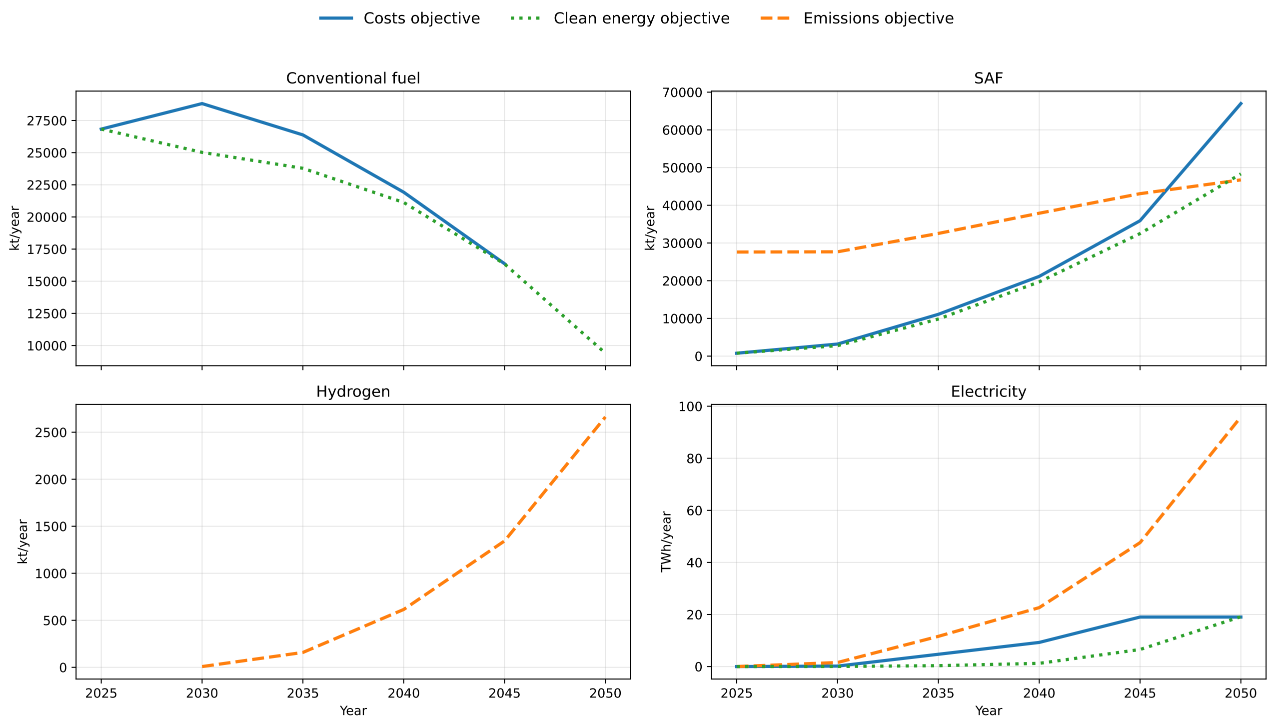


Figure 4: Energy carrier demand under single objective optimisation

Figure 4 shows the resulting energy carrier demand under single-objective optimisation and directly reflects the fleet composition outcomes discussed above. In the cost-optimal solution, the transition is primarily realised through fuel substitution rather than fleet renewal, with increasing SAF uptake enabling emissions reductions while the existing fleet remains in operation. When emissions are minimised, energy carrier demand shifts strongly towards hydrogen and electricity, mirroring the rapid deployment of hydrogen and electric aircraft in the fleet. The clean energy-optimal solution exhibits a more moderate transition, with increased reliance on electricity while largely avoiding hydrogen due to its high upstream energy requirements. Overall, the figure illustrates how each objective induces a distinct energy carrier structure that follows directly from the underlying fleet transition strategy.

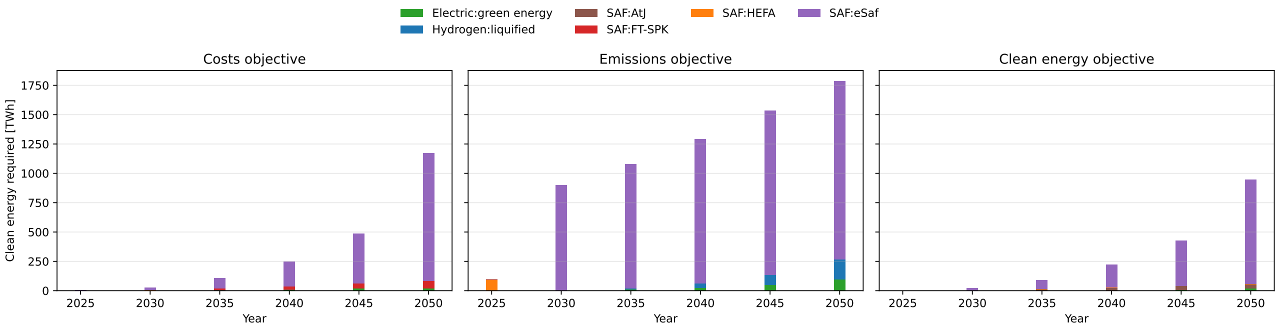


Figure 5: Clean energy demand under single objective optimisation

Figure 5 presents the evolution of clean energy demand for the three different objectives decomposed by their energy carrier and production pathway combinations. For all objectives, the main driver of the clean energy demand is the eSAF pathway. This reflects the eSAF mandates. For the cost optimal solution, the energy is furthermore driven by the SAF FT-SPK pathway which reflects the preference of SAF based operations. The emissions optimal solution shows a steep increase in the clean energy demand. This is mainly due to its preference for eSAF and its adoption of hydrogen. Both of these energy carriers require a significant amount of clean energy upstream. The clean energy optimal solution is, next to the dominant eSAF, also driven by the AtJ pathway and its electric uptake.

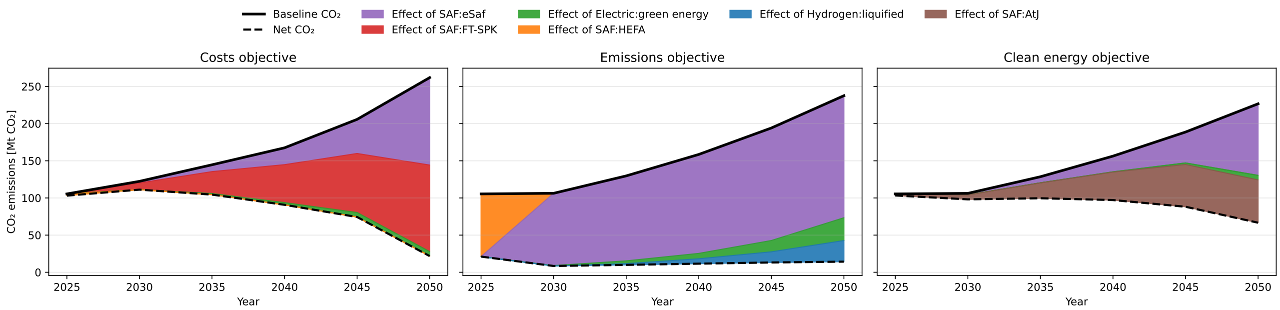


Figure 6: CO_2 emissions under single objective optimisation, decomposed into baseline emissions and the contributions of individual mitigation pathways. The dashed line indicates net emissions after accounting for all abatement effects.

Figure 6 decomposes the evolution of CO_2 emissions over time for each single-objective solution into the baseline emissions and the contributions of the different mitigation pathways. Although the cost- and emissions-optimal solutions achieve comparable net abatement levels by 2050, the underlying drivers differ fundamentally. In the cost-optimal solution, emissions reductions are dominated by SAF deployment, in particular the FT-SPK pathway, with additional contributions from eSAF in later years, while changes in aircraft technology play only a minor role. By contrast, the emissions-optimal solution relies primarily on deep decarbonisation pathways, with large contributions from eSAF, hydrogen and electrification, reflecting a strategy that prioritises maximum life-cycle emissions reductions irrespective of energy and cost penalties. The clean energy–optimal solution yields the lowest overall abatement, as it avoids both hydrogen and energy-intensive SAF pathways, limiting emissions reductions to those achievable through electrification and constrained SAF use. This confirms that minimising clean energy demand restricts the extent of achievable emissions reductions, particularly in later years when deeper decarbonisation would otherwise require energy-intensive mitigation pathways.

To enable a direct comparison between the single-objective solutions, Table 9 summarises the cross-objective performance of each solution across all three objectives. Each metric is normalised to its own single-objective optimum, such that the diagonal entries equal 100% by construction. The off-diagonal values therefore quantify the relative deterioration in the remaining objectives when optimising a single metric, allowing the severity and asymmetry of trade-offs between discounted system costs, CO_2 emissions, and clean energy demand to be assessed independently of their differing units and scales. The results show that cost minimisation leads to CO_2 emissions exceeding the emissions-optimal benchmark by more than a factor six, while emissions minimisation incurs an approximately fourfold increase in clean energy demand due to large-scale deployment of hydrogen and electric aircraft. Clean energy minimisation exhibits comparatively smaller cost penalties but still results in a sevenfold increase in emissions relative to the emissions-optimal solution. Overall, these findings demonstrate that none of the single-objective solutions represents a balanced transition pathway: one that achieves simultaneous progress across costs, emissions, and clean energy demand, without any single objective improving only through disproportionate deterioration in the others. Each solution strongly favours one objective while inducing substantial penalties in the others, motivating the multi-objective optimisation analysis presented in the next section.

Metric	Optimised for **Costs**	**Emissions**	**Clean Energy**
Costs	100.00%	418.09%	216.48%
Emissions	643.91%	100.00%	704.39%
Clean Energy	119.40%	391.61%	100.00%

Table 9: Cross-objective outcomes expressed as a percentage relative to the single-objective optimum.

4.2 Multi objective optimisation results

This section presents the multi-objective optimisation results by first interpreting the shape of the Pareto frontier and the dominant trade-offs between discounted system costs, emissions and clean energy demand. A representative compromise solution is then selected using a normalised distance-to-utopia metric, yielding the closest-to-utopia (C2U) point that balances the three objectives. Finally, the consistency of the Pareto structure and C2U location across all scenarios is summarised to support the robustness of the derived transition insights.

Figure 7 presents the 3D Pareto frontier for the optimisation problem for the first scenario, shown through its two dimensional projections and the full 3D objective space. As the qualitative structure of the Pareto frontier is consistent across all scenarios, only the first scenario (*WTW: best, SAF: high, Market growth: high*) is discussed in detail.

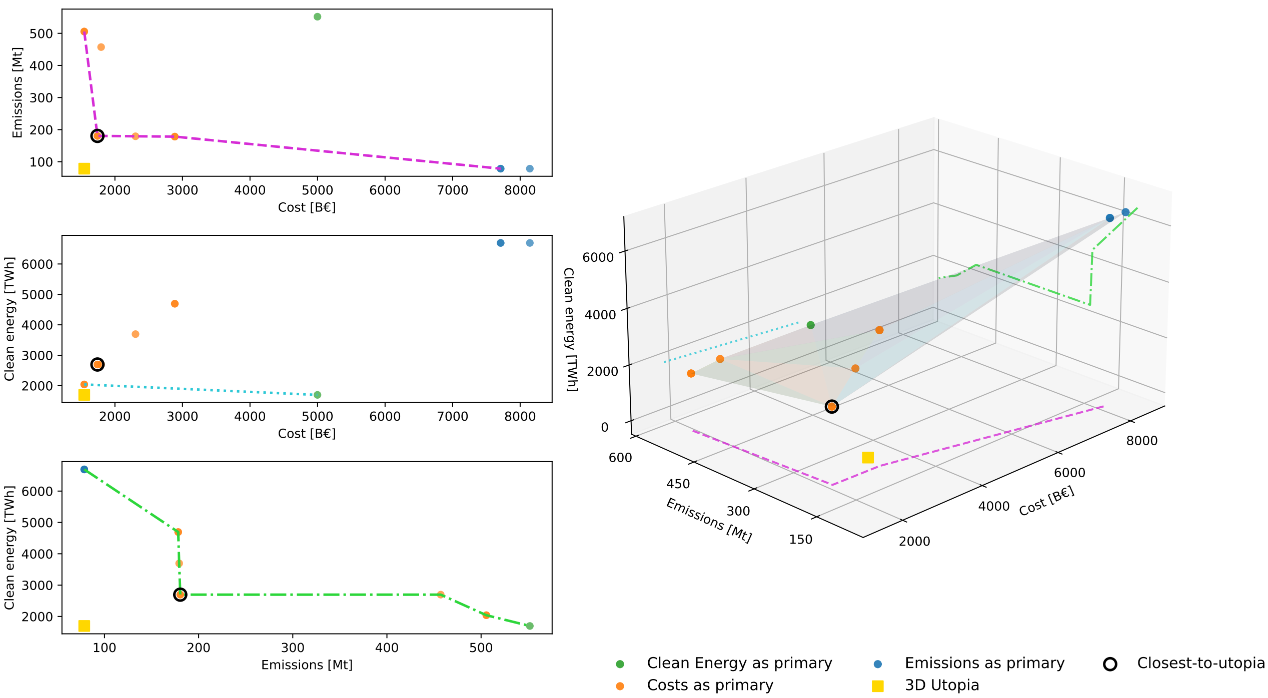


Figure 7: Pareto frontier overview for the first scenario

The cost–emissions projection (top left) shows a pronounced trade-off with a clear “knee”. Moving from the cost-optimal point (top left orange point) to the closest-to-utopia solution (black circle) yields a large emissions reduction for a relatively small cost increase, because this shift effectively tightens the emissions requirement relative to the pure cost optimum and the model can initially comply by selecting the lowest-cost abatement options. Beyond this point, approaching the emissions-optimal extreme (blue) rapidly increases costs while delivering smaller incremental emissions reductions, reflecting the growing capital intensity of deep decarbonisation as the optimisation increasingly relies on disruptive fleet turnover and new infrastructure deployment.

A similar pattern is visible in the trade-off between costs and clean energy in the middle-left projection. Moderate increases in costs lead to only limited reductions in clean energy uptake. In this near-cost-optimal region, the optimisation mainly applies marginal operational changes. It reallocates energy demand within the existing fleet across drop-in fuel pathways. Where feasible, it also assigns a limited share of short-haul operations to alternative propulsion. It avoids major fleet and infrastructure restructuring. Reducing clean energy demand further causes costs to rise rapidly. Additional reductions require a different technology portfolio. They also require accelerated fleet turnover and new infrastructure investments, consistent with Figure 3. Nevertheless, clean energy demand remains substantial across the Pareto frontier. This shows that large-scale clean energy provision is an intrinsic requirement of deep aviation decarbonisation.

The trade-off projection between emissions and clean energy uptake can be found in the lower left projection of the figure and it shows clearly that the two objectives are not aligned. Moving from the high emissions solutions (the right side of the projection) towards lower emitting options shows a marginal increase in clean energy demand. This shows that a substantial amount of emissions reduction can be achieved with the SAF based operations which require relatively low clean energy to produce. In order to really minimise the emissions, the clean energy demand rises enormously due to the larger scale introduction of the energy intensive propulsion methods such as eSAFs and hydrogen. This indicates once again that deep decarbonisation within the model increasingly relies on options with high upstream clean energy requirements, which explains the steep energy penalty when minimising the emissions.

Now that the shape of the 3D Pareto front is explained, a representative compromise solution has to be chosen. This is done by calculating the distance to the Utopia point as described in Section 2.3. The Utopia point is visually represented by the yellow square in Figure 7. The distances to the Utopia point are calculated in normalised space and the point with the lowest distance is specified as the closest-to-Utopia (C2U) point. This Closest-to-Utopia point is visually marked with the black ring in the figure. As can be seen, this C2U point lies well inside the Pareto surface rather than near any of the extremes. Compared to the cost-optimal solutions, it achieves substantial reductions in emissions with an acceptable increase in energy demand. At the same time, it avoids the steep increases related to the emissions oriented solutions. This position therefore reflects a balanced tradeoff between all objectives.

Across all evaluated scenarios, the Pareto structure and the location of the closest-to-utopia solutions exhibit consistent patterns. In every case, strong trade-offs are observed between discounted system costs and the sustainability objectives, while emissions and clean energy demand show a more complex, non-monotonic relationship. The closest-to-utopia solutions are systematically associated with cost-optimal primary runs, indicating that cost minimisation provides the most flexible baseline from which improvements in emissions and clean energy performance can be achieved through ϵ-constraints. This does not imply that costs dominate the optimisation outcome, but rather that economically efficient system configurations offer the largest feasible adjustment space for sustainability improvements at a marginal penalty. As a result, balanced transition pathways consistently emerge from cost-focused solutions that are subsequently steered towards lower emissions and clean energy demand, a trend that remains robust across all scenario assumptions.

To position the closest-to-utopia (C2U) compromise outcomes relative to established decarbonisation roadmaps Figure 2, Table 10 compares the implied attribution of emissions reduction across SAF and hydrogen/electric flight operations. The model's median C2U outcome assigns 67.4% of emissions reduction to SAF, which is broadly consistent with the SAF-dominant contribution reported in major roadmaps (approximately 51–65%). In contrast, the median contribution of hydrogen and electric operations is 5.3%, close to the NLR estimate (6%) but substantially below IATA (13%) and ATAG (22%). This suggests that, under the techno-economic structure and constraints modelled here, balanced (C2U) transition pathways remain SAF-led, while hydrogen/electric aircraft contribute primarily as niche abatement options rather than dominant system-wide levers. Across the scenario space, the corresponding attribution spans 33–85% for SAF and 1–17% for hydrogen/electric operations, highlighting scenario-contingency despite the SAF-dominant median.

4.3 Sensitivity analysis

This section examines how uncertainty in key modelling assumptions affects technology deployment and system-level outcomes. First, marginal abatement cost curves (MACCs) are used to assess the operational cost-effectiveness and abatement potential of individual energy carrier–pathway combinations. Second, technology deployment is analysed across scenarios in terms of passenger-kilometres and number of flights, followed by an evaluation of system-level outcomes for the closest-to-utopia solutions including fleet evolution, energy de-

Table 10: Emissions reduction contributions per pillar in 2050 comparison between developed model and industry roadmaps.

	SAF contribution	H_2 + electric flight contribution
NLR	51%	6%
FAA[a]	n/a	n/a
IATA	65%	13%
ATAG	61%	22%
Developed model median	67.44%	5.33%

[a] FAA does not report specific percentages per pillar; however, SAF is the main lever in the roadmap.

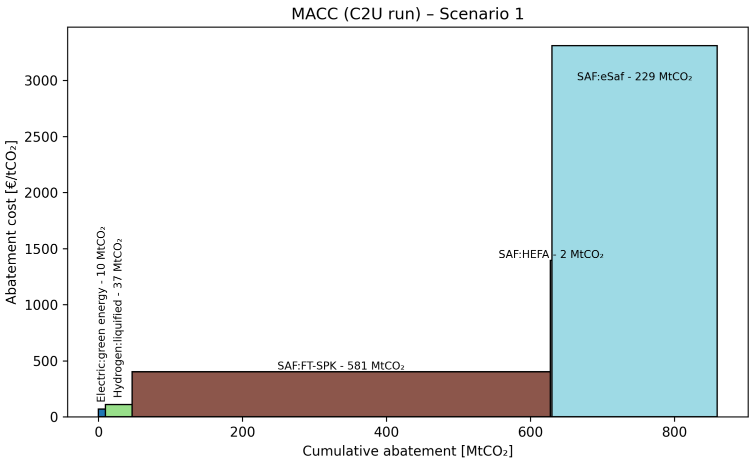


Figure 8: Marginal Abatement Cost Curve for Scenario 1

mand, and emissions. Third, learning-curve effects on infrastructure costs are assessed in post-processing as an additional sensitivity axis. Finally, the relative influence of well-to-wake assumptions, SAF deployment trajectories, and market growth on the system objectives is quantified to identify the dominant sources of uncertainty. Throughout the section, the scenario numbering references are consistent with Table B.1 in the appendix.

MACC

Figure 8 presents the marginal abatement cost curve (MACC) for the closest to utopia solution for Scenario 1. The MACC orders mitigation options by increasing abatement costs and displays their cumulative potential to reduce CO_2 emissions. As described in Section 3.3, the abatement cost for an energy carrier f with production pathway p is defined as the additional operational expenditures relative to a fossil baseline. In this model they include the fuel production costs, infrastructure investments and the emissions related charges. The abatement costs are therefore calculated with Equation 10. The electricity and hydrogen pathways can be found on the left side of Figure 8, indicating low abatement costs for these technologies. However, with 10 Mt and 37 Mt abatement potential, their abatement potential remains limited. This is due to the short ranges and limited aircraft availability throughout the transition. With these low abatement costs and low potentials, these technologies can contribute efficiently to abatement where possible, but cannot deliver the large scale emissions reductions on their own.

The major portion of the MACC is dominated by the SAF pathways. SAF produced via the FT-SPK pathway occupies a large share of cumulative abatement at moderate abatement costs. Its dominant presence reflects its broad compatibility with the existing fleet without requiring disruptive changes to aircraft technology. The SAF HEFA pathway appears at more than double the abatement cost of FT-SPK while contributing only a very limited abatement potential. Note that the MACC reflects the model-optimal 2025–2050 deployment under the assumed costs and constraints, rather than present-day SAF market shares. This outcome is driven by the early availability of HEFA in combination with the initial SAF mandates. As a result, the optimisation deploys HEFA primarily in the early years to satisfy minimum SAF requirements at lowest short-term cost, while avoiding its use in later periods when alternative SAF pathways with larger abatement potential become available. At the rightmost end of the MACC, the eSAF pathways can be found. This pathway exhibits the highest abatement costs at more than six times the abatement costs of FT-SPK but with a significant share of abatement potential. The steep increase in costs reflects the high production and infrastructure costs for this pathway. Its relatively high abatement potential is a result of the mandatory synthetic fuel share which the industry is required to use.

Importantly, the low abatement costs of electric and hydrogen options in the MACC do not imply that these technologies are adopted early or at large scale. Their favourable position reflects operational cost efficiency conditional on deployment. The timing and extent of their uptake are governed elsewhere in the optimisation by the capital costs of the aircraft using these novel technologies. The MACC therefore complements the system-level results by indicating operational cost-effectiveness, rather than determining deployment pathways.

As the trends throughout the different scenarios are consistent, only Scenario 1 is discussed here. A detailed breakdown of the ranges for abatement costs and potentials per technology, including inter-scenario variability, is provided in Figure B.1, which is included in the Appendix. Together, these results show that while low-cost abatement options exist, achieving deep decarbonisation in aviation ultimately requires accepting substantially higher marginal abatement costs driven by clean energy-intensive fuel pathways.

While the MACC provides insight into the operational cost-effectiveness of individual abatement options once deployed, it does not explain where and to what extent these technologies are actually adopted within the system. The following section therefore shifts focus from marginal abatement costs to system-level deployment outcomes, analysing how different propulsion technologies contribute to aviation activity over time, both in terms of passenger-kilometres and number of flights.

Technology deployment across scenarios

Figure 9 presents the evolution of technology shares expressed both in passenger-kilometres and number of flights across scenarios. Considering these two factors simultaneously provides a more complete picture of how alternative propulsion techniques reshape the aviation system. In 2025, aviation activity is almost entirely delivered by conventional technologies in both pax-km and number of flights. There is a small share of SAF based operations present, reflecting the SAF mandates starting in 2025. Differences across scenarios are negligible at this stage.

By 2030, a sharp transition occurs in both metrics in the scenarios with the best case WTW reduction. This is driven primarily by the widespread adoption of SAF. This is adoption is driven by more and more SAF pathways becoming available. Throughout the worst case WTW scenarios, conventional fuels are still dominant and SAF is only used to a minimum extent.

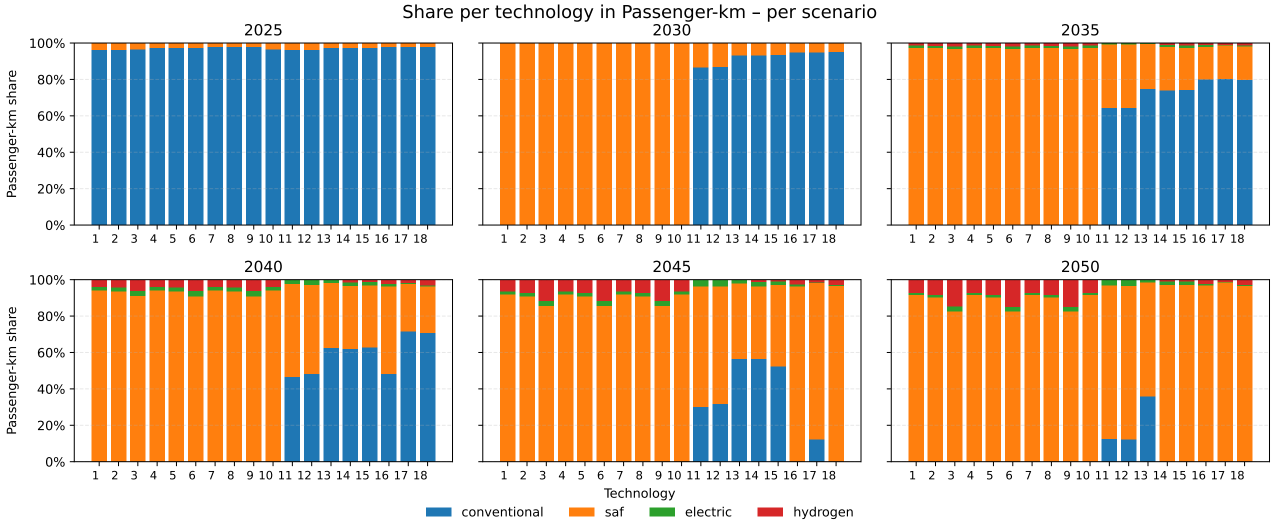
From 2035 onwards, a clear divergence emerges between the pax-km and number of flights perspectives. Electric and hydrogen aircraft begin to appear more visibly in the distribution of flights than in passenger-kilometres. Electric aircraft contribute for a small but noticable share in number of flights, but are only marginal in the passenger-kilometres share. This indicates that these aircraft are only deployed on high-frequency routes with short ranges which is to be expected given the limited ranges and capacities of these aircraft. Hydrogen technology shows a similar trend. However, from 2040 onwards, hydrogen-powered flights form a substantial part of total flight activity while their pax-km share remains more moderate.

By 2050, SAF remains the dominant energy carrier in terms of passenger-kilometres across all scenarios, underscoring its role as the backbone of system-wide transport capacity. At the same time, the flight-based perspective reveals a structurally different picture: a large fraction of flights is operated by hydrogen aircraft, with electric aircraft maintaining a smaller but stable niche. The contrast between the two metrics confirms that alternative propulsion technologies primarily reshape the operational structure of aviation rather than its aggregate transport output. In the WTW worst-case scenarios, the number of hydrogen and electric flights is around 30% lower on average than in the corresponding best-case WTW scenarios, as their higher upstream emissions intensities reduce their relative emissions benefit and make SAF-based operations comparatively more attractive within the optimisation.

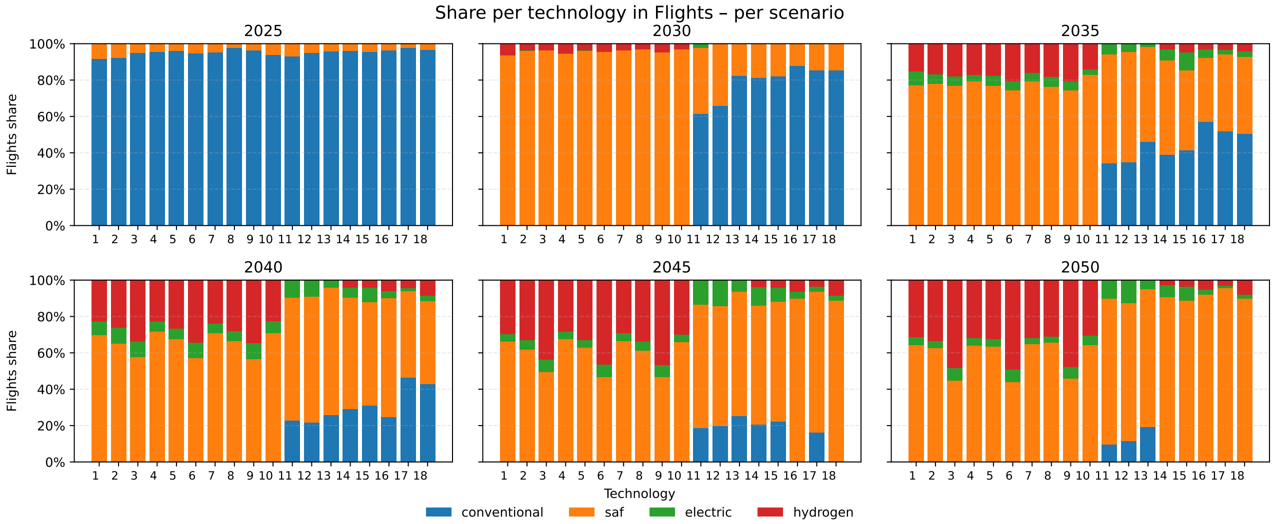
System level performance distribution

This section presents the system-level outcomes of the closest-to-utopia solutions across all scenarios. It reports the resulting fleet evolution, energy carrier production and consumption, clean energy demand, and well-to-wake CO_2 emissions, and shows how these outcomes differ across scenario assumptions.

Figure 10 shows the absolute fleet evolution by technology group for the closest-to-utopia solution across all scenarios. This figure is complemented by the corresponding fleet share distributions in Figure B.2 in the appendix. Together, these figures illustrate how differences in scenario assumptions influence the resulting fleet transition pathways. Hydrogen and electric aircraft in Figure 10 represent the set of conceptual aircraft types modelled in this work. The aircraft list and grouping for the hydrogen and electric concepts are summarised in Table B.2. The introduction of hydrogen aircraft may appear counter-intuitive, as the cost-optimal solution avoids these aircraft due to their higher capital (Figure 3). Their presence in the closest-to-utopia solutions instead reflects the effect of the imposed ϵ-constraints on emissions: in order to satisfy the emissions threshold, the optimisation is forced to deploy hydrogen aircraft despite their unfavourable cost characteristics.



(a) Technology shares by passenger-kilometres



(b) Technology shares by number of flights

Figure 9: Technology shares over time per scenario. Scenario definitions can be found in Table B.1.

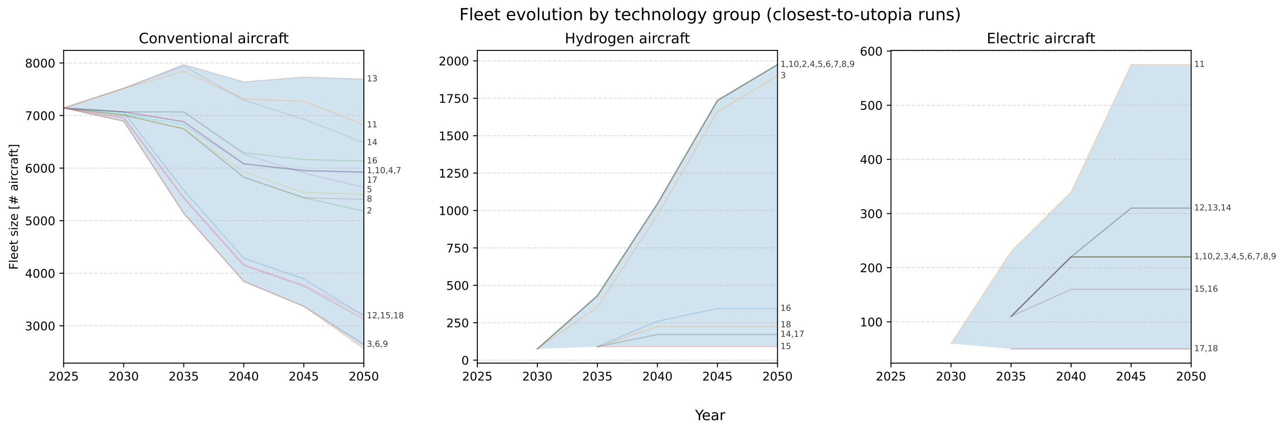


Figure 10: Fleet evolution across all scenarios. The numbers on the right correspond to the scenario defined in Table B.1.

Fleet evolution by technology group shows that market growth is the primary determinant of the remaining conventional fleet size. The smallest conventional fleets in 2050 occur in the market-low scenarios S03, S06 and S09, while the largest fleets are found in the market-high cases S13, S11, S14 and S16, indicating that high demand can sustain a substantial conventional backbone even under unfavourable WTW and SAF conditions. Hydrogen adoption exhibits a clear regime split: scenarios S01–S10 converge towards system-scale hydrogen fleets (around 2000 aircraft by 2050), whereas scenarios S14–S18 remain limited to a few hundred aircraft, reflecting threshold-type deployment once hydrogen becomes sufficiently effective in meeting the emissions constraint. Electric aircraft display the strongest sensitivity to upstream carbon-intensity assumptions, with the largest electric fleets observed in WTW-worst scenarios with high SAF availability (notably S10 and S11), while WTW-worst scenarios combined with low SAF availability (S17–S18) show only marginal electric aircraft uptake. Consistent with this, Table B.2 indicates that electrification is selected across the full scenario space, whereas hydrogen adoption is more scenario-contingent and, when deployed, typically enters later.

Building on the fleet transition patterns, the corresponding fuel and electricity production trajectories show how changes in the aircraft mix translate into shifts in the supply of aviation energy carriers. These dynamics are shown in Figure 11. The figure is complemented by Figure B.3 in the appendix, which details the shares of the production pathways used within each energy carrier.

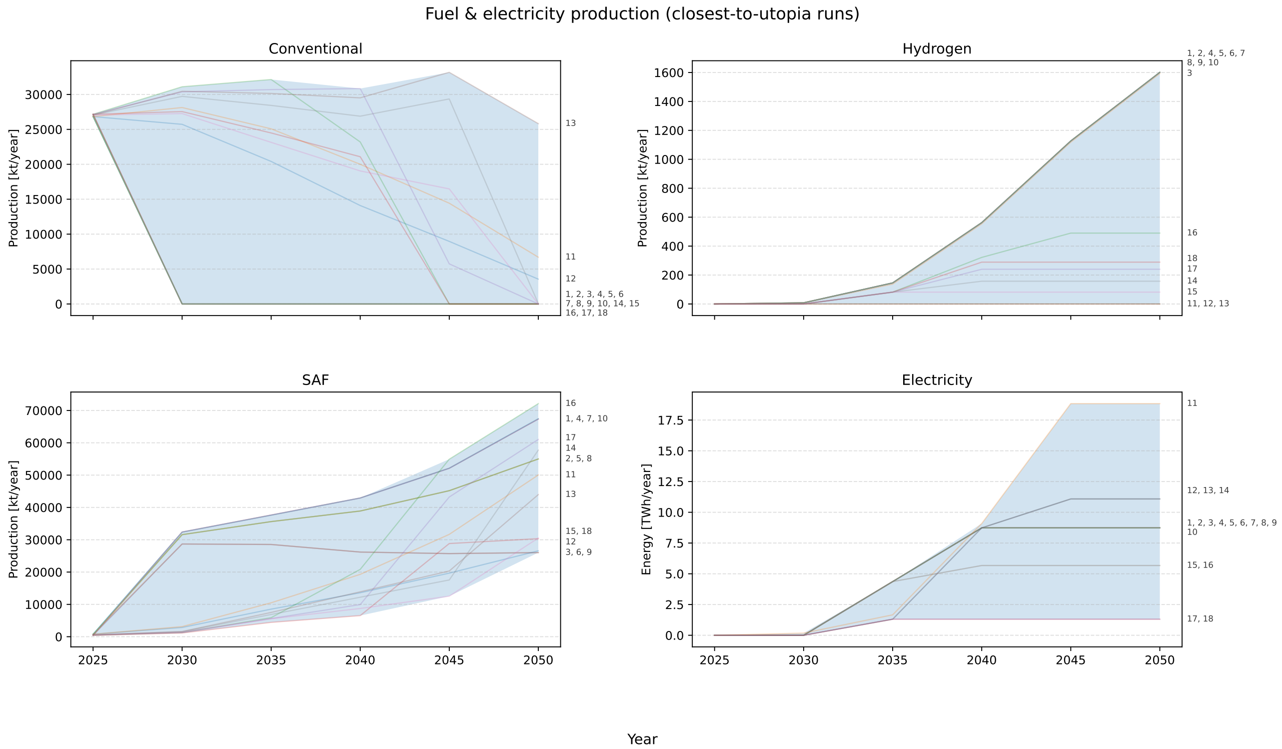


Figure 11: Energy carrier production requirements over all scenarios. The numbers on the right correspond to the scenario defined in Table B.1.

Conventional fuel declines in all scenarios, but the pace varies strongly. In WTW-best, high-SAF cases (S01–S03), conventional kerosene is effectively phased out by 2030. Scenarios with lower SAF adoption or higher market growth (S04–S09) retain conventional fuel well into the 2040s, reflecting the persistence of conventional aircraft under sustained demand.

SAF becomes the dominant liquid fuel across all WTW-best scenarios, though both timing and composition differ. High-SAF cases show rapid scale-up by 2030, initially driven by FT-SPK. From 2040 onwards, production shifts decisively towards e-SAF, which dominates by 2050 in scenarios with higher demand (e.g. S01, S04, S07). HEFA plays only a marginal, transitional role and disappears early.

Hydrogen exhibits clear threshold behaviour. In scenarios S01–S09, hydrogen production increases sharply after 2035 and reaches large-scale levels by 2050, directly reflecting the large hydrogen aircraft fleets in these cases. Where hydrogen fleet deployment remains limited, hydrogen production stays marginal.

Electricity demand remains negligible until the mid-2030s and then diverges. Scenarios with meaningful electric aircraft deployment show rapid growth between 2035 and 2045 before saturating, while scenarios with limited electric fleets maintain very low electricity demand throughout.

Overall, the results show that fleet transitions induce qualitatively different fuel supply regimes: fossil kerosene is progressively displaced, SAF evolves from bio-based to synthetic dominance depending on the WTW

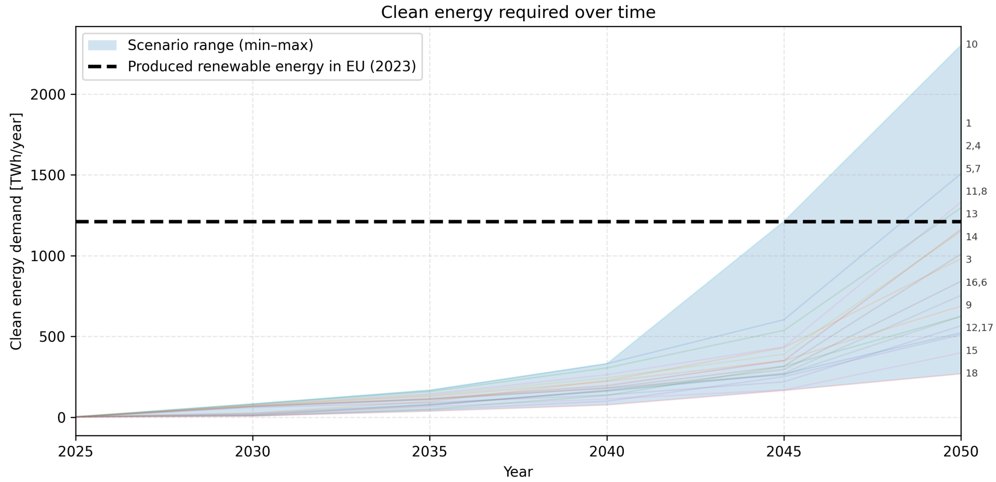


Figure 12: Clean energy demand over time. The numbers on the right correspond to the scenario defined in Table B.1.

case, hydrogen emerges only once a deployment threshold is crossed, and electricity scales selectively as a complementary carrier.

It is important to note that the electricity production shown in Figure 11 only reflects the renewable electricity supplied directly to electric aircraft. Consequently, a complete assessment of system implications requires analysing the total clean energy demand associated with all low-carbon energy carriers. The evolution of this demand across scenarios is shown in Figure 12, while its pathway-specific composition is presented in Figure B.4 in the appendix.

Across all scenarios, total clean energy demand increases monotonically over time, with modest growth until 2035 followed by a pronounced acceleration after 2040. This acceleration is driven by the increasing reliance on electricity-intensive synthetic fuels. The scenario spread remains relatively narrow in the early years but widens substantially between 2045 and 2050, primarily reflecting differences in market growth assumptions, indicating that long-term clean energy requirements are highly sensitive to this lever.

The dashed line indicates the amount of renewable energy produced within the European Union in 2023 (1,210 TWh) [Eurostat, 2024]. Although this value is expected to increase in the future, several scenarios already exceed this level by 2045. Given that only a fraction of renewable energy production can realistically be allocated to aviation, this result indicates that clean energy availability may become a binding constraint for aviation's transition towards net-zero.

The final system performance indicator to be considered is the total WTW CO_2 emissions. This evolution is decomposed in its Kaya identity drivers as explained in Equation 1. See Figure 13. The demand evolves as expected exponentially, as set by the different market growth factors. The aircraft energy intensity decreases across scenarios up to 2040, implying that fleet renewal and substitution reduces the required energy per unit of transport. After 2040, the stabilisation of fleet shares limits further reductions in aircraft energy intensity (see Figure B.2 in the appendix). The sharpest break in the Kaya drivers can be found in the carbon intensity panel. The carbon intensity drops steeply and remains low for the best-case WTW scenarios. In the WTW-worst scenarios, carbon intensity is largely governed by the SAF mandate level. Because the mandate includes a minimum share of eSAF, higher SAF ambition forces a larger deployment of eSAF even in cases where its well-to-wake performance is unfavourable. This constraint reduces the flexibility to substitute towards other energy carriers and pathways, such as FT-SPK, hydrogen, or electricity, that exhibit lower WTW emission factors under pessimistic assumptions. In low-SAF mandate scenarios, this restriction is weaker, allowing greater reliance on these comparatively cleaner options. As a result, scenarios with lower SAF ambition can exhibit a lower average carbon intensity despite deploying less SAF overall.

The interaction of demand growth, efficiency improvements, and carbon-intensity reductions leads to a rapid decline in total WTW CO_2 emissions after 2025, followed by increasing divergence across scenarios. Although all scenarios remain well below the fossil baseline, long-term emission outcomes are dominated by differences in carbon intensity, demonstrating that sustained decarbonisation depends more strongly on fuel and pathway choices than on further efficiency gains alone.

Learning curves

As explained in Section 3.3, learning-curve effects on infrastructure costs are introduced as a fourth sensitivity axis in post-processing, complementing the three uncertainty axes embedded directly in the optimisation. Direct

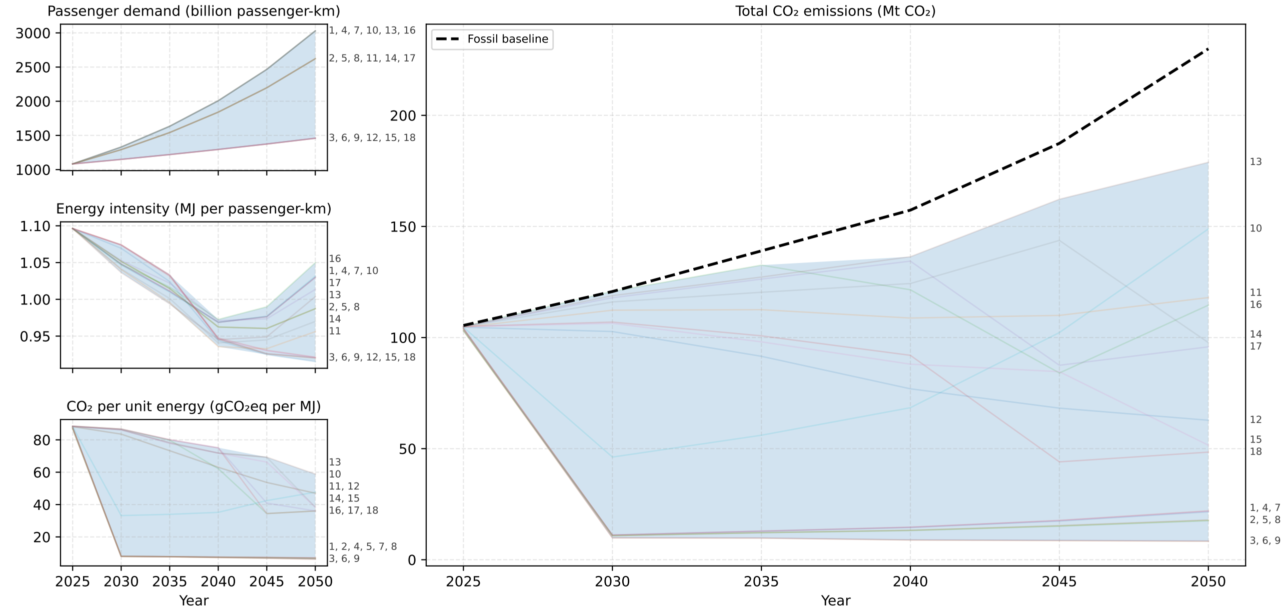


Figure 13: Kaya drivers evolution. The numbers on the right correspond to the scenario defined in Table B.1.

empirical evidence on learning rates for airport-specific infrastructure for novel energy carriers is scarce. Consequently, learning rates are inferred from expert judgement and from analogous infrastructure domains. Two studies by Melaina report learning rates in the range of 4–7 % for hydrogen refuelling infrastructure ([Melaina and Penev, 2013]; [Melaina et al., 2014]). These values are substantially lower than learning rates observed for highly modular and mass-produced technologies such as solar photovoltaics, which exhibit learning rates of approximately 20 % ([Roser, 2023]). Given the novelty, site-specificity, and regulatory complexity of aviation infrastructure, a conservative learning-rate range of 0–10 % is therefore adopted in this study.

The impact of SAF infrastructure learning on total discounted system costs for scenario 1 is shown in Figure 14. The results indicate that learning effects in SAF infrastructure can substantially reduce total system costs, with increasing learning rates leading to progressively larger cost reductions. Equivalent analyses are performed for hydrogen and electricity infrastructure; however, their total impact on system costs remains comparatively small. The aggregated results for scenario 1 are summarised in Table 11. Although the relative cost reductions for hydrogen and electricity infrastructure are marginal (below 0.01 %), the absolute savings still amount to several tens of millions of euros.

While Figure 14 and Table 11 present results for scenario 1, the qualitative conclusions hold across all scenarios. The distribution of learning impacts across scenarios is shown in Figure B.5 in the appendix. These distributions indicate that SAF infrastructure learning can reduce total system costs by approximately 10–57 %, whereas learning effects for hydrogen and electricity infrastructure remain negligible in relative terms.

Overall, the sensitivity analysis demonstrates that infrastructure learning effects are highly asymmetric across energy carriers. Learning in SAF infrastructure emerges as a dominant driver of long-term system cost reductions, reflecting both its large absolute cost contribution and its central role in most decarbonisation pathways. In contrast, learning effects for hydrogen and electric infrastructure remain limited due to their smaller share in total system costs. This finding suggests that uncertainty in future SAF cost trajectories may be as influential as uncertainty in demand growth or well-to-wake emission factors when assessing the economics of aviation decarbonisation pathways, and that endogenous learning representations for SAF infrastructure warrant consideration in future modelling work.

Table 11: Infrastructure learning rate effects of different energy carriers on total system costs for scenario 1

	SAF		**Hydrogen**		**Electricity**	
learning	**Δ [B€]**	**Δ [%]**	**Δ [M€]**	**Δ [%]**	**Δ [M€]**	**Δ [%]**
2.50%	−286	-16.4	-15	-0.0009	-7	-0.0004
5.00%	−527	-30.3	-27	-0.0016	-14	-0.0008
7.50%	−729	-41.9	-38	-0.0022	-21	-0.0012
10.00%	−898	-51.6	-46	-0.0027	-28	-0.0016

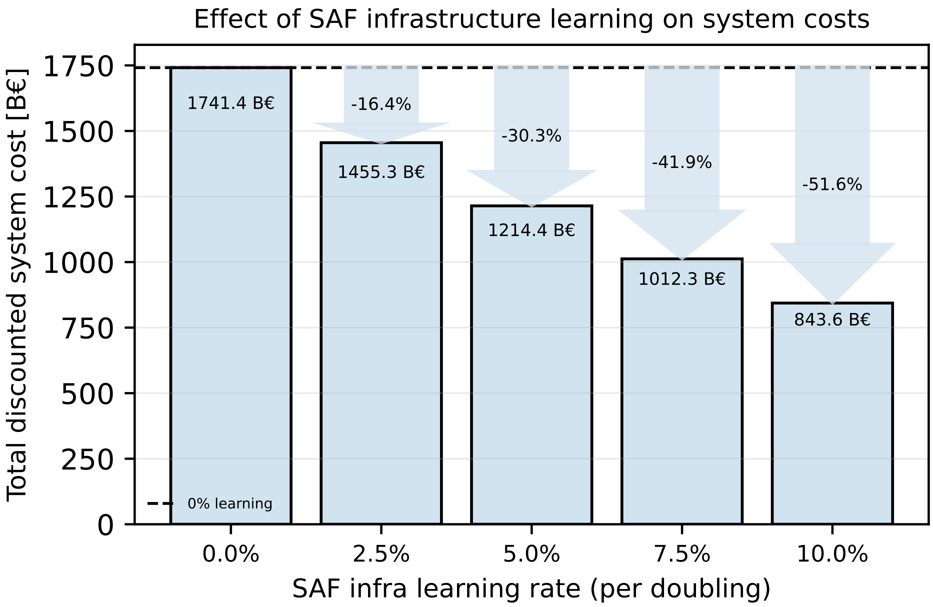


Figure 14: Impact of SAF infrastructure learning on total system costs in scenario 1

Influence on objectives

The sensitivity analysis demonstrates that different sources of uncertainty exert fundamentally different levels of influence on the evaluated system objectives, and that no single assumption dominates the aviation transition across all dimensions. The scenario dimensions related to well-to-wake (WTW) assumptions, SAF deployment trajectories, and market growth are embedded directly in the optimisation framework. As the effect of infrastructure learning rates on system costs has already been discussed in the previous section, this subsection focuses on the influence of these remaining three sensitivity axes on the three system objectives. In addition, the closest-to-utopia (C2U) distance is analysed to quantify how strongly each scenario dimension shifts the position of the selected compromise solution relative to the utopia point in the multi-objective space.

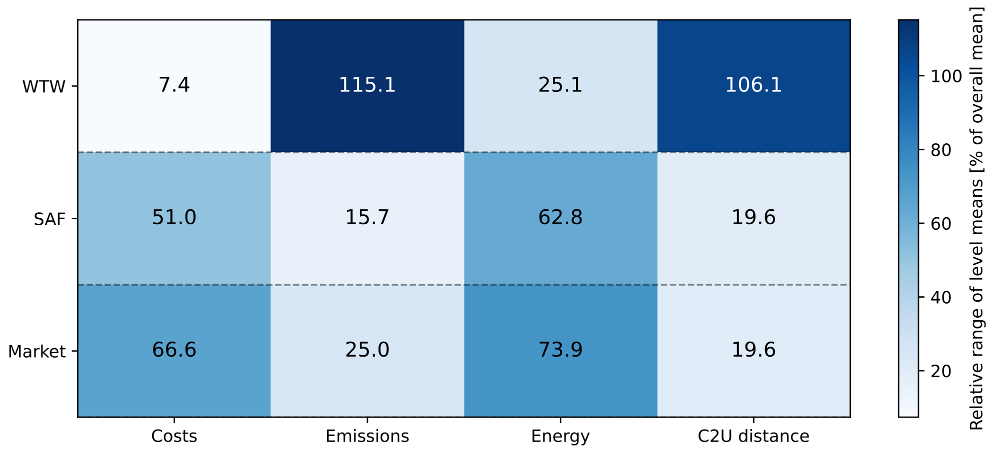


Figure 15: Scenario sensitivity heatmap. Each cell reports the normalised range across scenario levels as calculated with Equation 11. Higher values indicate a stronger influence of that assumption on the objective across its discrete levels.

Figure 15 summarises how strongly each scenario dimension affects the system outcomes. Each value indicates how much the average value of an objective varies when one scenario dimension is changed across its possible levels, while the effects of the other dimensions are averaged out. The values are normalised by the overall mean of the corresponding objective. As such, the figure provides a direct comparison of which sensitivity axis exerts the strongest influence on costs, emissions, and clean energy demand, independent of the direction of change.

Mathematically, the normalised range of scenario dimension s with $|\mathcal{S}_s|$ levels on objective O is calculated as

$$\text{Range}_{O,s} = \frac{\max_{k \in \mathcal{S}_s} \left(\overline{O}_k\right) - \min_{k \in \mathcal{S}_s} \left(\overline{O}_k\right)}{\overline{O}} \cdot 100\% \tag{11}$$

where $\overline{O}_k$ denotes the mean value of objective O across all scenarios with level k of scenario dimension s, $\mathcal{S}_s$ is the set of levels of dimension s, and $\overline{O}$ is the overall mean objective value across all scenarios.

The figure shows that different scenario dimensions predominantly influence different system objectives. Cumulative CO_2 emissions are strongly dominated by WTW assumptions, with variations between lifecycle emission factors leading to changes that exceed the overall mean emissions level across all scenarios. This indicates that emissions outcomes are primarily driven by energy carrier pathway carbon intensities rather than by mandatory SAF deployment levels or market growth.

In contrast, discounted system costs and clean energy demand are mainly governed by market growth and SAF deployment assumptions. Market growth directly scales fleet size, fuel consumption, and infrastructure requirements, resulting in substantial variation in both costs and energy demand. Increasing SAF ambition further amplifies clean energy demand through the deployment of synthetic fuels, which are significantly more energy-intensive upstream, and consequently also contributes to higher system costs.

The C2U distance column in Figure 15 indicates how changes in individual objectives translate into shifts of the selected closest-to-utopia (C2U) compromise outcome. Its sensitivity reflects the dominant drivers of the underlying objectives: WTW assumptions mainly affect C2U distance through changes in lifecycle emissions intensities, while market growth and SAF deployment influence it by scaling system costs and clean energy demand. Accordingly, the scenario dimensions that most strongly alter the multi-objective trade-off structure also induce the largest changes in C2U distance, implying that C2U distance is dominated by upstream carbon intensity (WTW), with SAF ambition and demand growth exerting a much smaller secondary influence.

5 Conclusions and future work

This research investigated the techno-economic drivers and uncertainties shaping the transition toward a competitive and sustainable European aviation sector by 2050, using a system-level techno-economic optimisation model combined with scenario-based sensitivity analysis. By evaluating trade-offs between costs, emissions and clean energy demand across 18 scenarios, the study provides quantitative insight into how different assumptions influence feasible transition outcomes.

The results show that the trade-off between discounted system costs, cumulative well-to-wake CO_2 emissions, and total clean-energy demand best captures the effectiveness of transition scenarios. Costs reflect economic competitiveness, emissions capture lifecycle environmental performance, and clean energy demand links aviation decarbonisation to energy-system feasibility. Supporting indicators such as fleet composition, energy carrier production, and marginal abatement costs aid interpretation, with clean energy demand in particular distinguishing low-emission outcomes with fundamentally different upstream energy requirements.

The transition is mainly driven by fuel carbon intensity, aircraft capital costs and availability, infrastructure learning curves and SAF deployment mandates. SAFs form the backbone of the transition due to fleet and infrastructure compatibility, with production shifting from bio-based to synthetic pathways as mandates tighten. Hydrogen and electric aircraft offer low operational abatement costs but are constrained by relatively late entry into service, limited range, and high capital costs, confining their role to specific market segments. Infrastructure learning effects are asymmetric: learning in SAF infrastructure can substantially reduce system costs due to its scale, while learning in hydrogen and electric infrastructure has a negligible relative impact.

Different sources of uncertainty affect different system objectives. Well-to-wake emission assumptions dominate cumulative emissions outcomes, often outweighing differences in technology deployment levels. Market growth assumptions strongly influence both system costs and clean energy demand by scaling fleet size and energy consumption. SAF deployment trajectories, particularly synthetic fuel mandates, significantly amplify clean energy demand and system costs and can even counteract emissions benefits under pessimistic lifecycle assumptions. Consistently, the closest-to-utopia (C2U) distance is most sensitive to WTW assumptions, indicating that upstream carbon-intensity uncertainty has the largest effect on the selected "balanced" compromise outcome, with SAF ambition and demand growth playing a much smaller secondary role. These uncertainties also induce threshold behaviour, especially for hydrogen aircraft deployment, demonstrating that small changes in assumptions can lead to qualitatively different system configurations.

In response to the main research question, an effective transition to a cost-competitive and sustainable European aviation sector by 2050 is driven by robust cost-efficient system configurations that are progressively steered toward lower emissions under policy and technology constraints, rather than by any single "optimal" technology pathway. Across the scenario space, the dominant techno-economic drivers are fuel carbon intensity (well-to-wake), demand growth that scales fleet and energy use, and the stringency and composition of SAF deployment mandates, complemented by aircraft availability and capital costs. The main uncertainties are likewise structural: well-to-wake assumptions dominate cumulative emissions outcomes, while market growth and SAF ambition primarily govern system costs and clean energy demand. In this transition architecture, SAF provides the backbone through fleet and infrastructure compatibility, while hydrogen and electric aircraft contribute in smaller but strategically important market niches. Finally, the results indicate that clean-energy availability can become a binding constraint, implying that aviation decarbonisation policy must be designed in concert with broader energy-system planning.

While this study provides a consistent system-level assessment of the techno-economic drivers and uncertainties shaping the transition toward net-zero aviation, several modelling assumptions were required to maintain computational tractability.

Future work should explicitly test model dependency by perturbing the assumptions and constraint structures that shape the feasible transition space. A potential improvement is to extend the SAF sensitivity analysis with policy-counterfactual cases that relax the mandate structure itself (including a no-minimum-share case study) and quantify how the Pareto frontier, closest-to-utopia solution, fleet mix, and energy demand shift. Complementary runs should vary hydrogen/electric cost items and production ramp-up limits to identify drivers of adoption thresholds. Finally, incorporating explicit feedstock availability (biomass/renewables supply caps or supply curves with cross-sector competition) would improve realism and may materially constrain SAF scaling.

In this research, learning-curve effects for infrastructure investments were applied in post-processing, as fully endogenising learning within a single optimisation problem would violate the linear structure of the MILP formulation. However, the sensitivity analysis demonstrated that infrastructure learning can significantly reduce total system costs, particularly for SAF-related infrastructure. Incorporating learning-curve effects more directly within the optimisation framework would therefore be a valuable extension, as it would improve the realism of long-term cost projections.

In the current formulation, infrastructure costs are allocated proportionally to energy use on a per-flight basis, expressed in €/MJ, which ensures tractability within a linear optimisation framework but abstracts from the discrete and location-specific nature of infrastructure investments. Future work could reformulate infrastructure requirements at the airport level, explicitly modelling the presence, capacity, and expansion of energy infrastructure at individual airports. Such an approach would require introducing a representation of flight scheduling, or suitable proxies for peak energy demand, to size infrastructure based on actual temporal uptake rather than annual averages. This would allow infrastructure investments to be represented more realistically, capturing capacity thresholds, scale effects, and the timing of investments. Making infrastructure airport-specific would therefore improve the realism of capital expenditure estimates and strengthen the model's applicability for assessing infrastructure deployment strategies and related policy interventions.

Finally, the current time horizon extends to 2050, which is consistent with prevailing net-zero targets.However, many capital-intensive investments in aircraft development, infrastructure, and energy production have economic lifetimes that extend well beyond this date. Expanding the model horizon beyond 2050 would allow the analysis to capture long-term lock-in effects, delayed benefits of early investments, and the full payoff period of emerging technologies such as hydrogen and electric aviation, whose deployment is characterised by high upfront costs and gradual scale-up. A longer horizon would also enable the assessment of post-2050 transition dynamics, including whether transitional solutions such as SAF plateau or decline in favour of alternative propulsion techniques. Making these longer-term dynamics explicit would improve the visibility of hydrogen and electric technologies' system-level contributions and provide a more complete representation of intergenerational cost-effectiveness, thereby strengthening the model's relevance for long-lived strategic decisions.

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Appendices

A Parameter input

This appendix contains the inputs used for the optimisation. It consists of the following tables:

- Table A.1 contains the full routes data set
- Table A.2 contains the energy carrier data
- Table A.3 the data for technology development
- Table A.4 the time dependent dataset
- Table A.5 the used infrastructure costs data
- Tables A.6 and A.7 contain the data for all the aircraft considered in the optimisation
- Tables A.8 until A.10 contain the different scenario input data

Table A.1: Selected high-demand air routes used as input to the optimisation model, including great-circle distance and annual passenger demand.

Route	Distance [nm]	Demand [# pax]	Route	Distance [nm]	Demand [# pax]	Route	Distance [nm]	Demand [# pax]	Route	Distance [nm]	Demand [# pax]
EGLL–LEMD	736	1011481	LFPG–LIPE	498	221910	EDDK–EDDB	287	231321	EGCC–LEMG	2584	1048
LEMD–EGLL	721	1013504	LFMN–EHAM	607	181793	ELLX–LEPA	677	98130	LIMC–HECA	1839	1471
LEMD–LIRF	789	799950	EDDF–EHAM	257	429707	LFRS–LFPG	227	291883	EKCH–LEMG	1934	1398
LIRF–LEMD	769	811578	LOWW–EDDK	438	251026	LROP–LSZH	787	84253	EBBR–LGAV	2252	1190
LEBL-EHAM	739	841036	EDDK-LOWW	442	248793	LROP-LSZH	787	84253	EBBR-LGAV	225237	1190
EHAM-LEBL	717	836017	LEVC-EBBR	800	137306	LIML-LIRN	391	169328	ESSA-EGLL	320030	837
LFPO-LEMD	605	977658	LIPE-LFPG	492	222910	EGKK-EGPE	452	146099	EDDM-LTAI	236784	1124
LEMD-LFPO	591	977818	LIME-LICA	522	209885	EFIV-EFHK	513	128969	LIRF-EGLL	326044	815
LPPT-LPPD	807	654858	LFPG-EGPH	497	219514	EGSS-EGAA	306	215892	EGSS-LHBP	317470	830
LCLK-LGAV	533	881266	EGPH-EGLC	405	269517	LEMD-LEAS	256	257682	BIKF-EGLL	245802	1065
LEMD-EBBR	760	618168	LEBB-LEBL	285	382680	EVRA-EBBR	808	81697	EGSS-LPPT	278302	939
EBBR-LEMD	757	618837	EGKK-EGPF	352	308895	EHAM-LIPE	573	115065	LFPO-LTFJ	201016	1299
LGAV-LCLK	527	880290	LEBL-LIRN	606	179159	EHAM-LFBD	524	125694	LFPG-ESSA	299699	871
LPPR-LFPO	710	643977	LICA-LIME	518	209130	LHBP-LSZH	464	141827	LHBP-EGSS	318388	819
LFPO-LPPR	696	645183	EGGW-LSGG	495	218545	EHAM-EGNT	328	200871	LIRA-EGSS	299473	870
LEPA-EDDF	782	567679	EHAM-LYBE	790	137011	EDDF-LSZH	165	397751	ESSA-LFPG	299563	870
EDDM-EGLL	552	790862	EIDW-EGCC	175	616896	EDDF-ENBR	662	98955	LPPT-EGSS	277734	937
EGLL-EDDM	541	787333	LEBL-EDDS	632	170199	EHAM-EDDH	239	273602	EGLL-BIKF	244821	1061
EDDF-LEPA	713	573071	EDDF-LYBE	600	179377	LFPG-LFRB	303	216094	LSZH-LTFM	258721	997
EDDK-LEPA	794	502791	LFPG-LFMT	376	285852	LIME-LHBP	448	146021	EGSS-LTAI	156661	1638
EDDF-EGLL	396	1008182	EBCI-LHBP	662	161738	LEBB-LEPA	394	165963	EGSS-LROP	220646	1155
LFPO-LFMN	425	926780	LEMD-LIME	725	147499	EGBB-EHAM	261	250792	EGSS-LIRA	298213	849
EGLL-EDDF	388	1007672	LSGG-BKPR	792	134599	EDDB-EDDL	280	233126	EDDL-LTBJ	206392	1223
LEBL-EDDF	709	543909	EKCH-EGSS	530	200945	LHBP-LIME	449	145391	LROP-EGSS	219386	1148
LFBO-LFPO	348	1101555	LEGR-LEBL	412	257935	LEAL-LEBL	266	245050	EDDS-LTFJ	240822	1043
EGLL-LSGG	460	826373	EBBR-EDDB	391	271773	LSZH-LROP	790	82503	LFPO-DTTJ	246268	1016
LFPG-DAAG	771	492509	LOWW-EGKK	726	146375	LPPT-LFLL	799	81518	LFPG-LPPT	293357	851
LEBL-EGKK	682	555681	LDZA-EDDF	456	232939	LFML-EBCI	502	129502	EDDB-LTFJ	242604	1027
LPPT-LEBL	586	639694	LEBL-GMMX	797	133171	EPWA-ESSA	520	124888	EGNX-GCTS	144955	1703
LFMN-LFPO	405	924936	EGSS-LOWW	710	149390	EDDB-LIRF	670	96994	LPPT-LFPG	293194	839
LEMD-LEBL	298	1249533	LOWW-LBSF	471	224809	EBCI-LIPH	464	139905	EDDF-HEGN	131133	1861
LPMA-LPPT	552	668727	EHAM-EVRA	748	141477	LIRF-EHEH	708	91719	EDDF-LTFJ	222148	1098
LFPO-LFBO	335	1101201	LOWW-EGSS	702	150650	EGNT-EHAM	323	201066	EKCH-LTFM	211356	1148
LEBL-LPPT	574	637538	LGRP-LGAV	240	440008	EKBI-EGSS	436	148666	EGBB-GCTS	144500	1673
LSGG-EGLL	440	827361	EGSS-EKCH	525	201007	EIDW-EGGW	274	236589	EDDL-GCFV	139711	1731
LEBL-LEMD	289	1250070	LIRN-LEBL	586	179789	EGSS-LFML	620	104129	EIDW-GCTS	144745	1670
LPPT-LPMA	532	670311	LIME-LEMD	712	148067	EGGD-EGPH	310	208049	EDDS-LTFM	242351	993
EGKK-LEBL	635	554148	LGTS-LCLK	663	158855	EBCI-LFML	500	128934	BIKF-EDDF	176265	1366
EGLL-LSZH	481	728954	LIRF-LICJ	242	434150	LFLL-LPPT	805	79939	EDDM-LTFM	272439	880
EDDF-LEBL	641	544107	LEBL-LEBB	274	383477	EDDF-LDSP	533	120644	EDDF-BIKF	176537	1354
LFPO-DAAG	745	465086	LCLK-LGTS	661	158855	LFSB-EGKK	399	160991	LSGG-LTFM	217009	1097
EHAM-EIDW	439	776611	EGCC-EIDW	170	616095	EHEH-LIRF	694	92575	EDDH-LTAI	171130	1385
EGLL-LOWW	733	463923	EGPH-EGKK	377	278037	EGPF-EGGD	302	212126	LEAL-EHAM	251462	939
LSZH-EGLL	465	729374	EHAM-EDDF	236	443681	EGLL-LFLL	441	145177	LPPT-LPLA	274139	860
LPPT-LEMD	319	1062632	LPPR-LPPT	180	582972	EDDB-EDDK	275	232488	LPLA-LPPT	267837	878
LEMD-LPPT	317	1061628	LBSF-LOWW	464	225283	LFML-LPPR	685	93275	LEMD-LIPZ	283647	822
LOWW-EGLL	720	466315	LGAV-LGRP	237	441001	LEAL-LEPA	208	307969	LIPZ-LEMD	284635	818
EIDW-EGLL	290	1153546	EDDF-LIPZ	363	288074	EGPH-EGGD	308	207668	LPPR-EDDF	240732	964
EIDW-EHAM	426	777561	EVRA-EHAM	739	140893	LDZA-LFPG	637	100239	LIMC-LLBG	154405	1498
LIRF-EHAM	794	416203	LPPT-LPPR	179	580342	LGTS-LOWW	584	108938	LSZH-LTAI	187617	1231
ENGM-EGLL	705	461172	EGLL-LIPE	700	147822	LIPE-EDDF	422	150775	LPPT-EDDB	176646	1307

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Table A.1 – continued from previous page

Route	Distance [nm]	Demand [# pax]	Route	Distance [nm]	Demand [# pax]	Route	Distance [nm]	Demand [# pax]	Route	Distance [nm]	Demand [# pax]
EGLL-EIDW	281	1155047	EGCC-EKCH	587	176163	LFLL-EGLL	435	146278	EKCH-LTFJ	195141	1178
LEBL-EDDM	669	483067	LFPG-LIML	422	244809	LIMC-EHAM	525	121146	EDDF-LPPR	240596	954
EGLL-ENGM	686	469525	LIMC-LIBD	476	216806	LGIR-LGTS	354	179283	LIRF-LTFM	280628	816
EGKK-LIRF	807	398712	LSGG-EGGW	476	216779	LIRN-LIML	373	170184	LCLK-EGKK	124648	1831
EDDM-LEBL	654	484934	LIBD-LIMC	478	215600	EDDF-LKPR	244	259483	EGKK-LCLK	124803	1825
LEBL-LFPG	540	586232	EBBR-ENGM	635	162341	LEZL-LEBB	411	154292	EDDB-LPPT	173767	1309
LSZH-LEMD	716	437596	EKCH-EGCC	583	176825	LFSB-LWSK	735	86055	EDDB-LLBG	143636	1583
LEMD-LSZH	709	436779	EBBR-LEVC	753	136676	LIRF-EDDB	693	91260	EDDH-LTFJ	193071	1173
EHAM-ESSA	660	466805	LIRQ-EHAM	667	154159	LGAV-LGKR	230	275461	EGCC-GCLP	131152	1726
EHAM-LIRF	739	416071	LSZH-EDDL	321	319617	LGTS-LGIR	354	178583	EHAM-LEAL	249322	905
EDDH-EDDM	368	832652	LFPG-LYBE	809	126686	EGLL-EGNT	245	257892	BIKF-EHAM	196359	1142
LEBL-LFPO	500	611648	LIMF-LIBD	499	205446	LEPA-LEAL	205	307907	EHAM-BIKF	196359	1141
LIMC-LICC	614	494423	EGKK-LOWW	712	143916	LOWW-LIPZ	289	217965	EDDM-HECA	154207	1452
EDDM-EDDH	355	846385	LEBL-LEGR	396	258635	LEBB-LEZL	408	154292	LROP-EGLL	191375	1170
LICC-LIMC	605	495158	ESMS-ESSA	313	326557	EGSS-EKBI	423	148666	EGLL-LROP	190208	1174
LEBL-EGLL	690	434200	LFMN-EDDF	470	217397	EDDL-ESSA	664	94574	LSZH-ESSA	260449	852
ESSA-EHAM	643	464860	LEVC-LSZH	708	143636	LFML-EGSS	611	102806	EGNM-GCTS	125418	1766
LFPG-LEBL	510	585761	EGSS-LKPR	585	173938	LEJR-LEBL	537	116952	EDDN-LTAI	187146	1181
LFPO-LEBL	484	613881	LHBP-EBCI	636	159559	LFPG-LDZA	628	99834	LIMC-LPPT	227396	969
LEBL-LOWW	800	370145	ENGM-EBBR	629	160866	EGSS-EPPO	640	97430	EDDF-OJAI	128643	1707
LEBL-EBBR	676	436698	LEPA-EDSB	704	143476	LEAL-LEMD	237	263222	LHBP-EGGW	253341	864
LEPA-EDDM	734	400587	ENVA-ENBR	267	377829	EDDM-LHBP	339	183489	LPPT-LOWW	165559	1320
LEZL-LEBL	500	587065	LFLL-LFPG	262	385026	EGPH-EGSS	343	180567	LPPT-LIMC	226995	962
EIDW-EGKK	325	898326	LEMH-EGKK	763	132163	EGKK-LIRQ	712	86833	LOWW-LPPT	165559	1311
EDDM-LEPA	720	397397	LIMC-EGLL	539	186776	LEBL-LEAL	252	245517	EGKK-LMML	184606	1172
LFPG-LOWW	616	462635	LEBL-EGGW	711	141453	EHAM-EGGW	230	267883	EHAM-GCLP	120998	1788
EGLL-LEBL	652	436398	EDDS-EGLL	448	224011	EDDF-EGPF	628	98181	LEBL-LGAV	203054	1065
LOWW-LFPG	607	466525	ENBR-ENVA	268	372900	EPPO-EGSS	633	97306	EGKK-GMMX	167130	1292
LOWW-LEBL	768	367539	LICJ-LIPZ	468	213530	LFMP-LFPO	410	150467	EDDL-GCLP	120314	1790
LEMD-LEPA	353	798553	LFBO-EDDM	556	179770	ELLX-EGLC	293	210515	LGAV-LEBL	202704	1060
EBBR-LEBL	639	434854	LIPZ-LICJ	469	212900	LEPA-LEBB	369	166546	EGGW-LHBP	250598	857
ENTC-ENGM	628	440771	EGLL-EDDS	443	225209	LFBO-EGSS	561	109521	LEVC-EHAM	249178	860
LEBL-LIRF	523	525923	EDDF-LDZA	423	235530	EGPF-EDDF	645	95286	EDDL-GCTS	116540	1829
LEBL-LEZL	466	586174	EPKK-EDDF	480	207458	ESSA-EDDL	650	94403	EGSS-LCPH	118866	1777
ENGM-ENTC	633	427769	LSZH-LEVC	687	144784	EGLC-ELLX	293	209554	ESSA-LSZH	256111	824
EGKK-EIDW	300	896692	LEMD-LFML	495	200941	LOWW-LGTS	565	108354	LCPH-EGSS	118866	1775
LGAV-LLBG	667	402326	EGKK-LEBB	550	180536	EDDF-LIPE	394	155346	EGLL-LMML	178000	1183
LFPG-EPWA	766	347285	EDDB-EBBR	369	269548	EHAM-EDDS	307	198720	LEBL-ESSA	155206	1356
EHAM-LOWW	571	463343	LKPR-EGSS	571	173938	EDDH-EHAM	226	270248	LFSB-LTFJ	194301	1080
EPWA-LFPG	762	346616	LICC-LIPX	549	180622	LGAV-LIPE	745	81931	LMML-EGKK	182155	1151
EDDF-EIDW	640	411539	LIBD-LIMF	486	204186	LICC-EDDM	727	83965	LEMG-EFHK	110576	1883
EIDW-EDDF	642	410375	EDDM-LFBO	551	179840	EGLC-EIDW	312	195646	LBSF-EGGW	177654	1171
LFPG-LIRF	653	398000	LKPR-EGCC	697	142107	EGLL-LFSB	446	136676	LROP-EDDF	247673	840
LEPA-LEMD	324	799183	EDDM-ESGG	595	166188	EGSS-LFBO	561	108665	LFPG-GMMX	170694	1218
ESSA-EDDF	707	365407	LIPE-EGLL	681	145254	LHBP-LIMC	489	124336	LEAL-ESSA	131534	1579
EDDF-ESSA	704	366718	LFPG-LFLL	259	381956	LFSB-EHAM	360	168227	EGGW-LBSF	178840	1161
LIRF-LEBL	490	526196	EDDS-LEBL	584	169032	LHBP-EDDM	329	183956	LMML-EGLL	177417	1170
LOWW-EHAM	554	460880	LEBL-EGBB	750	131556	EHAM-LIMC	505	119959	EGKK-GCLP	128810	1610
LIRF-LFPG	638	399397	LGSR-LGAV	140	704352	LIPE-LGAV	745	81238	EDDF-GCTS	111992	1850
LFPG-LEMD	622	402346	EHAM-LIRQ	636	154922	EDDM-LICC	715	84549	EIDW-LEMD	241693	848
EGKK-LEMD	734	337859	ESSA-ESMS	303	325149	LEMD-LIRQ	762	79215	EHAM-LEVC	245304	831
LEMD-LFPG	616	402264	LFLL-DTTA	610	161345	LICJ-LSZH	636	94917	LEAL-EGSS	225961	901

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Table A.1 – continued from previous page

Route	Distance [nm]	Demand [# pax]	Route	Distance [nm]	Demand [# pax]	Route	Distance [nm]	Demand [# pax]	Route	Distance [nm]	Demand [# pax]
LOWW-EDDF	387	627773	ESGG-EDDM	592	166188	ENTO-EPGD	425	141862	LSZH-LTFJ	195098	1042
EDDM-LFPG	441	547569	EGCC-LKPR	692	142107	LSZH-EBBR	302	199552	ESSA-LEBL	154506	1315
LSGG-LEMD	590	407349	LIPX-LICC	551	178354	LOWG-EDDF	379	158754	LCLK-LOWW	169916	1193
LFPG-LFMN	451	531662	EGKK-LEMH	745	131580	LIRQ-EGKK	693	86716	LFPO-LEMG	242522	835
LEMD-LSGG	588	407465	LIRN-EDDF	669	146499	LIRF-EDDL	679	88334	EGBB-LTFM	136603	1479
LEMD-EGKK	708	335645	EIDW-EKCH	726	134887	LIPZ-LOWW	275	218448	LEMD-EIDW	241631	835
LIMC-LEMD	688	344192	LEMD-GMMN	535	182761	LFMN-EBBR	506	118364	EGSS-LEAL	225393	894
LEMD-LIMC	687	342590	EDDF-EPKK	473	206154	LIMC-LHBP	482	123908	LEBL-EDDB	219398	917
LICC-LIRF	349	672758	EKCH-EIDW	722	134887	LSGG-EPWA	728	81946	EDDF-LROP	245852	818
EGLL-LFMN	629	371133	EHAM-LEBB	682	142461	EGCC-LSZH	616	96819	EGSS-LBSF	175962	1139
EKCH-ESSA	329	705149	LICJ-LIPE	428	226653	LFOB-EIDW	440	135455	ESSA-LEAL	130250	1533
ENGM-EDDF	679	341559	LEBB-EGKK	530	182653	LEBL-EGGP	807	73784	LEMG-LFPO	240075	829
LEBL-LIMC	450	515396	EGGW-LEBL	687	140753	LEMD-LEAL	226	263222	EFHK-LTFM	147519	1349
EKCH-LFPG	585	394623	LEVC-LEPA	189	510027	LIRN-LTFM	704	84405	EGSS-LPFR	196721	1010
LFPG-EKCH	581	393375	LEBL-LIME	474	203676	LEMD-LEMH	414	143336	LBSF-EGSS	176467	1126
EDDF-EDDB	272	837554	LMML-LTFM	793	121371	EDDL-EPWA	572	103538	LEMG-EDDF	179938	1101
LFMN-LFPG	425	535552	EDDF-LIRN	665	144733	LEAL-LSZH	776	76278	LPFR-EGSS	196153	1006
EIDW-LFPG	486	465572	EGLL-EBBR	217	442860	LIRQ-LEMD	742	79698	LEAL-EGGD	225221	876
LFPG-EDDM	412	546966	LEPA-LEMG	425	225766	LOWW-LIRN	493	119660	LOWW-LCLK	169916	1161
EBBR-LOWW	539	416717	LFML-LEMD	477	200537	LFPO-LFMP	390	151098	LPFR-EGCC	182116	1082
ESSA-EDDM	749	300212	LIME-LBSF	656	145721	EBBR-LSZH	298	197802	EDDF-GCLP	107884	1814
EDDF-LOWW	370	606232	EGSS-EPGD	710	134241	LIMC-LIRF	315	186387	EDDB-LEBL	219398	883
EDDF-ENGM	654	342356	LSGG-EDDF	323	295310	EHAM-EPGD	552	106378	EGNT-GCTS	105880	1831
EDDB-EDDF	268	835465	EGBB-LEBL	726	131191	EPGD-ENTO	414	141862	EGPF-GCTS	106581	1818
LEPA-LSZH	619	360937	LSGG-EKCH	665	143134	LSZH-LICJ	619	94917	EGGD-LEAL	226435	853
LFPG-EIDW	481	463487	LIML-LFPG	389	244311	EETN-EPWA	493	119022	EDDF-LEMG	181167	1063
ESSA-EKCH	316	705013	EPGD-EGGW	742	128032	EDDM-EPKK	376	156237	EBCI-LTFJ	151577	1271
EDDM-ESSA	742	299710	LIPE-LICJ	423	224637	EPWA-LSGG	716	81946	EPKK-EGGW	237573	810
LFMN-EGLL	599	370659	EGKK-EGPH	340	278970	EGGP-LEBL	790	74267	EGSS-LEMG	192286	999
LIMC-LEBL	431	515486	LBSF-LIME	651	145597	EGGW-EHAM	218	268848	EHAM-LPPR	206754	928
LEMG-LEBL	460	482701	LFML-LFRS	401	236425	LIRN-LOWW	490	119660	BIKF-EDDB	140221	1369
LIRF-LICC	329	672820	EDDS-LGTS	809	117022	EPWA-EDDL	558	105071	EGKK-LGAV	140917	1361
LSZH-EHAM	427	518088	EPGD-EGSS	702	134871	LEIB-LIME	625	93470	LSZH-LEMG	206256	928
LEBL-LEMG	451	487230	LGTS-EDDS	808	117022	LEBL-LEJR	497	117605	LEMG-EBBR	191391	1000
LIMC-LICJ	523	418355	LIRF-LROP	681	138127	LRTR-LIME	531	109762	LEMG-LSZH	204972	933
EHAM-ENGM	552	394682	EDDF-LFMN	438	214565	EHAM-LFSB	346	168709	LEMG-EHEH	180972	1056
ENGM-EKCH	303	718466	LGAV-LGSR	137	684044	EGPF-EGLC	395	147375	EBBR-LEMG	193040	988
LOWW-EBBR	520	418650	LFRS-LFML	397	236425	ESGG-EFHK	444	131160	ESSA-LTFJ	142123	1341
LEBL-LSZH	535	404742	LEMG-LEPA	427	219876	EFHK-ESGG	443	131160	LEMG-EGSS	191745	992
LEPA-EDDN	776	278900	LEBB-EHAM	662	141434	LOWW-LYBE	274	211675	LGAV-EGKK	140917	1350
EKCH-ENGM	301	715459	EGGW-EPGD	732	127857	EPWA-EETN	490	118422	EDDK-LTFM	169223	1124
EGKK-LSGG	438	490708	EBBR-EGLL	212	441526	EGPH-EGGW	319	181271	LFLL-LTFJ	164057	1156
ENGM-EHAM	550	389414	EGPH-LSGG	767	122041	EDDF-LFLL	325	177860	EHEH-LEMG	181603	1043
EHAM-EPWA	630	335653	LEPA-EGLL	808	115610	LSGG-LFMN	237	243770	EDDB-BIKF	139637	1356
LICJ-LIMC	507	416195	EKCH-LSGG	653	142916	LEMH-LEMD	403	143336	EGPH-GCRR	107032	1766
LIRF-EDDF	592	356486	EBBR-EKCH	450	206532	EIDW-LFOB	429	134762	LPPD-LPPR	221891	851
EGLL-EKCH	563	374549	LIMC-EDDF	325	285627	LFSB-EGLL	420	137415	LRIA-EGGW	160030	1177
LGAV-LOWW	757	278196	LIPZ-EHAM	580	159369	LSZH-EGCC	595	97041	LEBL-EKCH	177354	1062
LGTS-LGAV	199	1057026	LDZA-EHAM	642	143842	EDDB-LHBP	415	139084	EDDM-HEGN	111245	1690
LOWW-LTFM	718	292454	EDDF-LIML	326	283265	LFLL-DAAG	572	100994	EPWA-EGGW	227178	827
LFPO-LIRF	633	331385	LIML-EDDF	322	286463	EINN-EGSS	396	145523	EGCC-LPFR	179739	1044
EKCH-EGLL	559	374942	LIEE-LIME	422	218288	EDDM-EGKK	554	103974	LPPR-EHAM	207088	906

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Route	Distance [nm]	Demand [# pax]	Route	Distance [nm]	Demand [# pax]	Route	Distance [nm]	Demand [# pax]	Route	Distance [nm]	Demand [# pax]
LSZH-LEPA	580	361520	EDDF-LATI	717	128541	LEPA-EDJA	700	82141	LPPR-LPPD	222249	841
LIME-EGSS	620	336369	LIME-LEBL	453	203108	EGCC-EBBR	348	164971	EGGW-LRIA	160003	1168
LIRF-LFPO	631	329405	LIPE-EGSS	706	130210	LIRF-EDDK	632	90591	EDDM-LTFJ	200455	929
LSGG-EGKK	418	495866	LROP-LGAV	482	190562	LIME-EPMO	652	87797	EGGW-EPWA	226206	823
EPWA-EHAM	618	335062	EDSB-LEPA	637	144060	EDDL-LIRF	648	88334	EGLL-LEMG	193460	960
LEPA-LEBL	143	1446452	LROP-LIRF	662	138536	LEBB-LEMG	449	127331	LEBL-EGCC	229232	810
EDDN-LEPA	742	278799	EDDF-LIMC	311	294987	LSZH-LEAL	748	76278	LPPR-ELLX	212990	870
EDDM-EHAM	404	511708	LIRF-LKPR	561	163271	LGTS-LCPH	611	93345	LEMG-EGLL	193460	955
EDDM-EDDL	293	705958	EHAM-ESGG	445	204614	EPMO-LIME	651	87673	EDDF-LTBJ	165792	1115
LOWW-LGAV	740	278916	LIRN-LIPZ	332	273625	EGGD-LEMD	711	80133	LEAL-EGBB	198378	929
LSZH-LEBL	506	407329	LIPZ-LIRN	331	273220	LIBD-LIPE	360	158423	LPPT-EKCH	132109	1394
LICC-LIPE	511	402439	LEBL-LEMH	156	578716	LSZH-LKPR	341	166741	EBBR-LLBG	102196	1796
EDDL-EDDM	294	699407	EGPH-EDDF	610	147857	LCPH-LGTS	608	93275	LEMG-EGGW	186621	983
EGLL-EHAM	229	889004	EDDS-EDDB	309	291556	LIMC-LIEE	420	134649	EKCH-LPPT	131471	1391
LIPE-LICC	503	403404	EKCH-EBBR	435	206415	LIME-LRTR	513	109762	EGGW-LEMG	186995	974
LEPA-EDDS	700	288945	ENGM-ENKR	761	117800	LFBO-EBBR	526	107109	ELLX-LPPR	214383	849
EGSS-LIME	601	336244	EHAM-LIPZ	559	160291	LSZH-LGTS	793	70956	EKCH-LEBL	177354	1023
LEBL-EGSS	717	281717	EGSS-LIPE	684	130903	LIML-EBBR	429	131097	EGBB-LTAI	105542	1714
EGSS-LEBL	711	282612	EHEH-LHBP	639	140150	EPGD-EHAM	529	106074	EPWA-LTFM	214686	841
EDDH-EDDF	283	709234	LIRN-EDDM	513	174428	LHBP-EDDB	403	139193	EIDW-LIRF	166049	1087
EDDF-LIRF	556	360322	LIME-LIEE	411	217720	EKCH-EGKK	569	98286	EGSS-GCLP	107654	1670
EHAM-EDDM	388	514532	ESSA-ESNS	334	267432	EDDK-LIRF	622	89883	LEMD-LHBP	158190	1134
LIRF-LGAV	645	307985	LIME-LRSV	728	122644	EBBR-LIML	428	130413	LEPA-EGSS	214935	834
ESSA-ESPA	393	504223	LDZA-LTFM	652	136649	LEMD-EGGD	696	80133	LIRF-EIDW	166321	1076
EDDM-EIDW	808	241370	LHBP-LGAV	651	136917	LEMG-LEBB	440	126748	EGSS-GCFV	111249	1607
LGAV-LGTS	184	1056139	LRSV-LIME	737	120846	EGKK-EKCH	564	98869	EDDL-LEMD	214990	830
EHAM-EGLL	219	887985	EGLL-LEPA	765	116294	EPKK-EDDM	357	156163	LHBP-LEMD	158190	1127
EDDS-LEPA	661	293614	LKPR-LIRF	544	163271	LEBL-ELLX	645	86459	LIMC-LGAV	204396	870
LGAV-LIRF	628	308825	ENKR-ENGM	753	117224	LIRF-LIBD	243	229329	LPPT-EGCC	180762	982
LPPR-LEBL	535	361182	EDDF-EGPH	600	147305	LIBR-LIPE	420	132560	EGBB-LEAL	195375	907
EGSS-LEMD	781	247501	EHAM-LFLL	460	191986	LIME-LEIB	599	92777	LEBL-LHBP	201992	877
ESPA-ESSA	385	500986	LSGG-EGPH	720	122538	LIPE-LIBD	349	159054	LGAV-LIMC	202229	875
LEBL-LEPA	133	1448249	LFBO-EDDF	586	150479	EHAM-EYVI	779	71193	EBCI-LROP	180307	981
LEBL-LPPR	533	359968	EHAM-LDZA	621	142060	EGKK-LOWI	582	95236	LEMD-EDDL	213722	828
EKCH-EFHK	510	374993	EDDM-LIRN	506	174090	LEAL-LFSB	768	72174	EHAM-LTAI	119170	1482
LIRF-EBBR	697	274240	LFPO-LEIB	666	132292	EDDF-LOWG	359	154303	EGSS-LEPA	214616	819
EFHK-EKCH	508	375794	LFPG-LIMC	408	215713	LFPO-LFKF	562	98515	EGCC-GCFV	106269	1650
EGSS-EPMO	773	245972	LGAV-LHBP	648	135657	LFPG-LEBB	478	115831	LHBP-LEBL	202712	864
EIDW-EDDM	790	240514	ESGG-EHAM	433	203003	ESNZ-ESSA	259	213355	LEMG-LOWW	143695	1216
EGGW-EPKK	805	236133	EGPF-EHAM	427	205182	EYVI-EHAM	777	71193	LRCL-EGGW	169445	1031
EHAM-EKCH	369	514404	LHBP-EHEH	633	138438	LSZH-LFMN	292	188858	EGBB-GCRR	111366	1568
EPMO-EGSS	775	244836	LIMF-LICJ	510	171736	LFMN-LSZH	295	186920	EGCC-LPPT	179393	973
LOWW-LTFJ	758	249481	LEMH-LEBL	151	580280	LIPZ-EBBR	516	106674	EGGW-LRCL	168725	1034
EHAM-LSZH	366	515381	ENTC-ENBR	676	129541	LIBD-LIRF	240	229205	LOWW-LEMG	144325	1203
LFML-LFPO	373	500266	EDDK-EDDM	264	332070	EGSS-LIMF	604	90879	LROP-EBCI	179163	968
LEMD-EGSS	751	248256	EDDL-LSZH	276	316987	LIBD-LIPX	390	140808	EGGD-GCRR	115910	1495
EDDF-EDDH	259	716917	EDDW-EDDM	345	252952	EGLC-EDDB	529	103491	LFPO-LGAV	142586	1215
LICA-LIMC	559	332479	ESNS-ESSA	327	267361	EGKK-EDDM	525	103974	LEBL-LROP	151740	1135
LSZH-EDDB	401	462942	LOWW-EPWA	337	258507	EPWA-LHBP	322	169285	LIME-LTFJ	178428	964
EKCH-EHAM	361	514431	ENBR-ENTC	681	128001	LFLL-DTTJ	799	68112	LOWW-HECA	129063	1327
LFPG-EDDB	510	362656	EBBR-EPWA	661	131564	EFHK-EDDH	656	82903	LROP-LEBL	151678	1125
LIMC-LICA	554	332506	LFLL-EHAM	453	191254	EDDH-EFHK	659	82538	LEPA-ESSA	119458	1424

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Route	Distance [nm]	Demand [# pax]	Route	Distance [nm]	Demand [# pax]	Route	Distance [nm]	Demand [# pax]	Route	Distance [nm]	Demand [# pax]
EBBR-LIRF	671	272287	EGLL-LFML	570	151899	EDDB-LIME	510	106604	EGGW-GCTS	102332	1661
LFPO-LFML	363	502068	LEPA-LEVC	170	508580	LEBB-LFPG	472	115014	LGAV-LFPO	141438	1190
EGPH-EGLL	337	537941	EHAM-LKPR	423	204633	LIMC-EDDL	429	126584	LEAL-EHEH	180879	930
EGCC-LEBL	781	230757	LICJ-LIMF	496	173689	LSGG-LOWW	480	112937	LFPG-GMME	163707	1026
LPPR-EGSS	791	226933	LEBL-EHEH	737	116960	EGSS-EGPH	302	179910	LEBL-EFHK	109728	1530
EDDB-LFPG	498	359536	EDDM-EDDK	257	334859	EDJA-LEPA	660	82141	LEBL-GCRR	150522	1115
EGSS-EIDW	301	593507	EFKT-EFHK	456	188048	EGCC-EGLL	158	344262	EDDV-LTFM	151106	1110
LFBO-LFPG	388	456718	LSZH-EDDF	219	391344	LFKF-LFPO	551	98379	LBSF-EDDF	206283	812
EGSS-LPPR	780	226933	LGAV-LROP	449	190562	LIEE-LIMC	406	133326	LOWW-LTAI	173090	965
EIDW-EGSS	298	591593	EHAM-EGPF	413	207423	LSGG-LSZH	150	360384	LSZH-HEGN	94633	1765
LFML-LFPG	404	435204	EDDB-EDDS	297	287090	LIPX-LIBD	388	139485	BIKF-EDDM	109094	1526
EIDW-EDDB	752	231889	LROP-LIPE	684	124347	LEST-EGSS	693	77916	EGNM-GCRR	100208	1660
EDDB-LSZH	380	458025	EDDL-EIDW	536	158711	EGSS-EINN	370	145523	LIRF-EFHK	128433	1292
LSZH-LOWW	369	470132	EFHK-EFIV	522	162742	EGLC-LIRQ	740	72773	LPPT-GVAC	107717	1541
EGSS-EPKK	779	222529	EGLC-EGPH	312	271711	LPPR-LFPG	722	74520	EDDP-LTAI	134677	1227
LPMA-LPPR	673	257643	LEIB-LFPO	650	130354	LOWW-LWSK	471	114057	EFHK-LIMC	145706	1134
EDDB-EIDW	750	229998	LFMT-LFPO	367	231271	EDDM-LIRQ	321	167394	EDDF-GCFV	94466	1745
LROP-LIME	742	231426	EPWA-LOWW	327	259262	LKPR-LSZH	318	168725	EFHK-LEBL	109728	1499
LOWW-ESSA	746	230212	LEVC-LIRF	653	129152	ESSA-ESNZ	251	213550	ESSA-LEPA	117839	1394
EDDL-LOWW	472	362384	EPWA-LROP	565	148946	EDDL-LIMC	420	127534	LMML-EDDF	169749	966
EGLL-LIML	619	275761	EPWA-EBBR	643	130778	EGLL-EGCC	154	347869	LIMC-EFHK	145002	1130
EDDH-LOWW	468	364434	EKCH-LIME	681	123324	EGSS-EDDK	315	170017	LSGG-LGAV	164314	997
EDDF-EPWA	530	320928	LEAL-LFPG	743	112906	LSZH-ESGG	679	78741	EGKK-LGRP	104962	1561
LIME-LROP	734	231426	LKPR-EFHK	765	109638	LEIB-LEPA	108	495594	LPPT-ELLX	165831	987
EPKK-EGSS	767	221253	EIDW-EDDL	530	158128	LIPZ-LIEE	438	121651	EDDL-LPPT	153230	1066
ESSA-LOWW	736	230072	LKPR-EHAM	412	203139	LIPE-LIBR	402	132622	LFPG-LTFJ	125799	1297
EGPF-EGLL	331	510973	LOWW-EVRA	650	128779	LOWW-LSGG	475	111770	LEAL-EBBR	186559	874
EGLL-EGPH	311	542718	EKCH-LIMC	686	121589	LFQQ-LFML	479	110735	LPPT-EDDL	153596	1057
LOWW-EDDH	456	368488	LROP-LIPH	651	128109	LFSB-LEAL	737	72057	ELLX-LPPT	163987	989
EPWA-EDDF	524	320652	EDDH-EDDS	329	253473	EDDB-EGLC	515	103126	EFHK-LIRF	128433	1262
LPPR-LPMA	650	258227	EDDS-EDDH	329	252788	LOWI-EGKK	564	94069	EDDB-LEMD	151052	1072
LEMD-LIML	705	238016	LEMG-LEMD	290	286354	EIDW-EGPF	184	288214	LEMD-EDDB	150351	1073
LFPG-LFML	388	431788	EFHK-ENGM	440	188982	LKPR-EPWA	310	170764	LGAV-LSGG	163847	984
LIML-LEMD	700	238581	EGSS-EPKT	751	110595	LHBP-EPWA	317	166683	LFLL-LTFM	144216	1117
LHBP-EHAM	671	248019	LEMD-LEMG	284	291715	LFPO-LIMC	408	129549	LGRP-EGKK	102784	1562
EDDB-EDDM	284	585061	LFBO-LPPT	606	136972	EGPF-EIDW	185	285677	EGNM-LEAL	159513	1006
EGLL-LFPG	228	726297	LROP-EPWA	560	147888	LIMF-EGSS	585	90124	EDDM-BIKF	106468	1506
LIMF-LICC	610	271170	EVRA-LOWW	640	129362	EDDM-LRCL	525	100340	LEAL-EGNM	159513	1003
LFPG-LFBO	361	458612	LEVX-LEBL	524	157824	EDDL-LHBP	589	89377	LEMD-LTFJ	101702	1571
LOWW-EDDL	453	364481	EHEH-LEBL	691	119481	EGSS-LEST	675	77916	EGKK-LGIR	104923	1519
LSZH-LYBE	556	297275	LFML-EGLL	568	145363	EBBR-LIPZ	498	105592	LEMD-GCRR	175798	906
EGKK-LIMC	584	282732	LFML-DTTA	498	165737	EGGW-EGPH	291	180454	EHEH-LEAL	181509	877
LSZH-EDDH	424	389375	ESSA-ESNQ	514	160477	EGPF-EGSS	338	155400	EDDF-LMML	170935	928
ENGM-EDDM	752	219276	EDDM-EDDW	323	255278	EBBR-EGCC	321	163710	EDDL-LTAC	119217	1329
LOWW-LSZH	348	472240	EGKK-LEIB	790	104332	EGKK-LIMF	545	96208	LGIR-EDDF	130903	1208
EGKK-LFMN	611	268746	LIPH-LROP	631	130541	LIRA-EPKK	630	83292	LEAL-EGNX	168904	936
EDDM-EDDB	277	591955	LIME-EKCH	668	123324	EBBR-LFBO	490	106806	EGLL-LHBP	184863	851
LFPO-LFKJ	529	309300	ENGM-ENEV	545	151211	LEMD-LEVC	185	282604	EGNX-LEAL	169535	926
EHAM-LFPG	259	631084	LEBL-LEVX	520	158408	LIME-EDDB	487	107234	EDDL-LGIR	120520	1299
LFPO-LFKB	526	310875	LIMC-LATI	567	145114	EIDW-EGGD	213	244494	LGIR-EGKK	105040	1489
LPPR-LEMD	280	584326	LPPT-LFBO	591	139399	ESGG-LFPG	661	78741	EGCC-LGRP	92517	1690
EGLL-EGPF	319	511895	EFHK-LKPR	750	109638	LFPG-EDDL	268	193981	LEAL-EIDW	153467	1018

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Route	Distance [nm]	Demand [# pax]	Route	Distance [nm]	Demand [# pax]	Route	Distance [nm]	Demand [# pax]	Route	Distance [nm]	Demand [# pax]
LEMD-LPPR	278	586127	ESNQ-ESSA	510	161178	LIEE-LIPZ	427	121651	EGNX-GCRR	97750	1594
LIPZ-LEBL	567	288097	EHAM-EICK	525	156315	LOWW-EDDV	416	124647	LGRP-EGCC	92517	1684
LICC-LIPZ	550	296380	EPKT-EGSS	737	111350	LFPG-ESGG	661	78375	LEAL-EGPF	136171	1144
LFKJ-LFPO	525	310167	ENEV-ENGM	540	151763	EBBR-LKPR	412	125596	EGPH-LEAL	136186	1143
LICC-LIMF	599	271606	LECO-LEBL	512	159625	ELLX-LEBL	598	86459	LEAL-EGPH	136817	1135
EDDF-LBSF	793	205217	LIPE-LROP	664	123180	LFML-LFQQ	464	111428	EDDF-LGIR	130903	1185
LFPG-EDDF	283	569453	EICK-EHAM	522	156377	LFPG-LPPR	711	72629	EIDW-GCLP	93587	1657
EDDF-LFPG	284	567228	LEBL-LSGG	445	183034	LFMN-DTTA	453	113812	EDDK-GCLP	86600	1790
EDDM-ENGM	736	218693	LGAV-LGSA	171	475430	LIRF-LHBP	501	102733	LPPT-LIME	154393	1003
LFPG-LIPZ	513	312992	EIDW-EGPH	213	382478	LGAV-LYBE	487	105689	LHBP-EGLL	183696	842
LEBL-LIPZ	558	287844	LFTH-LFPO	426	190962	EDDV-LOWW	417	123301	LGIR-EDDL	118905	1300
LIPZ-LICC	543	295283	LIRF-LEVC	628	129214	LIME-EPKK	535	96029	LIME-LPPT	155024	995
LIPZ-LFPG	516	311004	LIRF-LSZH	426	190274	LIPE-EBCI	523	98216	EGGD-LEPA	188154	819
LSZH-EKCH	556	288159	EHEH-EPKK	586	138034	LEAL-LEST	492	104184	LPFR-EGGW	154129	999
LPPR-LSGG	772	206944	EGGD-LEBL	707	114408	EPKK-LIRA	616	83230	LEPA-EGGD	188668	816
LFKB-LFPO	512	309856	LFPO-LFMT	351	230854	LSZH-LSGG	139	369709	LPPT-EPWA	98442	1563
EHAM-LHBP	675	235355	EICK-EGLL	332	243926	LIRQ-EDDM	310	165465	EBBR-LEAL	185929	827
EGLL-EDDB	553	286681	LIMF-LIRN	431	187702	EPWA-LKPR	304	168188	LIRA-LPPT	145757	1055
ENGM-LFPG	777	203384	EYVI-EDDF	714	113221	LRCL-EDDM	515	99375	LFSB-LTAI	121442	1266
ENGM-ENVA	218	726114	LEBL-LECO	504	160345	EGGD-EIDW	210	243560	LPPT-LIRA	145126	1058
LIML-EGLL	566	278192	EDDF-LFBO	532	151708	ENZV-EKCH	324	157404	EGPF-LEAL	135541	1132
ENVA-ENGM	216	725239	EDDF-EYVI	707	114019	LHBP-EDDL	569	89486	LEMG-EGNM	140559	1089
LFSB-BKPR	745	209916	EDDF-LSGG	273	294625	ENGM-ENAL	220	231687	EPWA-LPPT	98232	1557
LSGG-LPPR	752	207994	ENGM-EFHK	428	187500	LFPO-LKPR	508	100192	LPPT-EDDH	122679	1245
LFPG-ENGM	766	203816	ESSA-ESNU	280	287023	EGKK-EDDB	554	91882	LKPR-LTFM	172935	883
EGLL-LIPZ	705	221521	LEBL-EGGD	698	114408	LFBD-LSGG	362	140777	EGKK-LEZL	166586	915
LSGG-EHAM	431	361703	EGPH-EIDW	209	381233	ESGG-LSZH	646	78741	LEMG-EGGD	163263	931
EDDM-EDDF	204	764606	EGCC-EDDB	609	131019	EDDM-LIMC	275	185014	LEVC-EDDF	175273	867
LEMD-LIPE	755	204800	LIMC-EKCH	653	121970	EGBB-EGAA	225	226124	LEZL-EGKK	166485	912
LFMN-EGKK	578	267548	LFPO-LFTH	417	190962	LDSP-EDDL	662	76609	EGNM-LEMG	139929	1085
LOWW-LROP	477	323729	LIML-EHAM	535	148682	LIRN-LHBP	492	102974	EIDW-LEAL	153467	987
LROP-LOWW	475	324885	EDDB-EGCC	616	129059	ENAL-ENGM	225	224696	EGGW-LPFR	154129	981
EKVG-EKCH	753	204835	EKCH-EPWA	395	200891	LEST-LEAL	486	104067	LPFR-EGGD	161661	935
EIDW-LSZH	738	208881	EPKK-EHEH	577	137205	LEBL-LIRQ	494	102270	EGGD-LEMG	162633	929
LFPG-EHAM	242	635807	ESNU-ESSA	274	288813	EDDL-LDSP	654	77192	LPPR-LSZH	167208	899
EDDB-EGLL	540	284394	EGKK-EPKK	810	97593	LOWW-LYPG	390	129160	EDDM-GCTS	79321	1886
EKCH-LSZH	534	287576	LPPR-EGLL	750	105203	LEZL-LEVC	325	155093	LPMA-EGKK	109514	1365
EDDH-LSZH	397	385812	LIMC-LFPG	362	217744	LEVC-LIMC	635	79386	EDDH-LPPT	119567	1250
LSZH-EIDW	727	210321	EBBR-ESSB	727	108541	EDDK-EGSS	301	167496	EGGD-LPFR	161435	925
LEMD-GMMX	635	240339	EIDW-LFPO	531	148483	LFLL-LEMD	543	92812	EHEH-LPFR	136132	1094
EKCH-EKVG	741	205901	EPWA-EKCH	392	200696	LFOB-LIME	441	114306	LPFR-EHEH	135502	1099
LFPG-LIRQ	533	285483	LIMC-EIDW	802	98060	EYVI-ENGM	597	84382	EGKK-LPMA	109413	1359
LFPG-EGLL	211	720384	EGLL-EICK	322	243342	LKPR-LFPO	518	97041	EDDS-LTBJ	140256	1058
EHAM-LSGG	419	362403	EGLC-EDDF	380	205520	EKCH-ENZV	318	157941	BIKF-ENGM	150487	985
LIPE-LEMD	751	202194	LEST-LEPA	617	126584	EPKK-LIME	523	96029	LFPO-GMFO	161995	908
EHAM-EGCC	299	506577	LFPG-LEAL	695	112392	LEVC-LEMD	177	283129	LGAV-EKCH	121302	1212
LIRF-EDDM	435	345601	LGSA-LGAV	163	478422	LFMN-LSGG	206	244035	LEBL-LKPR	180272	813
LGAV-LTFM	337	444883	EPKK-EGKK	799	97593	ENZV-ENBR	106	473497	EKCH-LGAV	121302	1206
LIPZ-EGLL	675	220669	EGSS-EPWR	647	120204	LIMF-EGKK	518	96792	LSZH-LPPR	167722	872
LPPR-LFOB	713	208609	ESSB-EBBR	712	109023	LHBP-LIRN	494	101324	ENGM-BIKF	148266	982
LIMC-EGKK	525	282950	EGSS-ESSA	805	96419	EBCI-LIPE	507	98784	LROP-OTHH	80920	1796
EGLL-EDDH	437	340018	LDZA-EGLL	783	99192	ENGM-EYVI	592	84382	LEBB-GCXO	128009	1131

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Route	Distance [nm]	Demand [# pax]	Route	Distance [nm]	Demand [# pax]	Route	Distance [nm]	Demand [# pax]	Route	Distance [nm]	Demand [# pax]
LEBL-EDDL	753	196938	EDDB-EGPH	697	111365	EGAA-EGBB	221	226240	EGKK-LPPT	164209	881
LEPA-EGKK	801	183905	LFBO-EHAM	588	131766	LKPR-EBBR	394	126662	EDDV-LTFJ	128141	1129
LGAV-LGIR	195	757389	LFSB-LHBP	524	147841	LHBP-LIRF	483	103316	EDDM-LTBJ	151441	952
EKCH-EDDF	414	354463	EGPH-EDDB	694	111435	EBBR-LHBP	658	75807	LEBL-LTFJ	110845	1297
LFOB-LPPR	701	208609	ESMS-ESSB	291	266023	LIME-LFOB	435	114493	LPPT-EGKK	162551	884
LGAV-HECA	637	229162	EPWR-EGSS	643	120204	EGLL-EGPE	425	117092	EHAM-HECA	78698	1824
LGIR-LGAV	191	764481	EGLC-EHAM	203	380322	LHBP-EBBR	637	78161	EGCC-LMML	107794	1326
LEPA-LFPO	626	232107	LEVC-LIME	654	118065	LBSF-LTFM	292	170098	EDDB-LGAV	138377	1031
LEVC-EGKK	794	182886	LIRN-LIMF	409	188332	EGPE-EGLL	423	117427	EDDF-LEVC	174689	816
LIME-LICC	586	248065	LFPO-EIDW	513	150374	EGGW-LFPG	265	187064	LEBL-EPWA	131569	1078
EGCC-EHAM	286	506985	EDDH-EIDW	622	123900	LFRS-LSGG	387	128156	LEAL-EGNT	130460	1083
ENGM-ENBO	460	315583	LSZH-LIRF	406	189690	EGAA-EGCC	185	266070	LSZH-GCTS	81756	1729
ENBO-ENGM	458	316120	EDDV-EDDM	308	250053	EDDL-LFPG	257	191546	LGAV-EDDB	138104	1023
EDDL-LEBL	734	197039	EGLL-LDZA	776	99192	EGBB-LFPG	302	162590	EGKK-LTFE	92299	1531
EDDM-LROP	659	219436	EDDS-LOWW	329	234002	EGLL-LTFM	787497	1397	LMML-EGCC	107794	1309
LICC-LIME	578	250080	EGLL-LPPR	735	104619	LFPG-LLBG	500496	1822	EPWA-LEBL	133117	1059
LROP-EDDM	658	219654	EHAM-LIML	517	148581	EGLL-LGAV	637193	1377	LEMG-EGPF	114291	1233
EDDM-LIRF	416	346842	EIDW-EDDH	623	123208	LGAV-EGLL	636181	1373	EGKK-GCFV	90334	1558
LKPR-LEBL	791	180738	EGGD-LSGG	529	144682	LFPG-LTFM	636555	1253	ESGG-LTFM	111564	1259
EDDH-EGLL	425	336334	LIMF-LICA	562	135995	LFPO-LPPT	952546	833	LEMG-EGBB	137583	1015
LIRQ-LFPG	506	282137	LOWW-BKPR	495	154408	LPPT-LFPO	950733	827	LEMD-EFHK	84402	1649
LFBD-LFPG	322	443420	ESSB-ESMS	286	266630	EHAM-LTFM	601720	1241	EGNT-LEAL	129830	1070
EDDF-EDDM	183	778444	EICK-EGSS	368	207115	LPPT-EGLL	819643	894	LSZH-GCLP	82262	1682
LIRF-LOWW	478	296777	LHBP-LFSB	511	148892	EGSS-LTFJ	507663	1435	EETN-EDDF	166438	831
EKCH-EDDM	477	297597	EVRA-EDDB	517	146729	EGLL-LPPT	818332	882	EFHK-LEMD	84402	1638
LEZL-GCLP	794	177867	LFBO-EGLL	539	140703	EGCC-GCTS	407489	1731	LEMG-EGNX	134366	1028
EDDF-EKCH	398	354058	LEMD-LIMF	665	113808	LFPG-OLBA	378852	1778	EGLL-KJFK	2511543	3061
LEIB-LEBL	186	754242	LEBL-GMMN	701	107833	EDDL-LTAI	480831	1395	EGLL-WSSS	1087320	6287
LSZH-EPWA	627	222109	LEPA-EDFH	758	99554	LFPG-HECA	356599	1812	EGLL-OMDB	1957465	3079
LEMD-LEVX	288	482246	EGBB-EDDF	464	162699	EHAM-LPPT	589652	1069	EGLL-KLAX	1229183	4851
EGKK-LEPA	742	187375	ENTO-EPKK	673	112089	LEPA-EDDL	731211	850	LFPG-KJFK	1322711	3251
EDDM-EKCH	467	297380	LIRP-LICJ	374	201669	EDDF-LTFM	588139	1049	EGLL-KSFO	882274	4765
LEVX-LEMD	288	481499	ESSA-EGSS	787	95788	LFPG-LGAV	509911	1207	LEMD-MMMX	739171	5064
LFPG-LFBD	314	440650	LICA-LIMF	548	137345	LPPT-EHAM	589839	1041	EGLL-OTHH	1227961	2952
LEBL-LEIB	183	754709	EBBR-LIMC	426	176778	LGAV-LFPG	508880	1200	LEMD-SKBO	799106	4430
ENGM-ESSA	231	595542	EKBI-EDDF	406	185329	EDDL-LEPA	729958	818	EGLL-KORD	997227	3512
LHBP-EDDF	510	269731	EHAM-EGLC	197	381054	EDDF-LPPT	515288	1092	EDDF-WSSS	563128	5898
LEZL-LFPO	800	171826	EDDB-EVRA	515	145951	LPPT-EDDF	517081	1086	EGLL-KMIA	789361	3976
LFPG-EDDH	443	308977	EDDM-EGBB	617	121811	EDDK-LTAI	394243	1358	EGLL-KEWR	990540	3108
LFPO-LEZL	799	171195	LICJ-LIRP	374	201101	LPPD-LPPT	636302	822	EGLL-KDFW	719097	4232
LECO-LEMD	309	439993	LHBP-LFPO	741	101324	EGCC-LTAI	294571	1749	LFPG-OMDB	1003051	2965
EGPD-EGLL	411	331012	ESGG-EGLL	625	120049	EDDF-LLBG	314272	1633	EGLL-VIDP	738910	3988
LFPO-LEPA	585	232107	EHAM-LFBO	568	132008	EDDM-LEMD	573332	871	LFPG-KLAX	582401	5050
EGKK-LEVC	745	182302	EDDL-EKCH	359	208975	LFPO-GMMN	457971	1089	LEMD-SAEZ	503803	5546
LEZL-LEPA	478	283958	LFPO-LHBP	734	101955	LEMD-EDDF	573313	862	EGLL-KBOS	941319	2899
ESSA-ENGM	229	591476	EPKK-ENTO	664	112657	LOWW-LLBG	375059	1309	EGLL-RJTT	377533	6731
LEMD-LECO	308	437371	LFML-EDDF	508	147254	LEMD-EDDM	569912	858	LFPG-CYUL	809260	3080
EDDH-LFPG	440	305125	EDDF-EGBB	466	160217	LEPA-EDDH	483729	1004	EGLL-FAOR	496983	4985
LEBB-EDDF	712	187846	LIBD-LIPZ	358	208597	EDDL-LTFJ	404155	1196	LFPG-KATL	625082	3941
EDDB-EFHK	650	205866	LIRF-EPWA	772	96695	EHAM-LLBG	264973	1824	EGLL-VHHH	404603	6032
EDDM-EGCC	665	201066	EGBB-EDDM	613	121764	EKCH-BIKF	410411	1176	EDDF-KSFO	478920	5081
LEZL-GCXO	784	169371	LIMF-LEMD	661	112774	EGKK-GCTS	293801	1638	LFPG-WSSS	385983	6122

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Route	Distance [nm]	Demand [# pax]	Route	Distance [nm]	Demand [# pax]	Route	Distance [nm]	Demand [# pax]	Route	Distance [nm]	Demand [# pax]
EGCC-LFPG	359	369281	LMML-LSZH	798	93423	EDDF-LEMD	569780	842	LFPG-RKSI	408933	5752
EDDF-LEBB	708	186971	EKCH-ENBR	396	188216	BIKF-EKCH	403755	1181	EDDF-KJFK	675170	3441
EPWA-LSZH	594	222692	EGLL-ESGG	617	120632	EGSS-GCTS	277345	1689	EHAM-KATL	586797	3920
EGLL-LKPR	612	216102	ENZV-EHAM	435	170911	LEMD-LTFM	304348	1537	LIMC-KJFK	640363	3583
EGKK-LIPZ	670	197055	LSGG-EGGD	517	143827	LCLK-EGLL	252680	1849	EGLL-VABB	557055	4102
EDDF-EGCC	505	260830	EDDF-EGLC	368	201863	EGLL-LCLK	253380	1843	LFPO-TFFR	607077	3722
LOWW-LIRF	445	296104	LOWW-EDDS	314	236235	EHAM-LEMD	556662	833	EGLL-KIAD	680197	3261
EFHK-EDDB	642	204999	LOWW-LICC	690	107424	EHAM-LTFJ	357475	1288	LFPG-MMMX	427252	5165
LEBB-LEMD	234	562014	LIMC-EBBR	420	176443	EDDH-LEPA	481527	955	LEMD-SPJC	420153	5233
LEST-LEBL	509	256192	EGSS-EICK	358	207115	LEBL-GCXO	371815	1229	LFPO-TFFF	562073	3775
EDDF-LHBP	491	265903	LIPZ-LIBD	356	207967	LEMD-EHAM	554542	822	EDDF-KORD	547737	3868
EIDW-EBBR	480	271314	LFML-DAAG	440	167951	LEMD-GCLP	444553	1019	EHAM-WSSS	345450	6080
ENZV-ENGM	207	630131	LICC-LOWW	680	108591	EGKK-LTAI	277061	1634	EGLL-KATL	559342	3739
LIME-LIBD	446	291793	EKCH-EDDL	355	208041	EFHK-EGLL	429361	1043	EGLL-VTBS	373433	5528
LEBL-LEST	506	256542	LEPA-LEST	583	126584	EGLL-EFHK	430427	1037	EDDF-RJTT	320563	6331
LOWW-EKCH	515	251469	LIRQ-EDDF	466	158229	LPPT-EDDM	392846	1134	EGLL-CYYZ	641865	3150
EGCC-EDDF	503	257289	EPWA-LIRF	755	97278	EDDM-LPPT	392527	1126	EDDF-SBGR	372398	5420
EGSS-LIMC	588	219977	ENBR-EKCH	393	187080	LFPO-GMMX	372923	1184	LEMD-KMIA	508020	3964
LIMC-LOWW	395	327059	LOWW-LATI	441	166379	EDDK-LTFJ	372702	1159	LFPG-SBGR	386738	5166
EGCC-EDDM	653	198051	EHAM-EPKK	611	120095	LEMD-GCXO	430092	1000	EDDF-RKSI	355666	5475
LFPG-EGCC	348	371087	EDDM-LFMN	404	181139	LHBP-LLBG	351289	1209	LEMD-SBGR	422619	4602
LKPR-EGLL	596	216219	LEMD-LFMN	570	127814	LGAV-EHAM	335074	1249	EDDF-KIAD	532328	3643
EKCH-LOWW	514	250182	EHAM-LFML	597	122079	LEPA-EDDK	505608	825	LEMD-KJFK	604366	3199
LIPZ-EGKK	654	196510	EHAM-ENZV	426	170546	LEMG-EIDW	389006	1068	LFPG-KSFO	388427	4963
EGLL-EDDL	320	401681	EPKK-EHAM	604	120056	LEAL-EGCC	419157	986	LPPT-SBGR	440600	4347
LEPA-LEZL	453	282114	LFPO-LFBZ	382	189702	EHAM-LGAV	335265	1227	LFPG-OTHH	669109	2829
EGLL-EGPD	387	330063	EHAM-EGBB	289	250602	EIDW-LEMG	389053	1054	EGCC-OMDB	595927	3169
LIMC-EGSS	584	219020	LSZH-LMML	775	93423	EGCC-LEAL	419795	965	LFPO-FMEE	359459	5194
EPKT-EDLW	475	268879	EDDF-LIRQ	452	160158	EDDF-HECA	249206	1617	EGLL-KSEA	438640	4252
EGKK-LPPR	732	173946	EDDM-EDDV	285	253469	EGKK-LEMG	419647	952	EHAM-KJFK	574017	3242
LPPR-EGKK	734	173378	LFML-EHAM	587	122943	EFHK-LFPG	371274	1070	EDDF-CYYZ	528079	3513
EDLW-EPKT	478	266428	EVRA-EFHK	231	312319	LFPG-EFHK	370873	1065	EDDF-OMDB	671428	2737
EDDB-LOWW	315	401295	LFMN-LEMD	564	127775	LEMG-EGKK	416760	946	EGLL-SBGR	349375	5194
LOWW-EDDB	312	404781	LFBZ-LFPO	381	189072	LEBL-GCLP	319170	1226	EGLL-OMAA	578611	3099
LFPG-LSGG	270	467140	LIMC-EPWA	680	105787	LSZH-LLBG	248832	1565	LEMD-SCEL	301473	5929
ENBR-ENGM	194	649552	LIME-LATI	536	134221	EGCC-GCRR	240981	1614	EHAM-OMDB	587905	2924
LIBD-LIME	434	290595	EDDM-EVRA	756	95119	EGCC-LTFM	257014	1513	EGLL-KIAH	396701	4322
EGCC-LSGG	592	212503	LGTS-LLBG	806	89058	EHAM-EFHK	456255	847	EGKK-OMDB	552375	3057
ENGM-ENZV	198	634799	EVRA-EDDM	754	95119	EFHK-EHAM	456621	844	EGLL-CYVR	398829	4184
EVRA-EDDF	747	167889	LGAV-OLBA	632	113478	LGAV-EDDF	364614	1056	EGLL-WMKK	277656	6005
EBBR-EIDW	463	269991	EDLV-LEPA	805	89073	LFPO-DTTA	459107	833	LFPG-FMEE	312533	5164
LIME-LIBR	497	251286	EGGW-LEPA	794	90178	EIDW-GCRR	241012	1586	EDDM-WSSS	277656	5734
LOWW-LIMC	388	321259	EGKK-LIRP	695	102775	LPFR-EIDW	364131	1048	EDDF-VTBS	308643	5156
LFPG-LHBP	730	170799	EBBR-EDDF	196	364757	LPPT-EBBR	389286	973	LSZH-WSSS	270459	5826
LIRP-LICC	475	262596	EHAM-EGKK	229	312202	LGAV-OMDB	203058	1866	LFPG-FIMP	301317	5211
LICC-LIRP	475	262106	EINN-EGLL	355	200976	EHAM-LEMG	350713	1074	EDDF-KLAX	301698	5187
LHBP-LFPG	727	171106	LSGG-LEBL	390	183150	EBBR-LTFM	308682	1217	EDDM-KORD	386602	4029
EDDM-LMML	793	156867	EGKK-EHAM	229	311140	EBBR-LPPT	385042	974	EDDM-KSFO	296968	5214
EGSS-LIRP	721	172382	LIPE-EHAM	618	115252	EDDF-LGAV	364987	1026	LSZH-OMDB	571068	2703
LKPR-LFPG	497	250256	EDDF-EBBR	195	365274	EDDL-LTFM	325294	1151	EDDF-KIAH	327725	4698
EFHK-EFOU	296	419802	LIME-LEVC	610	116680	LFPG-GMMN	333483	1121	EHAM-KDTW	438099	3495
LSGG-EBBR	335	369733	LIBD-LIML	443	160594	LROP-EGGW	312432	1192	EGLL-KLAS	321010	4634

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Route	Distance [nm]	Demand [# pax]	Route	Distance [nm]	Demand [# pax]	Route	Distance [nm]	Demand [# pax]	Route	Distance [nm]	Demand [# pax]
EBBR-LSGG	336	368566	EFHK-EFKT	459	154642	LEMG-EHAM	348826	1067	LIMC-OMDB	530141	2679
EDDF-EVRA	743	165768	EGKK-LIPX	633	112229	EIDW-LPFR	359844	1031	EGLL-FACT	261184	5341
ENGM-ENBR	193	637779	EGLL-LIRP	708	100317	EGGW-LROP	312568	1180	EGLL-KMCO	353771	3899
LFPG-LKPR	496	248003	LEPA-ELLX	723	98130	LIRF-LLBG	289580	1273	EHAM-MMMX	267747	5143
LIRP-EGSS	715	171861	EIDW-EGLC	366	193452	EGKK-GCRR	236745	1529	EDDF-KEWR	394180	3486
ESGG-EDDF	528	231979	EPWA-LIMC	679	104355	EDDF-OLBA	227287	1584	EGLL-KDEN	331623	4138
LIBR-LIME	489	249964	LIML-LIBD	443	159660	EDDB-LTFM	355483	998	EIDW-KORD	418705	3260
ENBR-EHAM	519	235122	EIDW-LSGG	716	98854	LGAV-EDDM	401809	865	LFPG-KIAD	387306	3452
EFOU-EFHK	290	420031	LEVC-LIPE	654	108210	EDDM-LGAV	402626	861	LFPG-VTBS	243588	5482
EDDL-EGLL	304	400934	EGPD-EHAM	418	168919	LEMG-ESSA	203280	1700	EHAM-RKSI	234418	5688
EGBB-EIDW	218	558883	EFHK-EPWA	554	127390	ESSA-LEMG	203280	1697	LFPG-KMIA	321551	4146
EHAM-ENBR	514	236807	LEVC-LFPG	665	106168	LPPT-EIDW	362501	944	LFPG-KORD	359280	3708
LIPZ-LTFM	796	152514	LSZH-BKPR	704	100177	EIDW-LPPT	362734	939	EHAM-RCTP	210150	6336
LIBR-LIMC	537	225828	LIPE-LEVC	655	107580	EDDS-LTAI	276559	1231	LSZH-VTBS	259756	5122
LSGG-LFPG	259	465938	LKPR-EDDF	267	263845	EDDM-LLBG	231364	1467	EGLL-KPHX	283919	4677
LSGG-EGCC	572	210496	EHAM-EGPD	415	169519	LEBL-LTFM	267981	1263	EIDW-CYYZ	448152	2906
EFHK-EFRO	394	304830	EGLL-LFBO	504	139469	EGKK-LTBS	212430	1585	EDDM-VTBS	259130	5006
LSZH-LFPG	299	401183	EDDM-LOWW	221	317598	LFPO-LLBG	182770	1837	EHAM-KMSP	348122	3714
LIME-LIRN	389	308343	EGAA-EGGW	296	236970	EGPH-GCTS	178000	1846	EHAM-VTBS	236305	5404
EDDF-ESGG	520	230811	EGCC-LIME	740	94567	EGKK-LCPH	182886	1790	EDDF-VIDP	353110	3589
ENGM-ENDU	603	198759	EPWA-EFHK	549	127366	BIKF-LFPG	258418	1264	EGLL-OERK	432442	2924
LIPZ-EGSS	691	173067	EGGD-EHAM	316	221432	LCPH-EGKK	183470	1775	EGCC-OTHH	406346	3055
LGTS-EDDM	707	168344	EGLL-EINN	343	202999	LIMC-LTFM	339867	950	EDDF-OTHH	477493	2596
LEBL-EDDK	746	159427	LIRA-LROP	663	105180	LIRF-EGKK	395542	816	EGLL-TBPB	333502	3703
LFPG-LIRN	776	152794	ENGM-EPWA	643	108346	LFPG-BIKF	259173	1245	LEBL-KJFK	360540	3407
ENDU-ENGM	598	198276	LIPX-EGKK	621	112229	EIDW-LEBL	377502	853	EDDM-OMDB	476936	2570
ESGG-ESSA	246	480678	LSGG-EIDW	704	98737	LPPT-LTFM	174794	1834	EDDF-MMMX	228828	5351
EDDM-EPWA	465	254624	EKBI-EHAM	282	246525	LEBL-EIDW	376989	844	LFPG-CYYZ	361085	3349
EGPH-LFPG	537	220335	LMML-LOWW	774	89657	LFPO-GMAD	247381	1285	EDDF-CYVR	268860	4469
LEMD-LEBB	209	563672	LEAS-LEMD	269	258165	LPPT-LSGG	365668	864	EDDF-ZSPD	233236	5141
EFRO-EFHK	388	303600	EHAM-EKBI	281	247279	EGCC-LTBS	184906	1708	EGCC-KMCO	309927	3817
LEMD-LEIB	287	410165	LIME-EBCI	434	159964	LEBL-LLBG	186769	1688	LEMD-OTHH	380008	3090
EHAM-EDDB	350	336451	LEIB-LIRF	580	119512	LEMD-LROP	224276	1401	EDDM-KDEN	253691	4627
LIMC-LIBR	528	222957	LFMN-EDDM	384	180454	LPPT-LSZH	317742	989	LPPT-FNLU	358961	3264
ENGM-LSZH	791	148752	EDFH-LEPA	695	99554	LROP-LEMD	225132	1391	EHAM-KSFO	238441	4867
EGLC-LSZH	467	251450	LFLL-EDDF	389	177665	LEPA-EGCC	336428	929	EGLL-RKSI	199374	5820
LHBP-LTFM	633	185582	LHBP-LTFJ	648	106674	LSGG-LPPT	366364	852	EDDM-KCLT	281453	4091
EDDM-LGTS	695	168826	LDSP-EDDF	565	122216	EHAM-LROP	311043	1001	EIDW-KJFK	406785	2829
EGPF-EGKK	376	310833	EDDF-EKBI	377	182742	EPWA-LLBG	217958	1428	EDDF-KDEN	256403	4479
LPPT-LFML	771	151413	EGGW-EGAA	291	236892	LROP-EHAM	311747	996	LIRF-KJFK	295762	3852
EGLL-LIMC	609	191095	EGPE-EGKK	470	146682	LSZH-LPPT	317225	976	EGLL-HKJK	297477	3827
LEBB-EDDM	765	151946	EDDM-LFML	478	143928	EDDV-LTAI	230143	1342	EGLL-KPHL	356020	3191
LICJ-LIRF	267	435472	EGKK-LFSB	425	162041	EDDF-LTAI	239355	1288	EHAM-KLAX	228050	4962
EGKK-EGAA	346	335840	EDDF-LFML	463	148557	ESSA-LTFM	230719	1334	EDDF-ZBAA	260293	4329
EGLL-EGAC	302	383509	LOWW-LMML	767	89657	LPPT-LIRF	287720	1065	EDDF-FAOR	231069	4873
EGSS-LIPZ	671	172436	EDDL-EDDB	293	234573	EGLL-EPWA	366030	835	LFPG-RJTT	170768	6578
EGSS-EDDB	517	223890	EGAA-EGSS	317	216475	LOWW-LEMD	296839	1028	EDDF-RCTP	181875	6155
LEVC-LFPO	622	186131	EFHK-EVRA	219	312972	LROP-LFPG	288222	1057	EHAM-CYYZ	338723	3303
EGPH-EHAM	399	290116	EPWA-ENGM	633	108346	EDDH-LTFM	263106	1153	EFHK-VTBS	203614	5463
EGAA-EGKK	346	334190	LFPG-LFRS	234	293015	LEMD-LOWW	287156	1048	LGAV-KEWR	247354	4476
EDDM-EBBR	352	327343	LEVC-LPPT	454	150713	LEAL-EGKK	347776	863	EHAM-KIAH	246980	4481
LFPG-LSZH	288	400163	LFRB-LFPG	317	216110	LFPG-LROP	287207	1043	LSZH-KSFO	210107	5230

Continued on next page

Table A.1 – continued from previous page

Route	Distance [nm]	Demand [# pax]	Route	Distance [nm]	Demand [# pax]	Route	Distance [nm]	Demand [# pax]	Route	Distance [nm]	Demand [# pax]
LIRN-LFPG	737	156163	EGNT-EGLL	264	258480	EFHK-EDDM	334856	893	EGLL-LLBG	549457	1976
EHEH-LEVC	807	142434	EDDS-EHAM	349	195709	EGCC-LEPA	334459	892	LIMC-ZSPD	207586	5216
LIRN-LIME	372	308592	LEAS-LEBL	417	163348	LGAV-OTHH	166516	1792	LEMD-MDSD	292576	3688
LIME-LICJ	499	230380	LOWW-EDDM	211	323052	LIRF-LPPT	286285	1039	LFPG-KDTW	302659	3554
EHAM-EGPH	395	290455	EHEH-LEPA	789	86412	EIDW-LTFM	177720	1668	LPPT-SBKP	249241	4306
LIPE-LEBL	492	232939	LGKR-LGAV	249	273438	EPWA-EGLL	365213	811	EDDF-KDFW	234302	4581
EBBR-EDDM	352	325476	LIRF-LIMC	303	224731	EDDM-EFHK	333568	887	EGLL-OBBI	373274	2864
LSZH-EGLC	454	252018	EHAM-ENVA	728	93322	EFHK-EDDF	334428	876	EIDW-KIAD	351184	3019
EDDB-EHAM	344	332899	LOWW-LFMN	523	129848	LPPT-GVNP	176082	1649	LSZH-KJFK	300936	3515
EDDM-LEBB	743	153875	LROP-LIRA	646	105180	EDDF-EFHK	332331	871	LFPG-KBOS	340808	3090
EPKT-EGGW	777	147036	ENVA-EHAM	732	92738	LEPA-EDDB	294859	976	EIDW-KBOS	393219	2672
LICJ-LIME	494	231072	LIRP-EGLL	673	100900	LGAV-LSZH	299485	955	LFPG-VIDP	272700	3849
EDDB-EGSS	516	221307	ENBR-EDDF	689	98329	LSZH-LGAV	301080	949	LPPT-KEWR	337560	3068
LFML-LPPT	760	150051	LFML-EDDM	473	143165	LEPA-LOWW	333000	856	EGBB-OMDB	323757	3134
EDDM-LBSF	629	181244	LIRP-EGCC	803	84242	EGSS-GCRR	180840	1573	LSZH-KORD	254115	3988
LEBL-LIPE	487	234052	ESSA-EPWA	545	124134	EGKK-LEAL	348002	817	EDDM-KEWR	275715	3647
EIDW-EGBB	204	559513	LPPT-LEVC	449	150386	ENGM-LTFM	198755	1425	EGLL-MMMX	200385	4981
EGAC-EGLL	297	383291	LSZH-LHBP	478	141243	LGAV-LEMD	210757	1334	EDDL-OMDB	353791	2818
EPWA-EDDM	449	253177	LIPH-EBCI	473	142426	LFPG-DTTA	327340	858	LFPO-SOCA	254734	3905
LFMT-LFPG	400	284654	EGGW-EIDW	284	237219	LEMD-LGAV	209890	1338	LGAV-KJFK	223942	4427
EHAM-LFMN	621	182454	EBCI-LIME	421	160026	EDDB-LEPA	294610	943	LFPG-KSEA	218658	4447
ESSA-ESGG	233	486670	EGGD-EGPF	317	212025	LEMG-LTFM	166924	1658	EGLL-OKBK	356712	2702
EGGW-EPKT	777	145499	LFPG-LEVC	624	107615	LROP-LLBG	304519	907	LIRF-KATL	213134	4519
LIRN-LIMC	428	263522	LPPR-LFML	727	92015	EGKK-LPFR	286736	962	EHAM-TNCC	221673	4322
EDDK-LEBL	714	157731	ELLX-LEMD	763	87517	LEMG-EGCC	257200	1072	LEMD-MUHA	230260	4145
LBSF-EDDM	625	179960	LEBL-LEAS	407	164282	EDDB-LTAI	222806	1237	LEMD-SEQM	196728	4826
LIPZ-EDDF	393	286024	LIRP-EGKK	651	102659	EGKK-LTFM	197281	1396	EHAM-KORD	258908	3667
LEIB-LEMD	274	409535	EHAM-EGGD	303	220358	LPFR-EGKK	285763	954	EGLL-ZSPD	180113	5186
LFPO-LEVC	600	186131	LEMD-ELLX	759	87782	LOWW-LEPA	332417	819	EHAM-SBGR	172071	5402
ESSA-EFHK	231	482818	LIRF-LEIB	554	120251	LGAV-EBBR	227941	1193	EGLL-KAUS	210917	4360
EFHK-ESSA	230	482717	EBBR-LFMN	559	118948	EGGD-GCTS	170321	1595	EHAM-KSEA	211169	4351
LIMC-LIRN	421	263568	LFBD-EHAM	529	125662	LEMG-EKCH	193394	1403	LSZH-SBGR	173238	5284
LROP-LTFM	306	361835	LIME-EGCC	708	93936	EGLL-LIRF	326433	831	EGLL-KCLT	256531	3559

Table A.2: Energy carrier input data. As WTW reductions will be varied in Sensitivity Analysis, the values will not be shown here.

		Production Costs [€/1000kg]									
Energy carrier	Production Pathway	2025	2030	2035	2040	2045	2050	LHV [MJ/kg]	EIS	E_{req}	Remarks
Conventional	Jet A1 fuel	780	1010	1055	1100	1175	1250	43	2025	–	Price trends from [Neiva et al., 2022]
SAF	HEFA	1025	1005	1023.5	1042	1045	1048	43	2025	0.29	Electricitiy prices in €/GJ
SAF	AtJ	2493	2086	2125	2164	2162.5	2161	43	2030	0.15	Drop-in fuels WTW reductions and FS info from [ICAO, 2023]
SAF	FT-SPK	2066	2057	2048	2039	2063.5	2088	43	2030	0.16	Energy requirements from [Boter, 2023]
SAF	eSaf	2814	2968	2639	2310	2117.5	1925	43	2035	2.72	H_2 energy required from [World Nuclear Association, 2024, DOE, 2009]
Hydrogen	Gaseous	3609.5	2743	2480.5	2218	2134.5	2051	120	2030	1.65	
Hydrogen	Liquefied	3609.5	2743	2480.5	2218	2134.5	2051	120	2030	1.95	
Electric	Green energy	12	11	10	9	8.5	8	–	2030	1.00	

Table A.3: Technology in development dataset

Technology in development	RDC [€]	Start year RD	Technology EIS	Growth rate	List price increment	Remarks
Electric	7.06×10^8	2020	2035	0.02	7.00×10^6	All price values from investment scenario EU study
Hybrid electric	4.33×10^9	2020	2035	0.02	4.33×10^7	
Hydrogen fuel cell	3.17×10^8	2020	2035	0.02	1.06×10^7	
Hydrogen combustion	1.40×10^9	2020	2035	0.02	1.40×10^7	
HEFA	2.30×10^8	2020	2025	0.02	0	
AtJ	2.47×10^9	2020	2025	0.02	0	
FT-SPK	3.73×10^9	2020	2030	0.02	0	
eSaf	9.84×10^9	2020	2030	0.02	0	

Table A.4: Time-dependent dataset. As the inputs for SAF adoption are varied in the sensitivity analysis, the values are not shown here.

Year	Offset price [€/kgCO_2]	Emission price [€/kgCO_2]	Remarks
2025	0.018	0.085	Emission price follows the EU ETS, starting near €85/tCO_2 today and rising to €150–200/tCO_2 by 2050 as allowances decline.
2030	0.027	0.10	Offset price reflects voluntary markets, starting at €15–40/tCO_2 today and reaching €80–100/tCO_2 by 2050 as demand for high-quality credits grows.
2035	0.045	0.13	–
2040	0.065	0.15	–
2045	0.078	0.17	–
2050	0.091	0.18	–

Table A.5: Infrastructure costs input in [€/MJ]. Values for SAF are independent of airport size, shown value applicable for all sizes

Airport size	Electric - green energy	Hydrogen - gaseous	Hydrogen - liquified	SAF - HEFA	SAF - AtJ	SAF - FT-SPK	SAF - eSaf
Small	0.00792	0.00042	0.00042				
Medium	0.00608	0.00022	0.00022	0.07348	0.07348	0.07348	0.46511
Large	0.00158	0.00035	0.00035				

Table A.6: Conventional aircraft performance and fleet characteristics used in the optimisation model. Unless specified, all data regarding Seats, range and cruise speed is retrieved from Eurocontrol Aircraft Performance Database

AC Type	IF	Seats	Range [nm]	ABT	Price [M€]	L_a	Age	Fuel [kg/h]	Speed	PR	MTOW [N]	Fuel wt [N]	L/D	η_{fuel}	Remarks
A20N	368	180	3500	3650	94.56	25	9	2418	450	600	774990	211318.39	19	0.28	
A21N	278	220	4000	3650	109.68	25	9	2970	450	600	951570	258994.99	19	0.28	
A306	1	266	4150	3650	127.07	25	35	5746	470	0	1684377	335858.46	19	0.28	
A310	2	220	5100	3650	109.68	25	35	5199	480	0	1471500	258994.99	19	0.28	
A318	18	107	1500	3650	66.97	25	18	1820	460	0	578790	170256.5	19	0.28	
A319	297	124	1800	3650	73.40	25	18	1952	450	0	627840	174516.1	19	0.28	
A320	981	150	2700	3650	83.22	25	20	2283	450	0	724959	187258.19	19	0.28	
A321	303	185	2350	3650	96.45	25	20	2552	450	0	814230	216303.19	19	0.28	
A332	179	253	6750	3650	199.56	25	18	5500	470	10	2256300	1208035.6	20	0.29	
A333	239	295	5650	3650	239.57	25	20	5681	475	10	2256300	1154789.6	20	0.29	
A338	2	260	8150	3650	206.23	25	6	6349	475	10	2462310	1193877.8	20	0.29	
A339	51	300	7200	3650	244.34	25	5	6438	475	10	2462310	1153518.7	20	0.29	
A343	32	295	7200	3650	239.57	25	25	7521	490	0	2697750	1154789.6	20	0.29	
A346	1	380	7750	3650	320.56	25	20	10421	480	0	3610080	1279827.5	20	0.29	
A359	272	366	8100	3650	307.22	25	7	7077	490	60	2629080	1237797.1	20	0.29	
A35K	59	410	8700	3650	349.15	25	5	8593	490	50	3129390	1398358.9	20	0.29	
A388	129	555	8000	3650	487.30	25	10	15857	520	0	5493600	2518480.7	20	0.29	
AT43	1	50	1700	3650	18.46	25	18	298	255	30	163827	47700.831	17	0.3	
AT45	14	42	1000	3650	16.88	25	18	410	300	30	182466	39817.562	17	0.3	
AT46	5	48	726	3650	18.06	25	18	387	289	30	182466	45672.837	17	0.3	ATR 42-600
AT72	7	72	1500	3650	22.80	25	17	400	275	30	210915	72524.533	17	0.3	
AT75	48	78	825	3650	23.98	25	17	432	280	30	225630	80095.107	17	0.3	
AT76	111	78	740	3650	23.98	25	15	417	270	30	225630	80095.107	17	0.3	ATR72-600
B190	21	18	1500	3650	12.14	25	30	148	270	0	75438.9	19827.058	17	0.3	
B38M	185	178	3550	3650	93.81	25	5	2569	453	400	810306	209402.45	19	0.28	
B39M	9	193	3550	3650	99.48	25	5	2744	453	400	866223	224858.17	19	0.28	
B733	8	128	1600	3650	74.91	25	35	1599	429	0	553970.7	175986.25	19	0.28	
B734	7	146	2100	3650	81.71	25	30	1805	430	0	616264.2	184807.69	19	0.28	
B735	2	108	1600	3650	67.35	25	30	1473	430	0	513945.9	170417.94	19	0.28	
B736	7	108	3200	3650	67.35	25	25	1724	460	0	553480.2	170417.94	19	0.28	
B737	45	128	2500	3650	74.91	25	20	2078	460	0	650599.2	175986.25	19	0.28	
B738	1020	162	2000	3650	87.76	25	15	2192	460	0	691899.3	195679.12	19	0.28	
B739	30	177	2745	3650	93.43	25	12	2478	460	0	775137.15	208461.19	19	0.28	
B744	23	416	7260	3650	354.86	25	30	11839	510	0	3893490.9	1426723.3	20	0.29	
B748	28	467	4390	3650	403.46	25	5	12877	510	0	4338472.5	1730511	20	0.29	
B752	57	200	3900	3650	102.12	25	30	3858	470	0	1134820.8	232928.64	19	0.28	
B753	15	243	3395	3650	118.38	25	25	4199	490	0	1212516	294480.13	19	0.28	
B763	112	269	6105	3650	214.80	25	25	3909	460	0	1833292.8	1178780.3	20	0.29	
B764	36	304	5645	3650	248.15	25	20	4592	460	0	2002417.2	1153278.2	20	0.29	
B772	199	305	5210	3650	249.10	25	20	6366	480	35	2424247.2	1153326	20	0.29	
B77L	33	301	9380	3650	245.29	25	15	10162	490	35	3408975	1153393.9	20	0.29	
B77W	588	365	7930	3650	306.27	25	15	10134	490	35	3448215	1235118.4	20	0.29	
B788	232	250	8000	3650	196.70	25	10	5413	470	60	2236680	1214750.2	20	0.29	
B789	369	296	7565	3650	240.53	25	7	6750	490	60	2491847.9	1154449.2	20	0.29	
B78X	47	336	6430	3650	278.64	25	5	6673	488	60	2491847.9	1176198.2	20	0.29	
BCS1	9	120	3400	3650	32.27	25	7	2148	445	120	619011	142694.79	18	0.27	
BCS3	85	150	3350	3650	38.19	25	6	2292	445	120	685719	197700.64	18	0.27	
CRJ2	6	50	1800	3650	18.46	25	25	693	420	0	211140.63	47700.831	18	0.27	
CRJ9	60	80	1550	3650	24.38	25	20	1328	450	0	376017.3	82694.867	18	0.27	
CRJX	38	104	1345	3650	29.11	25	15	1321	440	0	400483.44	116865.17	18	0.27	
D228	2	19	1000	3650	12.34	25	30	96	210	0	62784	20550.407	18	0.27	
DH8A	29	37	1000	3650	15.89	25	35	297	250	0	152643.6	35200.225	18	0.27	
DH8B	12	37	1100	3650	15.89	25	30	341	270	0	160884	35200.225	18	0.27	range from Skybrary.aero
DH8C	12	50	1000	3650	18.46	25	25	350	250	0	182878.02	47700.831	18	0.27	
DH8D	46	78	1300	3650	23.98	25	20	773	360	0	284470.38	80095.107	18	0.27	
DHC6	3	19	900	3650	12.34	25	30	63	160	15	55622.7	20550.407	18	0.27	

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AC Type	IF	Seats	Range [nm]	ABT	Price [M€]	L_a	Age	Fuel [kg/h]	Speed	PR	MTOW [N]	Fuel wt [N]	L/D	η_{fuel}	Remarks
E135	3	35	1200	3650	15.50	25	25	507	320	0	196101.9	33419.997	18	0.27	
E145	19	49	1200	3650	18.26	25	25	716	440	0	207952.38	46682.069	18	0.27	
E170	22	70	2100	3650	22.40	25	19	1291	460	0	353110.95	70077.245	18	0.27	
E190	144	94	2400	3650	27.14	25	15	1623	460	50	451210.95	101960.48	18	0.27	
E195	83	124	2300	3650	33.06	25	14	1719	447	50	512964.9	149533.37	18	0.27	
E290	15	106	2950	3650	29.50	25	5	1958	450	40	553284	119960.46	18	0.27	Embraer E290
E295	20	132	3000	3650	34.63	25	4	2062	450	40	603315	163667.95	18	0.27	Embrear E295
E75L	18	78	2200	3650	23.98	25	12	1356	450	50	381609	80095.107	18	0.27	Embraer E175
E75S	13	72	2150	3650	22.80	25	12	1368	450	50	380529.9	72524.533	18	0.27	Embraer E170
F100	2	100	3100	3650	28.32	25	34	1319	405	0	425655.9	110788.94	18	0.27	
J328	5	32	2000	3650	14.90	25	25	427	350	0	153624.6	30821.125	18	0.27	
JS31	1	18	550	3650	12.14	25	35	100	250	0	55622.7	19827.058	18	0.27	
JS32	4	12	850	3650	10.96	25	33	133	235	0	72201.6	15687.081	18	0.27	
JS41	8	16	1000	3650	11.75	25	30	250	290	0	106791.66	18408.948	18	0.27	
L410	2	19	600	3650	12.34	25	25	92	200	12	62784	20550.407	18	0.27	
RJ1H	1	100	1100	3650	28.32	25	25	1465	420	0	451456.2	110788.94	18	0.27	
SF34	10	34	930	3650	15.30	25	35	243	250	0	126549	32544.177	18	0.27	

Table A.7: Future aircraft performance and fleet characteristics used in the optimisation model.

AC Type	Technology	REF_AC	Seats	Range	Annual block hours	List price [€]	unique_aircraft	Economic lifetime	Current age	Fuel consumption [kg/hr]	Energy consumption [Wh/pax-km]	EIS	Cruise speed [kts]	EIS Production rate	Max Production rate	learning parameter	MTOW [N]	Assumed L/D	n_fuel	n_elec	Hybrid electric part	Source/remarks
Eviation Alice	Electric	Cessna 208 Caravan	9	250	3650	4.50E+06	0	25	0	0	272.61	2027	260	15	60	0.85	81874.26	13	0	0.82	0	Eviation
Cosmic	Electric	Beechcraft 1900D	24	540	3650	1.20E+07	0	25	0	0	92.05	2029	251	12	50	0.85	84022	15	0	0.81	0	Cosmic Aerospace
Elysian	Electric	Embraer E175	90	540	3650	4.50E+07	0	25	0	0	178.92	2033	300	10	90	0.7	745560	17	0	0.87	0	Elysian
Vaeridion	Electric	Cessna 208 Caravan	9	216	3650	4.50E+06	0	25	0	0	89.24	2030	222	10	40	0.9	26802	13	0	0.82	0	Vaeridion
Heart Aerospace ES30	Hybrid Electric	Dornier 328	25	432	3650	1.25E+07	0	25	0	147.49	21.14	2029	200	12	60	0.8	87746	17	0.26	0.78	0.25	Heart Aerospace
Volt Aero Cassio 330	Hybrid Electric	Cessna 208 Caravan	5	648	3650	2.50E+06	0	25	0	6.24	309.95	2025	156	15	50	0.9	13875	13	0.82	0.22	0.38	Volt Aero
Ampaire Eco Otter	Hybrid Electric	Beechcraft 1900D	19	605	3650	9.50E+06	0	25	0	59	240.4	2025	253	20	60	1	64343	15	0.82	0.3	0.1	Ampaire
Dovetail Beechcraft King Air	Hybrid Electric	Cessna 208 Caravan	9	250	3650	4.50E+06	0	25	0	16.45	244.49	2028	180	20	60	1	26864	13	0.84	0.3	0.25	Dovetail
Electra	Hybrid Electric	Cessna 208 Caravan	9	1100	3650	4.50E+06	0	25	0	20.38	341.4	2028	175	12	60	1	27509	13	0.81	0.22	0.1	Electra
Embraer E19 HE	Hybrid Electric	Beechcraft 1900D	19	200	3650	9.50E+06	0	25	0	46.97	236.18	2030	225	20	80	0.85	63214	15	0.8	0.3	0.2	Embraer Commercial Aviation Sustainability
Embraer E30 HE	Hybrid Electric	Dornier 328	30	300	3650	1.50E+07	0	25	0	83.86	238.66	2030	237	24	90	0.85	107585	16	0.8	0.3	0.15	Embraer Commercial Aviation Sustainability
Embraer E50HE	Hybrid Electric	ATR 42-500	50	350	3650	2.50E+07	0	25	0	161.6	258.31	2030	250	28	110	0.85	194066	16	0.79	0.3	0.15	Embraer Commercial Aviation Sustainability
Maeve MJ 500	Hybrid Electric	ATR 72-600	76	1450	3650	3.80E+07	0	25	0	491.97	274.89	2031	450	12	70	0.85	333540	17	0.8	0.3	0.1	Maeve
ZeroAvia DHC-6	Hydrogen Fuel Cell	Beechcraft 1900D	19	400	3650	9.50E+06	0	25	0	31.24	0	2030	180	22	55	1	55622.7	13	0.35	0	0	ZeroAvia
ZeroAvia DHC dash 8	Hydrogen Fuel Cell	Embraer E175	82	862	3650	4.10E+07	0	25	0	249.24	0	2030	360	18	60	0.9	290120.9	17	0.35	0	0	ZeroAvia
Stralis B1900D-HE	Hydrogen Fuel Cell	Beechcraft 1900D	15	432	3650	7.50E+06	0	25	0	57.27	0	2030	270	20	50	1	76184.46	15	0.35	0	0	Stralis
Stralis SA-1-HE	Hydrogen Fuel Cell	ATR 42-500	50	1620	3650	2.50E+07	0	25	0	153.45	0	2037	313	15	60	0.85	198883	16	0.34	0	0	Stralis
Blue spirit 6S	Hydrogen Fuel Cell	Cessna 208 Caravan	5	540	3650	2.50E+06	0	25	0	30	0	2029	300	15	70	0.85	27468	13	0.36	0	0	Blue Spirit
Embraer E19H2FC	Hydrogen Fuel Cell	Beechcraft 1900D	19	600	3650	9.50E+06	0	25	0	44.02	0	2035	253	24	90	0.85	64335	15	0.35	0	0	Embraer Commercial Aviation Sustainability
Embraer E30H2FC	Hydrogen Fuel Cell	Dornier 328	30	600	3650	1.50E+07	0	25	0	71.16	0	2035	258	30	100	0.85	108785	16	0.35	0	0	Embraer Commercial Aviation Sustainability
Embraer E50H2FC	Hydrogen Fuel Cell	ATR 42-500	50	600	3650	2.50E+07	0	25	0	132.52	0	2035	267	36	110	0.85	195747	16	0.35	0	0	Embraer Commercial Aviation Sustainability
Embraer E50H2GT/DF	Hydrogen Combustion	ATR 42-500	50	600	3650	2.50E+07	0	25	0	159.93	0	2040	267	30	120	0.9	195747	16	0.29	0	0	Embraer Commercial Aviation Sustainability
Fokker Next gen	Hydrogen Combustion	Airbus A220-100	120	1400	3650	6.00E+07	0	25	0	541.56	0	2035	354	16	80	0.8	543033	18	0.28	0	0	Fokker Next Gen
Conscious aerospace dash 8	Hydrogen Combustion	Dash 8-100/200	36	405	3650	1.80E+07	0	25	0	81.13	0	2030	240	18	60	0.9	133320	16	0.3	0	0	Conscious Aerospace

Table A.8: Sensitivity analysis input WTW assumptions

Energy carrier	Production Pathway	WTW reduction worst	WTW reduction best	Remarks
Conventional	Jet A1 fuel	0	0	Drop-in fuels WTW reductions from [ICAO, 2023]
SAF	HEFA	0.27	0.8	Non-drop-in WTW reductions from [Neiva et al., 2022]
SAF	AtJ	0.12	0.72	
SAF	FT-SPK	0.63	0.91	
SAF	eSaf	0.45	0.92	
Hydrogen	gaseous	0	0.95	
Hydrogen	liquified	0.64	1	
Electric	green energy	0.64	1	

Table A.9: Sensitivity analysis input SAF adoption trajectories

	SAF blend			e-SAF blend		
Year	Low	Medium	High	Low	Medium	High
2025	0.016	0.02	0.028	0	0	0
2030	0.04	0.05	0.1	0.006	0.012	0.02
2035	0.16	0.2	0.296	0.025	0.05	0.07
2040	0.256	0.32	0.491	0.05	0.1	0.15
2045	0.304	0.38	0.687	0.1	0.15	0.25
2050	0.504	0.63	0.882	0.2	0.35	0.5

Table A.10: Sensitivity analysis market growth factor input

Scenario	Market growth factor	Source
Low	1.2%	[Eurocontrol, 2022]
Medium	3.6%	[Airbus, 2025]
High	4.2%	[Boeing, 2025]

B Supplementary Scenario Results

Table B.1: Scenario definition matrix

WTW	SAF	Market	Scenario ID
Best	High	High	1
		Medium	2
		Low	3
	Medium	High	4
		Medium	5
		Low	6
	Low	High	7
		Medium	8
		Low	9
Worst	High	High	10
		Medium	11
		Low	12
	Medium	High	13
		Medium	14
		Low	15
	Low	High	16
		Medium	17
		Low	18

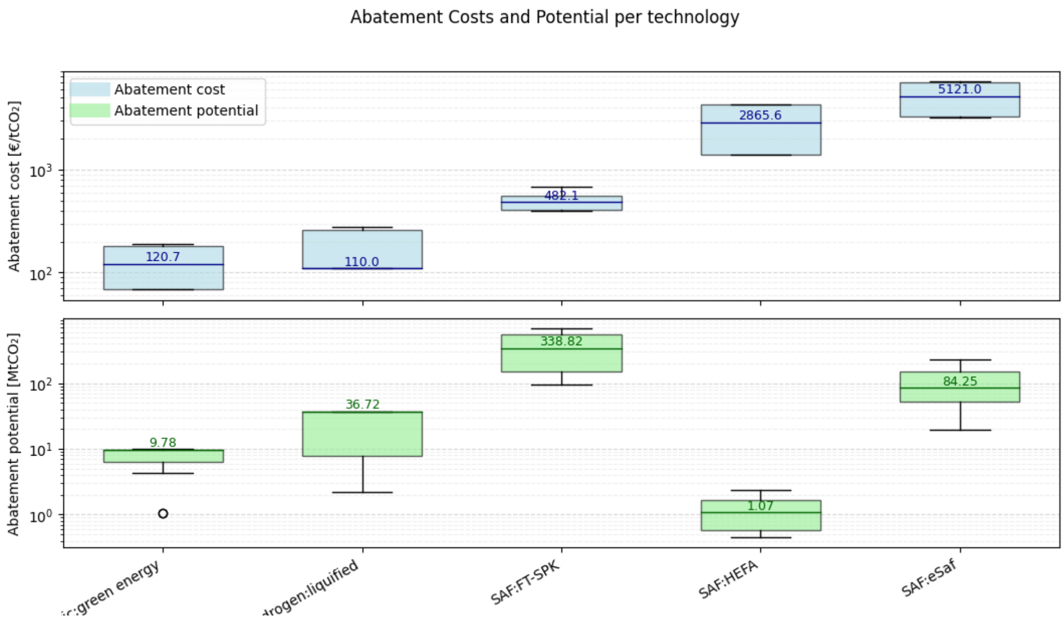

Figure B.1: Abatement costs and potential ranges over the 18 scenarios

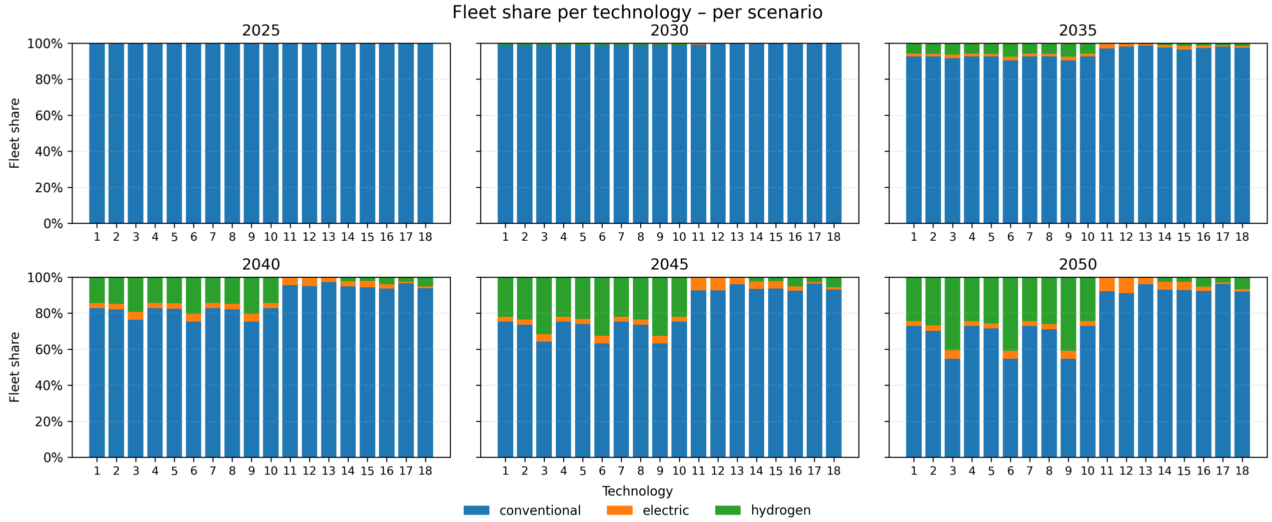

Figure B.2: Fleet share distributions across scenarios and years

Table B.2: Across-scenario adoption summary for hydrogen and electric aircraft in closest-to-utopia solutions.

AC	technology	Scenarios used	Scenarios share	Fleet 2050 min	Fleet 2050 median	Fleet 2050 max	First EIS year median
Elysian	Electric	18	1.000	50	100	190	2035
Maeve MJ 500	Electric	16	0.889	0	120	265	2035
Cosmic	Electric	1	0.056	0	0	120	2030
Fokker Next gen	Hydrogen	13	0.722	0	405	405	2040
Embraer E50H2FC	Hydrogen	10	0.556	0	365	365	2040
Stralis B1900D-HE	Hydrogen	10	0.556	0	200	200	2035
Conscious aerospace dash 8	Hydrogen	10	0.556	0	180	180	2035
Stralis SA-1-HE	Hydrogen	10	0.556	0	150	150	2040
Embraer E50H2GT/DF	Hydrogen	10	0.556	0	150	150	2045
Blue spirit 6S	Hydrogen	10	0.556	0	112	150	2030

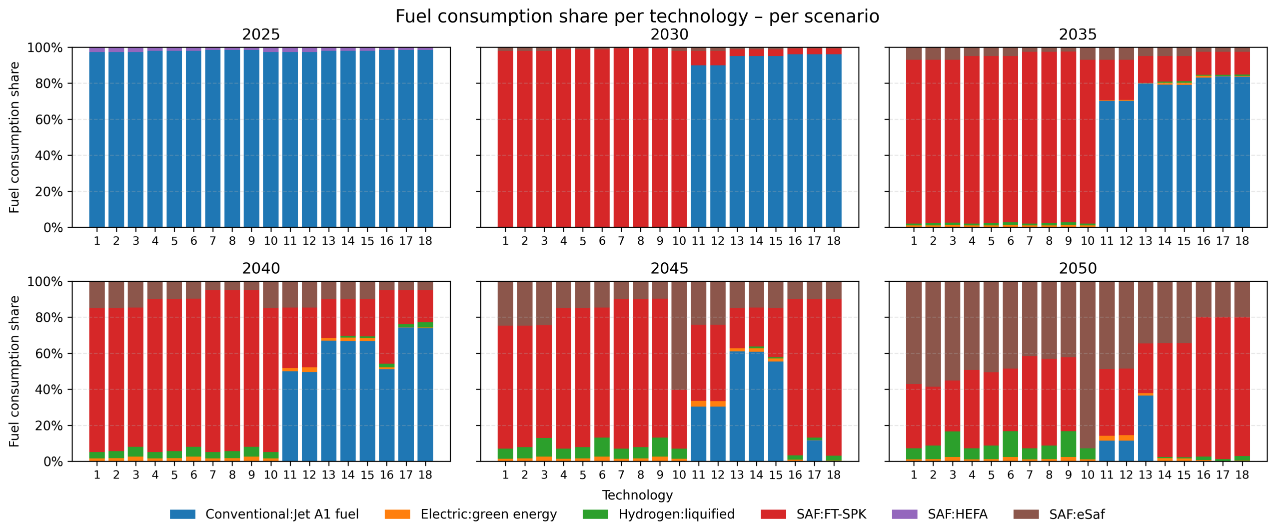

Figure B.3: Fuel consumption shares across scenarios

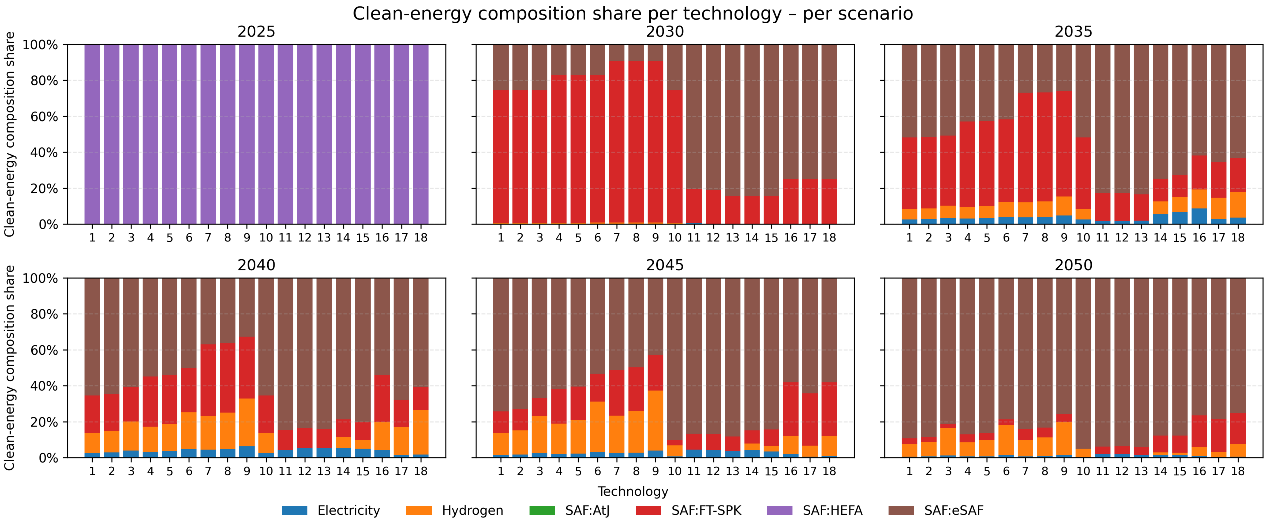

Figure B.4: Clean energy pathway composition over scenarios

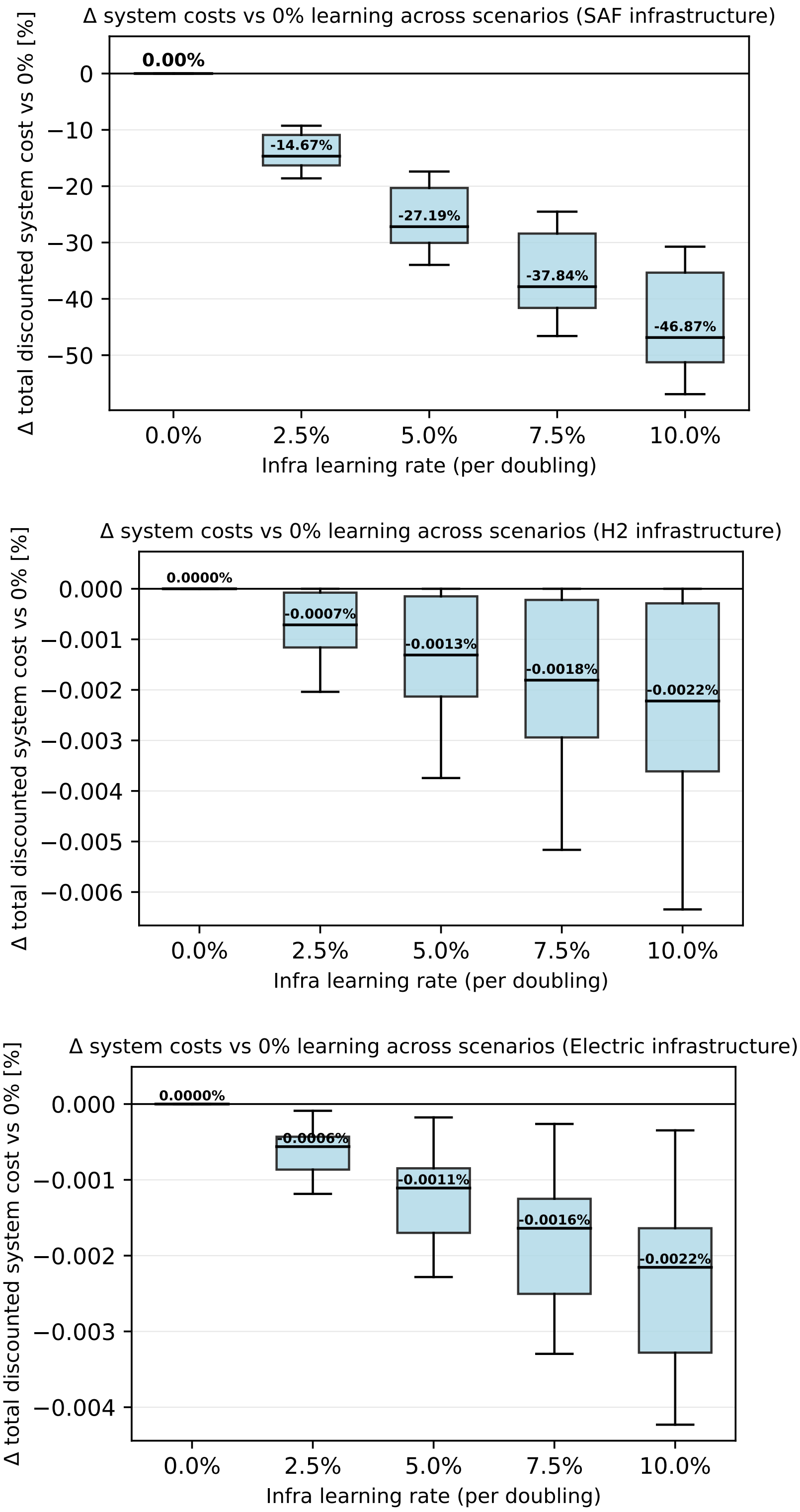

Figure B.5: Impact of infrastructure learning curves on total system costs across all 18 scenarios.

Part II

Research proposal

Research proposal

A techno-economic assessment for net-zero aviation

MSc Thesis Control & Operations

Bram Buijvoets

Delft University of Technology | Skyfinity

TU Delft

Research proposal

A techno-economic assessment for net-zero aviation

by

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1
Introduction

The aviation industry has committed to achieving net-zero carbon emissions by 2050 (NLR SEO Amsterdam, 2021). To reach this ambitious goal while accommodating an expected Average Anual Growth Rate of in air travel demand by 2050 of between 0.6 and 1.8% (Eurocontrol, 2022) , the sector must innovate and deploy sustainable technologies and solutions at scale. Many of the anticipated solutions—such as electric Sustainable Aviation Fuels (e-SAF), net-zero propulsion systems, and other emerging technologies—are currently in pre-commercial stages of development.
Due to the capital-intensive nature of aviation, complex and lengthy development cycles, and stringent safety regulations, these projects result in significant risks. The scale of these risks drive away investors resulting in underinvestment. To support effective policy design and complementary risk mitigation financial instrument, there is a critical need for a deeper understanding of the interaction of technological performance, development trajectories, and associated costs of sustainable aviation solutions.

This thesis proposes the development of a techno-economic model to analyse a range of predefined scenarios representing different technology development pathways. The model will assess key factors such as resource requirements, emissions abatement potential, technology adoption curves, and cost reduction curves. Accordingly, this thesis develops a system-level techno-economic optimisation framework to evaluate interacting pathways—SAF (including e-SAF), hydrogen, and electrification—under uncertainty in costs and technology development.

This research proposal has the following structure: Chapter 2 gives an overview of the state of the art in the literature. Chapter 3 defines the academic research gap. From that gap, the research questions and relevant hypotheses are defined in Chapter 4. In order to answer these research questions, a method has been compiled that will be eloborated upon in Chapter 5. Finally, the planning for the execution of the tasks will be shown in Chapter 6.

2
Literature Review

This chapter provides an overview of the current state of the art in literature on topics relevant to this research. Section 2.1 presents an overview of emissions in the aviation sector. Section 2.2 discusses the rationale for investing in aviation and reviews existing market-based mechanisms aimed at reducing emissions in the sector. Section 2.3 outlines methods for quantifying aviation emissions and shows various roadmaps for their reduction. Section 2.4 explores emerging technologies that support the decarbonisation of aviation. Section 2.5 reviews current models used to ensure a competitive aviation market. Finally, Section 2.6 provides a general overview of how techno-economic assessments can be conducted.

2.1. Aviation emissions

The combustion of fossil hydrocarbons for aviation and oxygen leads to the emissions of Carbon Dioxide (CO_2) and water vapor (H_2O). The equation for this combustion can be found in Equation 2.1 (Grewe, 2024a).

$$C_xH_{2y} + (x + \frac{y}{2})\ O_2 \rightarrow x\ CO_2 + y\ H_2O \tag{2.1}$$

Equation 2.1 is the theoretical combustion. However, in real life air does not only consist of Oxygen but it also contains Nitrogen. Under combustor conditions (high temperature and pressure), a fraction of atmospheric nitrogen participates in secondary reactions that form NO_x emissions. Due to fuel impurities, Sulfur might be present in the fuel as well which leads to SO_x emissions. And lastly, the equation assumes perfect combustion which is also almost never the case. This might lead to Unburned Hydrocarbons, soot and other aerosols. The process of the combustion can be found in Figure 2.1.

All these byproducts mean that aviation emits more than it may seem at first sight. In literature, there is made a distinction between CO_2-effects and non-CO_2-effects. The CO_2-effects are considered to be the emissions related to the direct reinforcement of the greenhouse effect. This is primary done by the combustion of the jet fuel, but CO_2 emissions related to the life cycle of the fuel (such as production and transport). This emitted CO_2 is a long-lived climate forcer. As around 20% of the emitted CO_2

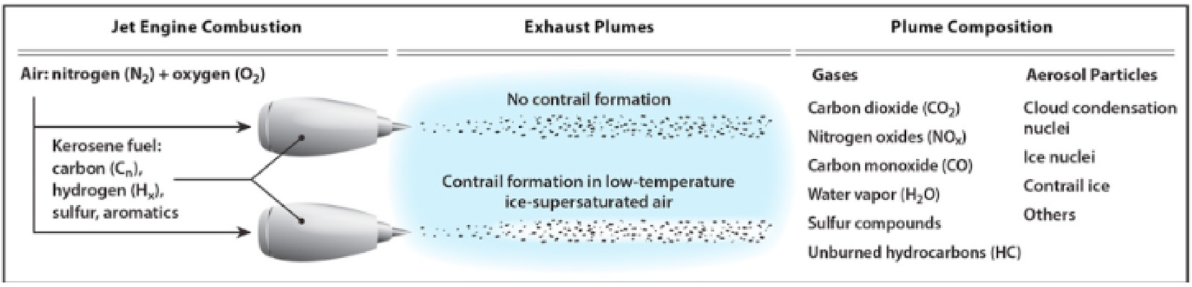


Figure 2.1: Process of aviation emission (Lee et al., 2021)

stays in the atmosphere for more than 1,000 years, the effects of these emissions are accumulative. (Delbecq et al., 2023)

The non-CO_2-effects can be described by the effects of all the byproducts of Equation 2.1 as described earlier in this section. This paragraph lists the main non-CO_2-effects as mentioned by Delbecq et al. (2023). The paper also notes nitrous oxide (N_2O) and methane (CH_4) as emitted gases, but these emissions take less than 1% of the non-CO_2 emissions and are therefore generally not considered in literature. The five main non-CO_2-effect are:

- Contrail formation: Contrails are thin clouds of ice particles that form behind aircraft when the ambient air is sufficiently cold and supersaturated with respect to ice. Whether persistent contrails can form is commonly assessed using the Schmidt–Appleman criterion (Schumann, 1996). Once formed, contrail cirrus affects the Earth's radiation balance by trapping outgoing longwave radiation (a warming effect) while also reflecting incoming shortwave solar radiation (a cooling effect). The net radiative impact is condition- and time-dependent: at night contrails are purely warming, whereas in daylight reflected sunlight can partially offset this warming and occasionally dominates. Contrails may persist and disperse over timescales of minutes to a few hours depending on atmospheric conditions (Grewe, 2024c).
- Nitrogen oxides (NO_x): This byproduct induces reactions that affects three different greenhouse gases. On the short term it increases the ozone (O_3) concentrations and decreases the concentrations of methane. Over time, reduced CH_4 lowers stratospheric ozone and water vapor. At cruising altitudes, aircraft emissions disrupt the radiation balance, adding to global warming.
- Aerosol interactions: Aerosols like soot and sulfate can interact with radiation. Soot absorbs shortwave radiation which leads to heating. Sulfate scatters the radiation which leads to cooling. These aerosols can also interact with the forming of clouds. The particular matters form nuclei for the forming for cloud droplets or ice crystals which eventually will form clouds. There is no scientific unison in literature on whether these clouds induce a warming or cooling effect.

The emission index can be used as a metric to quantify the emissions of a combustion process. This metric indicates how much of a combustion product is emitted per kg of fuel and can be calculated with Equation 2.2. Jet A1 fuel is unfortunately not just one hydrocarbon but a mix of hydrocarbon where the carbon number, the x from

Equation 2.1, varies between 8 and 16 (Grewe, 2024b). Therefore in 2008 a study was held to look at the different hydrocarbon ratios in jet fuels. This study concluded that the median Emission Index was 3.16 kg_{CO_2}/kg_{fuel}, see Figure 2.2. This value is widely used in literature.

$$EI_X = \frac{m_X}{m_{fuel}} \tag{2.2}$$

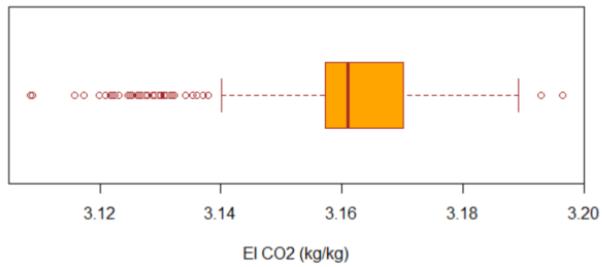


Figure 2.2: Emission index distribution of a 2008 fuel survey. Retrieved from supplementary information from (Grewe et al., 2021)

2.2. Investments in Aviation

(Jorge-Calderón, 2021) describes the main reasons to invest in transport projects are reducing transport time, costs in terms of resource usage and improving the safety of a transportation system. However, the latter one is rarely seen as a real reason to invest in aviation as safety is seen as a boundary condition for air transportation systems. Besides, aircraft have to pass multiple extensive safety tests by a governing institute before they can be introduced into a market. To invest in travel time means that an airline could invest in opening more routes to and from destinations with high demand. This means the capacity of the airline is growing and this will affect the door-to-door travel time of the passenger and the schedule delay. Schedule delay has two components. Frequency delay occurs when a passenger's preferred departure time is not offered. Stochastic delay occurs when the preferred departure is offered but fully booked. Schedule delay therefore depends mainly on service frequency and load factors. It is therefore highly desirable to have an optimum schedule for airlines as passengers who cannot get their preferred flight might be picked up by competing airlines, which means that they will miss out on revenues. In order to invest in time savings, airlines need to know the willingness to pay of the passengers for certain time savings. The last reason to invest in aviation is described by Jorge-Calderón as the reduction of costs for the airline. These costs consist of the operating costs and any return on capital. If the investment leads to reduced costs, the airline can either increase its profit margin or lower ticket prices. Given the price elasticity of demand, lower prices may stimulate additional demand, potentially leading to increased revenue despite the lower per-unit price.

Jorge-Calderón explains that economic activities often generate externalities, which are unintended side effects that affect third parties not directly involved in the activity. A key externality in aviation is the emission of greenhouse gases, as detailed in Section 2.1, which contributes to climate change and negatively impacts global populations. To address this, emitters can be taxed to compensate for the social cost of their emissions. When producers reflect these external costs in the prices of their goods or services, thus making consumers bear the cost of the damage, this process is known as internalising the externality. It is however important to realise that emission taxes do not limit overall emissions but help ensure that air travel occurs only when its societal value justifies its full cost. In order to really decrease aviation pollution, the emissions should be abated by the polluter itself. Currently this is done by two market based mechanisms:

- **Carbon Ofsetting and Reduction Scheme for International Aviation (CORSIA) by ICAO** (ICAO, 2025): The idea for CORSIA is that airlines can grow carbon neutrally compared to 2020 emission levels. This is done by buying offsets supplied by projects that capture carbon. For example by planting more trees to reduce the CO_2 concentration in the atmosphere. This basically means that as long as airline buy offsets, their total emissions can grow. This fact makes that CORSIA receives a lot of critique from the sector. (Transport & Environment, 2021) even calls it the worst possible option for the climate. Besides the growing emissions, CORSIA is also being questioned for its quality of offsets, lack of participation from key markets and the lack of over transparency.
- **Emissions Trading System (ETS) by the European Union**(EU, 2025): ETS is a so called Cap and Trade system. The European Union sets a cap for the yearly total emissions that can be emitted by the sectors included in the system. The sectors that are included in the CO_2 cap of ETS are electricity and heat generation, energy intensive industries such as oil refiniries or producers of steel etc., aviation within the European Economic Area including Switzerland and UK and maritime transport. Each sector of the ETS gets an allowance on how much they can emit. If a participant wants to emit more, it has to buy an allowance from another participant. This would mean that the selling participant can emit less and thus has to invest in greener production methods.

However, just investing and relying on these current Market-Based Measures will not be enough to counteract the growth of the sector. They need to be complemented with other measures,for example new emerging technologies, in order to bring emissions down (EASA, 2022).

2.3. Aviation net zero goals

To quantify the emissions from aviation, often the Kaya identity is used. The Kaya identity, introduced by Yoichi Kaya, states that the total CO_2 emissions can be calculated by the product of the following factors: Energy intensity, population, carbon intensity and GDP per capita (Kaya & Yokobori, 1997). In the context of aviation, this identity is often rewritten as the product of the fuel carbon intensity (CO_2 released per unit of energy), the aircraft energy intensity (amount of energy used for 1 RPK) and the total distance traveled by the passengers (RPK). (Delbecq et al. (2023), Bergero et al. (2023)).

Figure 2.3 shows graphs from how the demand and the former metrics and thus how the total aviation CO_2 emissions have evolved from 1990 to 2021. The total CO_2 emissions can be found in the lower right figure and shows that there is a sharp increase in aviation emissions over the last years. In the top left and top middle figure of Figure 2.3, the historic passenger and freight demand is shown. It can be seen that this demand has significantly increased over the years and thus the total distance travelled of the Kaya identity has increased. The top right graph shows the aircraft energy intensity. This has decreased over the years, which is mainly due to efficiency gains in fleet renewals and increase in load factors (Gössling & Humpe, 2023). The lower left graph shows the evolution of the carbon intensity over the years. This graph shows that the fuel carbon intensity has stayed constant over the years. This is because the jet fuel that is being used today, is the same fuel as was being used in 1990. From Figure 2.3 it becomes evident that the decrease of the aircraft energy intensity alone is not enough to compensate for the increase in demand. Therefore, methods should be found to reduce to carbon intensity of fuels for aviation.

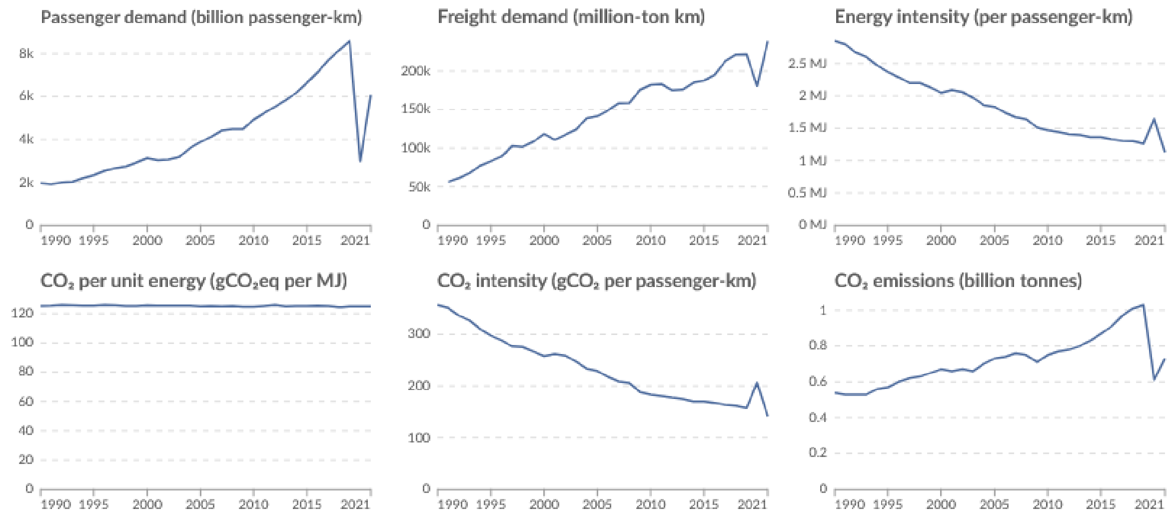
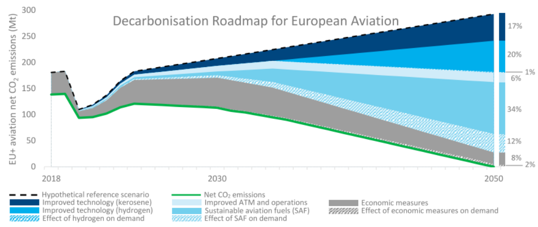


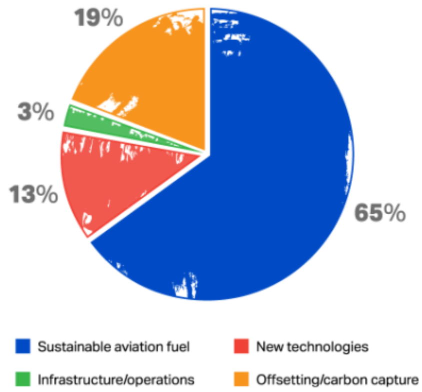
Figure 2.3: Historic aviation emission data from 1990 to 2021 (Ritchie, 2024)

While it is evident that the emissions of aviation are growing, the total CO_2 of aviation are only 2.5% of the total emissions globally in 2023 (IEA, 2025). Even though this percentage seems low, it is important to realise that this percentage is caused by only a small part of the worlds population. In 2018, no more than 4% of the worlds population flew internationally (Gössling & Humpe, 2020). Looking ahead, European traffic growth is expected to increase with 0.6-1.8% annually (Eurocontrol, 2022). In contrast, major OEM market outlooks project substantially higher global air traffic growth. With Airbus and Boeing forecasting annual growth rates of 3.6% and 4.2%. These higher global rates are largely driven by faster-expanding regions, particularly Asia-Pacific, which is expected to outpace mature markets such as Europe and North America ((Airbus, 2025) (Boeing, 2025)).

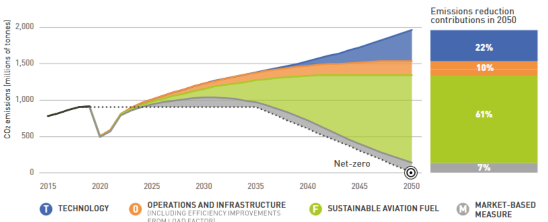
Officially, international aviation is not included in the Paris Agreement as the emissions of international aviation cannot be accounted into a country's National Determined Contribution (Delbecq et al., 2023). However, the sector also realises that doing nothing to reduce its emissions is placing its license to operate at risk (Project Skypower, 2024). Therefore, the industry has come up with various programs to reduce its emissions. Next to the market based mechanism discussed in Section 2.2, this can be done by voluntary carbon offset programs introduced by airlines. With these programs, the airlines ask the passengers if they want to offset their emissions by paying a premium. However, this is often not really effective as passengers are not aware of their emissions and there is a low willingness to pay for their offsets. (Mello, 2024). Besides this limited effect, this may also lead to greenwashing statements from the airlines which make it seem that a lot is already being done on an individual airline level (Guix et al., 2022). However, as an airline would have to transition all by itself, it would endanger its competitive nature as other airlines would fill in the routes that the airline would not be able to fulfill anymore. Therefore, joint action between the industry is needed. Throughout the sector, different roadmaps for decarbonisation have already been developed, see Figure 2.4. These roadmaps each offer a view on what pillar of the transition should contribute how much towards the decarbonisation.



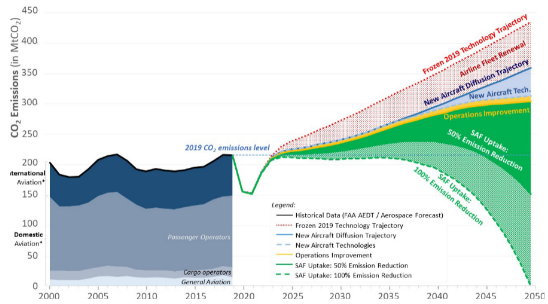
(a) EU Roadmap (NLR SEO Amsterdam, 2021)



(b) IATA Roadmap (IATA, 2021)



(c) ATAG Roadmap (ATAG, 2021)



(d) FAA Roadmap (FAA, 2021)

Figure 2.4: Overview of aviation decarbonisation roadmaps

Common pillars across these strategies include improvements in operational efficiency, increased use of Sustainable Aviation Fuels (SAFs), deployment of zero-emission aircraft (hydrogen and electric), and carbon offsetting mechanisms. While the end goal is consistent across initiatives, the effect of each pillar differs throughout the roadmaps. For example, the ATAG roadmaps expects that new technologies such as hydrogen and electricity can reduce the CO_2 emissions by 22% as the IATA roadmaps account a share of 13% for this pillar. The differing shares of decarbonisation pillars across aviation roadmaps primarily reflect variations in institutional perspective, policy context, system boundaries, and assumptions regarding technology readiness. For example, IATA, representing airlines, emphasises fleet-compatible measures such as

Sustainable Aviation Fuel, whereas ATAG, representing the broader aviation value chain, adopts a more diversified strategy that also assigns greater importance to aircraft technology and operational measures.

2.4. Emerging technologies

As became evident from the previos sections, new emerging technologies are needed to transition the aviation sector to net-zero emissions. These new emerging technologies can be split up in three main categories: Fuels, aircraft technologies and carbon capturing. This section will elaborate upon these technologies.

The aircraft technologies are mainly focused upon the optimisation of different subsystems of the aircraft design. Areas that are currently being worked on are to reduce fuel burn by optimizing the aircrafts aerodynamic configuration, impovements in flight controls using stability augmentation to reduce drag, structural optimisation that reduces weight and thus fuel burn and new propulsion system integration such as improvements in gas turbines, open fan and contra-rotating open rotor technology are being developed (Goobie et al., 2022).

However, the most emissions can be reduced by transitioning towards less carbon intense fuels. Currently there are three main different fuels to be considered for aviation:

- Drop-in SAF
- Hydrogen
- (Hybrid-) Electric propulsion

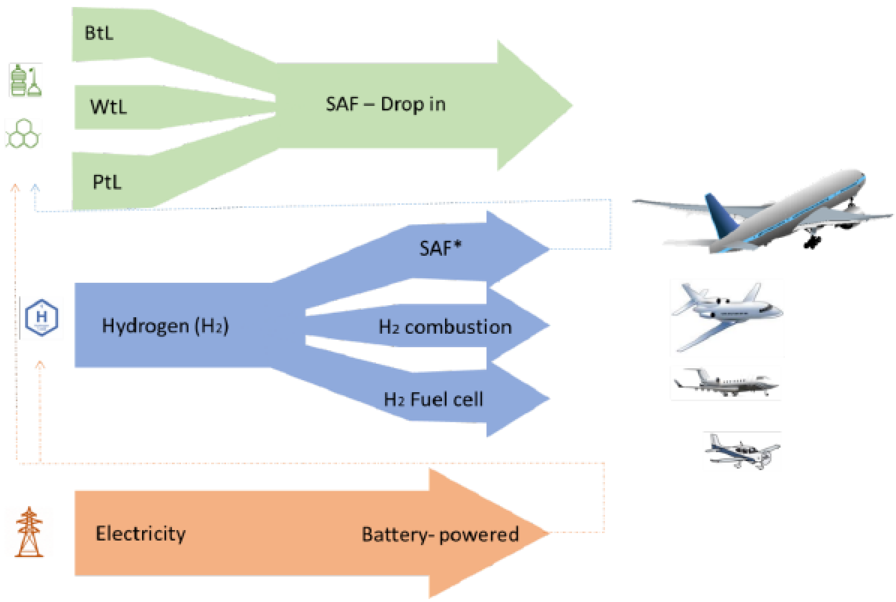


Figure 2.5: High level overview of alternative fuels and the uses for aviation (ACI, 2021). BtL = Biomass-to-Liquid, WtL = Waste-to-Liquid, PtL = Power-to-Liquid

SAF, or Sustainable Aviation Fuel, is an aviation fuel made from non-petroleum feedstock. SAF blends in with conventional jet fuels in percentages of 10 to 50%. In the future, this percentage might grow to 100% if the right chemicals are added to the SAF to ensure lubricity and other engineering requirements (ACI, 2021). One of the main advantages of SAFs are that they require very limited adjustments to existing infrastructure. If they are being blended in at a refinery that also processes conventional jet fuels, the SAFs can just use the same pipelines towards the airports as the conventional fuels do. Therefore airport fuel operations can also continue as usual (U.S. Department of Energy, 2025). The different pathways of production of SAF are summarised in Table 2.1. The pathways in the table meet the quality requirements set by the ASTM, the organisation in charge of the technical aviation fuel standards.

In literature, there seems to be no consensus on whether or not SAF will be a feasible solution to decarbonise the aviation sector. For example, Department of Energy (2024) states that SAF will be the way to decarbonise as other fuels such as electricity or hydrogen will not be able to serve heavy payloads and long haul flights. On the other side, Rau et al. (2024) states that SAF will not be a long-term solution as SAFs are unable to reach 100% lifecycle CO_2 and non-CO_2 emissions reductions. One of the solutions to make SAFs lifecycle carbon-free is the production of e-SAF or synthetic kerosene. E-SAFs are synthesised with renewable hydrogen and CO_2 captured from the atmosphere. This way the climate benefits of the fuels are maximised (ResourceWise, 2024). The problem with e-SAFs however is that their levelised costs are 5-8 times higher than conventional jet fuels. This fact scares investors away and this leads that Final Investment Decisions for e-SAF plants will only be postponed (Project Skypower, 2024).

Table 2.1: Sustainable Aviation Fuel Pathways derived from U.S. Department of Energy (2025)

Pathway	Type	Max Blend%	Feedstocks	Chemical process
Fischer–Tropsch (FT) Synthetic Paraffinic Kerosene (SPK)	WtL	50%	Municipal solid waste, agricultural and forest wastes, energy crops	Fischer–Tropsch synthesis
Hydroprocessed Esters and Fatty Acids	WtL	50%	Oil-based feedstocks (e.g., jatropha, algae, camelina, yellow grease)	Hydroprocessing followed by hydroisomerisation and hydrocracking
Hydroprocessed Fermented Sugars to Synthetic Isoparaffins	BtL	10%	Sugars	Microbial conversion
FT-SPK with Aromatics	BtL	50%	Same as A1	Biomass conversion followed by FT synthesis
Alcohol-to-Jet Synthetic Paraffinic Kerosene	BtL	50%	Cellulosic biomass	Series of chemical reactions
Catalytic Hydrothermolysis Synthesised Kerosene	WtL	50%	Fatty acids / fatty acid esters / lipids from fats, oils, greases	Hydrothermal liquefaction
Hydrocarbon-Hydroprocessed Esters and Fatty Acids	BtL	10%	Algal oil	Conversion of triglyceride oil
Fats, Oils, and Greases (FOG) Co-Processing	WtL	5%	Fats, oils, and greases	Co-processing with petroleum
FT Co-Processing	BtL	5%	FT biocrude	FT syncrude co-processing with petroleum crude oil

As can be seen from Figure 2.5, Electricity and Hydrogen have multiple use cased. Electricity can be used for battery-powered flight, but the dashed lines towards Hydrogen and SAF indicate that electricity is needed for the production of these energy carriers. Hydrogen can be used for three use cases in aviation: as feedstock for (e-)SAFs, combustion product in its liquid form and in fuel cell in its liquid or gaseos form. Hydrogen is gravimetrically quite dense, 143 MJ/kg (Mazloomi & Gomes, 2012) compared to 43 MJ/kg for kerosene (Gofman, 2003). The downside however, that its volumetric density is quite low with 0.0107 - 10.1 MJ/L (Mazloomi & Gomes, 2012) compared to kerosene with 35 MJ/L. This fact brings challenges along. For example, airports would require to have large spaces to store hydrogen tanks. In order to keep the same passenger capacity and range, aircraft would be larger to store all the fuel, which could lead to implications for ground operations and refueling might take longer. Furthermore, the logistics of getting the hydrogen towards the airport could be a challenge. As can be seen in Figure 2.6, there are different options available with the main difference of where the liquefaction will take place and how the hydrogen will be transported towards the airport. In literature, hydrogen is being spoken of as a long term solution for the decarbonisation of the aviation sector as the technology of producing is in its infancy and the Technology Readiness Level (TRL) is to scale it up towards an energy intensive sector such as aviation is too low still for it to be applied in the short term (Gössling & Humpe, 2023). (Hoelzen et al., 2023) states that green hydrogen can be cost competitive on the long term for airport with a good availability of renewable energy, but it might be too expensive for airports that do not have those resources.

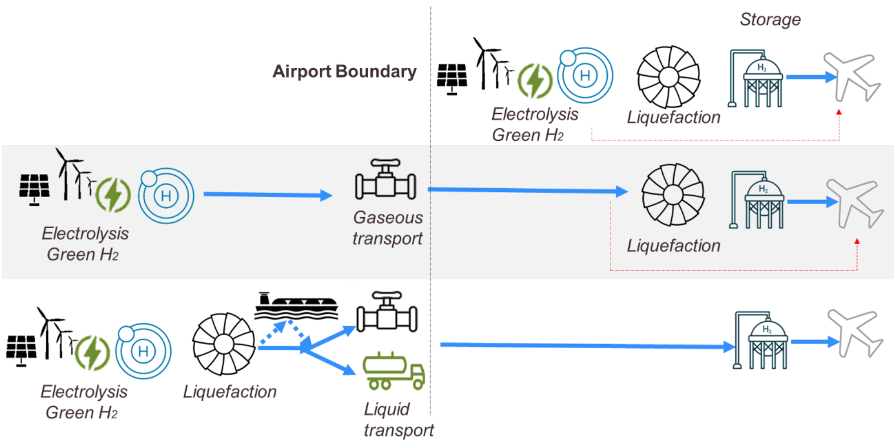


Figure 2.6: Schematic overview of hydrogen supply (ACI, 2021)

(Timmons & Terwel, 2022) describes long haul electric propulsion an infeasible solution for commercial aviation. This is due to the fact that batteries are often inefficient as they cannot store a lot of energy for their mass. This makes that the batteries heavy and thus this has an effect on the range or the passengers that the aircraft can take. Therefore, electric commercial aviation is usually described as a solution for short haul flights. However, on those routes they do also compete with other forms of transportation such as the train or the car (Timmons & Terwel, 2022). However, it is also argued that flights with ranges up to 1,000 km can be replaced by electric propelled aircraft which would save 14% of the sectors total CO_2 emissions (Wolleswinkel et al., 2024). In any circumstance, electric aircraft would require adjustments to the airport infrastructure as well. This is mainly due to the energy requirement of the airport. The European electricity grid is already overloaded and having to charge aircraft will need a significant supply of electricity. As an example, the energy requirement to charge 10 electric aircraft for an airport on a small Caribbean island would be as large as the energy requirement of the entire island (ACI, 2021). A solution could be that the airport generates its own energy for the aircraft, however this is also not always possible due to space requirements or other practical matters such as the glare of solar panels for pilots taking off (NLTimes, 2025).

It is clear that each emerging technology has its advantages and disadvantages. However, for every technology new aircraft are being developed. An overview of these new aircraft can be found in Figure 2.7.

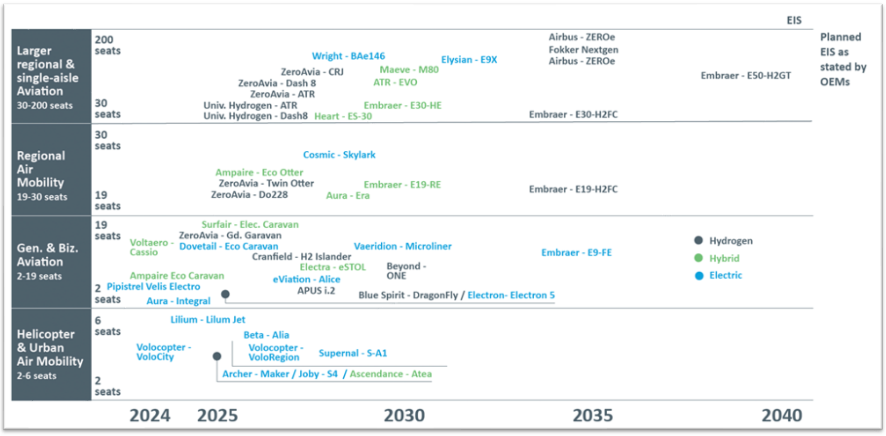


Figure 2.7: Future aircraft with new technologies and their expected Entry Into Service year (AZEA, 2024)

2.5. Network models

A flight network can be represented as a graph with nodes and weighted edges. The nodes on the graph represent the airports and there is a link between the nodes when a flight is operated between the two airports. The weight of the edges contain information like passengers numbers, deployed aircraft or costs to operate the link (Rau et al., 2024). Airlines typically use different models to develop their networks. Typical models are the Point-to-Point model, Hub & Spoke model, Fleet & Network model and Fleet Assignment Model. The first two models aim to answer the question: *"Given an airline fleet, what routes should be flown?"*.

The point-to-point network is usually operated by direct flights between origin-destination (OD) pairs. It is mainly focused on serving local passengers that do not make any connections. There must be sufficient demand for the flight in order to make the flight feasible (Abdelghany & Abdelghany, 2018). Santos (2023) describes the point-to-point network optimisation model as an Mixed Integer Linear Program (MILP) that for given sets of airports, demand and aircraft minimises the costs or maximises the revenue or profit such that the following constraints are met:

- Demand verification: the total passengers transported cannot exceed the demand for a given OD pair.
- Aircraft capacity: the total passengers on a flight leg cannot exceed the available seats on an aircraft
- Continuity: the number of aircraft inbound on an airport must be equal to the aircraft outbound of the airport

- Aircraft productivity: the total hours of operation cannot exceed the block time of the aircraft.

As an output, this model gives the optimal network for an airline, including what flight legs should be operated with how many passengers and how often the flight should be operated. If the MILP does not give a feasible solution, it is not profitable to fly and thus the network should not be operated. A summary of the point-to-point network optimisation can be found in Table 2.2.

Table 2.2: Point-to-point network model (Santos, 2023)

Input	**Objective**		**Output**
Set of airports	Minimise costs / maximise profit (revenues)		Operated flight legs
Demand per flight leg	**Subject to**		Passengers transported
Fleet aircraft set	Demand verification Aircraft capacity	Continuity Productivity	Flight frequency

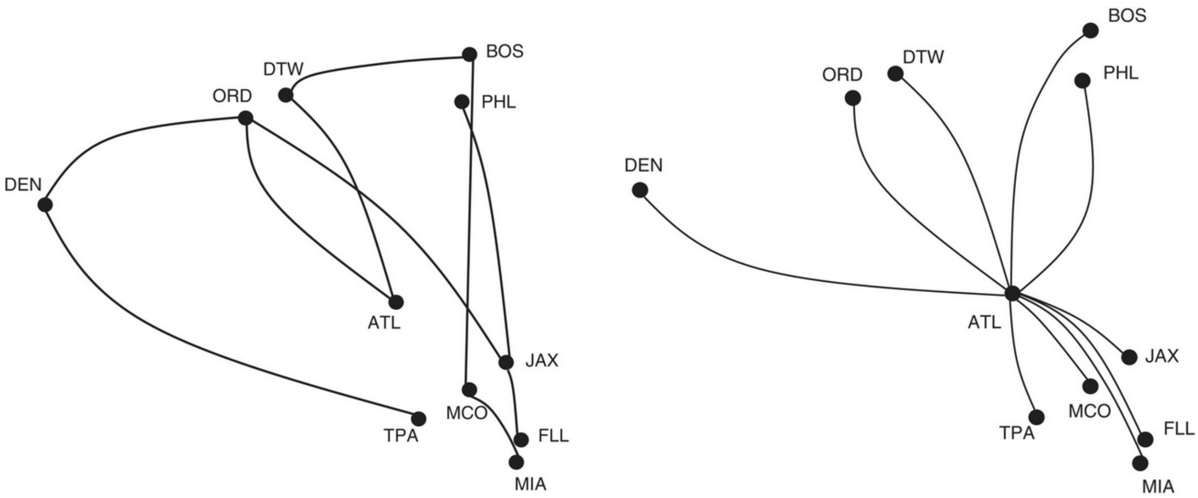
The hub & spoke model is based upon the idea that the airline only flies to spokes to or from the hub. The hub airport is usually a big airport with airline facilities. When an airline serves a big geographic area, multiple hubs could be selected. The airline can serve all OD pairs by connecting passengers via the hub. This way, the airline optimises its network as a single flight can serve local passengers (flying to or from the hub) and transfer passengers (transferring at the hub) (Abdelghany & Abdelghany, 2018). A comparison between the point-to-point network and the hub & spoke network can be found in Figure 2.8. Santos (2023) describes the hub & spoke MILP model similar to the point-to-point model. There are a couple of modifications necessary to the constraints:

- Demand verification: this constraint is similar to the one from the point-to-point model, except that there must be a modification such that the sum of local and transfer passengers cannot exceed the total demand of the flight leg.
- Hub verification: this constraint must be added. It ensures that transfer passengers are counted as such if the hub is neither the origin nor the destination of the passenger.
- Aircraft capacity: this constraint must be adjusted to the fact that there is a mix of local and transfer passengers on the aircraft.

The other constraints are kept the same as in the point-to-point model. And the outputs are also the same. The difference with the point-to-point model is that the hub & spoke model also gives numbers of the total passengers that must transfer at the hub.

Table 2.3: Hub & Spoke network model (Santos, 2023)

Input	**Objective**		**Output**
Set of airports	Minimise costs / maximise profit (revenues)		Operated flight legs
Demand per flight leg	**Subject to**		Passengers transported
	Demand verification	Continuity	Flight frequency
Fleet aircraft set	Hub verification	Productivity	
	Aircraft capacity		



(a) Point to point network **(b)** Hub & Spoke network

Figure 2.8: Comparison between point-to-point and hub-and-spoke networks. Retreived from Abdelghany and Abdelghany (2018)

As stated earlier, the previous two models aim to answer the question: *Given an airline fleet, what routes should be flown?*. The question could also be reversed and be: *"Given a network to operate, what fleet is needed to operate that network?"*. To answer this question, Santos (2023) defined the Fleet & network model. This model is very similar to the hub & spoke model, however this model needs a set of available aircraft in the market as input instead of available aircraft in the fleet. As output, this model gives the network to be operated and by what fleet. Compared to the hub & spoke model, the fleet & network model has two additional constraints:

- Range constraint: an aircraft is only able to execute a flight when range of the aircraft is smaller than the distance between the origin and destination
- Budget constraint: the total acquisition costs of these aircraft should be less than the budget that is available for the aircraft.

As output this model gives the same metrics as the hub & spoke model, however this model also gives an indication on fleet composition. An overview of the model can be found in Table 2.4.

Table 2.4: Fleet & network model (Santos, 2023)

Input	**Objective**		**Output**
Set of airports	Minimise costs / maximise profit (revenues)		Operated flight legs
Demand per flight leg	**Subject to**		Passengers transported
	Demand verification	Continuity	Flight frequency
Aircraft set	Hub verification	Productivity	Fleet size and composition
	Aircraft capacity	Range / budget	

The models thus far optimise the network for a single airline. In order to have an efficient transition, it would be ideal to have a model that optimises the fleet for an entire market. This is done by (Kühlen et al., 2023). The paper introduces a Fleet Assignment Model for the future global air transportation system. Where a Fleet & Network model focuses on assigning the fleet to a network, the Fleet Assignment Model focuses on which specific aircraft should fly what route. In order to be able to find an optimum fleet assignment for an entire market, the model should integrate market concentration. It would be understandable if a model would just pick the cheapest aircraft to operate a route. However, in reality there might be a lot of different airlines operating the route with a different aircraft type. Therefore, the market concentration of an aircraft type on a route has been modeled by the Herfindahl-Hirschmann market concentration index. An overview of the model can be found in Figure 2.9

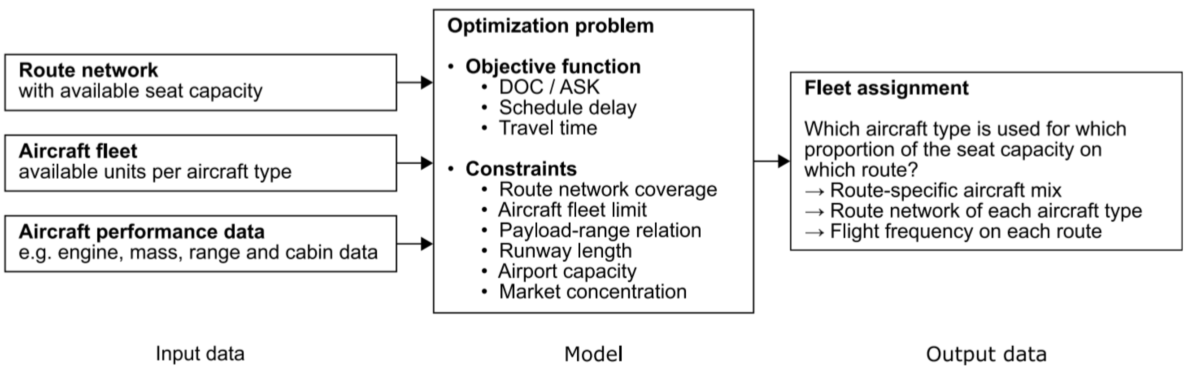


Figure 2.9: Overview of Kühlen et al. (2023) fleet assignment model for the global air transportation system.

The common factor between all previous presented models, is that they aim to minimise the operating costs for the operator. To estimate these costs, different models exist as well. Dahal et al. (2021) presents a model where the Direct Operating Costs can be estimated by an aggregation of

- Financial costs: Depreciation + Insurance + interest costs
- Crew costs: Cockpit + Cabin Crew
- Charges and Fees: Navigation fees + Landing fees + Ground handling fees

- Maintenance costs: Labor costs + Material costs. Both for airframe and engines.
- Fuel and oil costs

Table SV in the supplementary material of the paper gives a detailed overview with parametric formulas and assumptions on how to calculate each different cost aspect. Appendix A of (Hoelzen et al., 2022) gives a model of how to estimate the Direct Operating Costs (DOC) for Liquid Hydrogen aircraft that still have to be introduced. The paper also states that it is important to include the CAPEX for the manufacturing as this will a major influence on the total DOC.

2.6. Techno-economic modeling

To successfully introduce new technologies to the market, a techno-economic assessment (TEA) is often conducted. This approach evaluates the economic viability of a technology alongside its technical performance, providing a comprehensive basis for decision-making. In chemical engineering, TEAs are commonly applied to assess the feasibility of new production plants and processes, supporting the transition from conceptual design to industrial implementation.

The approaches of a TEA differ throughout literature. This is mainly because each TEA requires specific assumptions for each specific study. This also leads that the results are specific for a specific location or time horizon (Zimmerman et al., 2018) Zimmerman et al. describes a general method with the phases of a TEA and applies it to a carbon capture & utilisation technology development. It is described as a iterative process between the different phases of: Goal and Scope, Inventory, Calculation of Indicators and Interpretation. An overview can be found in Figure 2.10. The following paragraph will give a global idea on each different phase.

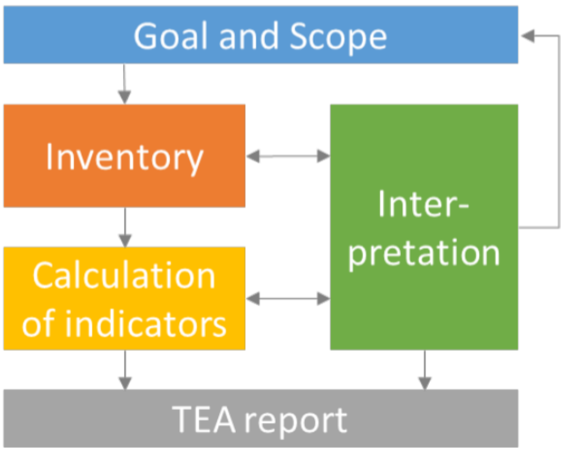


Figure 2.10: Graphical overview of TEA phases. Retrieved from Zimmerman et al. (2018).

Goal and Scope definition

The goal provides guidance for the overall study. The goal may address techno-economic questions such as the costs or profitability of a new product. The goal varies with the perspective of the practitioners of the TEA. Common perspectives may be:

- R&D perspective: Goals may be to assess the economic potential of a technology or to decide what R&D steps should be prioritised in funding.
- Corporate perspective: The goal might be to build a business case for a new technology. For this analyzes projects in development and assesses the investments in alternatives in comparison with the existing processes.
- Market perspective: This perspective focuses on the development and deployment of a new technology in current markets. It focuses on the implementation of the technology in the existing supply chains or assesses the effects of policy into the market.

Besides taking into account the perspective, the goal will also state the target audience and the intended application and reasons for the study. Whe the goal defines what will be studied, the scope defines what aspects will be taken into account and how the comparison should be done. The scope consists of six different elements:

- Product system: the subject of analysis
- Functional Unit: How is the system compared to other systems. Defining a good functional unit should be done by judgment of the practitioner. When comparing products with similar characteristics as benchmark products. The functional unit can be derived on a mass or energy basis.
- System boundaries: Determining what elements will be included and excluded from the assessment. This should be derived from the TEA goal.
- Assessment indicators: What measures will be used for comparison between different technologies? The choice of what indicator will be used is derived from the goal and maturity from the new system. As a TEA is an multidisciplinary assessment in the fields of economy and technology, usually multiple types of indicators can be used. Figure 2.11 shows a list of different indicators that can be used.

Area	**Criterion**	**Indicator examples**
Technical	Energy demand	*Heat demand, cooling demand, electricity demand, primary energy demand*
	Energy efficiency	*Lower heating value efficiency, higher heating value efficiency, energy/exergy efficiency, CO_2 capture penalty*
	Mass demand	*Mass demand of individual inputs, mass of CO_2 converted*
	Mass efficiency	*Atom economy, yield, percentage of CO_2 converted*
Economic	Processing effort	*Operational expenditure (OpEx)*
	Investment effort	*Capital expenditure (CapEx)*
	Product margin	*Market-derived margin for product, company-internal margin*
	Product volume	*Market volume for product, company-internal demand*
	Resource availability	*Market volume for feedstocks, company-internal availability of resources, number of suppliers*
	Profitability	*Profit, net present value, internal rate of return*
	Profit/cost per functional unit	*Cost per kg benchmark product equivalent, cost per km, cost per MJ stored*
Techno-economic	Technology maturity	*Technology Readiness Level (TRL) regarding market introduction (Horizon2020 definition), company internal maturity rating*

Figure 2.11: List of example assessment indicators. Retrieved from Zimmerman et al.

Often during the scope and goal definition, different assessment scenarios are defined. These scenarios represent states of the world that are plausible under certain assumptions. However, these scenarios are not equally likely states of the world and thus do not represent forecasts, predictions or most likely future conditions. A usual scenario is the base scenario or Business As Usual (BAU). It describes what would happen with the system if nothing is changed to the current state. This scenario forms the baseline for the assessment.

Inventory

Zimmerman et al. refers to inventory as the data that can be used to perform a techno-economic assessment. The process to collect the data is called inventory creation. This creation starts with the definition of the data quality requirements that are required in order to fit the goal of the study. After the definition of the requirements, two interrelated tasks should be performed:

- Identify processes: By identifying the processes, it becomes clear what specific technical and economic data are required to conduct the TEA.
- Collect technical and economic data: Collect the data required from the processes. Depending on the technical maturity of the technology, it may be needed to make assumptions and calculations to fill up potential gaps in the data.

Indicators

After defining the indicators and acquiring the required data, it is time to calculate the indicators. This section will explain how to calculate certain indicators that can be determined. The most common indicators are Capex, Opex, Net Present Value and Internal Rate of Return.

CapEx

Capital Expenditure (CapEx) refers to the investment required to implement a new technology and is often also called Non-Recurring Costs. CapEx can be estimated using a list of required materials and supplier quotations (Skyfinity, 2024). When a new technology is introduced, it is considered a First-Of-A-Kind (FOAK) technology. At this stage, CapEx tends to be high due to the novelty and lack of prior experience. Over time, as the technology matures and is deployed repeatedly, it transitions to Nth-Of-A-Kind (NOAK) implementations. In these cases, CapEx typically decreases as a result of learning curve effects and economies of scale. This reduction is important to consider, especially when the technology is expected to be scaled up in the future.

OpEx

OpEx, or Operational Expenditure, consist of variable and fixed cost that are required for keeping the operations running. Variable costs are costs that are related to the amount of production, for example costs for feedstock or energy costs. On the other side, fixed operational costs do not relate to the produced amount such as employee salary or insurance. Operational Expenditure can be expressed as increments per functional unit or as a factored estimation where it is estimated that a certain cost attribute is $x\%$ of another cost item.

Net Present Value

As Figure 2.11 indicates, a profitability indicator is the Net Present Value (NPV). As profitability is one of the most important factors for investors and companies, this is often a main metric to see if the investment should be made. In order to calculate the NPV, it is required to know what the cash flows per unit of time. The cash flow of a year can be seen as the sum of the CapEx and OpEx investments in a unit of time. These cash flows get discounted against a certain interest rate k in order to ensure that profit is made for an investor and summed for all the years. The interest rate is determined by the investor based on the risk the investor takes (Murthy, 2022). To get the NPV, the initial investment has to be subtracted from the sum. The value that remains is the Net Present Value. In other words, the Net Present Value is the expected profit from the project. Thus, profit is made when the NPV is positive. On the contrary, when NPV is negative, a loss is expected and therefore it is irresponsible to make the investment. When projects are compared and they both have a positive NPV, it is desirable to invest in the project with the highest NPV. The formula for NPV can be found in Equation 2.3 (Skyfinity, 2024).

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+k)^t} - initial\ investment \tag{2.3}$$

Internal Rate of Return

Another profitability indicator can be the Internal Rate of Return (IRR). The IRR is basically what the interest rate needs to be for the investment in order to earn itself back in T years. This can also be formulated as: *”For what interest rate is the NPV equal to zero?”* When the IRR is bigger than the interest rate k, it is thus probable that the investment will make a profit. The equation of IRR can be found in Equation 2.4. Just like the NPV, a higher IRR is more desirable. (Arnaboldi et al., 2015). The IRR could thus give an indication on what interest rate should at least be used and could therefore be a more tangible indicator than NPV as the interest rate for the NPV should already be known. (Jorge-Calderón, 2021).

$$\sum_{t=1}^{T} \frac{C_t}{(1+IRR)^t} - initial\ investment = 0 \tag{2.4}$$

Interpretation

Interpretation in the TEA process is an iterative review that ensures consistency, completeness, and reliability of data and assumptions in relation to the study’s goal and scope. It includes uncertainty and sensitivity analyses to enhance the robustness of results and identify key variables. The analyses can be done either by a Monte Carlo simulation if the input can be represented by a stochastic distribution or by a qualitative approach by changing one input by a certain amount to see how the model changes. Interpretation also helps pinpoint data needing improvement, supports scenario development, and may involve multi-criteria decision-making when trade-offs are required. The outcome is a set of conclusions and limitations that guide future research, development, and implementation.

3 Research Gap

The literature shows that it is clear that the aviation sector simply needs to decarbonise in order to reach its net-zero target. Various studies have looked at different decarbonisation pathways using different emerging technologies. Such as Sustainable Aviation Fuels, Hydrogen propulsion and electric propulsion. The studies also focused on one of the following stakeholders: Fuel Producers (FP), Airports (AP) or Airlines (AL). However, transitioning towards net zero aviation requires coordination between stakeholders and technologies.

Table 3.1 shows the reviewed techno-economic studies for this research and their specific focus combination of stakeholders and technologies. Even though each study shows specific insights for their part of the transition, there is a lack of studies that takes into account the interactions between multiple technologies and stakeholders. Particularly, there is a lack of TEAs that assess multiple decarbonisation technologies for various stakeholders such that there can be a competitive and sustainable aviation market in Europe in 2050.

Table 3.1 also indicates there is a gap in the literature for a quantitative model that optimises reduction potential for a given combination between stakeholders and technologies that ensures a competetive market. Without such research, stakeholders may pursue conflicting strategies and policymakers could fail to account for sector-wide implications. This research aims to fill in that gap by making a model that can support policy makers and industry in identifying effective strategies to ensure net-zero aviation by 2050.

Table 3.1: Summary of literature on sustainable aviation transition

Study	**Stakeholders**	**Technology**	**Scope / Methodology**
(Bergero et al., 2023)	FP	SAF	Production and distribution economics of SAF supply chains
(Dahal et al., 2021)	FP	SAF, H_2	Analyzes minimum jet fuel selling prices of SAF and H_2
(Department of Energy, 2024)	FP	SAF	Common fact base on the U.S. SAF market and the need to reach "liftoff" by 2030
(Gössling & Humpe, 2023)	Policy-level	SAF	Models costs of biomass-based and synthetic fuels in combination with carbon taxes
(Hoelzen et al., 2022)	AL, AP	H_2	DOC modelling for short- and medium-range H_2 aircraft and comparison with conventional aircraft
(Hoelzen et al., 2023)	AP	H_2	Infrastructure requirements and cost modelling for LH_2 at airports
(NLR SEO Amsterdam, 2021)	EU policy-level	SAF, H_2, Electric	High-level policy roadmap and scenarios for achieving net-zero aviation in Europe
(Project Skypower, 2024)	FP	SAF	Investment and adoption strategies for e-SAFs within the aviation industry
(Rau et al., 2024)	AL	H_2	Minimises DOC for fleet assignment using H_2 aircraft and assesses network structure
This research (proposed)	AL, AP, FP, policy-level	SAF, H_2, Electric	Integrated scenario-based assessment of decarbonisation pathways including a competitive market for airlines and implications for other stakeholders

4 Research Questions and Hypotheses

The main research question is defined as:

What are the key techno-economic drivers and uncertainties influencing an effective transition to a competitive and sustainable European aviation sector by 2050 based on scenario and sensitivity analysis?

This research question can be answered by finding answers to the following subquestions:

SQ1 Which quantitative metrics best capture the effectiveness of transition scenarios toward a competitive and sustainable European aviation sector by 2050?

SQ2 What are the key techno-economic drivers influencing the development, adoption and operational integration of sustainable aviation technologies in the European aviation ecosystem by 2050?

SQ3 How do uncertainties in key scenario parameters impact the optimal drivers and outcome metrics of transition scenarios for an effective net-zero aviation transition by 2050?

In these research questions, terminology such as drivers, metrics and scenario parameters are used. In order to assure consistent use of these terms, the definitions are given in Table 4.1.

Table 4.1: Terminology used in the research questions

Terminology	Meaning
Drivers	Decision variables of the model
Metrics	Outcomes of the model
Scenario parameters	Parameters that must be assumed within a scenario and are not decision variables in the same optimisation run

Now that the research questions are clear, the hypotheses on the questions can be formed. However, there will probably not exist a black and white answer for the research questions. Therefore, the expected results of these questions will now be discussed. For SQ1, it is expected that the two most important quantitative metrics to evaluate the effectiveness of transition scenarios are CO_2 reduction potential and the required investments to realise each scenario. The CO_2 reduction potential is critical because it determines whether net-zero aviation can technically feasible by 2050. The associated costs reflect the economic effort needed from public and private stakeholders to reach this target, making it a key metric of financial feasibility.

The model is expected to produce output that can be visualised in a graph, such as Figure 4.1, where each scenario is represented as a point in a cost–CO_2 reduction space. Scenario and sensitivity analyses will result in a range for both metrics. When combined, the most effective transition scenario will lie in the top-left corner (Scenario 2 in Figure 4.1) of the plot as it indicates the highest emissions reduction for the lowest investment.

Additional important metrics include the feedstock requirement and energy demand associated with each scenario. These are essential to assess the scalability and realism of fuel production pathways. If the demand for feedstock or energy exceeds sustainable supply thresholds, the corresponding scenario may be infeasible, regardless of its technical performance.

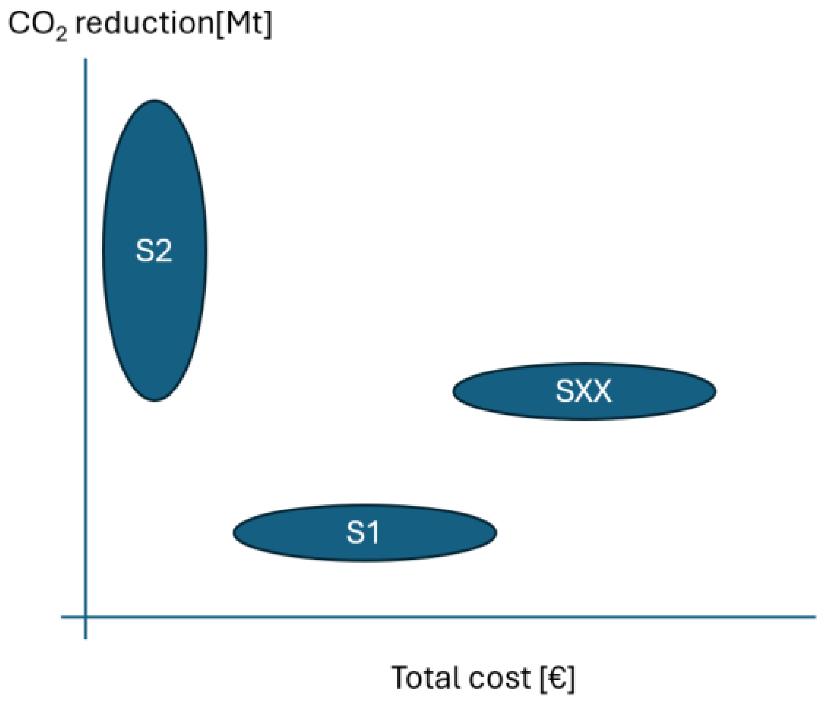


Figure 4.1: Expected output graph for scenario comparison

For SQ2, it is expected that the key techno-economic drivers influencing the development, adoption, and integration of sustainable aviation technologies in the European aviation ecosystem are technology maturity, carbon pricing policies, and fleet renewal rates.

Technology maturity is anticipated to play a central role, as it directly impacts the feasibility and timing of adopting various technological pathways, including sustainable

aviation fuels (SAFs), hydrogen, and electrified aircraft.
Carbon pricing is expected to be a critical driver because literature consistently indicates that sustainable aviation technologies, particularly alternative fuels, are not currently cost-competitive with conventional fossil-based options. As such, economic incentives or market-based mechanisms—such as emissions trading or carbon taxes—will likely be required to stimulate their uptake.
Fleet renewal rates are also expected to be highly influential, as they determine the speed at which newer, lower-emission aircraft enter service. In addition, the rate of fleet turnover affects long-term fuel demand and emissions trajectories by locking in specific aircraft technologies for decades.

For SQ3, it is expected that uncertainties in scenario parameters will have a significant impact on the perceived effectiveness of transition scenarios. These uncertainties introduce variation in key outcome metrics which can influence which scenario is considered optimal.
For example, as illustrated in Figure 4.1, the uncertainty range (e.g., standard deviation or percentile spread) around Scenario 1's total cost overlaps with that of Scenario XX. This suggests that, under certain assumptions, Scenario XX could achieve a greater CO_2 reduction for the same investment level as Scenario 1. As a result, the relative ranking of scenarios may change depending on which parameter values materialise in the future.

5 Methodology

This chapter contains the necessary research tasks in order to answer the research questions. For a structured overview of what has to be done in each phase, a work breakdown structure can be found in Figure 5.1. This work breakdown structure contains the phases for a techno-economic assessment as described in Section 2.6. Sections 5.1 until 5.4 each give a more detailed explanation of what each phase contains. Keep in mind that even though this work breakdown structure shows the steps in chronological order, it can happen that these phases might intervene with each other as also can be seen in Figure 2.10.

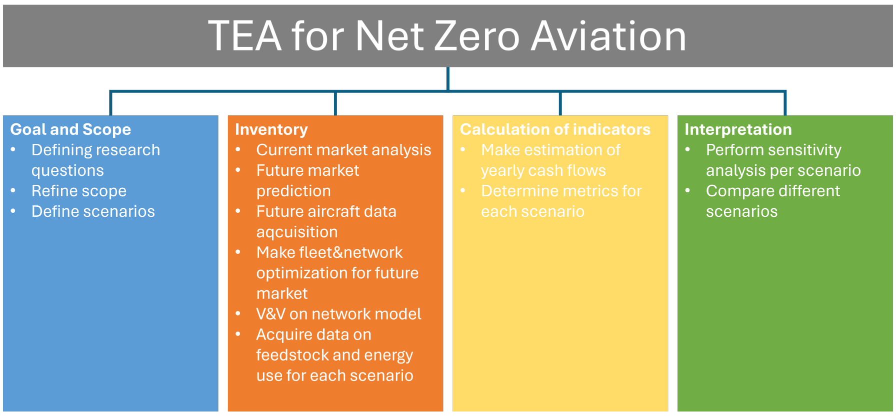


Figure 5.1: Work breakdown structure for the research

5.1. Goal and scope definition

The first step of the research involves the formulation of clear and structured research questions. This is achieved through an extensive review of academic and industry literature related to sustainable aviation. The literature review helps identify existing knowledge gaps, emerging technologies, and the key uncertainties influencing the aviation sector's transition to net-zero emissions.

Once the research questions are established, the scope of the study is defined. This includes setting the system boundaries of the analysis, such as the geographical focus, the timeframe, and the technological options under consideration (e.g., sustainable aviation fuels, hydrogen-powered aircraft, electrification).

The final part of the goal and scope definition involves developing a set of transition scenarios. Based on literature and current roadmaps (e.g. the roadmaps presented in Figure 2.4), these scenarios are constructed to represent a range of plausible futures. They will serve as the basis for quantitative modeling, sensitivity analysis, and the evaluation of key techno-economic drivers.

5.2. Inventory

The first step of building up the inventory is to collect the data of the current aviation market that fits the geographical scope. This can be based upon a flights database such as the Eurocontrol Aviation Data Repository for Research (EUROCONTROL, 2025). This database can provide Origin and Destination data for four sample months (March, June, September and December) of each year with a delay of two years. So at the time of writing (May 2025) the most recent flight data set of the database is March 2023. With these months, an approximation of OD demand and fleet composition can be made. Based on the fleet composition, fuel burn per aircraft type and flight frequencies, an estimate of total emissions can be made.

The second step is to predict the future market. This can be done with predictions from different industry sources. This could for example be done with the Compound Annual Growth Rate. This rate assumes the growth will be equal each year and thus averages out outliers in certain years.

The next step is to acquire data on the future generation aircraft. Both technical and economical data should be gathered. Technical data has to do with the performance of the aircraft. For example, what propulsion technology is used, what is the seat capacity, what is the range and what would be the fuel burn of the aircraft. The economical data would be what the capital investment (Capex) and operational investment (Opex) would be to introduce the aircraft into the market. However, as this regards data involving future technologies, it is important to keep in mind that this data might not always be available and quite some assumptions need to be made. Therefore, it is proposed to make and update a table with assumptions throughout the thesis and how it affect the results. An example of such a table can be found in Table 5.1.

Table 5.1: Example table for tracking assumptions and their impacts

ID	Assumption	Effect on results
FutureAC1.fuel		
FutureAC2.range		

Once all the data has been gathered, it can be combined in a fleet & network model. This model will allocate the future generation of aircraft on the routes that are being flown in the future ensuring that all the demand is being satisfied. As a baseline, the model of (Kühlen et al., 2023) can be used and will be expanded such that it fits the purpose of this research. This model will be minimised for costs and includes decision variable on what aircraft should be used on what route, how much carbon tax should be applied for using conventional aviation fuels. The constraints on the model will need to be specified in a later stage but at least include demand satisfaction, the range limit, market concentration and policy-specific constraints. This optimisation model can be made in Python and will be optimised using Gurobi.

After the fleet & network model has been made, it should be verified and validated. Verification is the process of checking if the created model actually does what it is supposed to do. This can be done by unit and system checks. Unit checks are meant to check one single element of the model. For example, a check if every single constraint is satisfied. Validation is the process of checking if the model produces real life results. Validation could be performed by comparing the models output under a baseline “no growth, only conventional fuels” scenario to current fleet compositions and emissions levels. The expectation is that in this scenario, the model should replicate the existing fleet with minimal deviation.

Lastly, data has to be collected on resource requirements of each alternative fuel pathway (e.g., SAF, hydrogen, electricity), including feedstock needs, energy use, and supply chain assumptions. This enables an evaluation of resource feasibility and sustainability alongside techno-economic performance.

5.3. Calculation of indicators

The first step in calculating the indicators is to estimate the cash flows for each time step. These cash flows include the Capex, Opex, and potential policy expenses required for each time period, and they should be discounted against an interest rate. With this estimation, the learning curve for the CapEx should also be accounted for.

The scenario performance metrics include the cumulative CO_2 reduction potential, which is calculated relative to a defined baseline, such as a business-as-usual scenario without additional decarbonisation measures. The total system costs represent the aggregated discounted expenditures over the analysis period, including capital, operational, and policy-related expenses. Additionally, the model estimates the feedstock consumption, such as biomass or synthetic inputs, required to support each technology pathway, as well as the overall energy demand across the transition, disaggregated by energy carrier (e.g., conventional jet fuel, electricity, hydrogen). These indicators allow for a quantitative comparison of different transition scenarios and will be used to evaluate trade-offs between cost-efficiency and environmental performance.

5.4. Interpretation

The final phase of the research is the interpretation of results. This begins with conducting a sensitivity analysis to evaluate how changes in key scenario parameters affect the outcome indicators. Sensitivity analysis may be performed locally by varying one parameter at a time while holding others constant or globally through simultaneous variation of multiple parameters to capture interactions. If probability distributions of the input parameters are available or can be reasonably assumed, a Monte Carlo simulation can be employed to assess uncertainty propagation across the model.

Following the sensitivity analysis, the resulting data will be visualised to highlight the range and robustness of each scenario's performance. These visualisations, as proposed in Figure 4.1, will support a more comprehensive understanding of the influence of uncertainty on techno-economic and environmental outcomes. This enables a more nuanced interpretation of which scenarios offer the most resilient pathways toward a competitive and sustainable European aviation sector by 2050.

6 Planning

Table 6.1 contains the planning of the research tasks as discussed in Chapter 5. The highlighted rows contain the different milestone deliverables and reviews. In this planning, the following holidays are taken into account:

- 28 May - 3 June 2025
- 19 - 25 July 2025
- 10 - 17 August 2025
- 20-27 December 2025
- 31 December 2025 - 1 January 2026

Please note that the exact dates of the midterm and green light reviews are subject to change due to the availability of the supervisors.

Table 6.1: Planning of research tasks

Task	Start	End	Duration [workdays]
Research phase 1			
Refine scope	19-05-25	23-05-25	5
Define scenarios	24-05-25	10-06-25	7
Current market analysis	11-06-25	17-06-25	5
Future market prediction	18-06-25	24-06-25	5
Future aircraft data acquisition	25-06-25	3-07-25	7
Make fleet & network optimisation for future markets	4-07-25	1-08-25	16
V&V on network model	2-08-25	8-08-25	5
Midterm deliverable	9-08-25	18-08-25	1
Prepare Midterm Review	19-08-25	25-08-25	5
MSM: Midterm review	25-08-25	25-08-25	1
Research phase 2			
Make estimation of yearly cashflows	26-08-25	3-09-25	7
Determine metrics for each scenario	4-09-25	17-09-25	10
Perform sensitivity analysis	18-09-25	15-10-25	20
Compare different scenarios	16-10-25	5-11-25	15
Work on draft thesis	6-11-25	3-12-25	20
Submit Draft Thesis	3-12-25	3-12-25	1
Prepare Green Light Review	4-12-25	17-12-25	10
Green light Review	17-12-25	17-12-25	1
Thesis Finalisation			
Request examination	18-12-25	18-12-25	1
Prepare research Portfolio submission	19-12-25	12-01-26	10
Submit Research Portfolio	12-01-26	12-01-26	1
Prepare for thesis defense	13-01-26	26-01-26	10
Thesis defence	26-01-26	26-01-26	1

7 Conclusion

Existing aviation decarbonisation studies often assess individual levers in isolation (e.g., SAF-only, hydrogen-only, electrification-only) and/or from a single stakeholder perspective (airlines, airports, or fuel producers). This fragmentation limits insight into system-level interactions between fleet renewal, energy-carrier supply, and infrastructure deployment, and it provides insufficient quantitative guidance on the resulting trade-offs between costs, emissions, and resource feasibility in a European context. In addition, key uncertainties are not consistently analysed, despite their ability to change pathway rankings and trigger threshold-type technology uptake.

Through scenario and sensitivity analyses, the research seeks to provide actionable insights into effective transition strategies for achieving sustainable aviation. The main research question that will be addressed in the thesis is: *What are the key techno-economic drivers and uncertainties influencing an effective transition to a cost-competitive and sustainable European aviation sector by 2050 based on scenario and sensitivity analysis?*

The research will deliver an integrated, transparent quantitative basis for comparing net-zero transition pathways under uncertainty. It will identify the dominant techno-economic drivers that steer effective outcomes, clarify which uncertainties most strongly determine system performance and technology adoption, and translate these findings into stakeholder-relevant insights on coordination needs and policy leverage points to support a cost-competitive and sustainable European aviation sector by 2050.

A system-level techno-economic modelling framework will be developed for the European aviation network to 2050. A consistent dataset will be assembled for demand, routes, aircraft technologies, energy carriers, and infrastructure parameters. An integrated optimisation model (MILP, implemented in Python and solved with Gurobi) will then be used to jointly determine fleet evolution and technology adoption subject to demand satisfaction and technical feasibility constraints, while reflecting policy constraints and competitiveness considerations where appropriate. Results will be evaluated using indicators such as discounted system costs, cumulative emissions, and clean-energy/resource requirements, after which structured scenario design and sensitivity analysis will quantify robustness and pinpoint the main drivers and uncertainties shaping transition outcomes.

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