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D8.1 – Scenarios for Techno-Economic Analysis

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DEC	Websites, patents filing, press & media actions, videos, etc.	
DEM	Demonstrator, pilot, prototype, plan designs	
DMP	Data management plan	
Dissemination level		
PU	Public, fully open, e.g. web	x
SEN	Sensitive, limited under the conditions of the Grant Agreement	

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1 Glossary

Abbreviation / acronym	Description
CCS	Carbon capture and storage
EIS	Entry into service
FAA	Federal Aviation Administration
GDP	Gross domestic product
GH_2	Gaseous hydrogen
GHG	Greenhouse gas
GOLIAT	Ground Operations of LIquid hydrogen AircrafT
GSE	Ground support equipment
H_2	Hydrogen
LH_2	Liquid hydrogen
MRO	Maintenance, repair, and overhaul
OEM	Original equipment manufacturer
RED	Renewable Energy Directive
S#	Scenario with number #
SAF	Sustainable aviation fuels (drop-in, excluding hydrogen)
SC	Steering Committee
WP	Work package

2 Executive Summary and Final Scenarios

Hydrogen-powered aviation is currently under investigation to replace traditional aircraft powered by fossil kerosene. The GOLIAT research project aims to mature liquid hydrogen refuelling processes, and size and assess the overall hydrogen value chain for hydrogen-powered aviation. In Work Package 8, an operational and techno-economic analysis of the hydrogen value chain will be performed. In preparation of this task, the current deliverable defines the scope and develops scenario to be assessed.

Through literature review and workshops with experts in the field of hydrogen supply and operations, scenarios are developed which will be used to assess the demand, supply chain size and cost, and ground operations. In this analysis, especially the development of liquid hydrogen infrastructure and operations is of interest. Forecasts will be made for these aspects in mid-term (2035) and long-term (2050) for intra-European networks. The focus lies on commercial passenger transport, with possible extensions to freight operations.

Based on expert insights, three key axes of driving forces are identified: 1) hydrogen availability and the energy market, 2) the readiness of airport infrastructure, and 3) the level of aircraft technology development. Furthermore, disrupting economic and safety forces should be considered in the techno-economic analysis. To capture varying levels of development along the above three axes and these disrupting events, five main scenarios are defined:

A. Smooth Skies – A baseline scenario covering “mid-level” developments from literature.
B. Aircraft Delayed – This scenario considers delayed arrival of hydrogen aircraft which are expensive to operate (misalignment of driving forces).
C. Grounded Potential – In this scenario many airports at European level are not ready to support hydrogen refuelling operations, and the hydrogen aircraft cannot be operated at full potential (misalignment of driving forces).
D. Economic Stall Warning – After initial investments in infrastructure and aircraft technology, an economics crisis occurs in 2035 to 2040 which lowers the overall demand for air travel (disruptive scenario).
E. Safety Checklist Failed – Major safety issues lower the social and regulatory acceptance of hydrogen aircraft and their operations at airports (disruptive scenario).

Table 2-1 provides a more elaborate summary of the five final scenarios. These scenarios consider different approaches to fuel delivery business models, different levels of hydrogen technology, and varying concepts of daily operations. Furthermore, the scenarios help to identify hurdles in the future development of the hydrogen supply chain and aid in deriving the optimal aircraft- and ground-based technology mix to make the aviation sector more sustainable.

Table 2-1 Final Scenarios for Operational and Techno-Economic Analysis

A. Smooth Skies (Baseline)

- Current, 2024, plans for hydrogen infrastructure and aircraft technology development move forward as expected, supported by a coalition of stakeholders that includes regional airports, large-scale OEMs, new aircraft manufacturers, hydrogen, and energy suppliers.
- A transition takes place to green hydrogen as a result of growth in renewable electricity, supported by grey and blue hydrogen where needed in the early stages.
- By 2035, many regional and local airports and some large hubs have completed the necessary upgrades to accommodate hydrogen-powered aircraft. Looking ahead to 2050, larger hub airports begin integrating hydrogen infrastructure, supported by increased investment and technological maturity.
- Hydrogen aircraft entry into service takes place according to current, 2024, outlooks. However, small energy and maintenance penalties do occur around 2035, which are mostly resolved by 2050.

B. Aircraft Delayed

- The development of hydrogen-powered aircraft progresses slower than anticipated. Persistent challenges in the design, testing, and certification of lightweight hydrogen tanks and propulsion systems result in delayed entry into service.
- First-generation hydrogen aircraft face energy efficiency penalties of approximately 10%, while maintenance costs increase up to 30% compared to kerosene aircraft.
- Misalignment between aircraft and the readiness of hydrogen infrastructure at airports and the availability and supply chains at airport.

C. Grounded Potential

- Hydrogen-powered aircraft are technologically mature, but their widespread deployment by airlines is hindered by the lack of infrastructure at most airports in Europe, with regional variations.
- Early adaptor airports benefit from their proximity to hydrogen production sites and cost-efficient trucking methods for the delivery of hydrogen over these short distances.
- Other airports cannot make timely investments and/or do not have the physical space for hydrogen storage and distribution processes.
- Aircraft technology develops as planned, meeting intended capabilities with a performance similar to that of kerosene counterparts.

D. Economic Stall Warning

- Economic issues or crises occurs after the initial hydrogen investments (i.e., 2035-2040).
- Drop or stagnation of European air travel demand of 3 to 5 years.
- As return on investments diminish, further development of the hydrogen supply chain stalls. For example, airport on-site production projects are haltered.
- Major airports are unwilling to make investments in expensive hydrogen facilities.
- The competitiveness of hydrogen aircraft is worsened due to the economic crises, delaying future programmes.

E. Safety Checklist Failed
• Minor and major safety incidents occur upon introduction of hydrogen aircraft operations in 2035. Safety issues occur during ground operations and/or at aircraft level. The concepts of operations and the technologies are not mature. • Social acceptance of hydrogen aviation is very low. • Moderate growth in green hydrogen production and supply for aviation, mostly used towards synthetic kerosene. • Airports face a large safety perimeter around liquid hydrogen operations and throughout the considered period (2024-2050), airports and aircraft have to be supplied through carefully planned mobile refuellers. • The entry into service of large commercial passenger aircraft is delayed to 2040-2045 due to long investigation and certification processes.

3 Introduction

Hydrogen (H_2) is currently being investigated as a sustainable energy carrier for aircraft to decarbonise primarily short- and medium-haul aviation. Although hydrogen-powered aircraft can eliminate in-flight carbon dioxide and possibly reduce non-CO_2 effects, depending on the powertrain, research is required to initiate and mature the hydrogen supply and daily airport operations for such aircraft.

The GOLIAT (Ground Operations of LIquid hydrogen AircrafT) project seeks to overcome the current obstacles to the widespread deployment of hydrogen at airports, such as

- the limited capacity, performance and cost effectiveness of existing liquid hydrogen (LH_2) technologies for the aviation market, and
- the absence of an operational, regulatory, economic, and safety framework.

This report discusses the work completed in Task 8.1 of Work Package 8 of the GOLIAT project. Work package 8 sets out to perform an operational and techno-economic assessment of the hydrogen value chain and ground operations of liquid hydrogen aircraft. The focus of Task 8.1 lies on the definition of the scope and scenarios to be considered in these assessments later in the project.

To size and study the economics of the hydrogen value chain, we will develop comprehensive liquid hydrogen demand and supply-matching models for air transport ground infrastructures. The goal of the scope and scenarios defined in this report is to support the following tasks in Work Package 8 of the GOLIAT project:

- Estimation of the LH_2 and gaseous H_2 (GH_2) demand at and around airports.
- Techno-economic analysis of LH_2 supply and refuelling infrastructure.
- Analysis of the effects of H_2 aviation operations on airport ground movements and equipment, and the associated operating economics.

Through these steps, the future technology mix can be derived, in terms of aircraft technologies and infrastructure to supply hydrogen to commercial airports. Additionally, by analysis of various scenarios and lessons learned, potential issues can be identified in the aviation hydrogen value chain, ground operations of hydrogen aircraft, and the refuelling infrastructure. The goal of the scenario development is to construct and analyse different possible situations for the future, not to predict or impose the future of a hydrogen value chain (Cordova-Pozo & Rouwette, 2023). This way of thinking is visually presented in Figure 3-1.

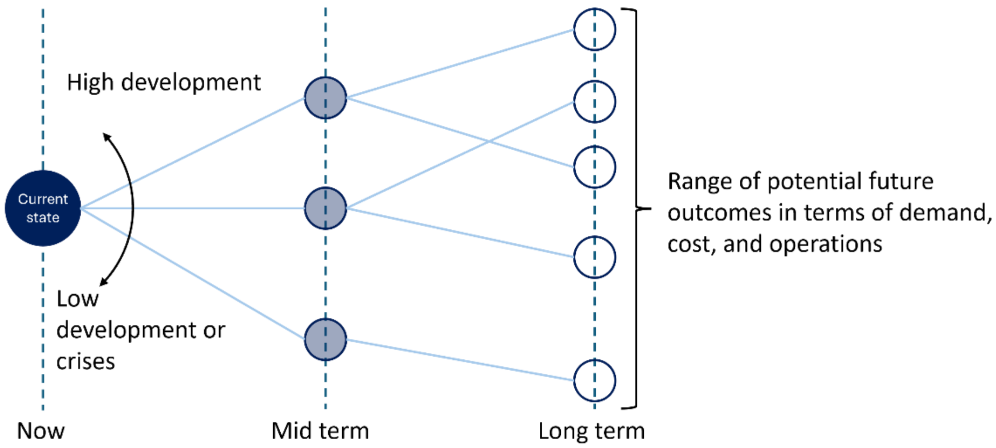

Figure 3-1 Example of scenario tree developing under different development assumptions and multiple time horizons

This report starts with an overview of the method for scenarios development within the provided timeframe. Following the steps proposed in the method, the scope is defined (Chapter 5) and factors and driving forces is investigated in Chapter 6. In Chapter 7, variations for the key factors are created, which are in turn used to formulate raw scenarios in Chapter 8. Chapter 9 validates the scenarios and selects the main scenarios. The final scenarios are presented in Chapter 10.

The scenarios presented in this report are developed using the insights from literature and experts available in the timeframe May-November 2024. In the following steps and years to come in the project, it is important to remain critical about the developed scenarios and to evaluate whether they are still relevant and aligned with the research goals of the project. Where necessary, the scenarios may have to be updated to reflect the latest insights and/or to provide the right input for the operational and techno-economic analysis.

4 Method

Several methods, tools, and schools exist to build scenarios for varying purposes. Reviews of scenario development methods (Amer et al., 2013; Cordova-Pozo & Rouwette, 2023) provide a classification consisting of three schools, namely the Intuitive-Logics school, the Probabilistic modified trends (PMT) school, and the French school – La prospective. Although these schools have common characteristics, they differ in scope, approach (qualitative vs. quantitative), techniques used, the use of internal and external experts, etc. A detailed comparison of the methods is outside the scope of the current discussion and the reader is referred to references provided in the bibliography (Amer et al., 2013; Cordova-Pozo & Rouwette, 2023).

The method selected in this project fits in the Intuitive-Logics Models school of scenario techniques (Amer et al., 2013; Bradfield et al., 2005), which makes use of literature research, brainstorming, matrices, and workshops involving external experts. This method allows tapping into the expertise of the GOLIAT partners and fits in the allocated research time of eight months. The scenario development in this method is mainly qualitative with limited quantitative analysis of the inputs from experts. No probabilities are assigned to the scenarios. The scope and scenario definition method employed in the current report consists of the following steps:

1. Define scope
2. Identify forcers, drivers, factors, and barriers of influence
3. Evaluate the impact and uncertainty of these forcers, drivers, factors, and barriers
4. Construct an impact and uncertainty matrix
5. Select main forcers to construct initial scenarios
6. Validate and select scenarios.

The first three steps are diverging in nature and intend to explore all possible aspects and barriers to include the scope and scenarios. From step four onward, the scope and scenario definition are narrowing to eventually lead a selection of refined scenarios. The following sections describe the steps in more detail and provide definitions for the terms specific to scenario development.

4.1 Scope Definition

Based on the GOLIAT project proposal, literature, and discussions with GOLIAT partners, the initial scope of the scenarios and the subsequent techno-economic analyses is determined. This scope frames the scenarios in terms of the research questions, time horizon, geographic location, stakeholders, and concepts of operations. In line with the chosen scenario definition method, the scope of the scenarios is quite broad at a regional level with a time horizon between 20 and 30 years. Chapter 5 describes the scope.

4.2 Identification of Forces, Drivers, Factors, and Barriers

The next step is to find all aspects which can potentially influence the setup and outcomes of the operational and/or techno-economic analysis of the hydrogen value chain. In scenario definition literature, different terminology is being used for such aspects. Amer et al. (Amer et al., 2013) explains that in this phase key drivers, trends, stakeholders, constraints, and issues have to be identified. Cordova-Pozo and Rouwette (Cordova-Pozo & Rouwette, 2023) mentions the terms “factors (of influence)”, “influencing areas”, and “driving forces”.

The exhaustive list of factors, drivers, factors, and barriers is developed through literature review of existing scenarios and through meetings with GOLIAT partners in the first months of the project. Simultaneously, the factors are divided into seven categories to provide structure to the scenario and narrative development. The seven categories in this step of the process are:

1. Policy, regulations, and standardization
2. (Socio-) Economic growth and investment
3. Airport infrastructure readiness
4. Hydrogen availability and energy market
5. Traffic growth rate
6. Aircraft technology development
7. Disrupting or non-nominal factors

These categories and the complete list of factors is further elaborated upon in Chapter 6.

4.3 Evaluation of Impact and Uncertainty

The impact of a factor is the effect that this factor has on the outcomes of the operational and techno-economic scenarios. Examples of the outcomes are the demand for hydrogen at and around airports, hydrogen-powered flight movements, infrastructure requirements, cost estimates, etc. The uncertainty of a factor corresponds to the probability that the factor will have a significant impact (Amer et al., 2013). Some research suggests that this uncertainty is one of the main reasons to perform scenario planning (Cordova-Pozo & Rouwette, 2023).

The impact and uncertainty of the factors identified in Section 4.2 are assessed in two ways: first, through an individual assignment by GOLIAT WP8 partners, and as a next step through a workshop with only GOLIAT partners. These partners represent a diverse group of stakeholders (e.g. original equipment manufacturer, airports, and a provider of equipment for cryogenic product supply and liquefaction.) In the individual assignment, participants were asked to consider all factors in all identified categories and mark the impact and uncertainty of each factor as “low”, “medium”, “high”, or “unknown”. Additionally, the participants were able to add initial variations for each factor and comments.

Based on this initial assessment, a selection and merging of the factors is made and the exercise is repeated during the online workshop with GOLIAT partners with a subset of the initial factors. For the online workshop, MIRO is used to capture input. Repeating the exercise during a workshop allowed to simultaneously discuss the factors and converge on the relative positioning of the factors.

4.4 Construction of Impact and Uncertainty Matrix

Based on the evaluation of each factor, the factors are graphically presented in an impact and uncertainty matrix, also sometimes referred to as the Wilson Matrix (Amer et al., 2013) or importance-uncertainty grid. An example of such matrix is shown in Figure 4-1.

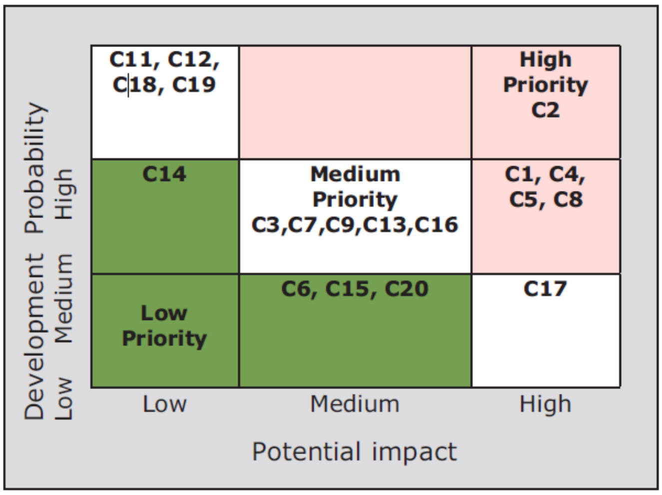

Figure 4-1 Example of Wilson Matrix to rank scenario factors (Amer et al., 2013)

The key idea of this matrix construction is to find the factors (factors, or drivers), which are expected to have both a high impact and a high uncertainty, i.e. the upper right corner in Figure 4-1. These will be the main factors to be considered in the scenarios. For factors with low impact and high uncertainty, we expect the outcomes of the scenarios to be insensitive to variations in these factors. Considering factors with a high impact and low uncertainty, we know how the factors will develop in the future, and it is therefore not of interest to construct different scenarios based on this factor.

4.5 Selection of Main Factors to Construct Scenarios

The next step is to develop variations for this set of main factors or key driving forces. These variations represent different ways in which that aspect can develop in the future. For example, when considering economic growth, variations such as “low”, “business as usual”, or “high” can be formulated. By putting these main factors and their variations together, compatible and novel combinations of factor variations can be created which lead to raw scenario definitions. Such raw scenarios summarize the storyline of a scenario and allow to distinguish scenarios, but often lack refinement.

The minimal approach to create variations would be to use a four quadrants matrix with opposing ideas for the two main factors (Amer et al., 2013). However, this approach is rather limiting as it only allows the consideration of two main factors or dimensions. The introduction of hydrogen aviation is a complex problem with challenges spanning more than two dimensions or disciplines. Therefore, an approach, such as morphological analysis is needed to consider more than two factors and their variations simultaneously to develop relevant and interesting scenarios.

By combining variations from more than two main factors, many possible scenarios emerge, of which the most valuable ones have to be selected. Some raw scenarios can be immediately discarded due to inconsistencies, contradictions, or irrelevance. An example of the latter would be a scenario where no hydrogen aircraft are developed, no infrastructure is built, and no policies imposed. Such scenario is plausible but would not yield any interesting techno-economic insight into the future of hydrogen aviation.

4.6 Scenario Validation and Selection

The final step is to validate the scenarios and to select key scenarios to investigate. The validation step is required to ensure the scenarios are logical and useful for the techno-economic assessment, and eventually can be used for decision making. Based on the review by Amer, Daim, and Jetter (Amer et al., 2013), the following four validation criteria are selected:

1. Consistency: the scenario does not contain any logical flaws, inconsistencies, or contradictions
2. Plausibility: it is possible that this scenario occurs
3. Relevance: the scenario contributes to insights into the future and provides support for decision making
4. Novelty: the scenario is structurally different and not a variation on a theme.

The assessment of these four criteria for each raw scenario is completed through a virtual workshop with GOLIAT partners and external experts. A total of 33 participants joined the workshop on 08/11/2024, the majority coming from organisations who are not involved in WP8 and/or the GOLIAT project. The experts represent diverse stakeholders in the hydrogen value chain: energy suppliers, airlines, aircraft original equipment manufacturers, aviation consulting, hydrogen enablers, transport infrastructure, and research institutes. Additionally, experts from the related ALRIGH2T[1] project joined the workshop. Involving these external experts allows to gather independent views on the suggested scenarios and interact with stakeholders which were not considered in the previous steps.

The participants are asked first to evaluate the consistency and plausibility of the initial scenarios in terms of answering “yes”, “no”, or “yes with comments”. Furthermore, they are given the opportunity to provide open feedback to each scenario. To assess the relevance and novelty, the participants ranked each scenario according to five levels. For relevance, the five levels were “irrelevant”, “low relevance”, “relevant”, “very relevant”, and “essential”. For novel the levels were “exhaustively assessed”, “frequently assessed”, “somewhat novel”, “rarely assessed”, and “completely new”. Chapter 9 presents the results of this workshop and the validation step. The final scenarios in Chapter 10 are built upon the feedback collected during the workshop, however, no additional validation step is added for the final scenarios.

Strictly speaking, there is no expectation or limitation to the number of scenarios to be developed. However, considering the many factors and dimensions, the number of scenarios can rapidly increase. Too many scenarios may be too difficult to manage, to distinguish, and to draw clear conclusions. Therefore, a minimum of three and a maximum of five scenarios is desired in the current project with clear and distinct narratives (or hypothesis). The selection of the final, main scenarios in Chapter 10 is based on the relevance and novelty ranking provided by the experts during the workshop, and discussions within the project.

[1] URL ALRIGH2T - liquid hydrogen aircraft accessed on 21/11/2024

5 Scope and Context Definition of Techno-Economic Analysis

One of the first steps of the scenario development method, as discussed in Section 4, is the definition of the scope and context to be considered in the scenarios and the subsequent analysis of demand, supply, and refuelling setups. The envisioned scope is developed together with the project partners during Work Package Management meetings and supported by literature. Figure 5-1 presents a summary of the considered scope.

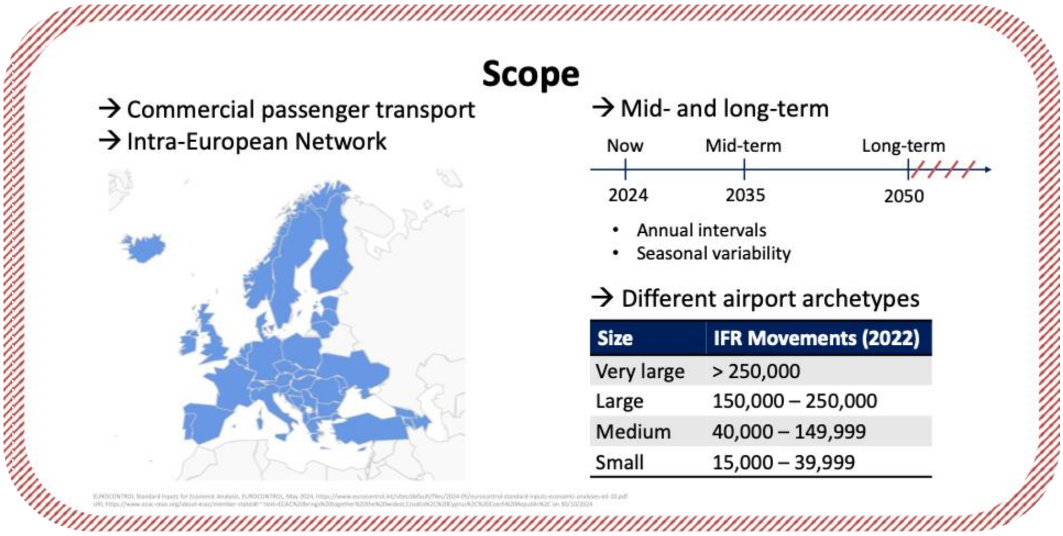

Figure 5-1 Summary of the scope of the scenarios and techno-economic scenarios

The timescale of interest will be **2035 (mid-term) to 2050 (long-term)**. This period is similar to other recent scenario definitions (AZEA, 2024; Hoelzen et al., 2023; Oesingmann et al., 2024a). It is expected that by 2030 the first, small (2 to 30 seats) hydrogen or hybrid aircraft will be introduced into the market (AZEA, 2024). Larger aircraft (>30 seats) fully powered by hydrogen will be introduced from 2035[2] onwards (AZEA, 2024), as further discussed in Section 6.6.1. However, these years mark the expected introductions into the market (EIS) and the fully operational ramp up can only take place after this point. On the other hand, preparation of infrastructure, operational procedures, and the associated investment have to start prior to the operational introduction of hydrogen aircraft.

Hence, 2035 marks the point where small demand for aviation hydrogen can exist and infrastructure for larger operations needs to be developed. The long-term end point of the scenarios is set to the year 2050. Beyond 2050 (26 years from time of writing), the predictions for travel demand and the introduction of novel technologies (both H_2-powered and non-H_2-powered), become more uncertain and/or are unavailable. In the analysis of demand and supply, annual time steps with seasonal variability will be considered.

The techno-economic analyses in the current work package focus on Europe, in particular on flight operations in intra-European networks. Currently there are no concrete plans for long-range (wide-body) hydrogen aircraft which can reach transatlantic destinations or major international hubs in other continents, for example hubs in Middle East or (South-)East Asia. Therefore, the scenarios and future analyses **focus on the intra-European market**.

The scenarios focus on **commercial passenger air transport**. This aligns with the focus of the GOLIAT project[3] and the currently proposed aircraft concepts, potentially including some cargo on board.

[2] URL https://www.airbus.com/en/innovation/energy-transition/hydrogen/zeroe accessed on 22/10/2024

[3] URL https://research.airbus.com/en/products-systems/goliat accessed on 01/12/2024

Plans for hydrogen-powered freighter aircraft, such as AEROHAULER[4] and Natilus[5], exist and show a potential use case of hydrogen, but are less developed, at the time of writing, and the application in European networks is still unclear. Therefore, these concepts are currently omitted in the scenario definition, although the freighter can be considered in later updates or as separate case studies. Also, other types of operations, such as military applications, search-and-rescue, surveillance, are not considered since limited plans with hydrogen propulsion are currently envisioned and the concepts of operations might significantly differ from those of commercial passenger transport.

The focus of the scenarios and techno-economic analysis mainly lies on the supply and operations of liquid hydrogen. However, smaller aircraft or ground vehicles may use gaseous hydrogen (GH_2). Therefore, it is of interest to include both forms of hydrogen in the scenarios, similar to previous studies on green H_2 supply to airports (Hoelzen et al., 2023). The detailed modelling of aircraft refuelling operations and equipment sizing only considers liquid hydrogen.

In Figure 5-2, the hydrogen supply pathways to and at the airport are displayed, highlighting varying airport boundaries. This study explores diverse supply chain structures, ranging from fully integrated supply chains with on-site hydrogen production and liquefaction at the airport, to scenarios with offsite production but on-site storage, and even configurations where mobile hydrogen refuelling trucks deliver hydrogen directly to the airport and aircraft. The figure also illustrates the anticipated build-up of hydrogen demand at airports for aircraft and ground support equipment (GSE), as well as demand in surrounding areas, such as road transport, terminal use (Airports Council International, 2021), and other industries. However, the focus of the demand and supply chain sizing lies on the usage for the aircraft. This distinction between at (for aircraft and GSE) and around airport demand can also be included in the scenarios as an on-off switch to analyse the differences in required infrastructure.

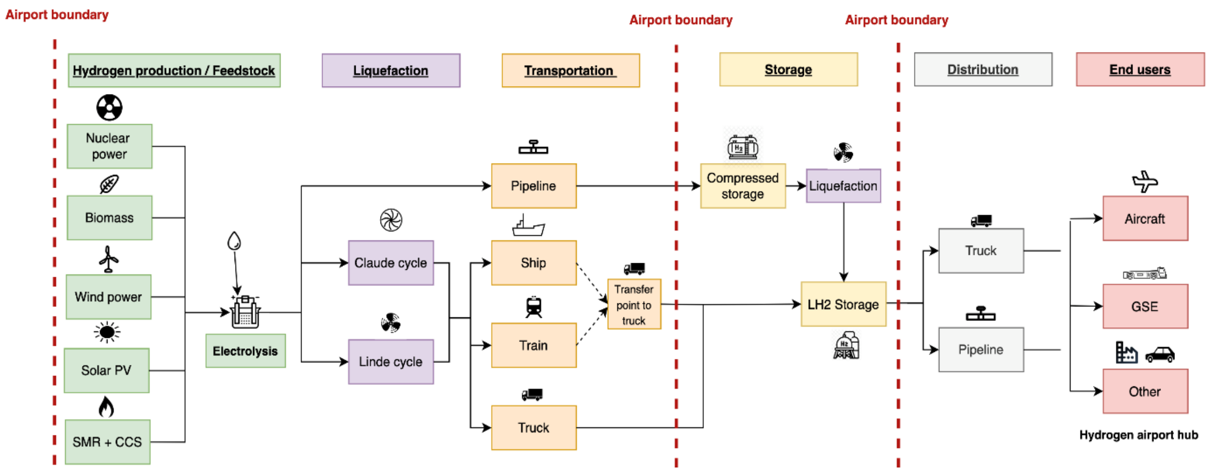

Figure 5-2 Hydrogen supply pathways to and at the airport considered in this report. Note that the airport boundary may include production and liquefaction in the future. Other sources of hydrogen production are excluded from this figure, although they may occur in future supply chains.

The aim of the scenarios is to mainly consider the infrastructure and operations required to supply aviation with green, renewable hydrogen. Hydrogen aircraft only contribute to decarbonisation if no carbon dioxide is produced from well to shaft. Hence, also the hydrogen source must be free of carbon dioxide. Nevertheless, it is possible that non-renewable grey or blue (low-carbon) hydrogen is required in certain regions and/or in the early adoption stages. Low-carbon hydrogen is made possible through carbon capture and storage. However, the techno-economic analyses should focus on the sizing of **infrastructure and operations for green hydrogen**.

[4] URL Aerohauler – The future of air cargo accessed on 22/10/2024

[5] URL https://natilus.co/natilus-selects-zeroavia-za600-hydrogen-electric-engines-for-zero-emission-propulsion/# accessed on 02/12/2024

The current context definition strongly depends on the available literature and expert perspectives at the time of writing (October to December 2024). Since the operational and techno-economic analysis will take place in the upcoming years (up to 2028 in the GOLIAT project), it is important to continuously evaluate the validity of the scope and scenarios set up in this document, and to update the scenarios where necessary. Additionally, the current scope and scenarios are set up at a high and broad level, and further refinement and/or assumptions may be required for the detailed technical analyses.

In the scenario development relevant stakeholders are also incorporated. Figure 5-3 presents the identified stakeholders ranked by their power and interest in the transition to hydrogen-powered aviation. Stakeholders in the key players category, who require close engagement, include aircraft OEMs, energy suppliers (covering both hydrogen production and liquefaction), airlines, airport operators, and policy makers. These stakeholders are key to driving the adoption of hydrogen aviation technologies and shaping the necessary infrastructure and policies.

Safety regulators and financial institutions, categorized as having high power but lower interest, need to be kept satisfied as their decisions significantly influence the feasibility and safety requirements of the transition. On the other hand, stakeholders with low power but high interest, such as research institutions, local communities, environmental groups, ground handling equipment providers, and port authorities or industrial hubs, play supporting roles and should be kept informed of developments. These groups contribute through research, advocacy, and the adaptation of their respective infrastructures to hydrogen technologies.

Passengers and MRO service providers, identified as having low power and low interest, require minimal engagement but may become more involved as hydrogen aviation matures. Lastly, it is important to note that additional stakeholders, such as startups and innovative companies, may emerge over time to accelerate and enable the transition towards hydrogen-powered aviation.

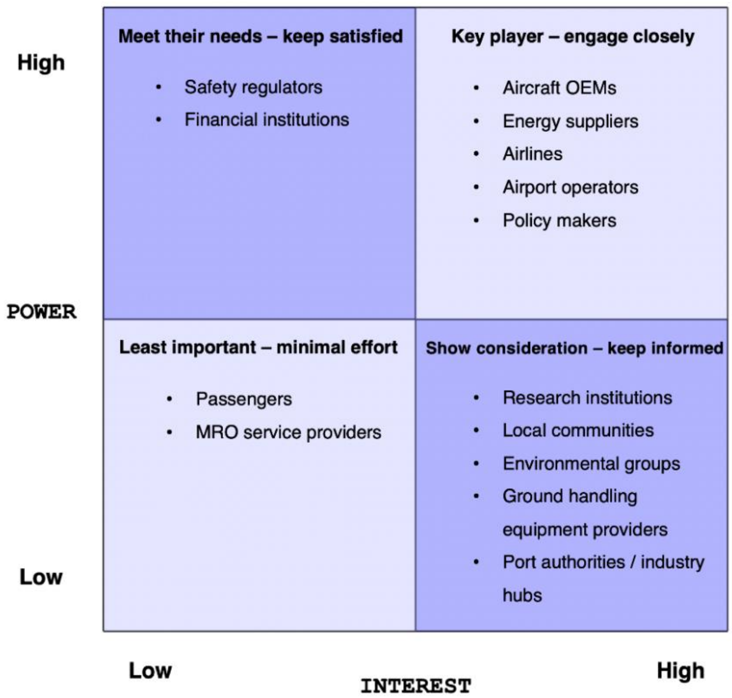

Figure 5-3 Relevant stakeholders to consider in scenario development

6 Driving Forces, Factors, and Barriers

This chapter discusses the factors that are (potentially) impacting the techno-economics of hydrogen value chain for aviation in Europe. We consider seven categories, represented by the seven subsections in this chapter. For each factor, a description is provided supported by literature and discussions with GOLIAT partners and other experts. Based on the individual assignments and the first workshop, we also briefly discuss the expected impact and uncertainty. Furthermore, the motivation to include or exclude a given factor in the scenarios building is presented, together with a conclusion and potential variations, which feed into the next chapter.

Annex 1 (Chapter 13) presents the scoring of each of the factors based on the inputs of GOLIAT experts during the individual assignments and the first workshop. The plots serve to indicate the relative importance of certain categories and/or the spread in insights. The decision to include, exclude, or combine factors in the scenario definition is based upon these insights, literature, and discussions during meetings.

6.1 Policies, Regulations, and Standardization

This section deals with factors from a policy or regulations perspective. Factors such as CO_2 taxes and SAF quotas serve towards greenhouse gas reductions (GHG) goals.

6.1.1 CO_2 Taxes

Carbon dioxide taxes directly target a reduction of emissions by imposing a cost penalty on using fossil kerosene. At the time of writing, such tax or CO_2 pricing is not applied in any of the EU member states[6], pricing plans are currently being proposed. Other current market-based measures which apply to aviation are the EU Emissions Trading System (ETS)[7], capping the amount of emissions, but allowing trading of allowances, and the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), which requires operators to monitor and report CO_2 emissions for flights between ICAO states[8]. Additionally, requirements for offsetting these emissions are set which must be met by dealing eligible emissions units or using eligible fuels.

The scenarios should include at least the current measures as guidelines for the transition in fuel mix and therefore possibly hydrogen-powered aircraft adoption. GOLIAT partners expect these measures to have varying impact on the hydrogen value chain, tending towards larger impact, but with low to medium uncertainty. Therefore, the current measures can be considered as the baseline variation, and a variation can be considered where actual fossil fuel taxes are imposed.

6.1.2 Local Pollution Targets

Using hydrogen to power aircraft can reduce pollution and improve local air quality. In the case of hydrogen fuel cells, no harmful particulate matter is emitted. If hydrogen is combusted, no soot, sulphur oxides (SO_x), or (unburned) hydrocarbons are emitted (Adler & Martins, 2023). However, hydrogen combustion still produces nitrogen oxides (NO_x), which will lead to secondary $PM_{2.5}$ and ozone formation, both deteriorating local air quality.

Considering these aspects, strict local pollution targets at airports could potentially drive the uptake of hydrogen operations. However, besides goals and regulations imposed by ICAO (ICAO, 2017) for engine emissions, limited concrete regulations on local pollution are in place at European scale. The

[6] URL Other carbon pricing initiatives | EASA Eco accessed on 28/11/2024

[7] URL What is the EU ETS? - European Commission accessed on 28/11/2024

[8] URL Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) | EASA Eco accessed on 28/11/2024

airport partners in the GOLIAT project foresee a limited impact of such regulations on hydrogen uptake. Therefore, this factor is not considered in the final scenarios.

6.1.3 Minimum Range Policies

This type of policies relate to so-called short-haul flight bans which can in particularly affect the regional market. The idea of this policy is to ban short-haul flights between destinations which can also be reached by (high-speed) rail in for example less than 2 or 3 hours. Examples of such connections would be domestic flights in France, Germany, or Spain, or international connections such as Amsterdam-Brussel (Reiter et al., 2022). In fact, France (Lottie Limb, 2022) imposed such policy for flights where railway connections under 2.5 hours are available, with the exception of flights supporting hub transfers.

Minimum range policies could prohibit hydrogen aircraft from being allocated to short-range flights while these ranges fit exactly in the range capabilities of the initial hydrogen-powered, regional aircraft. Alternatively, the policy could target only flights powered by fossil fuels, which could be beneficial for the demand for hydrogen-powered (or electric) flight. Additionally, banning short-haul flights can make more airport slots available for longer flights, increasing demand for fuels (Dobruszkes et al., 2022). Except for the cases in France and Austria (Gerhard Hegmann, 2020), and initiatives of individual airlines, limited concrete plans for cross-European short-haul flight bans are available, particularly for aircraft with different powertrains.

However, based on the discussions with GOLIAT experts, there is no clear need to include variations of such policies in the techno-economic scenarios. Although the short-flight bans, with or without exceptions, might have an impact on hydrogen demand, other driving factors are prioritized in the current scenarios.

6.1.4 Quotas on SAF Usage

As part of the broader “Fit for 55 package”, the RefuelEU measures prescribe requirements for the aviation fuel mix, targeting fuel providers and airports[9]. Starting in 2025, 2% of the aviation fuels shall be “green”, gradually increasing each five years up to 70% in 2050. Also, specific proportions are set for synthetic kerosene. Figure 6-1[10] presents these targets in total shares in fuel mix, although the targets may vary per country[11]. Specific requirements are set for what is considered as “green” SAF in line with the sustainability criteria of the Renewable Energy Directive (RED)[12]. Renewable hydrogen is one of the allowed fuel types in this definition of SAF, although specific targets are set for the usage of hydrogen.

[9] URL 70% of jet fuels at EU airports will have to be green by 2050 | News | European Parliament accessed on 26/11/2024

[10] URL Fit for 55 and ReFuelEU Aviation | EASA accessed on 27/11/2024

[11] URL SAF policy actions | EASA Eco accessed on 27/11/2024

[12] URL Renewable Energy Directive accessed on 27/11/2024

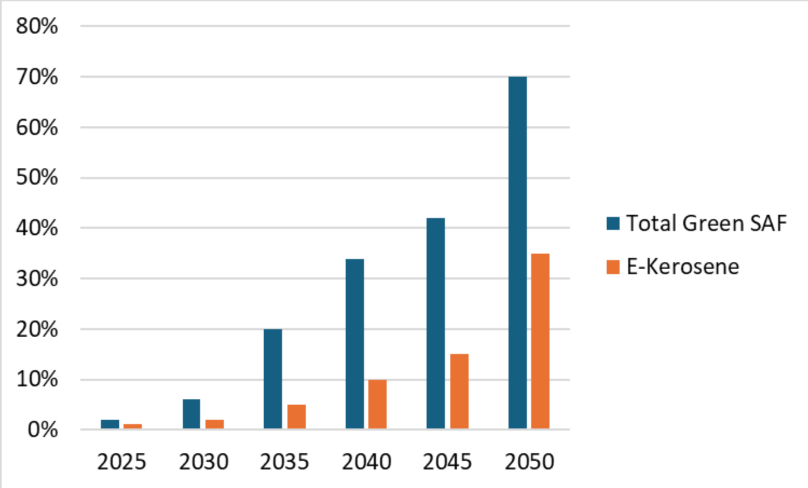

Figure 6-1 Targets for total SAF and specifically e-kerosene uptake in the aviation fuel mix set out by the RefuelEU

These SAF quotas will likely influence the future uptake of hydrogen in aviation, with a medium to high impact according to the GOLIAT partners, with medium uncertainty. Recent research suggests that, under certain conditions, such quotas can be more effective than carbon tax (Jiang & Yang, 2021). In the scenarios and techno-economic analysis, the targets should therefore be considered, but the variations may be limited. The RefuelEU targets can be imposed as guidelines, and possibly one scenario can consider even more strict targets, potentially on a national level. However, the overall impact and uncertainty is lower than for other factors, and therefore these quotas are not considered as a main driving force in the scenarios.

6.1.5 Government H_2 Incentives

This factor considers incentives from governments or public investments intended for the development of a hydrogen value chain and the use of hydrogen in aviation. As concluded by Terpstra "*policies and public investments are a big uncertainty in the development of H2*" (Terpstra, 2024). Public investments could help make private investments more attractive and derisk investments, further developing the technology and possibly reducing the H_2 price, leading to more customers or users. However, in particular the lack of clear policies and/or investments is seen as an issue[13].

GOLIAT partners expect that this factor can have a medium to high impact, with a low to medium uncertainty. This latter opposes the impression by Terpstra (Terpstra, 2024) and the study by Azadnia et al. (Azadnia et al., 2023). However, in the current scope, we also must look at the relative judgement between factors specifically for the supply chain for hydrogen in aviation. As a result, this factor is excluded from the scenarios. Nevertheless, a lack of government support can also be included in the economic aspect of the hydrogen value chain in one of the scenarios.

6.1.6 Standards and Regulations

At the time of writing, no standards are available for the hydrogen supply chain and aircraft operations (Terpstra, 2024). Through interviews (Terpstra, 2024), several stakeholders highlighted this clear lack of standards and the associated uncertainty. This lack can form a barrier for further developments.

The European Commission has set up regulations which target infrastructure development for alternative fuels, or Alternative Fuels Infrastructure Regulation (AFIR)[14]. This regulation is also related

[13] URL Navigating the hydrogen ecosystem | Strategy& accessed on 27/11/2024

[14] URL Alternative Fuels Infrastructure - European Commission accessed on 09/12/2024

to the broader Fit for 55 package introduced above. In AFIR, goals are set at national levels for the deployment of infrastructure for road vehicles, vessels, and stationary aircraft. However, these AFIR targets currently aim at hydrogen refuelling for cars and lorries, and in the context of airports, on the supply of electricity to stationary aircraft[15]. Hence, the targets do not provide concrete regulations for hydrogen refuelling of aircraft. Nevertheless, the supply of hydrogen to road transport at convenient locations may be aligned with the need for hydrogen at airports, creating refuelling hubs.

Under the RefuelEU aviation regulations[16], airport managing bodies, aviation fuel supplies and fuel handlers will also have to take steps to provide access to hydrogen (and electric power) for aircraft operators. This is important to align the regulations regarding the uptake of SAF in RefuelEU with the need for simultaneous infrastructure development for new fuels and energy carriers.

Additionally, the Trans-European Networks for Energy (TEN-E) policy[17] focuses on the overall energy infrastructure to reach sustainability goals. Among other initiatives, this policy supports the development of hydrogen electrolysers instead of initiating new fossil gas projects. Therefore, this policy and the potential investments it enables, can be seen as a driving force for the supply of hydrogen for various transport sectors.

The GOLIAT partners score this factor lower in terms of impact and uncertainty, compared to other factors. Therefore, this factor is left out of the scenario building. Nevertheless, if standardization develops over the course of the GOLIAT project (2024-2028), this decision might have to be reevaluated.

6.2 (Socio-) Economic Growth and Investment

The development and adoption of hydrogen-powered aviation are significantly influenced by socio-economic factors and investments. Even the current aviation sector is highly depending on the economic situation. But unlike conventional aviation, hydrogen-powered aviation also requires entirely new infrastructure and technologies, necessitating substantial investments. Economic growth creates favourable conditions for investment in new technologies, fostering innovation and enabling the long-term development of the hydrogen aviation sector (Amer et al., 2013; Bradfield et al., 2005). Sustainable economic development not only supports technological advancements but also ensures market viability, as these advancements heavily depend on robust economic conditions and are influenced by the overall economic environment (OECD, 2022; World Bank Group, 2023).

Understanding the interdependence of various economic factors in shaping technology uptake and market viability is crucial. Six key factors were initially considered: Economic (GDP) Growth, Population Growth, Social Acceptance of Hydrogen Technology, Economic Stability and Inflation, Disruptive Business Model Development, and Financing and Investment in New Technology. Among these, Economic (GDP) Growth, Disruptive Business Model Development, and Financing and Investment in New Technology were prioritized for detailed analysis due to their high impact and medium to high uncertainty.

6.2.1 Economic GDP growth

Economic GDP growth is a critical driver of demand for aviation, including sustainable aviation technologies like hydrogen-powered aviation. As nations experience higher GDP growth, disposable income levels increase, leading to greater demand for air travel (OECD, 2022; World Bank, 2023). Higher GDP growth also correlates with the ability of consumers and businesses to afford more expensive, sustainable travel options, thus promoting the adoption of hydrogen-powered aircraft.

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[15] URL Alternative fuels infrastructure: Council adopts new law for more recharging and refuelling stations across Europe - Consilium accessed on 09/12/2024

[16] URL https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32023R2405 accessed on 15/12/2024

[17] URL Trans-European Networks for Energy accessed on 09/12/2024

Additionally, economic stability and growth create a favourable environment for long-term strategic planning and investment by airlines and manufacturers, who are more likely to invest in the development and deployment of sustainable aviation technologies when economic conditions are robust (Azadnia et al., 2023). In conclusion, while GDP growth significantly impacts the availability of capital for investment, it also directly influences market demand for sustainable aviation options. Robust economic growth encourages airlines and consumers alike to support and invest in greener travel solutions, aligning with broader environmental and sustainability goals (European Commission, 2020).

Economic downturns or recessions, on the other hand, can reduce demand for aviation services as both consumer and business spending are curtailed (OECD, 2022). This can slow the adoption of costly new technologies like hydrogen-powered aviation, as airlines and manufacturers may delay or scale back investments due to lower anticipated demand and tighter financial conditions. Due to this coupling, this factor is combined with the economic disruption discussed in Section 6.7.1 to define variations in Chapter 7.

6.2.2 Investment

Financing and investments play a critical role in scaling hydrogen technologies. Both private and public investments are essential for funding research and development (R&D), pilot projects, and the necessary infrastructure for hydrogen aviation (European Commission, 2020). Public funding mechanisms, such as subsidies and grants, help de-risk private investments, encouraging private sector participation and venture capital funding targeting hydrogen startups (OECD, 2022; Azadnia et al., 2023).

Moderate investment growth, driven by private sector initiatives, can steadily advance technology adoption and foster a market-driven environment that encourages innovation and competition. On the other hand, government-backed, large-scale investment funds can catalyse rapid technological adoption by accelerating infrastructure development and market readiness, supporting comprehensive hydrogen ecosystems (OECD, 2022).

Investment levels have a high impact on the advancement of hydrogen technologies, determining the pace and scope of technology deployment. Financial support is crucial for scaling pilot projects to commercial operations. However, there is uncertainty influenced by economic stability, policy support, and investor confidence. Economic conditions affect the availability and cost of capital, and clear policy frameworks are essential for maintaining investor confidence (European Commission, 2020; Azadnia et al., 2023). Financing and investments are closely linked to GDP growth and economic stability. Robust economic growth creates a favourable investment climate, while stable macroeconomic conditions are essential for long-term financial planning and fostering a secure environment for investment in new technologies (OECD, 2022).

6.2.3 Disruptive Business Model Development

Disruptive business model development involves innovations in aircraft design, manufacturing, and service delivery that can redefine market dynamics and competitive landscapes (Christensen, 1997). This includes innovations like hybrid and electric propulsion systems as alternatives to traditional jet fuel (European Commission, 2020).

Incremental disruptions, such as battery-powered aircraft development, gradually improve efficiency and sustainability while competing with hydrogen solutions. Radical disruptions, such as entirely new value chains prioritizing hydrogen-powered aviation, can transform the industry through breakthrough innovations and establish new market ecosystems centred around hydrogen technology (Azadnia et al., 2023). These disruptive models can capture significant market share if successful, though they face high uncertainty due to market acceptance and competitive pressures.

The development of hydrogen-powered aviation requires substantial infrastructure, necessitating significant capital investment and operational capabilities for the different components of the supply chain. It is highly uncertain who will build and operate each part of this supply chain, adding complexity to the transition. Current Jet A-1 fuel providers may have limited interest in cooperating with new technologies, while new players, such as those developing electrolysers and liquefaction technologies, are emerging. These new entrants bring innovative solutions but also create uncertainties around market dynamics and collaboration within the industry. The integration of these diverse components into a cohesive supply chain will be critical for the successful implementation of hydrogen aviation.

Disruptive business models have a medium impact on market changes driven by technological innovations. Incremental innovations may lead to more sustainable, long-term growth, while radical disruptions offer the potential for significant market shifts. However, there is high uncertainty regarding consumer and industry acceptance of new models and competitors' responses (Azadnia et al., 2023).

Successful disruptive models often require substantial financial backing, highlighting the importance of interactions with Financing and Investment in New Technology. Collaborations between stakeholders can enhance innovation and market entry (OECD, 2022).

6.3 Airport Infrastructure Readiness

To enable airport operations of hydrogen-powered aircraft, it is important first to assess the level of readiness of airport infrastructure and its components, and to identify related requirements. In the following subsections we will elaborate on particular aspects of airport infrastructure readiness, which will be used in the process of scenario definition.

6.3.1 Choice of Refuelling Setup

Refuelling is an essential process, included in the critical path of the aircraft turnaround. There is currently no established procedure or setup for refuelling of hydrogen-powered aircraft. Furthermore, refuelling is the most distinct process of the turnaround of hydrogen-powered aircraft in comparison to the turnaround of conventional aircraft that use kerosine-based fuel.

Existing literature describes several pathways for delivering hydrogen to aircraft and other vehicles. Refuelling can be done directly from a trailer, in which hydrogen was transported to the airport, e.g., by a truck. If an airport has a stationary hydrogen storage tank, hydrogen can be delivered to aircraft by dispensing units, which pump hydrogen from the storage tank and transfer it to the aircraft tank. There could be different business models for such dispensing units: they can be owned by the airport, used on lease, or pooled (shared by multiple users). Finally, hydrogen can be delivered to aircraft using a pipeline system for hydrogen distribution. The choice of a particular pathway depends on many factors, such as the proximity of a hydrogen production site and of a liquefaction plant, the airport's level of demand for hydrogen, and the airport's category. Next to liquid hydrogen, an airport may also require gaseous hydrogen, e.g., to refuel ground support equipment, which could also be delivered using one of the pathways described above. Note that transportation of gaseous hydrogen in trailers by trucks is considered to be less preferrable from a safety point of view.

The IATA Airport Fuel Storage Capacity Guide (IATA, 2008) suggests airports store a minimum of three days' worth of fuel. It is important to ensure the robustness of hydrogen supply for each of the pathways described above.

Another important consideration is the choice of the place to refuel aircraft and other vehicles. For safety reasons, it should preferably be an open space, free of flammable and combustible objects. It is expected that hydrogen-powered aircraft will have the physical dimensions that fit the existing airport infrastructure (in particular, gates, apron, terminal). However, if this is not the case, the apron, gates and terminal area would need to be redesigned. Another solution could be to use remote refuelling stands, which may have a negative effect on the aircraft turnaround time.

Babuder et al. (Babuder et al., 2024) provides an extensive overview of the impact of hydrogen aircraft on the airport operations and infrastructure. As discussed above, the choice of the refuelling setup has many associated uncertainties, as well as significant techno-economic implications, and thus should be considered in future scenarios.

6.3.2 Airport Distance to H_2 Production Site

This factor has a high influence on the choice of the refuelling setup, considered in the previous section. Hydrogen can be transported using pipelines, trucks, ships, or trains.

Trucking method is cost-effective for low to moderate hydrogen demand (~500-800 kg per day), when the distance to the production site is short (< 100 km) (Degirmenci et al., 2023a). This mode of transport is considered to have a minimal environmental impact. LH_2 trucks with cryogenic tanks are considered to be more environmentally friendly than CGH_2 trucks over a distance of 400 km (Degirmenci et al., 2023a). It is also argued that from a safety point of view, when hydrogen is transported through a densely populated area, LH_2 distribution infrastructure is preferred (Degirmenci et al., 2023a).

Sea transport can be used to transport large quantities of both gaseous and liquid hydrogen transport over a long distance. The capital cost is expected to be high (Degirmenci et al., 2023a).

Rail transport of hydrogen is also considered to be a suitable option for transporting large quantities of hydrogen over large distances. However, it is also currently considered to be expensive. When hydrogen is transported as a liquid, it is expected that there would be a significant amount of boiling loss, which is approximately 1.65% per day (Ohmstede et al., 2023).

Hydrogen transportation using pipelines is a viable option, when hydrogen demand is high (> 5 tons per day). Long-distance pipeline transport of hydrogen has a lower environmental impact than transportation by trucks. Van Dijk et al. (Van Dijk et al., 2024) compares different supply routes for Rotterdam – The Hague Airport, where the vicinity to the Port of Rotterdam is considered. This close positioning allows for several supply pathways, and last-mile delivery via truck or pipelines.

Providing hydrogen to regional airports with a low to medium hydrogen demand, which are located far away from the hydrogen production sites may be problematic. One may consider options of using trucks which serve multiple airports or consider the option of fuel tankering, whereby an aircraft carries more fuel than required for its flight to reduce or avoid refuelling at the destination airport, which does not have the hydrogen refuelling infrastructure.

Although different ways of supplying the fuel is considered in the scenarios, the distance between the airport and the production site is not considered as a factor in the scenarios with variations.

6.3.3 H_2-powered Ground Vehicles

Diesel-powered ground support equipment (GSE) produces a substantial amount of emissions generated by the airport ground operations. Hydrogen has already been used by some airports (such as Gatwick, CDG, Vancouver) as a sustainable solution to refuel ground vehicles.

In (Marksel et al., 2022) several examples of the implementation of hydrogen refuelling infrastructure at different airports are provided: At Vancouver airport hydrogen was used for buses and tractors for baggage carts equipped with fuel cells in 2006. In 2018, facilities for the production, distribution, and use of green hydrogen were placed at Liège airport. Electricity from solar panels was used to produce the hydrogen. In turn, this hydrogen was used for the airport's fleet and other modes of transport. More recently, Bremerhaven Airport, built in 2020 an electrolysis hydrogen pilot plant with a wind turbine capable of supplying the energy required for the hydrogen fuel cell with a capacity of up to 1000 tonnes per year.

In general, the hydrogen demand for GSEs is much smaller than for aircraft, thus, is not an issue when hydrogen supply for aircraft is established. Therefore, this factor is excluded from the scenario development.

6.3.4 Readiness per Airport Archetype

There exist different schemas for the characterization of airports by type of activities, size, location, and aircraft types served. In particular, the Federal Aviation Administration (FAA) distinguishes four commercial service airport categories: nonhub primary, small hub primary, medium hub primary, and large hub primary. General Aviation airports are usually divided into national, regional, local, basic and unclassified airports. In the scope definition in Chapter 5, the classification by EUROCONTROL is used based on IFR movements in 2022 (EUROCONTROL, 2024). The World Economic Forum distinguishes four airport archetypes defined by traffic volume and number of aircraft types (World Economic Forum & McKinsey & Company, 2023).

The airport archetype largely determines the amount of daily demand for hydrogen: large international hub airports will have (much) higher demand for hydrogen than smaller regional and local airports. The airport type also largely influences the choice of the refuelling and turnaround setup. Large airports may require more significant, time- and resource-consuming infrastructural changes than smaller airports to enable safe and efficient turnaround for hydrogen-powered aircraft. At the same time, it might be challenging to establish hydrogen supply for remote regional and local airports. Therefore, large hub airport operations in 2035 should be considered, without these airports necessarily acting as hubs for other transport sectors in that year.

Large airports may also serve as hubs for generation and distribution of (liquid) hydrogen to other airports and other customers located in the region. The following variations can be considered for this factor: no airports are ready by 2035, only regional and local airports are ready by 2035, all airports are ready by 2050.

6.3.5 Airport Physical Space Constraints for Production and Storage

Many existing airports struggle with challenges of physical infrastructure expansion. For some airports such an expansion is even not possible. Thus, not every airport would be able to accommodate hydrogen production and storage infrastructure, which should satisfy all the necessary safety requirements (e.g., safety zones around hydrogen production and storage sites). Such airports would have to rely on off-site production. Furthermore, any hydrogen production and/or storage sites at the airport should be located and be accessible in such a way that it ensures efficient refuelling of aircraft and other vehicles.

The following variations can be considered for this factor: no physical space for production and storage of hydrogen, a physical space for limited storage of hydrogen (less than for three days of operations), sufficient space for storage of hydrogen, sufficient space for production of hydrogen.

6.3.6 Airport Physical Space Constraints for Ground Operations

It is expected that the turnaround process of hydrogen-powered aircraft will be largely the same as for conventional aircraft. The main difference will be in the refuel process. To refuel an aircraft, for the same energy content, four times more volume of liquid hydrogen is currently needed than jet fuel (Degirmenci et al., 2023a). Furthermore, there should be a safety zone around such vehicles. Such vehicles would need to fit the existing airport infrastructure, and to coordinate the use of space around the aircraft with other vehicles involved in the turnaround process. There might be more hydrogen refuelling vehicles employed. In this case, airport surface movement operations would need to be planned accordingly, taking into account the increased traffic. Moreover, it might also be the case that the physical dimensions of some hydrogen-powered aircraft would not fit the existing airport infrastructure anymore.

The following variations can be considered for this factor: no additional significant physical space constraints, physical space constraints would significantly impact the duration of turnaround process, physical space constraints would not fit the airport infrastructure.

6.4 Hydrogen Availability and Energy Market

The hydrogen value chain for aviation is significantly influenced by the development of production, storage, and transportation of hydrogen, as well as competing energy carriers such as SAF, making these elements crucial for the sector's success (IEA, 2022). Without the availability of large amounts of cost-competitive hydrogen and an infrastructure to supply the airports, the scale-up of LH_2 aviation is likely to fail before the ramp-up takes off in favour of existing or competing sustainable fuels. Even if new types of airplanes are developed, the infrastructure at the airport and the supply of hydrogen to the airport are equally important (Hoelzen, Flohr, et al., 2022). Therefore, the components for production and distribution must be available, and hydrogen must be freely available in markets in sufficient amounts (BloombergNEF, 2021). A push for the development of a green-hydrogen market in transportation and industry can follow from the Renewable Energy Directive III (RED III), and in particular the target for renewable fuels from non-biological origin (RFNBO). This RFNBO target is set at 1% of the 29% renewable energy goal for transportation in 2030[18].

Within this category, thirteen factors were initially considered: the choice of hydrogen sources (grey, blue, green, white), the relative mixing of these sources, the availability of drop-in sustainable aviation fuel (SAF) and alternative fuels, the availability and growth in renewable energy sources, the price and cost of renewable energy sources, electrolyser capacity, the price of drop-in SAF and alternative fuels, the availability of energy carriers and transport, electric grid development, hydrogen grid development, liquefaction equipment development, storage equipment development, and the development of hydrogen road, railway, and pipeline transport (ICAO, 2022). Prioritization was given to factors with high impact and medium to high uncertainty. Additionally, factors were merged as they are similar or highly affected by each other. For example, the choice of hydrogen sources (grey, blue, green, white), the relative mixing of these sources, as well as the growth in renewable energy sources, and the price and cost of renewable energy sources (REN, 2022) were combined. Furthermore, the different components of the hydrogen supply chain from production, transportation, and storage are linked but split into two categories: hydrogen transport development (CAPEX & OPEX) and hydrogen electrolyser, liquefaction, and storage development (IRENA, 2018).

6.4.1 Availability of Different H_2 Sources

The availability of different hydrogen sources (grey, blue, green, white) could play a pivotal role in the hydrogen-powered aviation sector. Grey hydrogen, produced from natural gas, emits CO_2, while blue hydrogen uses carbon capture and storage (CCS) to mitigate these emissions (BloombergNEF, 2021; IEA, 2022). Green hydrogen, generated from renewable energy, and white hydrogen, naturally occurring but not commercially extracted, are prioritized for their environmental benefits (Hydrogen Council, 2020; IRENA, 2018). However, availability might be limited, and costs could be higher compared to other less sustainable sources. There might be a transition from grey and blue hydrogen to green and white hydrogen, which has to be supported by policy and regulatory frameworks aimed at promoting sustainability (BloombergNEF, 2021; European Commission, 2020). This transition is also significantly affected by regulations such as specific fuel quotas or CO_2 taxes, which could strengthen the already existing focus on green hydrogen. Variation to be considered in the availability of these hydrogen types range from exclusive reliance on green hydrogen to initial dependence on grey/blue hydrogen with progressive integration of green/white hydrogen, influenced by technological advancements and regulatory support (Clean Sky 2 JU, 2020; IEA, 2022).

[18] URL https://ecer.minbuza.nl/-/herziene-richtlijn-hernieuwbare-energie-red-iii-in-het-eu-publicatieblad-verschenen accessed on 15/12/2024

6.4.2 Availability and Price of SAF

The availability and price of sustainable aviation fuels (SAF) are equally crucial. SAF and alternative fuels are integral to the transition towards sustainable aviation but are also competing fuels with both positive and negative correlations to the uptake of hydrogen-powered aviation (Bauhaus Luftfahrt, 2024). Both have specific use cases based on their energy density as well as costs and efficiency. SAF is suitable for medium to long distances, while LH_2 is preferable for regional to medium distances; however, there will be some overlap. SAF is expected to be more expensive but also more convenient due to its drop-in characteristics and no need for new specific infrastructure. The availability of relatively cheap SAF is linked to that of gaseous hydrogen as this is the base product for SAF, but it could be more competitive compared to LH_2. The availability and cost of SAF therefore impact hydrogen demand, with government incentives and mandates playing a significant role in promoting different fuel adoptions (European Commission, 2020; ICAO, 2022). Variants in SAF availability range from no SAF in the near future to nearly unlimited availability, with limited and costly SAF potentially incentivizing hydrogen adoption (ATAG, 2021).

6.4.3 Growth and Price of Renewable Energy Sources

The growth and price of renewable energy sources directly and significantly affect hydrogen production costs. The supply of hydrogen (and SAF) is highly dependent on substantial amounts of electric energy for fuel production. Therefore, the expansion of renewable energy capacity and advancements in renewable energy technology are crucial for reducing hydrogen production costs (IEA, 2022). Electric energy production can account for more than half of the overall supply cost of LH_2 depending on the location and availability of renewables (Hoelzen, Flohr, et al., 2022). Especially as aviation is one of the hard-to-abate industries and in the later stages to achieve climate neutrality, the rapid expansion of renewable energy is even more crucial for this sector. Variants in renewable energy development range from highly developed renewable grids with enough additional energy (in peak power availability) to power large-scale electrolysers as well as liquefaction plants possibly directly at the airport, to growing sectors and limited renewable availability, each influencing hydrogen production costs differently (IRENA, 2018; REN, 2022). The impact of the availability renewable energy sources is judged as high, with a high uncertainty. Therefore, this factor is included in the variation generation in Chapter 7.

6.4.4 H_2 Transport Development, CAPEX & OPEX

Hydrogen transport development, including their capital expenditures (CAPEX) as well as operational expenditures (OPEX), is essential for the feasibility and cost-effectiveness of hydrogen distribution to airports. For hydrogen aviation to become a reality and scale up, a network of airports with cost-effective and reliable hydrogen supply is essential. This can only be realized if extensive gaseous and/or liquid hydrogen transport networks are developed with low operational costs, as the transport to the airport can constitute a significant portion of the overall supply costs. Different transport routes are possible, but one of the most promising options is the European Hydrogen Backbone (EHB). The EHB initiative outlines the development of extensive EU hydrogen grids focusing on pipelines and terminals, hydrogen trade markets, and the uncertainties impacting transport routes, costs, and regional availability (EHB, 2023; Hydrogen Council, 2020). The lack of international initiatives or their slow progress could significantly influence the available amounts of LH_2 and their costs.

6.4.5 H_2 Electrolyser, Liquefaction, and Storage Development

The development of hydrogen electrolysers, liquefaction equipment, and storage facilities is critical for hydrogen aviation. More specifically, technological advancements, cost development, and investment support are key to scaling hydrogen production and ensuring a continuous supply. The capital costs, as well as the availability and efficiency of these key components of the hydrogen supply chain, are crucial for scaling up the supply. Liquefaction stands out as its development is more uncertain because the use of LH_2 is unique in aviation compared to different applications of gaseous hydrogen. The lack of significant advantages through cooperation with other industries results in an even lower technology readiness level (IEA, 2022; BloombergNEF, 2021; EHB, 2023). Additionally, the integration of these components into the electric grid and the development of the electric grid itself are crucial for supporting hydrogen production and distribution, impacting hydrogen production scalability and cost, as electrolysers and liquefaction require substantial amounts of energy (IEA, 2022) This factor is included in the scenario variation development.

6.4.6 Electric Grid Development

The integration of these components into the electric grid and the development of the electric grid itself are crucial for supporting hydrogen production and distribution, impacting scalability and cost as electrolysers and liquefaction require substantial amounts of energy (Hoelzen et al., 2022). The role of electric grid development in supporting hydrogen production and distribution is paramount (HydrogenEurope, 2024). This includes the integration of renewable energy sources into the electric grid and the impact on hydrogen production scalability and cost. Projects for hydrogen production must be closely developed with renewable energy industry operators and transmission system operators. Variants in grid development range from highly developed grids for levelling deviations and dispatch to moderate development supporting hydrogen production, to limited development impacting hydrogen production and availability. This factor is included in the scenario variation development.

6.5 Air Traffic Growth Rate

Just after the COVID-19 pandemic, the demand for air travel appears to increase again at a high pace[22]. This demand will play a pivotal role in the increase of airline fleets and flight operations over the coming decades. Increasing travel demand and greenhouse gas reduction goals (as discussed in Section 6.1) will drive the uptake of new technologies, such as hydrogen-powered passenger aircraft. Literature provides several approaches for future demand estimation. Costa-Alves et al. (Costa-Alves et al., 2024) rely on data World Bank and ICAO to forecast future demand based on gross domestic product (GDP) and population. Alternatively, a future forecast can be derived from past demand data offered by OAG: Flight Database & Statistics[19] , the ICAO Data[20]. Growth factors can be derived from market outlooks by Airbus[22] or Boeing[21]. Wang and Gao (Wang & Gao, 2021) provide an overview of data and methods for air travel demand modelling referring to studies in the past decades.

GOLIAT partners expect that the growth in passenger impact will influence the overall techno-economic quantities of interest, although the individual assignment shows this impact is limited with varying uncertainty. Therefore, this factor is not considered as a key factor. Instead, in the scenario definitions, the air traffic growth is considered a part of the economic development and related disruptions. Although more variations could be identified, we assume a steady increase in global travel demand of approximately 3 to 5% p.a. (measured in revenue-passenger kilometres), although the intra-European market may grow at more modest rate (1.6%[22]). A crucial variation occurs in the event of a crisis, economic or another pandemic, in which this travel demand can stagnate or decrease significantly.

[19] URL https://www.oag.com/ accessed on 02/12/2024

[20] URL https://data.icao.int/newdataplus accessed on 01/11/2024

[21] URL https://www.boeing.com/commercial/market/commercial-market-outlook accessed on 02/12/2024

[22] URL https://www.airbus.com/en/products-services/commercial-aircraft/global-market-forecast accessed on 02/12/2024

6.6 Aircraft Technology Development

The current section focuses on how technological aspects at aircraft level can affect the future hydrogen demand, supply, and operations.

6.6.1 Entry Into Service Date of New H_2 Aircraft

Several original equipment manufacturers (OEM) have proposed concepts for hydrogen-powered aircraft of varying sizes. AZEA (AZEA, 2024) provides an overview of the expected entry into service (EIS) years and seating capacity of the concepts of ZeroAvia[23], Universal Hydrogen[24], Embraer[25], Airbus[26], Fokker Next Gen[27], Cranfield Aerospace Solutions[28], Beyond Aero[29], APUS[30], and Blue Spirit Aero[31]. Furthermore, concepts by H2FLY[32] and Conscious Aerospace[33] can be added to this list. An overview of the categories and expected EIS is shown in Figure 6-2.

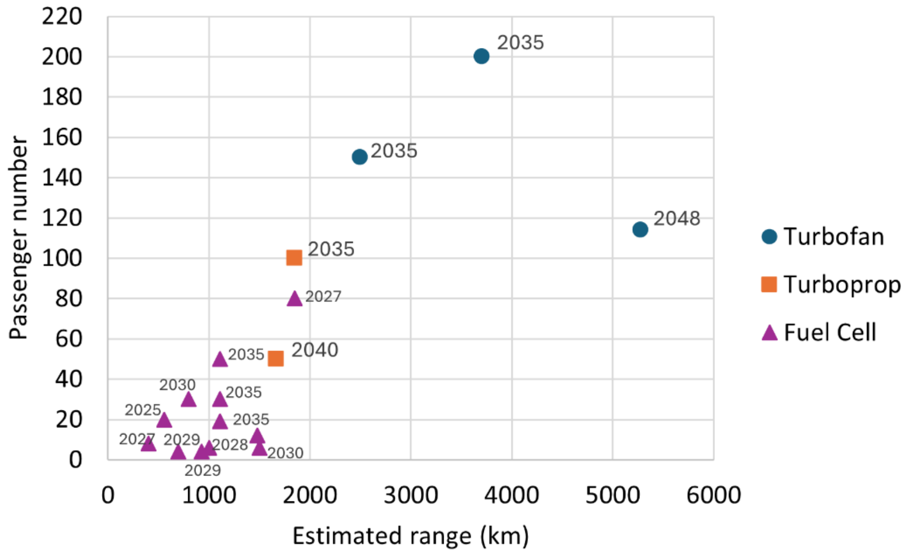

Figure 6-2 Range and payload of planned hydrogen aircraft, with expected entry-into-service year in brackets (footnotes 21 to 31)

Based on this figure, it appears that larger aircraft (e.g., Airbus – ZEROe and Fokker Next Gen) will be introduced around 2035, later than the general aviation and smaller regional aircraft (e.g., ZeroAvia). The Embraer concept also show an EIS around 2035, although the larger, gas turbine-powered variant is expected to arrive later. In the DLR EXACT project (Oesingmann et al., 2024a), four commercial

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[23] URL Home - ZeroAvia accessed on 29/11/2024

[24] This company does no longer exist at time of writing, but was considered in earlier outlooks

[25] URL https://embraercommercialaviationsustainability.com/concepts/ accessed on 29/11/2024

[26] URL https://www.airbus.com/en/innovation/energy-transition/hydrogen/zeroe accessed on 29/11/2024

[27] URL https://www.fokkernextgen.com/the-aircraft accessed on 29/11/2024

[28] URL https://cranfieldaerospace.com/hydrogen-technology/ accessed on 29/11/2024

[29] URL https://www.beyond-aero.com/ accessed on 29/11/2024

[30] URL https://group.apus-aero.com/zero-emission/ accessed on 01/12/2024

[31] URL https://bluespiritaero.com/en/dragonfly accessed on 01/12/2024

[32] URL https://www.h2fly.de/ accessed on 29/11/2024

[33] URL https://www.consciousaerospace.com/technology-1 accessed on 29/11/2024

passenger transport aircraft scenarios are considered, all with an EIS in 2040. Hence, no distinction is made based on propulsion technology or payload-range capabilities.

This discussion mainly focused on the introduction of completely new aircraft into the market. However, after the initial introduction in 2035, for example, newer versions or derivatives can be produced with improved technologies as laid out in technology roadmaps (Aircraft Technology Institute (ATI), 2022a; Costa-Alves et al., 2024; Mukhopadhaya & Rutherford, 2022).

The impact and uncertainty evaluation indicates that this factor is important, and at the same level as the range of these aircraft (Section 6.6.2) and the propulsion type selection (Section 6.6.5). However, it appears to be less critical than the aircraft operating cost and efficiency. Therefore, variations in the EIS date, range, and propulsion type selection are combined into one factor for the scenario building in Chapters 7 and 8. Variations in the EIS can comprise a baseline where the concepts are introduced as planned by the OEMs, short delays of 2 to 5 years, or large delays ranging from 6 to 10 years.

6.6.2 Range of New H_2 Aircraft

The targeted use of hydrogen-powered aircraft is the regional, short-, and possibly medium-range markets in the foreseeable future looking at the concepts in Figure 6-2. Nevertheless, concepts with a longer range are being studied, for example, by ATI (Aircraft Technology Institute (ATI), 2022b). The achievable range can determine which connections are operated in future networks and longer routes can increase the demand for hydrogen.

Therefore, this factor is expected to have a medium to high impact in the techno-economic analyses, and similar levels in uncertainty. Therefore, the range is included in the scenarios but combined with EIS year and propulsion type selection. It is expected the hydrogen with short- to medium ranges to be powered by turbofan engines rather than fuel cells or turboprop engines. For example, the Airbus ZEROe turbofan concept features range larger than 2000nm, whereas the turboprop concept aims at a 1000nm range[34]. Current outlooks (AZEA, 2024) do not consider rotorcraft to be powered by hydrogen before 2040. Therefore, the operations and hydrogen demand for helicopters is left out in the scenarios and future analyses.

6.6.3 Operating Cost and Efficiency of H_2 Aircraft

The direct operating expenses of new hydrogen aircraft, similar to existing kerosene aircraft, can be broken down into several categories. Considering that the indirect operating cost are mostly driven by airline service level decisions, the main differences with current operations will likely occur in the direct operating costs (Hoelzen et al., 2023). The latter category comprises of flight related costs (fuel and crew salaries), maintenance costs, and depreciation and amortization costs.

Efficiency of hydrogen aircraft primarily relates to the in-flight energy consumption of these aircraft. Depending on the configuration of the aircraft including the tank integration, tank technology, powertrain layout, hydrogen aircraft may consume less or more energy in flight, compared to kerosene counterparts (Aircraft Technology Institute (ATI), 2022b; Onorato et al., 2022). This justifies the high uncertainty of this factor.

This factor scores high both in terms of impact and uncertainty according to project partners and should therefore be included as a driving force in the scenarios. Since the maintenance costs also influence the total direct operating cost, this factor is combined with the maintenance consideration discussed in Section 6.6.7. Considering a baseline case, hydrogen aircraft feature a similar energy efficiency and maintenance cost as similar kerosene aircraft. However, variations can account for in-flight energy penalties and/or extra maintenance cost (or modelled as lower annual utilisation). The

[34] URL https://www.airbus.com/en/innovation/energy-transition/hydrogen/zeroe accessed on 29/11/2024

best variant is one where new aircraft concepts are introduced which overall have a lower in-flight energy consumption.

6.6.4 Development of New Aircraft with Drop-In Fuels and Their Retirement

This factor considered the potential introduction of new commercial passenger aircraft in the considered period (2030 to 2050) which are fuelled by kerosene or drop-in alternatives such as bio-based fuels or synthetic kerosene. Such concepts could introduce technologies reducing fuel consumption and CO_2 emissions at lower development and/or operating cost than currently proposed hydrogen aircraft. Therefore, such new alternative aircraft could (partially) uptake part of the market intended to be captured by hydrogen aircraft, hence influencing the hydrogen demand.

Considering openly available literature and news sources, limited concrete plans are available for next-generation aircraft concepts powered by drop-in fuels in the market covered by the commercial hydrogen aircraft. Although it can be expected that by 2030 many aircraft, especially if newly produced, can fly on 100% SAF[35,36] (currently the limit is a 50% mix with certified Jet-A), no clear plans for clean sheet designs are publicly available.

Nevertheless, a reduction in fuel consumption of non-H_2 aircraft can be expected due:

- Retirement of kerosene aircraft and their replacement by models which are currently already available
- Through improvements in technology, the fuel consumption of the same aircraft model can improve by approximately 2-3% over 10 years (ATAG, 2021).

The inputs from the homework and first workshop show that experts do not agree on the impact and uncertainty of this factor, ranking both indicators from low to high. Although this makes the exact position in the impact-uncertainty domain inconclusive, it is clear that this factor has a lower relevance compared to other aspects such as range, EIS date, and operating cost of H_2 aircraft.

Based on the limited concrete plans for novel aircraft powered by drop-in fuels in the considered range and based on the judgement of stakeholders, it is decided to not consider this factor further in the scenario definition. Nevertheless, the competition of drop-in aircraft and fuel consumption reduction over the considered period should be considered in the fleet development models in Task 8.2, although no variations are considered.

6.6.5 Propulsion Type Selection

When hydrogen becomes the energy carrier onboard of future aircraft, different powertrain architectures can be selected. The hydrogen can be fed to fuel cells, which generate electricity to power electric motors. These electric motos drive propellers which provide thrust force. Alternatively, the hydrogen can be combusted to power a gas turbine engine, such as a turboprop or turbofan engine. The optimal propulsion type selection, in terms of energy usage, strongly depends on the mission range and cruise speed (Adler & Martins, 2025). The propulsion type selection, in combination with range and passenger number, can affect the demand. For example, Oesingmann et al. (Oesingmann et al., 2024b) show the differences in hydrogen demand for different propulsion types.

Likely a mix of propulsion types will enter service past 2030, and these technologies will also further develop. The propulsion type is in the scenario building combined with EIS date and range capabilities of the hydrogen aircraft. For example, as shown in the results from Adler and Martins in Figure (Adler & Martins, 2025), hydrogen combustion is likely to be more suitable for aircraft with higher cruise speeds and longer ranges, where the majority of available seat-kilometres lie.

[35] URL Sustainable aviation fuels | Airbus accessed on 23/10/2024

[36] URL Boeing: Sustainability (gnieob.com) accessed on 23/10/2024

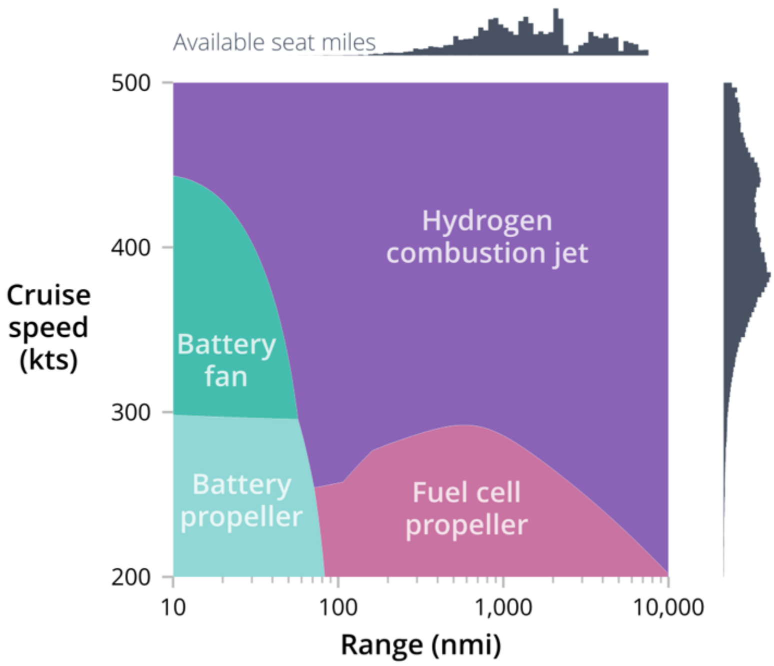

Figure 6-3 Most efficient sustainable propulsion types for different cruise speeds and ranges (Adler & Martins, 2025)

6.6.6 Fleet Retirement Strategies

This factor considers the strategies which drive the retirement aircraft in a fleet, and the subsequent introduction of new aircraft. While this often is driven by the lifespan of the aircraft, dependent on many other factors, and financial considerations, sustainability targets and emission policies can potentially influence an airline's fleet plan. This can affect the uptake of hydrogen aircraft and therefore the H_2 demand.

For sustainability reasons, it is desirable to switch to newer aircraft as soon as possible. Newer kerosene aircraft have a lower fuel consumption, are typically quieter, and also cheaper to operate. When hydrogen aircraft are introduced, operators may want to assign these as soon as possible to eliminate the climate impact of their fleet, if their financial situation allows it. Also, production availability may limit the rate of market uptake.

Research into the relationship between fleet retirement and emissions revealed that retirement has limited effects on global emissions (Dray, 2013). Substantial changes to decision making of aircraft retirement and acquisition are only expected in the case that fuel prices become significantly higher than historical prices. Other decisions to consider are also retrofitting of new technologies and the usage of new aircraft vs. second-hand aircraft.

Based on the relatively low impact of retirement on emissions observed in history and the discussion with experts, variations in fleet retirement strategies are not considered of high importance in the current scope and are therefore not considered in the scenario definition.

6.6.7 Maintenance, Repair, and Overhaul Intensity and Availability

Since hydrogen aircraft introduce many new components into the aircraft, such as a tank, novel fuel system, and fuel cells or combustion system, the maintenance procedures and associated cost and resources are still to be determined. Furthermore, airports also have to acquire the right infrastructure to repair and overhaul hydrogen aircraft. These considerations can directly affect the operating cost and the airports at which hydrogen operations take place. In turn, this can affect the assignment of hydrogen aircraft in a network and the overall hydrogen demand.

Recent research (Ramm et al., 2024) considers the economic and environmental impact of hybrid aircraft using hydrogen fuel cells and compares this to baseline kerosene aircraft. This research introduces six LH_2 tank maintenance scenarios, considering different intervals for visual inspection, testing, and replacement. This analysis shows a big variation in annual maintenance cost depending on the assumed procedures, highlighting the uncertainty in this factor. The maintenance cost increase and longer downtime of H_2 concepts contributes to lifecycle revenue losses (Ramm et al., 2024). Research by (Meissner et al., 2023) indicates an increase of 22 to 32% in total scheduled maintenance time, compared to kerosene alternatives, when a cryogenic tank and distribution system is used. Hoelzen et al. (Hoelzen, Silberhorn, et al., 2022) foresees an increase in maintenance cost between 12 and 14%.

Although maintenance performs an important role in the operating cost, it does not directly influence the hydrogen consumption in a single flight leg. Therefore, it is recommended to include this factor in the overall operational expenditure of H_2 aircraft (treated in Section 6.5.3). Furthermore, potential limits to maintenance, repair, and overhaul (MRO) availability at airport can be considered in the infrastructure readiness at airports.

6.7 Disrupting factors

In this category, we investigate factors which can drastically impact the techno-economic future of hydrogen supply chains for aviation. Originally, technology reliability issues were considered as a third pillar in this category. However, since safety is already included here and we consider the influence of hydrogen technology on maintenance in the Aircraft Technology category, it is decided to leave out reliability issues in this category.

6.7.1 Economic Crises

Financial and economic crises, including recessions and medical emergencies, can have significant impacts on the development and adoption of hydrogen-powered aviation. These crises can disrupt investment flows, undermine economic stability, and influence government policies. The COVID-19 pandemic, for instance, drastically changed the demand in aviation, with a significant reduction in air travel as global lockdowns and travel restrictions were imposed. This sharp decline in demand severely affected the financial health of airlines and airports. Similar crisis could lead to decreased investments in new technologies, including hydrogen-powered aviation as economic downturns typically lead to reduced investments in research and development (R&D) and infrastructure projects as resources are redirected to stabilize the economy (OECD, 2022). Consequently, the progress of hydrogen aviation development may be hindered.

New investments in hydrogen aviation require substantial funding and cooperation between political and private entities. The complexity of coordinating these efforts during times of economic instability adds another layer of challenge, but also an opportunity for targeted stimulus measures that support sustainable technologies. Economic growth and stability significantly influence financial resources available for investment, determining the capital availability for hydrogen projects and enhancing investor confidence and market stability (European Commission, 2020). However, economic fluctuations, potential crises, and inflationary pressures introduce medium uncertainty, which can affect stability and investment decisions (European Commission, 2020; Azadnia et al., 2023).

However, crises can also accelerate change. For instance, the COVID-19 pandemic underscored the necessity for resilient and sustainable energy sources, potentially enhancing the focus on renewable hydrogen technologies (IEA, 2022). Similarly, economic recessions can prompt government interventions and stimulus packages aimed at economic recovery, which might include funding for green technologies and infrastructure (World Bank, 2023). Governments often respond to economic crises with stimulus packages designed to spur recovery. These packages may include investments in infrastructure, research, and development, fostering an environment conducive to the adoption of hydrogen technologies (European Commission, 2024). Post-crisis economic recovery efforts can prioritize sustainable energy projects to drive economic growth and job creation. Additionally, the pursuit of energy independence in the wake of geopolitical events can lead to increased investments in hydrogen technologies. These investments aim to enhance energy security and reduce dependency on external energy sources (EEHB, 2023).

Since experts indicate that economic problems can have a large impact and are possible, a disruptive variation in economic development (together with the factor discussed in Section 6.2.1) is included.

6.7.2 Safety Issues

IATA's fact sheet 7 on 'Liquid hydrogen as a potential low-carbon fuel for aviation' (IATA, 2019) reviews safety hazards and safety implications associated with liquid hydrogen use. In the following we consider essential safety hazards and risks, associated with the properties of hydrogen.

The auto-ignition temperature of hydrogen is considerably higher than that of kerosene. At the same time, the minimum ignition energy of hydrogen is considerably lower than that of kerosene, which presents a safety hazard, as a weak spark can cause ignition. Therefore, it is important to ensure that hydrogen storage and refuelling takes place away from flammable objects.

Hydrogen is approximately 14 times lighter than air, and if spilled it quickly evaporates, rises and disperses. Therefore, it is important to ensure that there is an effective ventilation system installed at the hydrogen storage and refuelling place with the necessary sensors, fire alarm etc. A fire can occur if the concentration of kerosene in air is more than 1.4%, however this number is three times larger for hydrogen (Degirmenci et al., 2023b). The hydrogen flame is invisible, and the gas is odourless, which makes it difficult to detect leaks or fire.

Based on these observations, several safety issues can occur during hydrogen ground operations (e.g., in storage or distribution) or hydrogen flight (e.g., leakage, emergency landing, etc.). Since a safety issue or a combination of them can have a significant impact and cannot always be foreseen (i.e., high uncertainty), safety is included as a disrupting factor in the scenario building. One variation can be an outlook without major safety issues. In a disruptive scenario, a huge safety issue can delay the implementation of infrastructure at airports or the aircraft technology readiness.

7 Variation Generation

Based on the discussions of the individual factors in Chapter 6, this chapter highlights the most important categories and factors and summarizes the possible variations for these factors. From the project meeting discussions and the impact and uncertainty evaluation, the factors in the following three categories are the most important:

- Hydrogen Availability and the Energy Market
- Airport Infrastructure Readiness
- Aircraft Technology Development

These three categories establish the main dimensions along which scenario storylines are developed in Chapter 8 using the variations summarized here. Additionally, safety issues, economic disruptions, and extreme policies are considered in the setup of the raw scenarios, but these aspects do not form the principal factors. Table 7-1 provides an overview of the factors and their variations which are considered for the raw scenario building. Variation A mostly represents baseline, current or optimistic cases. Variations B or C provide slightly more pessimistic, non-nominal, or disruptive outlooks.

Table 7-1 Variations of key factors, ranging from baseline or optimistic outlooks (Variation A) to more pessimistic or disruptive case (Variations B and C)

Category	Factor/driver	Variation A	Variation B	Variation C
Policies	**CO_2 taxes**	Current ETS and CORSIA measures	ETS, CORSIA, and fossil fuel taxes such as €10.75/GJ[37]	
Policies	**SAF quotas**	Current RefuelEU targets	5% more strict targets	
H_2 Availability & Energy	**Availability of different H_2 sources**	Exclusive reliance on green hydrogen	Initial dependence on grey/blue hydrogen as well with progressive integration of green hydrogen	
H_2 Availability & Energy	**SAF price & availability**	Nearly unlimited availability and affordable (High competition with H_2)	Limited availability and high price in 2035	No SAF availability in 2035, limited in 2050
H_2 Availability & Energy	**Renewable electricity growth & price**	Highly developed renewable grids with high (peak) availability and low cost (>90% and 65% renewable on average for 2050 and 2030). Able and cost-efficient to power	Moderate growth with regional variations and temporal fluctuations results in higher electricity prices and lower plant utilization (>70% and 50%	Limited growth and availability of renewable energy, highly depending on region (>60% and 40% renewable on average for 2050 and 2030)

[37] URL Other carbon pricing initiatives | EASA Eco accessed on 28/11/2024

Category	Factor/driver	Variation A	Variation B	Variation C
		large electrolysers and liquefaction	renewable on average for 2050 and 2030)	
H_2 Availability & Energy	**H_2 transport**	Starting in 2030 with large hydrogen networks connecting major production sites to consumption hubs and resulting in large scale cross-border hydrogen trade in 2050	Initiatives face initial delays and limited investments, resulting in high uncertainties regarding transport methods and operating costs. Limited deployment of H_2 transportation infrastructure results in smaller regional networks	
H_2 Availability & Energy	**LH_2 electrolysis, liquefaction, & storage**	Investments and technological advancements drive rapid deployment of large-scale electrolysers as well as storage capacities across various regions (up to 20 GW in 2030)	Moderate growth in electrolyser capacity with high regional variations, lack of sufficient storage capacities and very limited advances in liquefaction technology and deployment	Electrolyser capacity reaches around 5 GW, with slow progress in investments and technological advancements. Deployment is limited to pilot projects and small-scale facilities
H_2 Availability & Energy	**Electric grid**	Well-developed grids for highly efficient electrolyser and liquefaction plant operation	Limited grid capacity results high regional differences in electrolyser and liquefaction efficiency, capacities and hydrogen costs	
Airport Infra.	**Choice of refuelling setup**	Cryogenic pipelines to aircraft stand (hydrant system)	Hydrogen storage tanks and dispensing units	Mobile refuelling stations bring fuel to airport and to aircraft
Airport Infra.	**Readiness per archetype**	• 2035: local, regional, some large hub airports ready • 2050: local, regional and large hubs are ready. Optional:	• 2035: only local and regional airports ready • 2050: only local and regional airports ready	• 2035: no airports are ready • 2050: only local and regional airports ready

Category	Factor/driver	Variation A	Variation B	Variation C
		• hubs serve smaller airports and other users (e.g., road transport		
Airport Infra.	**Space for H_2 production & storage**	Sufficient space for storage and production	Limited storage space (<3 days)	No physical space
Airport Infra.	**Space for H_2 Ground Operations**	Sufficient space, no space constraints	Space constraints impact duration of TAT process	No space available
Aircraft Tech.	**EIS, range & propulsion**	• GA before and around 2030 • Regional turboprops and medium-range turbofans around 2035	• GA: 2030-2035 • Regional turboprop 2040 • Medium-range turbofans 2040-2045	
Aircraft Tech.	**OPEX: efficiency & MRO**	No energy or maintenance penalties	• 2035: energy +10%, maintenance +12% • 2050: penalties 0 to 5%	• 2035: energy +10%, maintenance +30% • 2050: energy +10%, maintenance +12%
Economic Growth & Disrupting Factors	**Economics**	Steady economic growth as expected for the decades to come. Approximately 2% GDP growth and demand for air travel growth. No economic crises, the economic development is as projected	Economic crisis (possibly as result of financial crisis, war, or pandemic) lowers air travel demand, H_2 investments. This crisis occurs after midterm point, when initial investments for the infrastructure have been laid out	
Disrupting Factors	**Safety**	No major safety issues or concerns	Major incident leads to low social acceptance of H_2 flights, long aircraft certification procedures, slow H_2 refuelling processes, and/or need for special infrastructure	

Considering all of the main factors and the three main dimensions, no so-called “worst-case” scenario is defined. Such scenario would assume limited development takes places in hydrogen availability and supply, airport readiness, and aircraft technologies. Also, one could say that in such a case the overall economic growth is low, with limited travel demand, and big safety concerns for hydrogen aviation exist. In such case, the outcome will likely mean demand for hydrogen is low, supply is low and/or expensive, and limited hydrogen ground movements take place at airports. Since the outcome would be rather clear (low uncertainty) and since such scenario would yield limited insights in decision making, it is decided to exclude a worst-case scenario.

To visually summarize the scenarios, we will make use of a radar chart to show varying levels of development along the three main dimensions identified above. Figure 7-1 shows an empty chart indicating the different levels of development along each axis. In Figure 7-2, two conceptual scenario definitions are drawn with explanations. Scenarios are represented by triangles in this radar chart. Equilateral triangles indicate a scenario where there is an approximately equal level of development along the three main axis. Non-equilateral triangles indicate that there is a mismatch. If one of the three is smaller, disrupting factors are active. In this case a block is filled and accompanied by an icon, as shown at the bottom of the example in Figure 7-2**.**

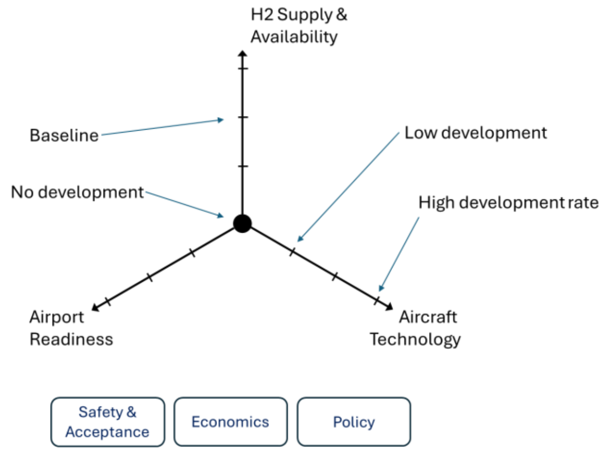

Figure 7-1 Empty radar chart showing the levels of development along each of the three m

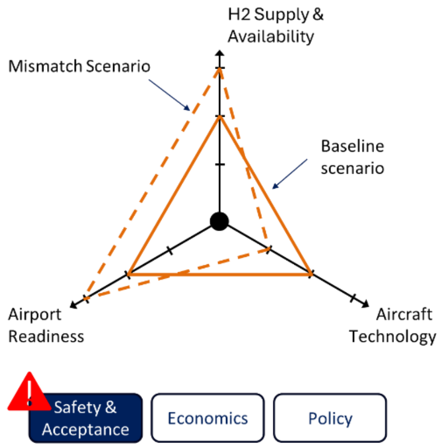

Figure 7-2 Example scenarios visually summarized in a radar plot

8 Initial Scenario Development

Starting from the three main factor categories, eight initial or "raw" scenarios are presented in this chapter. The initial scenario represents a baseline case, followed by mismatches between these three axes. Subsequently, we consider a very optimistic scenario representing extreme alignment between availability, airport readiness, and aircraft technology. Finally, three scenarios are proposed which introduce unusual events related to economics, safety, and policies. The following sections describe these scenarios at a conceptual level. After validation and selection, refined scenarios are formulated in Chapter 10.

8.1 Scenario 1 – Smooth Skies (Baseline)

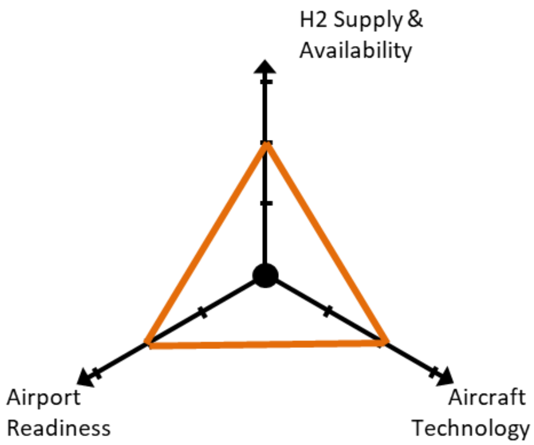

Figure 8-1 Raw scenario 1 - Smooth skies (baseline)

Figure 8-1 visually presents the baseline scenario along each dimension. In this scenario, current plans develop as expected (often called "mid" scenarios in literature), and investments do occur. By 2035, many regional and local airports and some large hubs have completed the necessary upgrades to accommodate hydrogen-powered aircraft. Over the span of 25 years, no economic crises or major safety issues happen.

8.2 Scenario 2 – Tough Competition

In this scenario, tough competition occurs between hydrogen and drop-in sustainable aviation fuels. Drop-in SAF is cheaply and highly available throughout Europe. This is the result of high availability of renewable energy sources and a push towards carbon capture. Although also hydrogen is needed in the production process, the infrastructure required for hydrogen transport and storage at airports does reach the needed investment levels.

Airlines prefer this drop-in fuel option also for regional and SMR aircraft, and further investments in H_2 supply and infrastructure therefore lack (as shown in Figure 8-2). The supply of hydrogen, mostly for general aviation aircraft and perhaps larger demonstrators, occurs mostly by mobile refuellers. OEMs, although initially committed to the development of H_2 aircraft, also put more focus on developing and/or producing more aircraft which can be powered by 100% drop-in SAF.

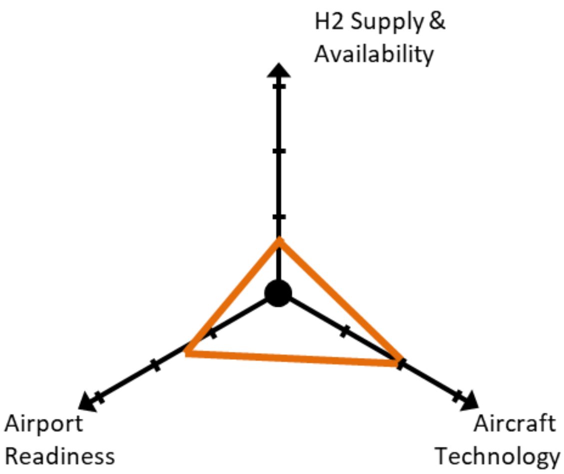

Figure 8-2 Raw scenario 2 - Tough competition

8.3 Scenario 3 – Aircraft Delayed

Hydrogen-powered aircraft face slower than expected technological developments and operational setbacks. This creates a misalignment with the readiness of hydrogen infrastructure and presence of hydrogen supply chains at airports. Figure 8-3 illustrates the radar chart of the “Aircraft Delayed” scenario. While some general aviation and small regional hydrogen-powered aircraft enter service by 2035, their limited seating capacity and range restrict their impact. Regional turboprops do not become available until 2040 and hydrogen-powered turbofan aircraft for large commercial operations are delayed until 2050. These delays are caused by technical challenges including difficulties with the hydrogen tank integration, certification hurdles and safety concerns.

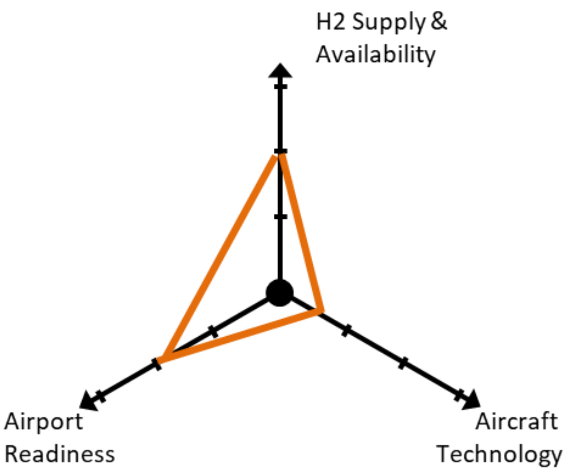

Figure 8-3 Raw Scenario 3 - Aircraft delayed

The slow rollout of hydrogen aircraft is also impacted by their high operational costs and lower efficiency compared to conventional aircraft. Hydrogen aircraft have higher in-flight energy consumption. This consumption is largely dependent on tank design and powertrain configuration. For hydrogen aircraft it introduces significant uncertainty in performance. MRO costs are also much higher for hydrogen-powered aircraft. These aircraft incorporate new and complex systems, including fuel cells and advanced fuel tanks, increasing maintenance requirements and resulting in longer downtimes.

Manufacturers and airlines further delay hydrogen adoption by prioritizing alternative sustainable aviation fuels, such as biofuels and synthetic kerosene. These drop-in fuels require fewer modifications to existing aircraft and infrastructure. In other words, they offer lower development and operational costs while still reducing CO_2 emissions. As a result, alternative fuel technologies begin to capture a significant portion of the market originally envisioned for hydrogen-powered aviation.

Meanwhile, airports across Europe have prepared for hydrogen adoption by exploring supply chain options and scalable infrastructure. However, without a substantial rollout of hydrogen-powered aircraft, larger investments in storage, production, and distribution facilities are set at hold from 2035.

8.4 Scenario 4 – Grounded Potential

By 2050, hydrogen-powered aircraft are technologically mature, but their widespread deployment is hindered by the lack of infrastructure at most airports in Europe. Figure 8-4 shows the radar chart associated with the "Grounded Potential" scenario. Only a select network of regional and local airports is equipped to handle the requirements needed for handling hydrogen aircraft. These smaller airports, often located near hydrogen production sites, benefit from the cost-effective trucking methods for hydrogen delivery over these short distances. With relatively moderate demand and sufficient space for compact hydrogen storage facilities, they have become the primary nodes in a limited network of airports supporting hydrogen-powered operations.

Figure 8-4 Raw Scenario 4 - Grounded potential

In contrast, major airports struggle to adapt to the needs of hydrogen-powered aviation. Space limitations are a primary challenge. Many large hub airports cannot expand their physical infrastructure to accommodate hydrogen storage and production facilities, and the same time meet the safety requirements. The ground operations at these airports add another layer of difficulty. Refuelling a hydrogen-powered aircraft requires significantly more volume than conventional jet fuel. The result is the need for additional refuelling trucks, large safety zones, and additional coordination on already congested aprons. Furthermore, the larger physical dimensions of the developed hydrogen-powered aircraft are incompatible with existing stand layouts. Hydrogen-powered aircraft cannot be introduced at the airports without negatively affecting the overall airport capacity.

To overcome the infrastructure gap, airlines have decided to opt for hydrogen tankering as a solution. By carrying extra hydrogen, aircraft can avoid refuelling at destinations without hydrogen capabilities. An important requirement is that the destination is located within half of the operational range of the aircraft. While this strategy enables airlines to expand their networks without requiring expensive comprehensive infrastructure at every airport, it comes with trade-off of increased fuel-burn and added operational complexity. In the event of diversions mobile hydrogen refuellers are used to refuel the aircraft.

The slow pace of the development of hydrogen infrastructure is also the result of misalignment among stakeholders. Airports delay investing in facilities and equipment for hydrogen since they are unsure if airlines will use them. On the other side, airlines are hesitant to invest in hydrogen-powered aircraft due to the lack of infrastructure. The cat-and-mouse game creates a standstill. In addition, the absence of standardized requirements among aircraft manufacturers, airports, ground service providers, and air traffic controllers further delays the transition.

8.5 Scenario 5 – Full H_2 Throttle

The optimistic scenario, "Full H_2 Throttle", is depicted in the radar chart in Figure 8-5.

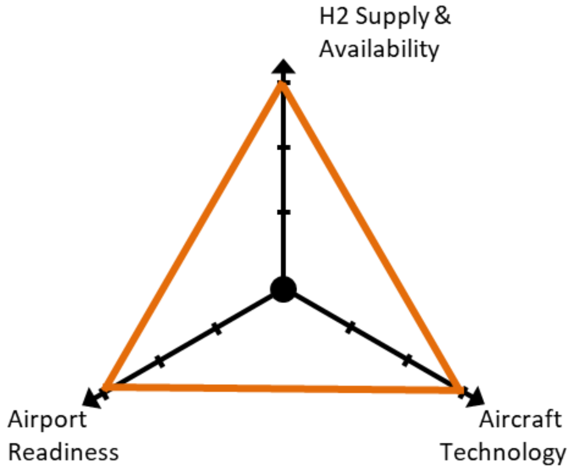

Figure 8-5 Raw scenario 5 - Full H_2 Throttle

Hydrogen-powered aviation has become a cornerstone of sustainable air travel. This is fueled by a convergence of technological advancement in hydrogen aircraft, robust hydrogen supply chain, and airport readiness. Across Europe, large hub airports now function as hydrogen hubs, equipped with facilities for hydrogen production, liquefaction, storage, and distribution. These hubs supply hydrogen not only to aviation but also to ground transportation and nearby industries. Innovations in infrastructure design and limited safety zone restrictions have minimized the space required for hydrogen operations. This allows for the integration without major disruptions to airport layouts. The distribution of hydrogen is carried out via pipeline systems. In addition to hub airports, most regional hydrogen airports have access to hydrogen from either larger airports hubs or nearby hydrogen production sites. For the transportation to these airports, mobilie fuel trucks are used. These trucks are owned by private operators.

The widespread availability of hydrogen is supported by significant public and private investments. Economic stability and strong GDP growth have enabled funding for green hydrogen production. This is driven by cheap and a large supply of renewable energy. The result is that liquid hydrogen is cost-competitive with alternative fuels. Government policies, such as CO_2 taxes and environmental targets, further promote hydrogen uptake. While sustainable aviation fuels remain relevant for long-haul routes due to their compatibility with existing aircraft, the lower cost and suitability of hydrogen aircraft for regional and medium-range flights make it the preferred option in these markets.

Aircraft technology has advanced rapidly to meet this demand. Regional hydrogen-powered turboprop aircraft entered service in 2035. By 2040, medium-range hydrogen turbofan aircraft became operational with higher capacity for passengers. These aircraft have performance comparable to kerosene-powered aircraft. In other words, the improved operating costs, efficiency, and reliability encourage the widespread adoption by airlines. MRO facilities have been upgraded at most airports to accommodate these new aircraft.

8.6 Scenario 6 – Economic Stall Warning

Economic instability disrupts the development and adoption of hydrogen-powered aviation. Financial and policy priorities shift in response to a global economic crisis. Figure 8-6 illustrates the radar chart for the "Economic Stall Warning" scenario. Many initial investments in hydrogen infrastructure and technology are stalled or scaled back as airlines, airports, and governments redirect resources toward immediate economic recovery. The decline in air travel demand leads airlines to prioritize cost-saving measures. These measures favor conventional kerosene and sustainable aviation fuels since they are more flexible and cheaper than hydrogen.

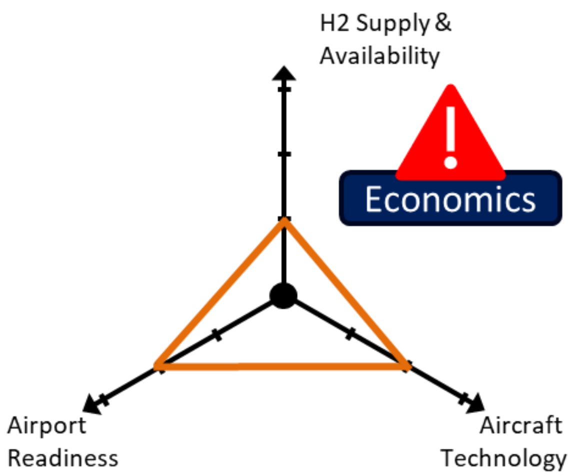

Figure 8-6 Raw Scenario 6 - Economic stall warning

With fewer funds available for research and infrastructure, the hydrogen supply chain is sparse. Only a limited number of major hub airports operate with hydrogen production, storage, and distribution facilities. Most airports rely on cost-effective trucking solutions for limited hydrogen delivery. The reduced scale of hydrogen adoption and weaker environmental policy incentives, such as diminished CO_2 taxes and local pollution mandates, further inflate the price of hydrogen. The result is that hydrogen is less competitive against SAF and kerosene.

The reduction in investments in hydrogen technologies also significantly affects the development of new hydrogen aircraft beyond 2035. Consequently, the next generation of hydrogen-powered aircraft lacks the range needed to effectively serve regional, short, and medium-range markets. Additionally, their operating costs and efficiency remain less competitive compared to kerosene-powered alternatives. The insufficient properties of hydrogen aircraft, together with survival strategies of airlines, which prioritize extending the lifespan of existing fleets and relying on lower-cost SAF and conventional kerosene and the limited availability of hydrogen at airports restricts its adoption.

8.7 Scenario 7 – Safety Checklist Failed

Upon introduction of hydrogen aircraft into the market around 2035, minor and major incidents occur with hydrogen refuelling at airports. Additionally, issues at aircraft level lead to grounding of aircraft, awaiting long investigations, redesign steps, and certification. Overall, it can be concluded that the technologies available in 2035, which were supposed to initiate the uptake of hydrogen in aviation, are not mature enough. Either the ground-based technology or the aircraft technology lead to safety issues and are underdeveloped, as shown in Figure 8-7.

The incidents involved casualties and high claims, and the news that hydrogen aircraft are unsafe spreads widely over social media. Passengers are unwilling to travel with hydrogen aircraft or airlines which initiated operations with this new technology. Also, people in the vicinity of airports are wary about the storage and handling of hydrogen close to their homes. Overall, the social acceptance of hydrogen powered aviation is very low. The public's trust in this technology must be regained over the years and additional regulations are put in place.

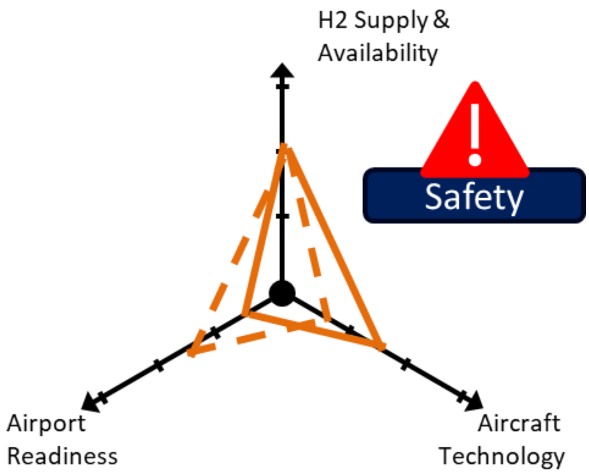

Figure 8-7 Raw Scenario 7 - Safety checklist failed

Airports, no matter the archetype, stop further investments in the onsite production and storage. Construction projects which were initiated by 2035 are halted. Only by 2040 or 2045, new investments pick up and infrastructure development can continue. This means that the main refuelling setup for the hydrogen aircraft that do fly will happen through mobile refuellers in a limited number of airports. Also, to avoid incidents, refuelling has to take place at a remote location at the airport, away from terminal buildings, without passengers on board. This slows down the turnaround process and reduces the operational efficiency.

From an aircraft technology perspective, general aviation H_2 aircraft may be ready by 2035, which can be refuelled by the designated mobile refuellers with a tank capacity able to supply several general aviation aircraft. Large-scale applications, such as regional H_2 turboprop aircraft are only fully operational by 2040-2045 after the investigations and certification have been completed. These steps delayed the development of H_2 turbofan aircraft with a longer range, of which none to only few are available in 2050.

8.8 Scenario 8 – Policy Glidepath

In the EU there is an extreme push towards reaching the GHG reduction goals. Region-wide policies and directives are made stricter. For aviation this means that the ETS and CORSIA are heavily enforced and that, in addition, fuel taxes (or carbon pricing) are added and/or SAF quotas in RefuelEU are raised. On top of increasing kerosene prices by 2035, a tax of €10.75/Gigajoule is imposed. There is also a push for infrastructure development for sustainable fuels and energy.

As a result, airlines feel the urgent need for eligible SAF and hydrogen aircraft to reduce their operational cost and remain profitable over the course of multiple decades (2050, long term). Especially for regional and short-range operations hydrogen-powered aircraft are needed, leaving room for drop-in SAF for long haul connections. Therefore, also airports, fuel providers, and OEMs feel the pressure to quickly scale up and make investments to ensure operations of hydrogen-powered aircraft can be brought up to speed as quickly as possible. Airports invest in on-site LH_2 storage and refuelling facilities. OEMs try to bring the aircraft to market as soon as possible, possibly with small penalties in efficiency and maintenance.

However, not only aviation is affected by these strict policies, and the overall energy market has to move quickly. As a result, the hydrogen supply for aviation purposes may be slightly hampered, as indicated in Figure 8-8, due to competition with other sectors who have to transition quickly.

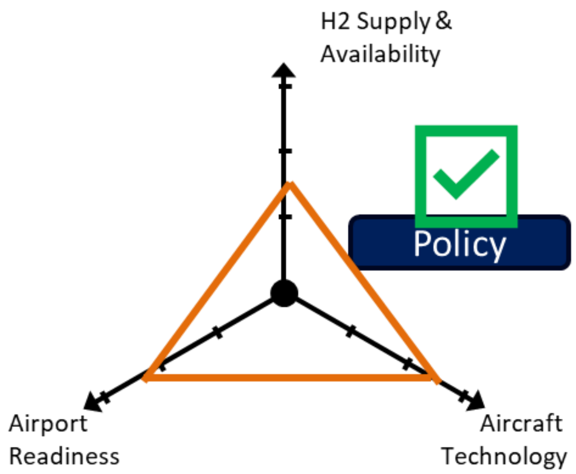

Figure 8-8 Raw Scenario 8 - Policy glidepath

9 Scenario Validation and Selection

This section assesses the validation criteria discussed in Section 4.6 for each of the raw scenarios presented in Chapter 8. The assessment is completed through an online workshop involving GOLIAT partners, experts from aviation, infrastructure, consultancies, research institutes, and energy supply stakeholders. In this section, we present the feedback from this workshop on the scenarios in a quantitative manner and summarize the discussions in an anonymous fashion.

First, the scenarios are checked for plausibility and consistency. Figure 9-1 and Figure 9-2 show the relative votes for these two criteria for each of the eight scenarios. The exact number of votes are presented in Table 14-1 and Table 14-2 in Annex 2 (Chapter 14). Each scenario received between 16 and 20 votes for each criterion. Overall, consistency with the scenario is rather high (including comments), except for Scenarios 2 (Tough competition) and 5 (Full Throttle). In Scenario 2, experts identify the flaw that if SAF is highly and cheaply available, also hydrogen should be (cheaply) available to make the e-SAF or synthetic kerosene. Although one may make a distinction between availability of hydrogen for e-SAF production and availability at airports, this competing availability seems contradictory to experts.

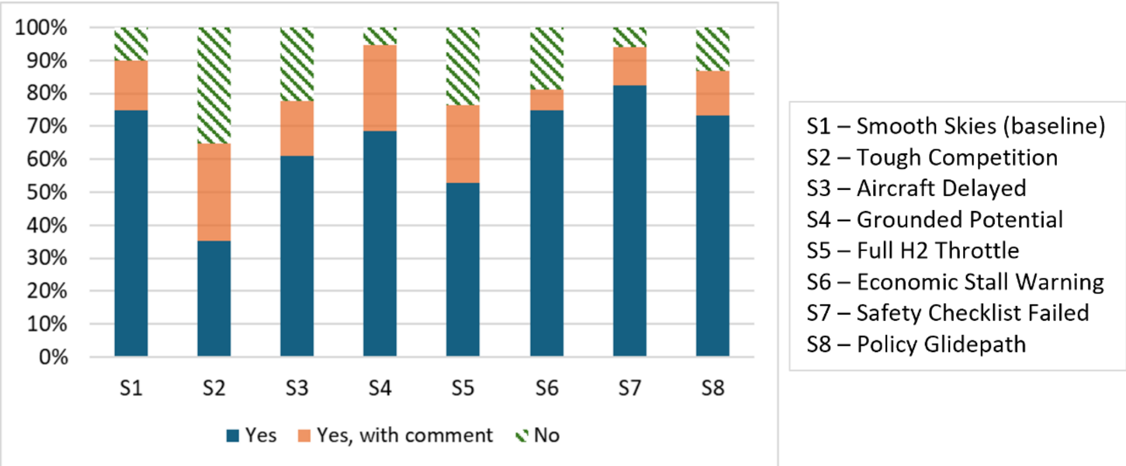

Figure 9-1 Poll results considering the consistency of the eight raw scenarios

Considering the results for plausibility in Figure 9-2, in particular Scenario 5 (Full Throttle) scores low because of its extreme optimistic outlook. Experts judge this scenario to be implausible because of several arguments:

- This would require extremely high investments
- Such scenario would require a very strong push from policy stakeholders
- These high investments and the regulatory push cannot be observed today

Also, it is commented that the baseline in Scenario 1 already can be seen as quite an optimistic outlook. Alternatively, participants suggested to investigate which prerequisites, in terms of investments, infrastructure, and other developments, are needed to make Scenario 5 happen. Since this opposes the current philosophy of scenario design, this exercise is left as a recommendation.

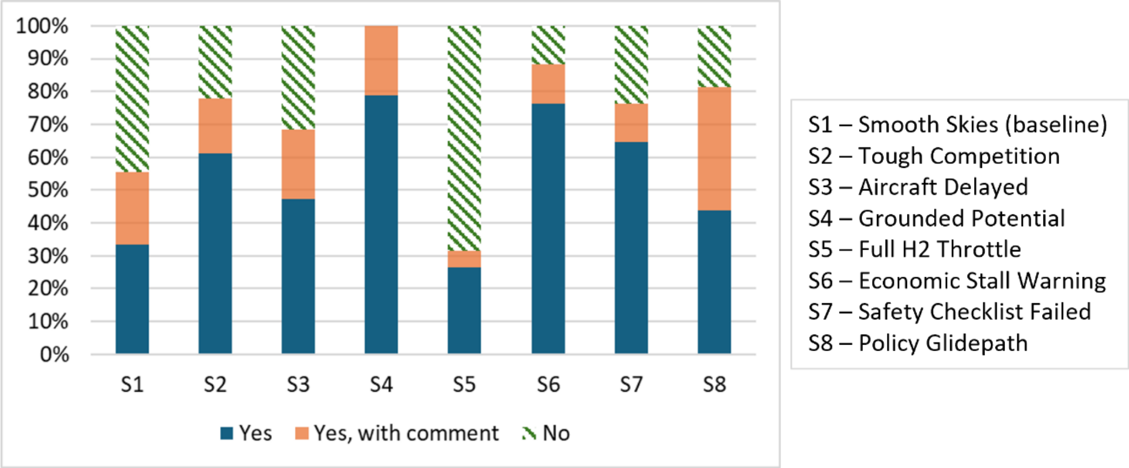

Figure 9-2 Poll results considering the plausibility of the eight raw scenarios

Two other criteria for scenario validation are the relevance and the novelty. Section 4.6 provides definitions for these two terms. During the second workshop, the experts were asked to rank each scenario in terms of these criteria. For each criterion, five levels are provided. For relevance, the five levels are "irrelevant", "low relevance", "relevant", "very relevant", and "essential". For novel the levels are "exhaustively assessed", "frequently assessed", "somewhat novel", "rarely assessed", and "completely new". Table 14-3 and Table 14-4 in Annex 2 provide the votes per scenario and per level for these criteria.

In the postprocessing step, each of these five levels are given a score between one and five, allowing to calculate the weighted average scores for each scenario for relevance and novelty. Figure 9-3 shows the result of this weighting where each dot corresponds to one of the eight scenarios. From this figure, it is clear that scenarios 3, 4, 6, and 7 are thought to be the most relevant and novel. As a result, these four scenarios will be included in the selection of main scenarios to assess.

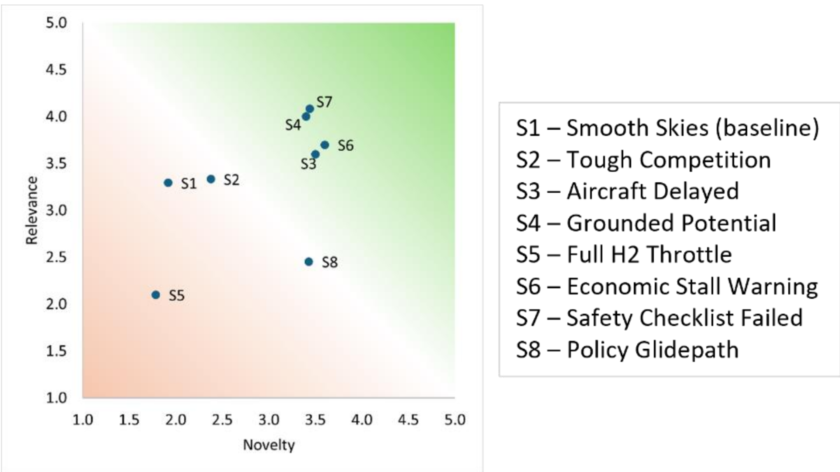

Figure 9-3 Ranking of the eight raw scenarios in terms of novelty (1=exhaustively assessed, 5=completely new) and relevance (1=irrelevant, 5=essential)

Scenario 1 (baseline) scores relatively low on the novelty criterion. This can be expected, since we intend to let scenarios match with existing scenarios in literature. Nevertheless, this baseline scenario can help with validating the models to be developed in later tasks and to make relative comparisons with the other main scenarios which have a high score in terms of relevance and novelty. Therefore, the baseline scenario is also included in the final, main scenarios.

The discussion above already discussed the inconsistency in Scenario 2 (Tough competition). Experts add to that this scenario might be plausible, but unlikely to continue beyond 2035 if the market saturation of H_2 is expected to increase. H_2 supply will also benefit from high availability and low cost of renewable energy. One participant notes that the principle of strong competition between H_2 and SAF might be valid, but it is unlikely to be caused by low cost and high availability of SAF. Also, it is unlikely that the airport infrastructure for H_2 will be ready if SAF is a lot more competitive than H_2. Considering the low score on novelty, it is concluded to leave out this scenario or rewrite it such that the competitiveness has another cause.

Scenario 3 (Aircraft Delayed) receives a low score in terms of plausibility with experts commenting that they deem it unlikely that airports are ready to provide hydrogen when no hydrogen aircraft are operational. Experts consider that the investments and programmes from OEMs will drive the investment for supply and airport refuelling infrastructure. It is argued that if the OEM programme is stopped or delayed, this will also be the case for investments in airport infrastructure. Yet, this scenario scores relatively high in terms of relevance and novelty, as can be seen in Figure 9-3. Other experts note that the scenario is relevant since airports prepare with retrofits or demonstrators, and that barriers of certification may be a driving force in the occurrence of this scenario. It is decided to include Scenario 3 in the main scenarios, but to refine it based on the comments.

Scenario 4 (Grounded Potential) has a high acceptance in terms of plausibility and consistency, and is also ranked high in terms of novelty and relevance. Experts recognize that the airport readiness may differ largely between airport types but especially between locations (in the EU). Airports also have varying levels of restrictions and (regional) airports focusing on operations of low-cost carriers may postpone investments. Based on the high scores, this scenario will be one of the main scenarios.

Scenario 5 (Full H_2 Throttle), which present a very optimistic view of the developments, has the lowest score. This is in line with the responses from the experts indicating it is implausible (14 no vs 4 yes, 1 yes with comment). As pointed out by experts, such a scenario would require a strong push from policy stakeholders, regulators, and investors.

Experts note that Scenario 6 (Economic Stall Warning) could be a realistic outlook given the geopolitical developments worldwide at the time of writing (e.g., war between Russia and Ukraine, war in the Middle East, election outcomes, etc.). The pandemic in 2020 has had a major impact on air travel and economy, and a similar event would make such scenario relevant. Also, a financial and/or economic crisis can hit every dimension currently considered. Since the scope of the scenario is Europe, also the relative economic or policy position of Europe compared to other regions can perhaps be considered.

Comments on Scenario 7 (Safety Checklist Failed) reveal that this is a plausible scenario, although the actual safety issue can vary (airport refuelling, aircraft technology, a combination of both, transport towards airport, etc.). An incident with a hydrogen aircraft can indeed influence the public's choice to travel with these aircraft, although one expert also notes that there might be cultural factors. Alternatively, a long certification process following a short-term issue can lead to this scenario, possibly in combination with unknowns or missing elements in the certification process that first must be resolved.

Considering Scenario 8 (Policy Glidepath), comments are made that similar outlooks (may) exist for SAF and that opposite policies can also occur. Additionally, there is an opportunity that extreme policy can derisk hydrogen production. The relatively low relevance score however shows that this scenario does not greatly help with decision making, since it is obvious that stricter policies can help the hydrogen uptake, but at the same time the policy throughout the years may go in the opposite direction.

10 Refined Scenarios

Considering the validation and selection steps in Chapter 9, this chapter presents the five main scenarios which will be considered in the operational and techno-economic analyses later in the GOLIAT project. Table 10.1 provides a summary of the final scenarios with the driving force category causing a disruption highlighted in red. The following five sections provide more refined versions of scenarios 1, 3, 4, 6, and 7 from Chapter 8. In Section 10.6, additional options are provided to extend these scenarios based on concepts discussed in the scope definition in Chapter 5.

Table 10-1 Summary of Final Scenario Definitions

Scenario Name	Hydrogen Availability and Market	Airport Readiness	Aircraft Technology Development	Economics	Safety
A – Baseline	Steady growth in hydrogen infrastructure and availability. Coordinated efforts ensure production, storage, and distribution readiness	Regional airports and hubs develop scalable hydrogen infrastructure with modular storage and refuelling systems, ensuring efficient operations and timely adoption of hydrogen-powered aviation	First regional aircraft ready by 2030. Large-scale commercial operations of hydrogen aircraft possible by 2035	Steady economic and demand for air travel growth of approximately 2%	No major safety issues
B – Aircraft Delayed	Initial growth in hydrogen availability, but scaling back of investments in LH_2-specific infrastructure	Ramp up of airport infrastructure halted due to lack of demand	Hydrogen aircraft delayed due to certification and technical challenges. Turboprops operational by 2040, turbofans by 2050	Steady economic and demand for air travel growth of approximately 2%	Minor safety issues
C – Grounded Potential	Fragmented hydrogen network, where only a selected airports have access to affordable	Space and operational challenges prevent large hub airports from supporting hydrogen	Technologically mature aircraft by 2040, but rollout restricted to airports with infrastructure.	Steady economic and demand for air travel growth of approximately 2%	No major safety issues

Scenario Name	Hydrogen Availability and Market	Airport Readiness	Aircraft Technology Development	Economics	Safety
	hydrogen depending on location	operations. Smaller airports adapt			
D – Economic Stall	Hydrogen infrastructure investments are stalled and prices high. The scale of hydrogen production and distribution is significantly reduced, resulting in a sparse supply network	Few major hubs operate hydrogen infrastructure. Trucking is used for delivery, but limited infrastructure hinders rollout	Limited aircraft development beyond 2035 due to reduced investments. New models lack competitiveness with SAF or kerosene	Economic crisis lowers air travel demand, H_2 investments, and government incentives	No major safety issues
E – Safety Checklist Failed	Hydrogen generally available but further investments in hydrogen infrastructure for aviation paused	Refuelling takes place at remote locations for safety. Slow turnaround times affect operational efficiency at airports	General aviation aircraft operational by 2035. Turboprops ready by 2040-2045. Turbofan development severely delayed	Steady economic and demand for air travel growth of approximately 2%	Major safety incidents result in low social acceptance of H_2 flights

10.1 Scenario A – Smooth Skies (Baseline)

Current, 2024, plans for hydrogen infrastructure and aircraft technology development move forward as expected, supported by a coalition of stakeholders that includes regional airports, large-scale OEMs, new aircraft manufacturers, hydrogen and energy suppliers. These groups remain dedicated to achieving the milestones planned. The global economy continues to grow steadily, with GDP increasing by approximately 2% annually. This steady growth supports a parallel rise in air travel demand, with no major economic crises disrupting progress. The public generally accepts the transition to hydrogen-powered aviation, with safety concerns remaining minor and manageable. However, the industry faces challenges, including longer aircraft certification procedures, slow hydrogen refuelling processes, and the need for specialized infrastructure.

Despite these hurdles, active research and development aim to enable the first large-scale commercial operations of hydrogen-powered passenger aircraft by 2035. This progress is further supported by current RefuelEU regulations, which mandate airports and fuel providers to develop infrastructure for hydrogen and other alternative fuels. Additionally, current ETS and CORSIA measures impose CO_2 emission reductions through carbon pricing and offsetting requirements.

10.1.1 Hydrogen Availability and Supply

The availability of hydrogen initially relies on grey and blue hydrogen sources. These act as a bridge while the transition to completely green hydrogen production progresses, which is the objective to achieve sustainable aviation. Growth in renewable electricity, which is essential for green hydrogen, is moderate but uneven. Some regions see faster development than others, and fluctuations in energy prices drive up costs and reduce the efficiency of hydrogen plants. By 2030, about half of the electricity in the EU comes from renewable sources, increasing to 70% by 2050, aligning with broader goals for a decarbonized economy and the steady expansion of sustainable aviation. It is important to note that the initial reliance on grey hydrogen limits the adoption of hydrogen-powered aircraft, as airlines and OEMs exclude grey hydrogen due to its high carbon intensity.

Building hydrogen transportation infrastructure initially faces delays and limited investment. This causes uncertainties in logistics, transport methods, and eventually costs. Large hydrogen networks begin to appear by 2030, starting regional without cross-border trade. Larger network scales are achieved by 2050. Electrolysis and liquefaction technologies grow moderately, but progress is slowed by challenges such as insufficient storage and slow development of liquefaction technology.

By 2050, significant investments in electricity grids result in efficient hydrogen production and liquefaction in some regions. However, earlier grid limitations create inefficiencies that lead to regional differences in costs. Some areas struggle to build the storage and infrastructure needed to keep up with demand.

10.1.2 Airport Readiness

By 2035, many regional and local airports have completed the necessary upgrades to accommodate hydrogen-powered aircraft. However, the progress remains uneven. These airports focus on general aviation and the first generation of hydrogen-powered regional passenger aircraft. Hydrogen fuel supply operations are often coordinated through shared business models or pooled ownership to reduce costs and logistical complexity. These airports maintain storage capacity sufficient for three days of operations but are unable to power all flights with hydrogen at this stage. Next, to the regional and local airports, hydrogen operations occur at a limited set of large hubs from 2035 using tankering. It allows to concentrate the H2 demand and to lower the number of airports to be equipped with hydrogen infrastructure.

Looking ahead to 2050, larger hub airports begin integrating hydrogen infrastructure, supported by increased investment and technological maturity. Some of these airports have on-site production and liquefaction of hydrogen, using renewable energy sources. By this time, hydrogen-powered aircraft serve a broader network of airports, combining both regional and larger hub facilities. Earlier technological and investment barriers are overcome.

10.1.3 Aircraft Technology

The first hydrogen-powered flight tests occur before 2030, creating the possibility for general aviation and small business aircraft to enter the market as expected by current outlooks (AZEA, 2024). These flight tests and smaller aircraft also mature the technology quickly enough for the introduction of regional turboprops or fuel cell-powered aircraft by 2035. In addition, hydrogen-powered turbofan aircraft enter the market in the period between 2035 to 2040, mainly focused on the medium-range segment.

However, it is important to note that this first-generation aircraft suffer from in-flight energy penalties and higher maintenance costs. The increased maintenance times can also lead to lower annual utilisation of the aircraft. The energy penalties for these commercial transport aircraft are up to 10%

and maintenance costs are approximately 12% higher than current aircraft powered by fossil kerosene. By 2050, these aircraft designs may have further improved in terms of technology and MRO capabilities. The penalties are lower to the interval of 0 to 5%.

10.2 Scenario B – Aircraft Delayed

Hydrogen-powered aircraft experience delays in technological advancements and face operational setbacks. This creates a misalignment with the readiness of hydrogen infrastructure at airports and the availability and supply chains at airport. Compared to the baseline scenario the economic situation does not vary. Regarding safety, however, issues occur in the development of hydrogen-powered aircraft in terms of certification issues and testing.

10.2.1 Hydrogen Availability and Supply

Hydrogen availability continues to grow steadily, but investments in LH_2-specific infrastructure slow down due to delays in the development and certification of hydrogen aircraft. Grey and blue hydrogen remain the primary sources in the short term, while green hydrogen gradually increases but at a slower pace. By 2030, renewable energy accounts for about 50% of global electricity production, with the share reaching 65% by 2050. However, the slow adoption of hydrogen-powered aviation limits the urgency for building the necessary infrastructure. The result is that hydrogen transportation infrastructure remains underdeveloped, especially for cross-border transport.

The delays and reduced investments result in fragmented regional systems for hydrogen supply rather than a comprehensive network. Electrolysis and liquefaction capabilities develop at a moderate pace. Storage and transport systems face regional inefficiencies, limiting hydrogen availability in certain areas. In addition, the lack of investments in the energy grid slows the development of hydrogen production facilities resulting in regional cost differences.

10.2.2 Airport Readiness

By 2035, only a small number of local and regional airports are equipped to handle hydrogen-powered aircraft. These facilities rely on basic hydrogen infrastructure such as mobile refuelling trucks and compact hydrogen storage tanks resulting in limited hydrogen operations. Investments in larger-scale storage, production, and distribution facilities remain on hold due to the slow rollout of hydrogen aircraft.

By 2050, the hydrogen infrastructure expands also to include local, regional, and some large hub airports. However, significant gaps between airports remain. Airports have yet to incorporate on-site hydrogen production or liquefaction facilities. The benefit of this is that it avoids imposing significant additional space constraints on airport layouts. The limited number of hydrogen-powered aircraft in operation also reduces the overall impact on airport operations. Only minor adjustments are necessary, such as allocating extra space for ground operations during the turnaround process. These sparse hydrogen flights are typically managed at remote areas of the airport, ensuring minimal disruption to existing activities.

10.2.3 Aircraft Technology

The development of hydrogen-powered aircraft progresses slower than anticipated. Challenges in the design, testing, and certification of lightweight hydrogen tanks and propulsion systems result in delayed entry into service. By 2040, a limited number of regional turboprop aircraft enter the market, but medium-range turbofan models do not become available until 2045 to 2050.

First-generation hydrogen aircraft face energy efficiency penalties of approximately 10%, while maintenance costs increase by around 30% compared to conventional aircraft during the period from 2035 to 2045. This increase in maintenance issues together with longer downtime resulting in reduced annual utilisation of hydrogen-powered aircraft. It is not until 2050 that advancements bring energy and maintenance efficiency in line with what was initially expected for 2035 in the baseline scenario.

Meanwhile, manufacturers and airlines also divert attention toward alternative sustainable fuels, such as biofuels and synthetic kerosene. These fuels offer immediate compatibility with existing aircraft and infrastructure reducing development costs and operational complexity. As these alternative fuels capture a larger share of the market originally intended for hydrogen, the overall uptake of hydrogen-powered aviation remains limited.

10.3 Scenario C – Grounded Potential

Hydrogen-powered aircraft are technologically mature, but their widespread deployment by airlines is hindered by the lack of infrastructure at most airports in Europe. The hydrogen infrastructure at airports develops unevenly resulting in limited opportunities for widespread hydrogen-powered aviation. The economic situation and the number of safety issues in terms of social acceptance and certification procedures does not vary compared to the baseline scenario.

10.3.1 Hydrogen Availability and Supply

Hydrogen availability becomes increasingly fragmented with some regions experiencing growth while others struggle to establish extensive hydrogen infrastructure. The grey and blue hydrogen are initially the primary source. The transition to green hydrogen proceeds at a slower pace due to limited investments. This is because renewable electricity development remains uneven due to regional variations and fluctuating energy prices driving up hydrogen costs and reducing plant utilization. It is important to note that the widespread deployment of hydrogen-powered aircraft by airlines is also hindered by the lack of green hydrogen availability. Grey hydrogen, with its high carbon intensity, conflicts with the sustainable purpose of hydrogen aviation. This creates a significant mismatch that undermines its environmental goals and discourages adoption by airlines.

Hydrogen transport infrastructure is concentrated in select regions or airports. Local investments in storage and distribution systems drive hydrogen availability in these regions. However, the lack of an extensive transportation infrastructure means that hydrogen availability remains limited in many areas. Regional networks struggle to connect with each other and the scaling of electrolysis and liquefaction capabilities faces delays due to funding shortages and technological challenges. The result is that some areas experience difficulty in accessing affordable hydrogen.

10.3.2 Airport Readiness

By 2035, only a limited number of regional airports are equipped to support hydrogen-powered aircraft. The early adaptors benefit from their proximity to hydrogen production sites and cost-efficient trucking methods for the delivery of hydrogen over these short distances. The delivery method is possible given the moderate hydrogen demand at these airports and the available space for compact hydrogen storage tanks. By 2050 most regional airports have the necessary hydrogen infrastructure in place. This is supported by the advancements in hydrogen supply chains and increased use of regional aircraft by airlines.

In contrast, during the same time horizon major hub airports face significant challenges to facilitate hydrogen-powered aviation. Space constraints limit their ability to expand infrastructure to accommodate hydrogen storage and production facilities. Safety requirements around refuelling zones add further constraints. These constraints are large safety zones, additional refuelling vehicles, and increased operational coordination. The additional constraints have an impact on already congested aprons and impact the efficiency of ground operations at the hubs. In addition, the larger dimensions of hydrogen-powered aircraft conflict with existing stand layouts. The required infrastructural changes reduce overall airport capacity and complicate the turnaround processes.

The slow pace of airport readiness is also the result of a lack of stakeholder alignment. Airports wait to invest in hydrogen facilities without guaranteed airline demand. These airlines are, however, also hesitant to invest in hydrogen-powered aircraft without the assurance of adequate hydrogen infrastructure at the airports. This cat-and-mouse game together with the lack of standardized guidelines among aircraft manufactures, airports, airlines, ground service providers and air traffic controllers delay the progress.

10.3.3 Aircraft Technology

Hydrogen-powered aircraft development proceeds as planned. General aviation models are introduced around 2030, and regional turboprops and medium-range turbofans enter service by 2035. These aircraft meet the performance needs of their intended markets with ranges and operating efficiencies comparable to those of kerosene-powered counterparts. Despite their technological readiness, it is important to consider that "To take off, hydrogen-powered aircraft first need places to land". Therefore, instead many airlines prioritize sustainable aviation fuels (SAF) in their strategies for fleet renewal and sustainability goals. This choice is made given SAF's compatibility with existing infrastructure.

To overcome the hydrogen infrastructure gap, airlines adopt hydrogen tankering as a temporary strategy. By carrying additional hydrogen onboard, aircraft can avoid refuelling at destinations lacking hydrogen capabilities. An important requirement for this is that these destinations are within half the aircraft's operational range. While this approach enables some network expansion, it results in increased fuel burn and adds operational complexity. It is important to note that in case of diversion scenarios, mobile hydrogen refuelling units are used at airports lacking hydrogen infrastructure.

10.4 Scenario D – Economic Stall Warning

Economic instability disrupts progress in hydrogen-powered aviation as stakeholders across the industry, airlines, airports, aircraft manufacturers, and policymakers, shift their focus to addressing a global economic crisis. Investments in hydrogen infrastructure and technology are delayed or scaled back as resources are redirected toward immediate economic recovery. Despite these setbacks, social acceptance and safety certification processes remain consistent with the baseline scenario.

10.4.1 Economic Issues

Looking at past crises in Figure 10-1[38], the impact of an economic, financial, or geopolitical crisis can lead to worldwide stagnation of passengers. In the particular case of the COVID-19 pandemic, the capacity (seats) decreased by 50% in 2020[38]. In the current scenario, we expect a drop in or stagnation of the European air travel demand for 3 to 5 years after 2035, around 2040. This will directly affect airlines, airports, and fuel providers. The focus of these stakeholders will lie on survival, which might mean limited investments in expensive in new technologies which carry more risk in the investment. Simultaneously, less flights may be offered, resulting employee lay-offs, affecting the overall aviation industry.

[38] URL https://www.icao.int/sustainability/Pages/Economic-Impacts-of-COVID-19.aspx accessed on 01/12/2024

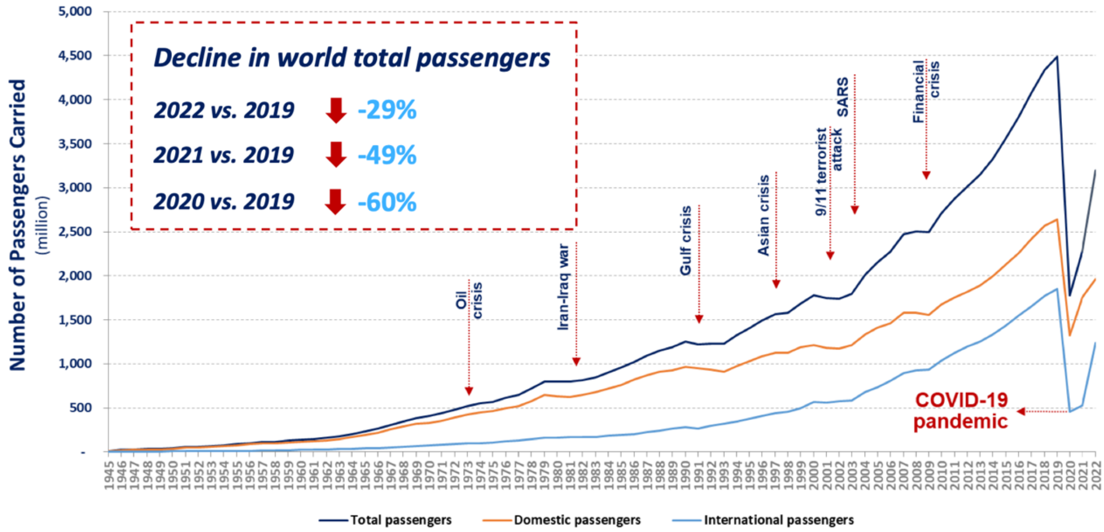

Figure 10-1 World passenger traffic evolution 1945-2022[38]

The role of governments around 2040 is still unclear in this scenario: on one hand the priority might lie on keeping business afloat and allowing more profitable operations over choices which contribute greenhouse gas reduction goals. Alternatively, as discussed in 6.7.1, governments may respond to the crisis with interventions or stimulus packages targeting new infrastructure development and/or research, possibly targeted at more sustainable technologies. This can offer two outcomes in the scenario development around 2050.

10.4.2 Hydrogen Availability and Supply

Initially, significant progress is made in green hydrogen development supported by developed renewable energy grids. Hydrogen transport infrastructure also begins to take shape by 2030 with networks connecting production sites to consumption hubs. Investments and technological advancements drive rapid deployment of electrolysers (up to 20 GW by 2030), as well as expanded storage capacities across various regions. At the same time, SAF is increasingly affordable and available resulting in competition between SAF and H2.

However, the economic crisis that unfolds after 2035 significantly undermines these initial achievements. Returns on earlier investments in hydrogen infrastructure and renewable energy diminish leading to reduced funding for the further development of hydrogen transport and storage. Plans for hub airports to establish on-site hydrogen production and support services for other sectors are cancelled. Instead, the focus shifts to cheaper grey and blue hydrogen, since green hydrogen projects struggle financially.

The result of the crisis is a growing gap between hydrogen supply and demand. Investments in infrastructure stall, leading to a fragmented and undeveloped hydrogen. Many regions face significant challenges in scaling up production and storage capacities. Consequently, most airlines shift toward the more affordable and widely available SAF as an alternative fuel.

10.4.3 Airport Readiness

By 2035 and extending into 2050, most airports lack extensive hydrogen infrastructure, relying instead on mobile refuelling solutions for limited hydrogen supply. Only smaller regional and local airports are fully equipped to handle hydrogen operations. Larger airport hubs face higher costs due to the need for additional land acquisition for hydrogen facilities and the impact of safety measures, such as larger turnaround safety zones, which reduce operational capacity. In times of economic crises, airports are particularly unwilling to make these costly investments, as the trade-off of reduced operational capacity during such uncertain periods becomes a significant concern. These factors hinder the readiness of major airports to accommodate hydrogen-powered aircraft.

10.4.4 Aircraft Technology

Reduced investments in hydrogen technology slow the development of next-generation hydrogen aircraft, with limitations in range and efficiency making them unsuitable for regional, short, and medium-range markets. Hydrogen-powered general aviation aircraft are expected by 2035, while regional turboprops and medium-range turbofans are delayed until 2045, reflecting slower progress.

The decline in air travel demand pushes airlines to focus on cost-efficiency, favoring kerosene and SAF over hydrogen, which remains more expensive and less flexible. Weaker environmental policies, such as reduced CO_2 taxes and local pollution mandates, further diminish hydrogen's competitiveness.

Survival strategies among airlines focus on extending the lifespan of existing kerosene-powered fleets and adopting SAF, which are less costly. These measures, combined with limited hydrogen availability at airports, severely restrict the adoption of hydrogen-powered aviation.

10.5 Scenario E – Safety Checklist Failed

Upon introduction of hydrogen aircraft into the market around 2035, minor and major incidents occur with hydrogen refuelling at airports. Additionally, issues at aircraft level result in grounding of aircraft, awaiting long investigations, redesign steps, and certification. Overall, it can be concluded that the technologies available in 2035, which were supposed to launch hydrogen aviation, are not mature enough. Either the ground-based technology or the aircraft technology can lead to safety issues.

10.5.1 Safety Issues

Critical safety issues occur with the first-generation large hydrogen aircraft around 2035. These issues can vary from leaks in the onboard fuel systems or issues with novel powertrain layouts. In-flight warnings lead to more emergency landings and deviations, disrupting overall operations. A couple of major incidents with casualties show that the aircraft technology has not reached the right level of maturity and reliability to be deployed widely.

At airports, issues can occur during refuelling due to leaks or incorrect handling, leading to evacuations significantly disrupting daily airport operations. Furthermore, boil-off gas management appears to be problematic for a variety of reasons, often resulting in dangerous levels of H_2 concentration. Certain airports fail to train ground personnel correctly and emergency services sometimes have a difficult time dealing with new situations involving hydrogen aircraft.

News about these incidents spreads widely over social media and deteriorates social acceptance of hydrogen-powered flight as a solution for sustainable aviation. Passengers actively avoid flights or airlines intended to be operated by hydrogen-powered aircraft. Additionally, people in the vicinity of airports are wary of hydrogen handling at the neighbouring airport and complain about plans involving hydrogen operations.

A strong driver in the avoidance and containment of these safety issues is the lacking standardisation and regulation. Also, the aircraft certification appears to not be complete for hydrogen aircraft, leading to low reliability. There is a societal and political push to further develop the standards and certification before large-scale hydrogen supply and operations are continued. These regulatory developments take time, pushing smooth operations of hydrogen-powered aircraft towards the long-term point, between 2045 or 2050.

10.5.2 Hydrogen Availability and Supply

Due to the low, delayed demand for hydrogen for aviation purposes, there is only moderate growth in electrolyser capacity with highly regional variations. Sufficient mature storage capacity lacks. We see very limited advances in liquefaction technology and deployment. Initiatives for hydrogen transport to airports receive less investments or are also delayed.

The produced hydrogen is more directed towards e-kerosene development, resulting in higher-than-expected availability of SAF. Airlines also have to rely on this drop-in alternative for their operations and meeting the imposed SAF quota. The hydrogen that is available has high supply cost due to the low offtake. While the renewable electricity grid is well-developed, its potential to drive down hydrogen costs remains underutilized in the aviation sector. Despite the general availability of gaseous hydrogen, the pause in further infrastructure investments for aviation limits the expansion of hydrogen aviation, keeping costs high and availability inconsistent across regions.

10.5.3 Airport Readiness

Additional safety checks and procedures during refuelling and other turnaround processes lead to significant turnaround times in comparison to kerosene- or SAF-powered aircraft. The safety perimeter around the aircraft during refuelling has to be at least 45 meters, which is a pessimistic outlook (Gijzen, 2024). Airports need to provide enough resources to complete the refuelling procedure, possibly needing additional physical space to store and handle liquid hydrogen far away terminal buildings. Overall, this leads to long turnaround times and expensive airport fees.

As a results, throughout the period between 2024 and 2050, airports and aircraft have to be supplied through carefully planned mobile refueller operations for all airport sizes and archetypes.

10.5.4 Aircraft Technology

From an aircraft technology perspective, general aviation H_2 aircraft may be ready by 2035, which can be refuelled by the designated mobile refuellers where the tank capacity can supply several general aviation aircraft. Large-scale application, such as regional H_2 turboprop aircraft are only fully operational by 2040-2045 after the investigations and certification have been completed. These steps delayed the development of H_2 turbofan aircraft with a longer range, of which none to only few are available in 2050.

Although safety issues exist, the energy penalties are as expected (up to 10%), but do not drastically decrease towards 2050 since the priorities are to have a certified and reliable product. Although maintenance cost also matches the baseline level, the long downtime due to safety issues leads lower annual utilisation levels.

10.6 Scope Extension and Other Elements to Consider

As discussed in the scope definition in Chapter 5, the main focus of the techno-economic scenarios lies on the supply, demand, and operations for liquid hydrogen for the use in aircraft. However, additional considerations may apply for future hydrogen supply. The following aspects can be included in the scenarios:

- The introduction of hydrogen freighter aircraft: it is agreed upon by experts and supported by qualitative research that there is an interesting market opportunity for hydrogen-powered cargo aircraft (Subias Botana, 2024). Among other driving forces, the turn-around operations of such aircraft are different and are often done at more remote locations at the airport. However, more insights into the opportunities for hydrogen-powered freighter aircraft and the design of such concepts is needed before these can be included in a concrete way.

- Introduction of hydrogen business aircraft: Similarly to cargo aircraft, experts think hydrogen business aircraft may be part of the first movers in the aviation industry. However, more concrete plans have to be developed before adding this type of aircraft to the scenarios.
- Gaseous hydrogen supply: airports may need gaseous hydrogen for certain aircraft concepts and ground equipment. This would require additional facilities for storage, transport, and/or refuelling.
- Other uses of hydrogen around the airport: besides the fuel to power aircraft, also other offtakes of hydrogen at airports are possible (Airports Council International, 2021). For example, Airbus[39] proposes the concept of hydrogen hubs which also use hydrogen for other transport types (heavy-duty, logistics transport or ground transportation), local industries, and/or heat and power. Additional offtake could reduce the hydrogen supply unit cost, although the availability has to be weighted the demand from aircraft refuelling.
- The supply and operations of hydrogen for smaller and/or more remote airports can be analysed. Some remote airports might still be reached by refuelling truck. However, airports on islands probably need to be supplied in another way, possibly by ship, or by having a local production plant.

An important unknown in the supply of hydrogen to the aircraft are the business models which will be used in the future decades. As discussed in Section 6.2.3, breakthrough innovations and new market ecosystems centred around hydrogen technology can result in disruptive business models. Open questions in business model choices include the following elements, among others:

- Which stakeholders own, lease, and/or operate the infrastructure (storage, trucks, etc.). Additionally, concepts such as pooled ownership may be introduced.
- Which stakeholder will invest: the airport and/or fuel providers themselves, or financial institutions raising capital for CAPEX of green technologies.
- Early market with fixed rate contracts versus spot rates (possibly later) for hydrogen

The current scenarios do not consider variations in the exact business models of fuel supply to the airport and/or aircraft. Additionally, the optimal business model may vary between the scenarios depending on the assumptions made. Therefore, it is suggested to try out different business models within the baseline scenario and possibly within other scenarios. The following three variations can be considered for the investments and ownership of refuelling equipment:

A. Mutualisation or pooled ownership: equipment is purchased by an airport equipment provider and/or operator, but the equipment is operated by multiple smaller fuel operators
B. Large companies (possibly current energy provides) control the entire supply chain up to the aircraft (if this is allowed from a legal point of view).
C. Syndication: non-aviation financial institutions raise the capital for green investments, expecting a clear return on investment, with committed operators taking care of the equipment and refuelling.

Moreover, for airport storage of hydrogen, the airports have or purchase land but lease this land to a third party. In the upcoming years, other business models may appear which can be taken into account in the techno-economic analyses.

[39] URL https://www.airbus.com/en/newsroom/stories/2024-09-developing-a-global-ecosystem-to-support-hydrogen-powered-flight accessed on 02/12/2024

11 Conclusions

The aim of this deliverable is to define the scope and develop scenario for future operational and techno-economic analysis in the GOLIAT project. These actions are completed through a literature review, meetings with GOLIAT partners, and a workshop with external experts in the field of energy and hydrogen supply, airports, airlines, aviation consultancies, and research institutes. The scope of the scenarios focuses on hydrogen supply and operations for aviation in Europe in the mid (2035) to long term (2050). Commercial passenger transport is of main importance, while cargo can be considered at a later stage. Overall, the focus lies on the supply and infrastructure to refuel large aircraft powered by liquid hydrogen. Demand for gaseous hydrogen and other uses of hydrogen, such as road transport or terminal use, should be considered, but may be modelled in less detail.

The most important driving forces are identified by considering several categories and by evaluating their uncertainty and impact on hydrogen demand, supply chain size and economics, and ground operations. The three most important categories are the hydrogen availability (including supply to the airport), the airport readiness, and the aircraft technology development. Additionally, disrupting factors, such as an economic crisis or a major safety issue with hydrogen technology, may lead to relevant and relatively novel scenarios. Based on these observations, eight raw scenarios were created of which five were further refined and taken as main scenarios. The five main scenarios are:

A. Smooth Skies – A baseline scenario covering “mid-level” developments from literature.
B. Aircraft Delayed – This scenario considers delayed arrival of hydrogen aircraft which are expensive to operate.
C. Grounded Potential – In this scenario many airports at European level are not ready to support hydrogen refuelling operations, and the hydrogen aircraft cannot be operated at full potential.
D. Economic Stall Warning – After initial investments in infrastructure and aircraft technology, an economics crisis occurs in 2035 to 2040 which lowers the overall demand for air travel.
E. Safety Checklist Failed – Major safety issues lower the social and regulatory acceptance of hydrogen aircraft and their operations at airports.

These scenarios will serve as case studies in future operational and techno-economic analyses. However, these scenarios are developed based on currently available literature and current insights from experts. Over the course of the GOLIAT project (2024 to 2028), new insights or technologies may make factors and scenarios more or less relevant. Therefore, the scenarios may have to be updated later in the project. Also, for some of the modelling approaches, further refinements or new assumptions may have to be added to the scenarios.

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13 Annex 1: Workshop 1 – Impact and Uncertainty

The following figures show for each factor considered in Chapter 6, per category, how the GOLIAT experts scored them in terms of impact and uncertainty. These plots are only intended for illustrative purposes and no quantitative insights or relations to specific partners can be derived. Dots outside low-high quadrants indicate that the response was unknown. For example, the expert identifies the infrastructure readiness per airport archetype to have a high impact but cannot judge the uncertainty. The decision to include, exclude, or combine factors in the scenario definition is based upon these insights, literature, and discussions during meetings.

Table 13-1 Policy factors impact and uncertainty evaluation

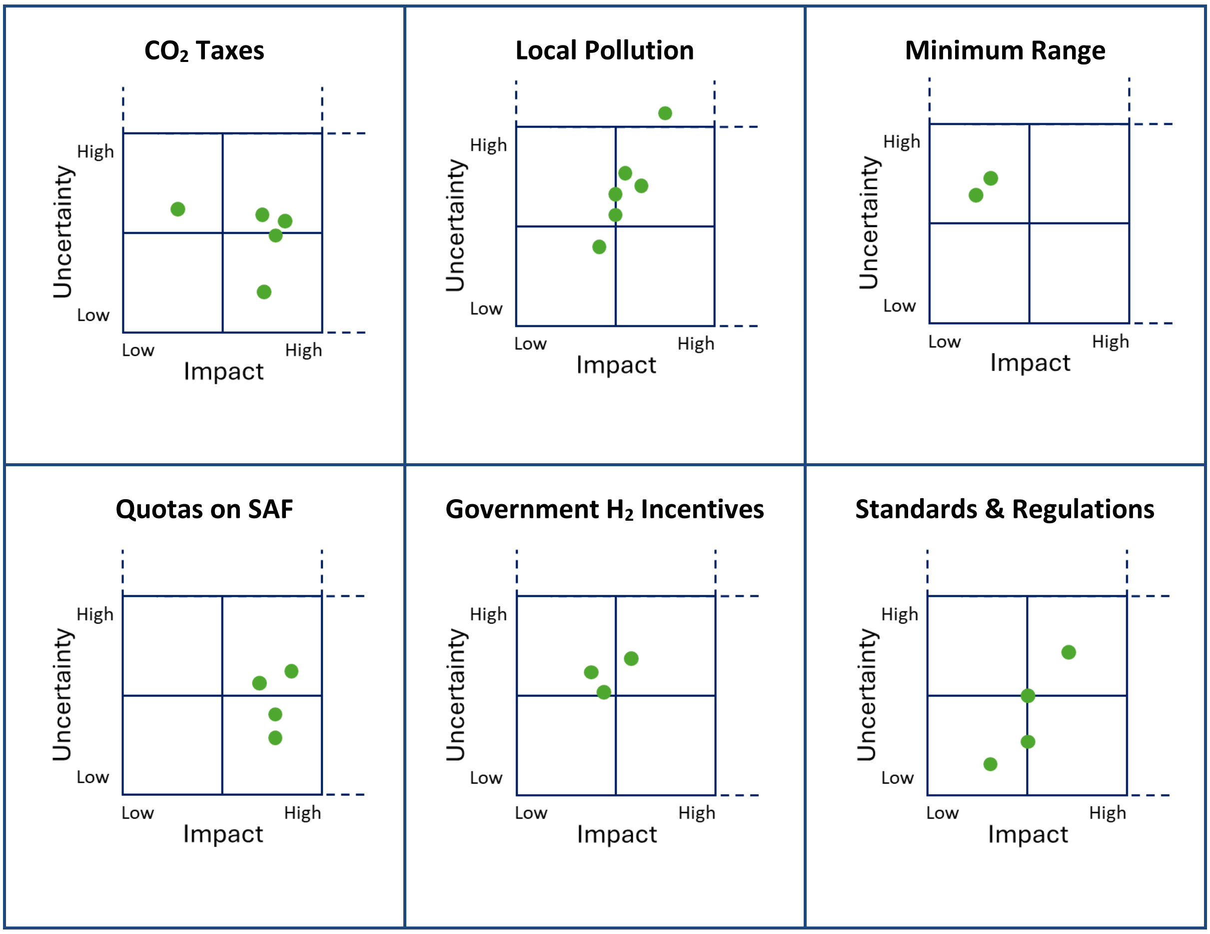


Table 13-2 Economic factors impact and uncertainty evaluation

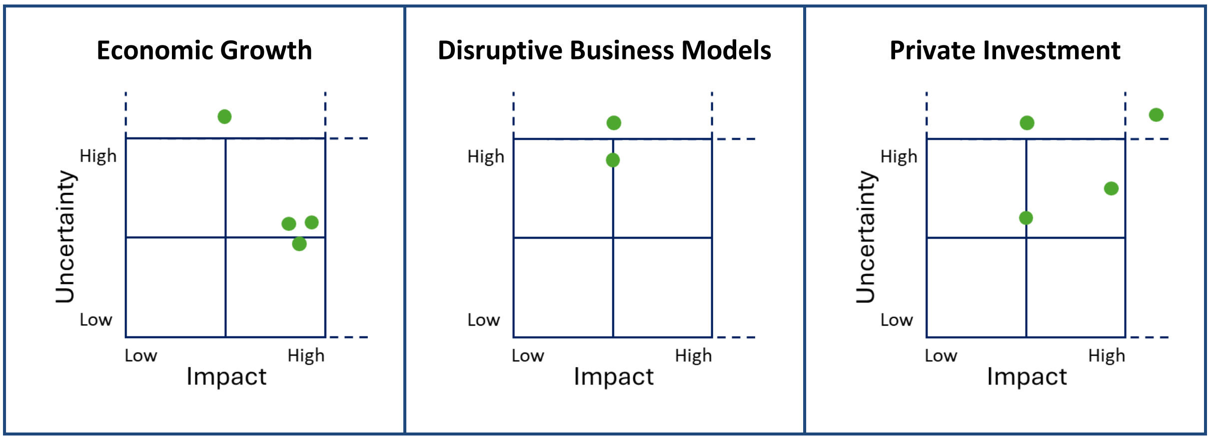


Table 13-3 Airport factors impact and uncertainty evaluation

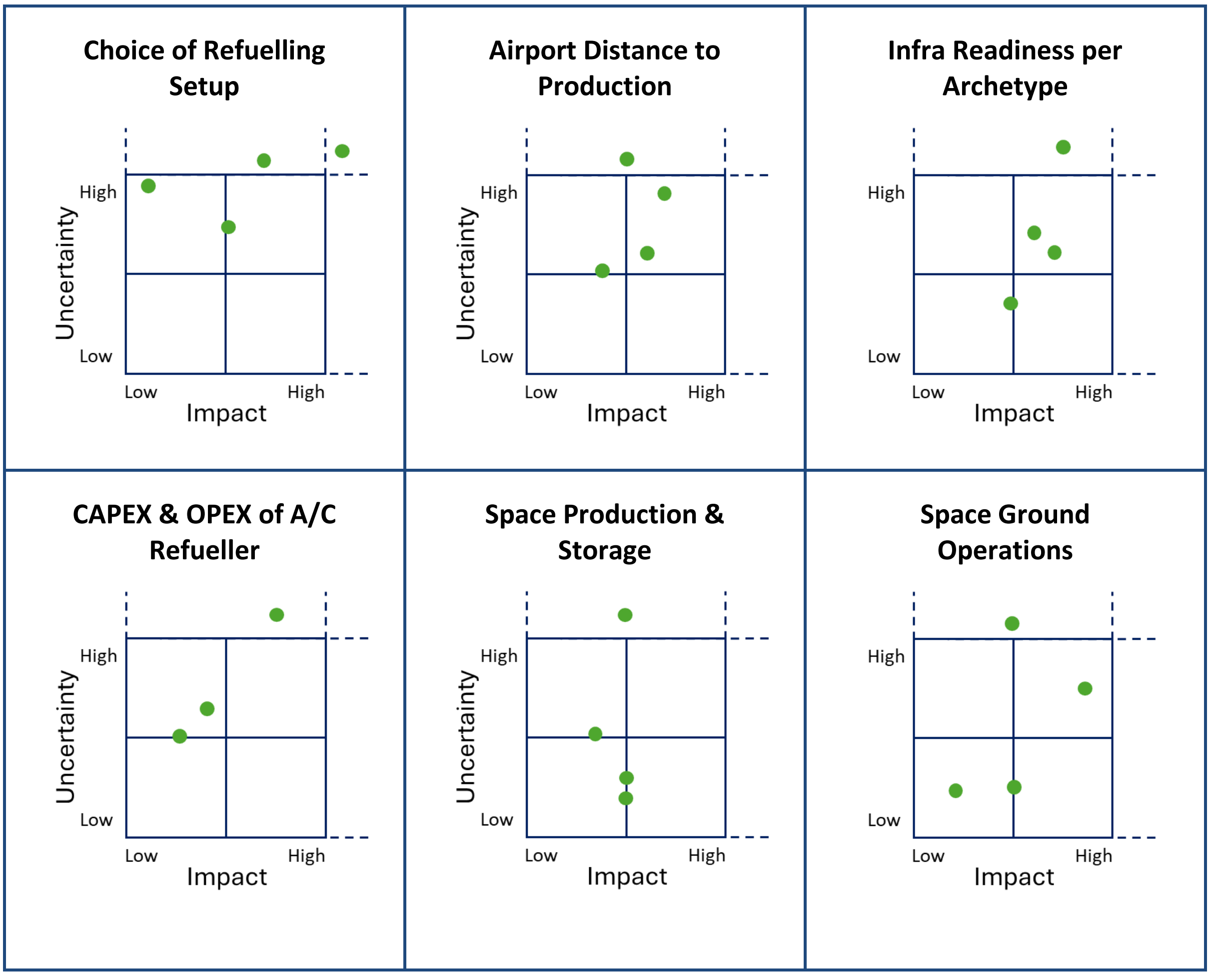
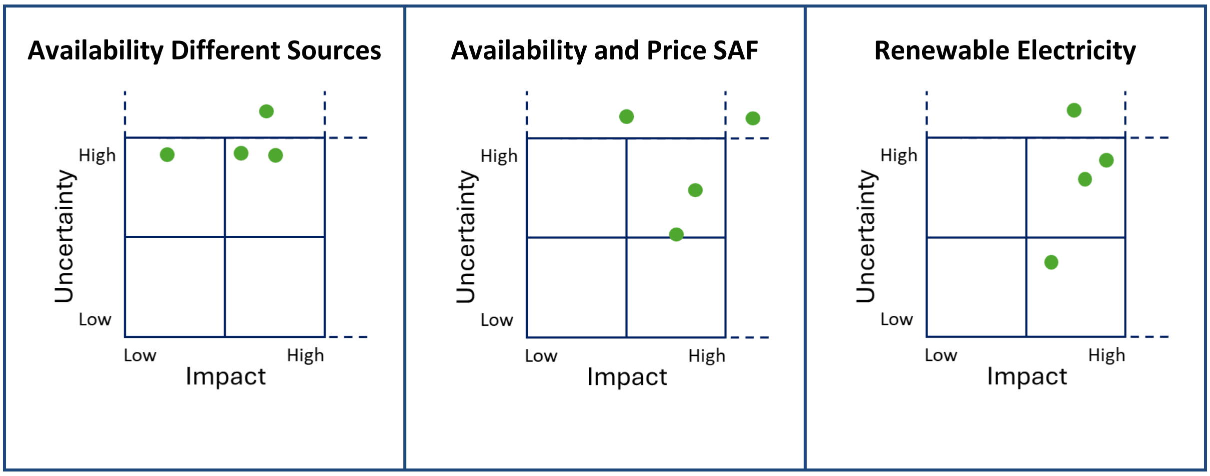


Table 13-4 Hydrogen and energy market factors impact and uncertainty evaluation



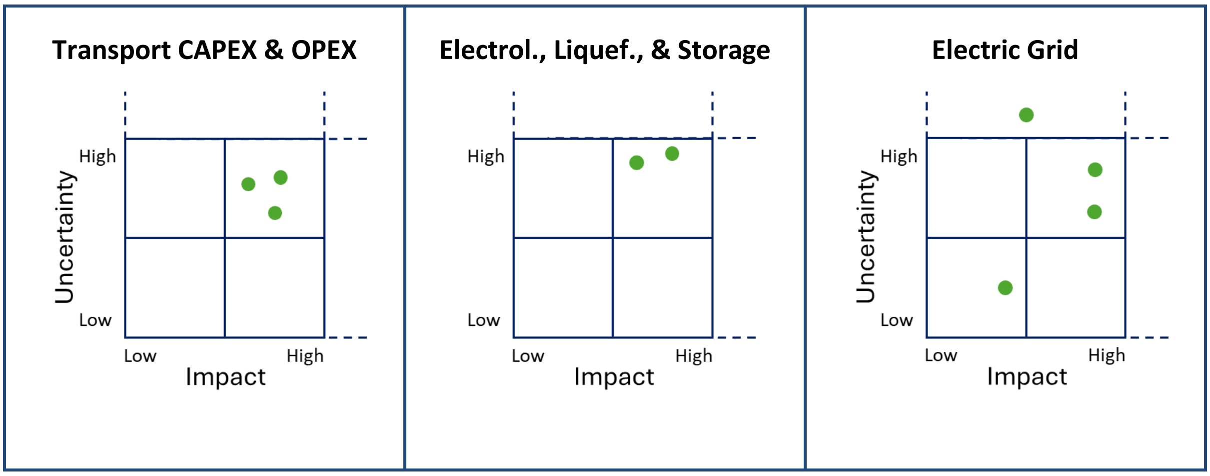


Table 13-5 Traffic growth factors impact and uncertainty evaluation

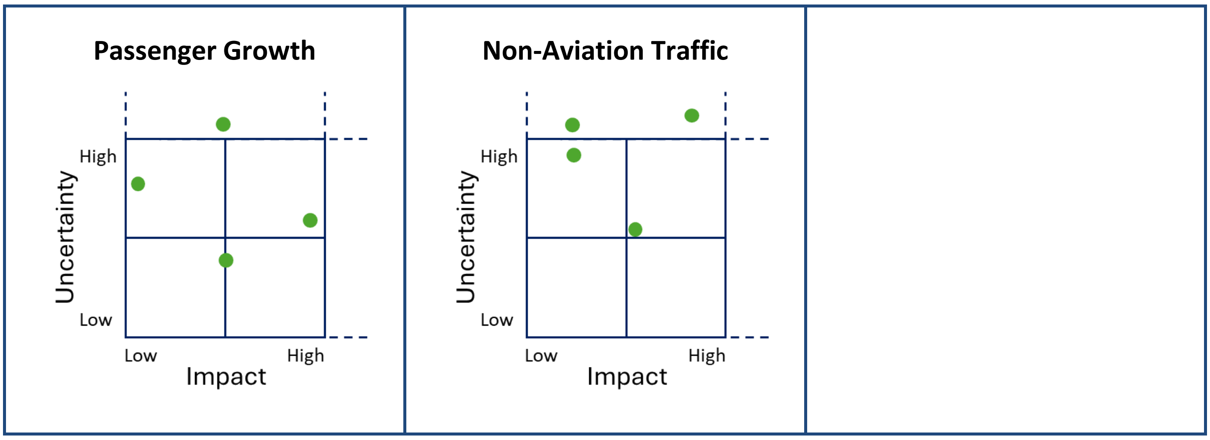
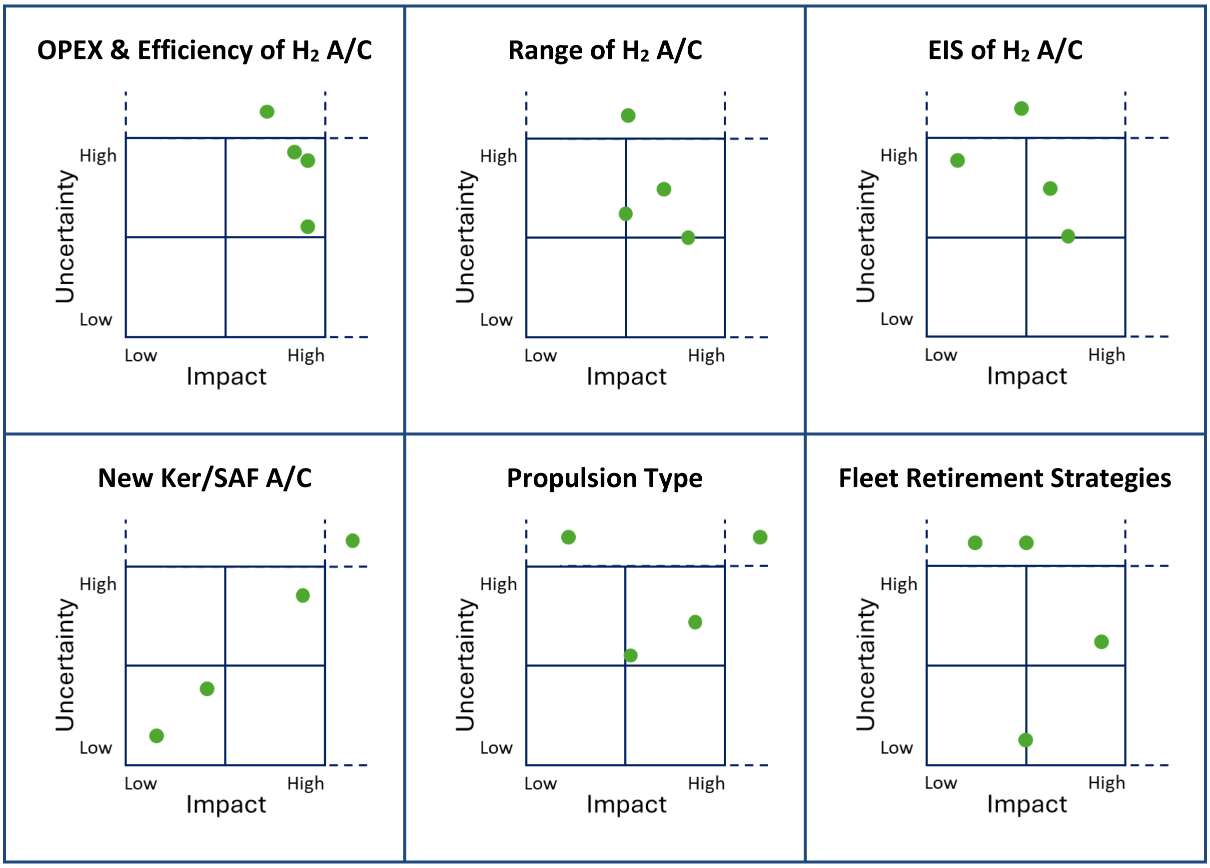
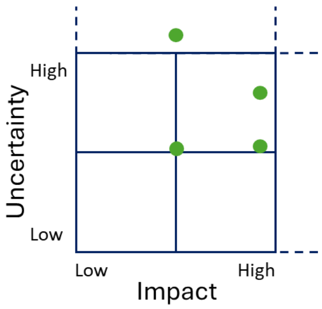
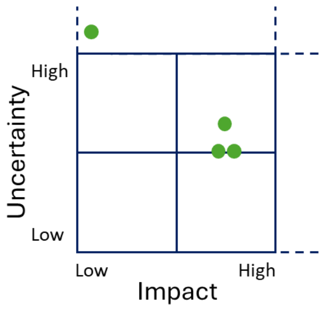
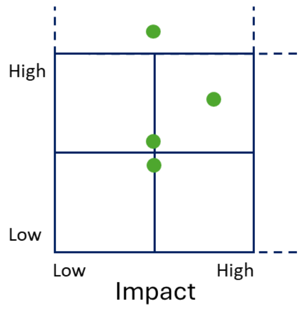


Table 13-6 Aircraft technology factors impact and uncertainty evaluation



MRO **[no data]**		

Table 13-7 Disrupting factors impact and uncertainty evaluation

Economic or Financial Crises	**Safety Issues**	**Tech Reliability Issues**
		

14 Annex 2: Workshop 2 – Raw Data

Table 14-1 and Table 14-2 show the votes for the consistency and plausibility, respectively, for each of the eight raw scenarios.

Table 14-1 Count of consistency votes for the eight raw scenarios

Answer	S1	S2	S3	S4	S5	S6	S7	S8
Yes	15	6	11	13	9	12	14	11
Yes, with comment	3	5	3	5	4	1	2	2
No	2	6	4	1	4	3	1	2
Total	20	17	18	19	17	16	17	15

Table 14-2 Count of plausibility votes for the eight raw scenarios

Answer	S1	S2	S3	S4	S5	S6	S7	S8
Yes	6	11	9	15	5	13	11	7
Yes, with comment	4	3	4	4	1	2	2	6
No	8	4	6	0	13	2	4	3
Total	18	18	19	19	19	17	17	16

Table 14-3 and Table 14-4 show the votes per level for the relevance and novelty criteria.

Table 14-3 Count of relevance ranking for the eight raw scenarios

Relevance Level	S1	S2	S3	S4	S5	S6	S7	S8	Total
Essential	7	3	3	7	2	2	5	1	30
Very relevant	0	3	7	4	0	5	3	0	22
Relevant	3	5	1	4	0	2	4	5	24
Low relevance	5	4	4	1	3	0	0	2	19
Irrelevant	2	0	0	0	5	1	0	3	11
Total	17	15	15	16	10	10	12	11	

Table 14-4 Count of novelty ranking for the eight raw scenarios

Novelty Level	S1	S2	S3	S4	S5	S6	S7	S8	Total
Completely new	0	0	1	2	0	0	0	2	5
Rarely assessed	0	0	5	3	0	9	8	6	8
Somewhat novel	0	3	2	2	1	6	7	2	23
Frequently assessed	11	5	2	3	9	0	1	4	35
Exhaustively assessed	2	0	0	0	4	0	0	0	6
Total	13	8	10	10	14	15	16	14	