Delft University of Technology

# Developing Effective Strategies for the Deployment of Sustainable Aircraft Technologies by the Aviation Industry

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## A Qualitative Case Study


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## A Qualitative Case Study

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I hope you enjoy reading my -admittedly lengthy- master thesis report.

Charlotte Verdegaal,
Utrecht, November 2023

# EXECUTIVE SUMMARY


*Problem statement*

Globally, a call for decarbonisation is present across industries. In 2019, the European Union introduced the *European Green Deal*, with its main aim to become a climate neutral continent by the end of 2050. This poses challenging targets for the aviation sector, which needs to be operating net carbon-free by this timeframe. In Europe, Airbus is the main aircraft original equipment manufacturer and aims to take large steps in the developments and deployment of sustainable aircraft technologies. The largest improvement of sustainability within the aviation industry is expected from a range of different technological solutions, however, research on which to implement in which timeframe within the aviation industry is currently missing.

*Objective of research and research question*

This research takes a Technological Innovation System (TIS) approach, which structurally analyses technological change by addressing the wide functional dynamics of innovation systems through so-called TIS building blocks. These represent the essential dimensions of a Technological Innovation System to assess technologies on, including: *(I) Product performance and quality; (II) Product price; (II) Production system; (IV) Complementary products and services; (V) Network formation and coordination; (VI) Customers; (VII) Innovation-specific institutions* (Ortt & Kamp, 2022). From the academic literature analysis (Section 1,2), it is evident that the role of companies in accelerating transitions is currently lacking in literature, while these can make significant investments in the development of new technology and ensure successful implementation. Especially within the aviation industry, where product innovation is characterized by large-scale investments and powerful incumbents, it is of importance to take a managerial perspective into consideration for steering the innovation system towards sustainable transitions. The TIS framework of Ortt & Kamp (2022) takes on a company perspective, however, still offers little insight into how incumbent firms can, in practice, effectively formulate strategies for implementing sustainable innovations, considering the required changes in TIS building blocks, represented over time. Also, sustainable transitions within aviation are expected to be achieved through the contribution of multiple aircraft innovations, while these innovations are currently researched in isolation. Following from these knowledge gaps, the following research question has been formulated for this Master Thesis Research:

*How can a TIS analysis from a company perspective guide incumbent firms in the aviation industry in taking steps towards the deployment of sustainable aircraft technologies over the next decades?*

*Methodology*

A qualitative research approach with extensive literature study and interviews with relevant actors within the value chain of the aviation industry has been chosen. A case study approach with Airbus' perspective has been taken to investigate which pathways towards sustainability would be most accessible to take first, accelerating deployment of sustainable aircraft technologies. A focus has been laid on the Dutch/German ecosystem since key players in the value chain of aviation have agreed to intensify cooperation to realise climate neutral aviation by 2050 in the *Flying Vision* initiative. For the research, the TIS framework of Ortt & Kamp (2022) has been used to evaluate the compatibility of both sustainable aircraft technologies *hydrogen aircraft* and *ultra-efficient* aircraft to the benchmark technology *conventional aircraft with 50% SAF deployment,* which represents a future business-as-usual scenario for aviation.

Here, the framework has been modified to be applied to the aviation industry. For evaluating compatibility, the TIS building blocks have been dismantled in a set of indicators (see results SQ1) which have been evaluated on their completeness. For incomplete or partially complete indicators, one or

more influencing conditions have been identified, representing the main bottlenecks hampering completeness. Subsequently, a prospect of completeness of the indicator has been formulated based on academic knowledge, e.g. by assessing expected technological developments and price projections or based on interviews with knowledgeable experts. Since every indicator is assumed to be equal in importance, the completeness of the overall TIS building block is evaluated based on the mean of the completeness of its indicators. Also, the longest prospect of completeness of the indicators is considered the prospect of completeness of the overall TIS building block, as this represents the last expected timeframe in which an indicator of the TIS building block is considered non-complete. Lastly, deployment strategies in the form of a three-phased approach are proposed (see results SQ4). The regional market segment of aviation has been chosen, focusing the analysis on an Embraer 175 aircraft design with a passenger capacity of 70-90 PAX.

*Results SQ1: How can the TIS framework of Ortt & Kamp (2022) be modified to be applied to the aviation industry?*

First, the TIS framework from a company perspective of Ortt & Kamp (2022) has been specified to the aviation industry, by altering TIS building blocks to represent industry-specific aspects. Here, TIS building block 4 has been altered from *Complementary products and services* to *Complementary infrastructure and services* and TIS building block 7 has been altered from *Innovation-specific institutions* to *Innovation-specific and industry-wide regulations.* Subsequently, the influencing conditions proposed by Ortt & Kamp (2022), explaining potential bottlenecks in the formation of TIS building blocks, have been adjusted to the aviation industry. These include: *(I) Knowledge and awareness of technology*; *(II) Knowledge and awareness of application and market*; *(III) Natural resources*; *(IV) Human resources*; *(V) Financial resources*; *(VI) Competition*; (*VII) Macro-economic and strategic aspects*; *(VIII) Socio-cultural aspects* and *(IX) Accidents and events.* For each TIS building block, a set of indicators, representing most important elements for the deployment of aircraft in the aviation industry, have been formulated to evaluate completeness of the sustainable aircraft technologies on as described in the methodology.

*Results SQ2: To what extent are the TIS building blocks of hydrogen aircraft considered complete, and which influencing conditions and prospects for completeness are present?*

Hydrogen aircraft developments within its TIS currently shows to be incomplete in TIS building blocks *Production system* and *Complementary infrastructure and services*. Furthermore, the TIS building blocks *Product performance and* quality, *Product price*, *Customers* and *Innovation-specific and industry-wide* institutions are partially complete. Only TIS building block *Network formation and coordination* is considered complete for hydrogen aircraft. The prospect of completeness of the TIS building blocks vary between 15-22 years, leading the prospect of completeness of the overall TIS to be 22 years. Furthermore, from a total of 36 analysed indicators for hydrogen aircraft, 10 are considered complete and 26 are hampered by one or more influencing conditions. The foremost influencing conditions hampering indicators of TIS building blocks are *Knowledge and awareness of technology*, *Macro-economic and strategic aspects,* and *Competition.*

*Results SQ3: To what extent are the TIS building blocks of ultra-efficient aircraft considered complete, and which influencing conditions and prospects for completeness are potentially present?*

Ultra-efficient aircraft developments within its TIS currently shows to be partially complete in TIS building blocks *Product performance and quality, Production system* and *innovation-specific and industry-wide institutions*. TIS building blocks *Product price, complementary infrastructure and services, network formation and coordination* and *customers* are currently considered complete. The prospect of completeness of the TIS building blocks vary between 10-20 years, leading the prospect of completeness of the overall TIS to be considered 20 years. Furthermore, from a total of 36 analysed indicators for ultra-efficient aircraft, 20 are considered complete and 16 are hampered by one or more influencing conditions. The foremost influencing conditions hampering indicators of TIS building blocks are *Knowledge and awareness of technology* and *Macro- economic and strategic aspects*.

*Results SQ4: How do the TIS analyses compare to each other and how does it affect the deployment of the sustainable aircraft technologies in terms of building on or circumventing non-complete TIS building blocks?*

Based on the results of SQ2 and SQ3, it can be concluded that both alternatives currently do not prove to be fully ready for deployment. Nevertheless, an overall higher compatibility of ultra-efficient aircraft to the current socio-technical regime of aviation is evident, stressing the importance to deploy this alternative first. A dual strategy for deployment of both aircraft technologies is proposed, divided into three phases based on the distinguishable stages of developments that are required for building TIS building blocks of ultra-efficient aircraft and hydrogen aircraft. Phase 1 (2023-2028) represents the predevelopment of maturation work of technological bricks of both sustainable aircraft technologies. Also, the anticipated introduction of the hydrogen retrofit aircraft by 2025 will challenge the incumbent socio-technical regime to experiment with hydrogen aircraft technology already.

Phase 2 (2028-2038) represents the timeframe in which incomplete or partially complete TIS building blocks of both aircraft technologies are further built on or circumvented. By 2035, ultra-efficient aircraft are expected to be deployed as a main business product competing with conventional aircraft types. The overall TIS of ultra-efficient aircraft is expected complete by 2038. Hydrogen aircraft are expected to be deployed by 2035 as a niche product first, with the aim to gradually build on interlinked technological, social, economic, and institutional developments in the socio-technical regime of aviation for co-evolvement. Simultaneous with its deployment as a niche innovation, the yet non-complete TIS building blocks for hydrogen aircraft are built on further. Phase 3 (2038-2045) represents the timeframe in which last experiments and learning curves with hydrogen aircraft are established. The overall TIS of hydrogen aircraft is expected complete by 2045, making entry into service as a conventional business possible. Here, the incumbent socio-technical regime of aviation is expected to have opened sufficiently for integrating changes in infrastructure, industrial networks, and regulations in this timeframe.

*Recommendations for industry and policymakers*

It is recommended that ultra-efficient aircraft will be deployed first, with 50% SAF drop-in fuel to reach the most effective environmental performance of the aircraft. Here, the aircraft should be deployed as a main business product, aiming to substitute a large share of conventional aircraft in the regional market segment within Europe. For Airbus specifically, this means that business models need to be established to ensure that the aircraft would be both attractive for customers and profitable for the Original Equipment Manufacturer (OEM), since investment costs are expected to be relatively higher than conventional aircraft.

Simultaneously, it is recommended to support experimentation with hydrogen aircraft from all dimensions within the value chain of aviation. This is essential for establishing safety procedures and ground operations, that will drive learning curves of hydrogen aircraft deployment. It is recommended that hydrogen aircraft are deployed as a niche technology first, allowing the socio-technical regime to adapt to the radical technology by adjusting infrastructure, industrial networks, institutions, and cultural perspectives on the technology. Depending on developments within safety regulations, the cargo segment could be chosen first for deployment before the regional passenger market segment is targeted. By 2045, hydrogen aircraft could be offered as a main business product. For Airbus specifically, this means that a focus on its ZEROe aircraft technologies should be enhanced the coming decades, offering them as a niche technology first before deploying them on a larger scale. Also, business models need to be established for ensuring hydrogen aircraft is attractive for the customer as well as the OEM in both deployment phases.

Furthermore, both analyses have addressed the suboptimal performance of EU wide policies and regulations to help the deployment of sustainable aircraft technologies. While self-regulation within the aviation industry has formulated targets for the deployment of incremental sustainable innovations, supporting the deployment of ultra-efficient aircraft, hydrogen aircraft innovations are not targeted at all. This represents the need for more top-down policies for the deployment of hydrogen aircraft. Furthermore, policy makers should understand the influence of global business dynamics in the aviation industry on the deployment of the alternatives. This includes the influence of competition between large incumbent OEMs on the development on the sustainable aircraft alternatives. The development of these trends should be backed by governments in order to ensure they are being enrolled. Also, as hydrogen aircraft deployment specifically is highly intertwined with the availability of hydrogen, policy makers should ensure enough capacity of renewable energy sources is present for its production and facilitate its allocation across hard-to-decarbonize industries. Also, hydrogen distribution infrastructure needs a European wide standard to mitigate potential problems with a misalignment of cross-border hydrogen networks.

*Recommendations for future research*

This master thesis research has opened many opportunities for future research. These include recommendations regarding enhancing the case study and recommendations on broader opportunities of academics, all elaborated below.

- The case study could be improved by analysing the four indicators of TIS building block 5 to obtain a more robust evaluation of this building block, for which an in-depth methodology is provided by this research in Chapter 8.
- The overall proposed set of indicators could be enhanced, excluding arbitrary indicators and including more qualitative ones to reach a more realistic representation of the TIS building blocks.
- A hierarchy among indicators could be introduced, representing the importance and the depth of elements they symbolise, rather than considering the indicators equally relevant for the level of completeness of the overall TIS building block. The format of a Multi Criteria Analysis could be taken, where the indicators represent criteria which needs to be granted a weight to show their relative importance for the evaluation. This would require a quantification of what would be considered incomplete, partially complete, and complete in numerical terms, together presenting the importance of the indicator in the analysis where the total of weight adds up to 1.
- A Multi Criteria Analysis could be used to create a Composite Indicator Index, which provides a simplified representation of the overall TIS building blocks by aggregating the data of its weighted indicators and their performance and prospect of completeness into one overall value. When creating an index over time, the overall progress of building strategies on the level of completeness of TIS building blocks could be represented, granting insights in the level of completeness of TIS building blocks and the effectiveness of preceding building strategies.
- An improved data set could be obtained for the evaluation of the performance of the indicators, hampering influencing conditions and prospect of completeness through conducting more interviews or executing a survey study, enabling input from a wide range of actors in the value chain of aviation.
- A methodology for formulating an uncertainty range around the prospect of completeness of all non-complete indicators could be created, enhancing robustness of the values. Here, three steps can be distinguished, including (I) an explanation of obtaining the prospect of completeness, (II) an indication of the level of certainty of the prospect of completeness, and (III) an elaboration on what is required for lowering this uncertainty. For the latter two steps, the insights in the influencing conditions forming bottlenecks could be used. Also, an identification of indicators that never reach completeness should be established.
- More detailed deployment strategies could be formulated, incorporating the identified influencing conditions, indicating a specific type of deployment strategy that is relevant for building on the indicator. An orderly method needs to be established for structurally prioritizing importance, e.g.

by factoring the prospect of completeness, representing urgency, with the hierarchy of the indicator, representing relevance. Here, a high score indicates relatively higher prioritization.

- A practical tool from the methodology of this thesis could be created for companies. The following applications could be executed:
    - To simplify the procedure of creating a Composite Indicator Index, enabling to track the completeness of the TIS building blocks over time.
    - To help create heatmaps from the prospects of completeness, highlighting the timeframes in which indicators are considered complete through a traffic light colour scheme.
    - To ensure refinement of the values of prospects of completeness in real time when external trends accelerate or hamper the development of TIS building blocks, particularly interesting for developing innovations in a dynamic business environment where external trends are changing at a fast pace.
    - To perform a robustness analysis through what-if scenarios, by refining the weights of indicators to represent most importance given the business context the company is operating in.
- Broader opportunities of academics could be addressed by focusing on the influence of TIS building blocks on each other, providing essential knowledge on which TIS building blocks have large influence over the development of others, and are therefore more relevant to address. Here, three case studies of novel technologies from different sectors could be conducted to structurally research which generic dependencies of TIS building blocks are present.
- The TIS building blocks from the framework of Ortt & Kamp (2022) could be used to formulate system building strategies necessary for the introduction of a radical innovation, rather than taking the innovation itself as focal point. Here, an industry perspective should be taken opposed to a firm or a policy-maker perspective, to retain focus on the socio-technical system within the dynamics of a chosen industry and to allocate the responsibility of deploying the strategy to multiple actors within the value chain of the industry rather than to one specific firm.
- Such a system building perspective could help addressing transition pathway literature more clearly in future research. Here, system building strategies in a specific socio-technical regime should be translated into one practical roadmap for all firms in the industry, specifying on important activities and translating strategies into industry milestones. This would provide practical means for an industry to align actors and stimulate collaboration towards a similar goal, challenging socio-technical regimes actively and steering a socio-technical trajectory towards the deployment of sustainable technologies which draws on transition pathways literature.
- The industrial-level analysis could be applied to the case study of this research, in which transition pathways for the sustainable aircraft technologies should be created through the development of roadmaps. Here, the future development both sustainable aircraft technologies should be subsumed to one of the potential types of socio-technical transition pathways that new innovations can follow, enhancing an understanding in which strategies to employ for their implementation.

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| | |
|---|---|
| AZEA | Alliance for Zero Emission Aviation |
| CCS | Carbon Capture and Storage |
| CFRP | Carbon Fibre Reinforced Polymers |
| CORSIA | Carbon Offsetting and Reduction Scheme for International Aviation |
| CoSEM | Complex Systems Engineering and Management |
| DOC | Direct Operating Costs |
| EPNL | Effective Perceived Noise Level |
| ERF | Effective Radiative Forcing |
| EU | European Union |
| EU ETS | European Union Emission Trading System |
| GHG | Greenhouse Gas |
| IATA | International Air Transport Association |
| ICAO | International Civil Aviation Organisation |
| IRENA | International Renewable Energy Agency |
| LH2 | Liquid Hydrogen |
| MLP | Multi-Level Perspective |
| MRO | Maintenance Repair Overhaul |
| MWh | Megawatt-Hour |
| OEM | Original Equipment Manufacturer |
| PAX | Passengers |
| R&D | Research and Development |
| RES | Renewable Energy Sources |
| SFC | Thrust-specific Fuel Consumption |
| SNM | Strategic Niche Management |
| TIS | Technological Innovation System |
| USD | United States dollar |

# CHAPTER 1: INTRODUCTION

This chapter introduces the research topic of this Master Thesis research. Section 1.1 provides the introduction of the problem addressed in the study. Section 1.2 addresses the knowledge gap present in academic literature, of which its literature search method can be found in Appendix A. Section 1.3 presents the research question of the Master Thesis, including its sub research questions that will be addressed in the Master Thesis research. Section 1.4 addresses the research objective including a justification for a case study. Section 1.5 addresses the link of the Master Thesis research to the CoSEM Master program. Lastly, Section 1.6 presents the Master Thesis outline.

## 1.1 PROBLEM STATEMENT

Globally, a call for decarbonisation is present across industries. In 2019, the European Union introduced the *European Green Deal*, with its main aim to become a climate neutral continent by the end of 2050. This poses challenging targets for the aviation sector, which needs to be net carbon-free by this timeframe. The aviation sector is currently accountable for approximately 4% of human-induced CO2 emissions worldwide (Klöwer et al., 2021) and 3.8% in Europe (European Commission, n.d.e). While various efforts in the past decades have led to more efficient aircraft configurations increasing fuel efficiency to 50% (Fuel Cells and Hydrogen 2 Joint Undertaking, 2020), demand is expected to grow 3%-5% annually until 2050 which leads to an overall increase in emissions from the aviation sector (IATA, 2018). Moreover, in a global market forecast, Airbus has estimated that the number of kilometres travelled by air passengers will double within 15 years, which would generate a demand of 40.850 new commercial aircraft for the next 20 years (Airbus, 2023a). This underlines the importance to work towards a sustainable aviation sector in Europe for the coming decades, for which large-scale systemic changes must be made.

In Europe, Airbus is the main aircraft original equipment manufacturer (OEM) and aims to take big steps in the developments and implementation of sustainable aircraft technologies. Currently, various aircraft technology designs and operations are under investigation, varying from energy carriers used for propulsion, power systems and operations of flights, including flight altitude and speed (Batteiger et al., 2022). The implementation of any of those technologies would represent a socio-technical transition, which could be defined as the complex co-evolvement of interlinked technological, social, economic, and institutional changes, which are typically path-dependent and unpredictable (Geels, 2019; Geels et al., 2018). However, sustainable technological transitions do not only depend on technological developments, but also on other advancements in the socio-technical system, including changes in infrastructure, industrial networks, and regulations (Geels, 2002). Therefore, the objective of this research will draw on a socio-technical system perspective for investigating the current socio-technical system around sustainable aircraft technologies and how changes could be made in the short-term timeframe for implementing sustainable technologies successfully. Academically, the thesis contributes to our understanding of how socio-technical transitions to sustainability can be accelerated (Roberts et al., 2018). In particular, this understanding shall provide insights on how to successfully implement sustainable aircraft innovations, as well on which sustainable aircraft technologies to implement in which timeframe. Apart from strategic recommendations for industry, these insights can also support policymaking in how to address bottlenecks in the sustainability transition of the aviation sector.

## 1.2 ACADEMIC LITERATURE GAP

A variety of literature is present regarding enhancing sustainability of aircraft. When looking specifically at the energy-carrier configuration of aircraft, various reports propose the future use of hydrogen aircraft, aircraft with Sustainable Aviation Fuels (SAF) drop-in, biofuel aircraft, battery aircraft, or ultra-efficient aircraft configurations (Batteiger et al., 2022; Fuel Cells and Hydrogen 2 Joint Undertaking, 2020; TU Delft & NLR, 2021). The largest improvement of sustainability within the aviation industry is expected from a range of different technological solutions (TU Delft & NLR, 2021). Nevertheless, most of these options are investigated on their potential in an isolated manner opposed to taking a collective perspective on implementing sustainable technologies within the aviation industry. This leads to an incongruency between academic literature and scientific research that addresses a more real-life application of sustainable aircraft technologies for accelerating sustainable transitions in aviation and underlines an essential knowledge gap. An overview of existing literature on sustainable aircraft technologies is provided in Appendix A, of which Table A1-A3 present, respectively, the literature search string, the overview of the relevant academic literature and the review of the literature on sustainable aircraft technologies. While several studies compare sustainable aircraft technologies to each other in terms of economics (Timmons & Terwel, 2022), technological performance (Markatos & Pantelakis, 2023) and in types of emissions that the sustainable aircraft technologies emit (Proesmans & Vos, 2022; Karpuk & Elham, 2022), they lack a perspective on how different types of sustainable aircraft technologies relate to each other and how they can be implemented next to each other.

Socio-technical transitions do not solely focus on technological development but are part of larger socio-technical systems that requires changes in dimensions of culture, institutions, industrial networks, and infrastructure (Geels, 2002). In the aviation industry, this can be seen in the broad range of sustainable aircraft innovations introduce different technological trajectories, some incremental and some more radical, and all in need of their own supply chains and complementary infrastructures (Timmons & Terwel, 2022; Leal Filho et al., 2022). Most of the infrastructure requirements for such sustainable aircraft technologies cross with other sectors (Ansell, 2022; Sharma et al., 2021), such as the energy sector, forming dependencies between various actors and leading to chicken-and-egg problems for investments. Also, interdependencies between various dimensions within the socio-technical system is present, such as Original Equipment Manufacturers (OEMs), airports, airlines, safety regulators, etc. This leads to a high level of uncertainty in how socio-technological transitions will evolve over time given the large number of technological alternatives present. Also, it remains uncertain which technological trajectory might be most promising for large-scale implementation. Therefore, the multi-dimensional nature of socio-technical transitions should be analysed for providing grip on relevant elements to address for facilitating innovation and deployment of sustainable aircraft technologies.

Literature on socio-technical systems can help to gain more insights on the dynamics of these dimensions that together influence technological transitions. In Table A4-A6 of Appendix A, the literature search string, the overview of the relevant academic literature and the review of the theoretical literature on socio-technical transitions and innovation systems are presented. Several authors proposed looking at technological transitions as a process of evolutionary reconfiguration of above-described dimensions (Rip & Kemp, 1998; Rotmans et al., 2001). A Technological Innovation System (TIS) framework can be used for structurally analysing technological change, addressing the wide functional dynamics of innovation systems (Hekkert et al., 2007; Bergek et al., 2008). While this framework provides grip of the assessment of technological development within the innovation system, its main aim is to provide a lens for policymakers on determining how well incumbent key actors, networks and institutions are functioning within the TIS and how to formulate policy as a response. Therefore, this TIS framework neglects the role of company strategies in driving system change (Markard et al., 2015; Planko et al., 2017).

An overall neglection of a company perspective as a means to accelerate transitions in socio-technical transitions literature is currently lacking (Roberts et al., 2018), while this crucial to address. Companies hold significant economic importance in our society as they possess large key assets and have both capacities and capabilities to make significant investments in the development of novel technologies (Hockerts & Wünsterhagen, 2010). Hereby, companies encompass the economic means to accelerate the development towards sustainable transitions in the sector. Also, Penna & Geels (2015) discuss that the involvement of companies is crucial for driving innovations and ensuring successful implementation of sustainable technologies, as their involvement prevents a potential resistance to change. Especially within the aviation industry, where product innovation is characterized by large-scale investments and powerful incumbents, it is of importance to take a managerial perspective into consideration for steering the innovation system towards sustainable transitions. Also, as stated before, the uncertainties that are associated with socio-technical transitions affects decision-making within firms (Sniazhko, 2019), incumbent firms in the aviation sector might be hesitant in making large-scale investments for sustainable aircraft designs. This potentially hampers innovation on sustainable aircraft technologies, posing challenges to meet the EU Green Deal ambitions. Therefore, it is essential to involve incumbent companies in the aviation industry by adopting a company perspective in this master thesis research for addressing sustainable aircraft technologies and accelerating sustainable socio-technical transitions.

The framework of Ortt & Kamp (2022) addresses the importance to adopt a company perspective by proposing a TIS analysis framework from a company perspective, in which strategies are proposed to increase chances of successful implementation of innovation. Here, the TIS has been divided into 7 structural components that together represent all important dimensions of the TIS. The incompleteness or incompatibility of one or more TIS building blocks potentially hampers large-scale diffusion of the innovation. The TIS building blocks include*: (I) Product performance and quality; (II) Product price; (II) Production system; (IV) Complementary products and services; (V) Network formation and coordination; (VI) Customers; (VII) Innovation-specific institutions.* By investigating the completeness of TIS building blocks and assessing influencing conditions that are potentially hampering large-scale diffusion of innovation, specific niche introduction strategies can be formulated for sustainable innovations.

The framework of Ortt & Kamp (2022), however, currently still lacks a specific application to an industry. A specification of the framework on the aviation industry would enhance directionality of the deployment of sustainable aircraft technologies, thereby contributing to its sustainable transition. Furthermore, while the framework provides a method to assess the current state of the innovation system around a novel technology through assessing seven interdependent TIS building blocks, it does not provide a dynamic examination on how these building blocks are expected to develop over time. This prospect of the developments of TIS building blocks over time is essential for identifying bottlenecks and addressing these before implementation of the technology is possible. Moreover, the framework solely considers one innovation, whereas the sustainable transition of the aviation industry can be achieved through a wide range of sustainable aircraft technologies. These dynamic and evaluative dimensions would especially be interesting for companies to adjust their investment strategies upon. In this master thesis research, the framework of Ortt & Kamp (2022) will be expanded to address this knowledge gap.

## 1.3 RESEARCH QUESTIONS AND OUTLINE

From this literature analysis, it becomes evident that the current academic frameworks and studies offer little insight into how incumbent companies can, in practice, effectively formulate strategies for implementing sustainable innovations, considering the required changes in TIS building blocks over time. Moreover, it is still unknown how strategies can be devised that directly contribute to the acceleration of socio-technical transitions to sustainability. These issues are particularly true for the aviation industry, which currently introduces multiple sustainable aircraft options that are competing for dominance as the main alternative for the socio-technical transition to net-zero aviation. As sustainable transitions within aviation are expected to be achieved through the contribution of multiple aircraft innovations, which has not specifically been investigated in literature, the following research question is addressed:

*How can a TIS analysis from a company perspective guide incumbent firms in the aviation industry in taking steps towards the deployment of sustainable aircraft technologies over the next decades?*

To address the main research question, the sub questions presented below will be considered. Sub question one addresses the modifications and specifications that need to be made to the framework of Ortt & Kamp (2022) to apply it to the aviation industry. Sub question two assesses the current state of the TIS building blocks for a hydrogen aircraft. Since the sustainable aircraft technologies under consideration are emerging technologies, it is expected that not all building blocks will be complete at this stage, leading to the identification of influencing conditions that hamper completeness of incomplete TIS building blocks. Subsequently, the time frame in which the incomplete building blocks are expected to be complete is addressed. Sub question 3 addresses the same method for analysing the ultra-efficient aircraft. Based on these findings, sub question 4 addresses the comparison of these analyses and how it affects the sequence of steps that need to be taken for building or circumventing incomplete TIS building blocks towards completeness.

*SQ1: How can the TIS framework of Ortt & Kamp (2022) be modified to be applied to the aviation industry?*
*SQ2: To what extent are the TIS building blocks of hydrogen aircraft considered complete, and which influencing conditions and prospects for completeness are present?*
*SQ3: To what extent are the TIS building blocks of ultra-efficient aircraft considered complete, and which influencing conditions and prospects for completeness are present?*
*SQ4: How do the TIS analyses compare to each other and how does it affect the deployment of the sustainable aircraft technologies in terms of building on or circumventing non-complete TIS building blocks?*

## 1.4 RESEARCH OBJECTIVE

The main objective of this research is to evaluate which sustainable alternative is most compatible with the current socio-technical regime for implementation in the aviation industry. By providing grip on what potential bottlenecks might be present for which dimension of the value chain of aviation regarding the implementation of the sustainable aircraft technologies, valuable information on how to address sustainability challenges in a short amount of time will be provided. This will be presented in the form of a deployment strategy elaborating on which technological alternative to implement when, including the sequence of addressing the identified bottlenecks of the implementation TIS building blocks of the sustainable aircraft technologies.

A case study approach with Airbus' perspective has been chosen since innovation and industrial specialisation of aircraft takes place at the producer side. Airbus is Europe's main aircraft OEM making it a powerful incumbent which has the resources that new entrances often lack for commercializing new products (Eppinger et al., 2021). Moreover, Airbus has set ambitious sustainability goals for implementing hydrogen-fuelled aircraft and ultra-efficient aircraft in a short timeframe, making them a key actor in the pathway towards sustainable aircraft implementation in Europe (Dube & Nhamo, 2020; Modarress Fathi et al, 2023; Airbus, 2023b). By investigating which alternative would be most strategically advantageous for Airbus to deploy, the opportunity of rapid adoption and implementation of sustainable aircraft is expected to be stimulated. Nevertheless, the results of this Master Thesis research will provide valuable insights for more dimensions within the value chain of aviation than just the producer side. As the TIS framework provides an overview of the system surrounding the technology, its implementation will be evaluated from various perspectives which expands relevance to multiple other actors. Moreover, policymakers can benefit from the results of the research by understanding the development of sustainable technologies from an industry perspective and acknowledging their role in the sustainable socio-technical transition dynamics.

## 1.5 LINK TO COSEM MASTER PROGRAM

This research links logically to the CoSEM Master programme as it regards a socio-technical system perspective of the aviation industry for investigating how to enhance sustainable aircraft transitions. The actors, institutional environment and technological components in the aviation ecosystem together form an interconnected complex system in which trajectories towards sustainable transitions are highly dependent on interactions between key stakeholders. As the CoSEM program focuses on such complex systems surrounding an innovation, it has proposed the relevant tools to assess the socio-technical dimensions that influence the implementation of sustainable aircraft technologies for the aviation industry. This includes a thorough understanding of how technological innovations are subject to the interplay between technology, infrastructure, logistics, regulations, interests of actors within the value chain of aviation and changes in human behaviour.

## 1.6 MASTER THESIS OUTLINE

The Master Thesis research is structured as follows. Chapter 2 represents the theoretical framework proposed in this Master Thesis research. Here, relevant literature regarding technological transitions, innovations and technological innovation systems are presented. Chapter 3 elaborates on the methodology applied within the study. Here, the conceptual framework for analysing technologies within their TIS from a company perspective, derived from the framework of Ortt & Kamp (2022), is proposed. This is followed by a representation of the data collection method. Chapter 4 represents the application and scoping of the TIS framework to the aviation industry, after which a delineation of the industry segment and of the sustainable aircraft technologies that is considered is provided. Chapter 5 analyses hydrogen aircraft technology according to the conceptualised TIS framework. Chapter 6 analyses ultra-efficient aircraft technology according to the conceptualised TIS framework. Chapter 7 provides an evaluation of the outcomes of the TIS analyses and formulates a deployment strategy on which sequence the sustainable aircraft technologies should be deployed and which TIS building blocks should be built first for its implementation. Chapter 8 presents the conclusions and discussion of the Master Thesis research and elaborates on both the practical implications for the aviation industry and policymakers and on recommendations for future research in academics.

# CHAPTER 2: THEORETICAL FRAMEWORK

In this chapter, an overview of the theoretical context of the study is provided. Section 2.1 elaborates on technological transitions theory. Section 2.2 discusses the Technological Innovation System perspective. Section 2.3 elaborates on the Technological Innovation System framework from a company perspective, used as basis for this Master Thesis research. Section 2.4 describes how this framework will be applied to the Master Thesis research and which extension will be applied. Section 2.5 provides the main conclusions of Chapter 2.

## 2.1 SOCIO-TECHNICAL TRANSITIONS

The basis on sustainable transitions in the aviation sector can be found in wider socio-technical transition literature. Technological transitions do not solely focus on technological development but incorporate changes in dimensions of culture, institutions, industrial networks, and infrastructure (Geels, 2002). Several authors proposed looking at technological transitions as a process of evolutionary reconfiguration of these dimensions (Rip & Kemp, 1998; Rotmans et al., 2001). Following from this, Geels (2002) presented a multi-level perspective (MLP) as a framework to evaluate these interactions in which three distinguishable entities have been proposed to form the key interactions and changes of socio-technical systems. These include (I) the landscape, (II) the regime and (III) the niches. The landscape represents the slowly evolving cultural dimensions and external trends and shocks that actors cannot control, which drive change by putting pressure on the current circumstances. The regime represents the incumbent socio-technological configuration of technology, infrastructure, market, institutions, and knowledge. The niches represent actors and networks that drive novel system-changing innovations which could potentially be implemented in the socio-technical regime when this is opening. While the MLP framework grants thorough insights in the interplay between key levels of socio-technical systems, it has limitations for guiding innovations practically towards implementation.

As becomes evident in literature on socio-technical transitions, socio-technical regimes are inherently associated with path dependence and lock-in. Path dependency can be described as a path of the regime that has been stabilized over many years, making it highly difficult to change from the regime (Clausen et al., 2017). Thereby, it reinforces persistence of the regime in sub-optimal solutions, also referred to as technological lock-ins (Cairns, 2014; Foxon, 2007). As these concepts show that the socio-technical regime is hampered in change, there is a need for guidance of technological change for addressing sustainability challenges (Markard, 2011). Literature on Strategic Niche Management (SNM) addresses this notion and discusses how sustainable innovations pathways can be facilitated by providing technological niches to the innovations, referring to nurtured protected spaces, enabling technological development through experimentation with incumbent user practices and regulations (Schot & Geels, 2008). SNM comprehensively addresses what innovations require before they could potentially be implemented in incumbent socio-technical regimes, however, a focus on niche protection spaces does not provide a coherent representation on what changes need to be made within the socio-technical regime for the implementation of sustainable innovation.

## 2.2 TECHNOLOGICAL INNOVATION SYSTEMS

To identify which elements are essential in socio-technical system to enhance changes in incumbent socio-technical regimes towards the implementation sustainable aircraft technologies, the Technological Innovation System approach from a company perspective is suitable. Here, the sustainable aircraft technologies represent the innovations of the TIS framework, which can be distinguished in incremental innovation and radical innovation. Incremental innovations refer to new features in already existing products or services, meaning that only minor modifications over an already deployed technology are made (Ali, 1994). Compared to radical innovations, they have a limited range of novelty and therefore require less systematic changes (Sandberg & Aarikka-Stenroos, 2014). Radical innovations on the other hand refer to entirely new technologies with differences in such a substantially number of dimensions that it changes entire business environments (Utterback, 1994). Here, a radical innovation can lead to new comparative advantages for firms resulting in only major players that proof to be withstanding towards such changes to survive. The process of exchange the old business environment for a completely new one has been discussed before by Schumpeter in the 1940s, who referred to the situation as *'creative destruction'*.

The notion of technological innovation systems (TIS) as an approach for analysing technological change has gained wide-spread attention (Hekkert et al., 2007; Bergek et al., 2008). Carlsson & Stankiewicz (1991, p. 94) had defined a TIS as *"a network of agents interacting in the economic/industrial area under a particular institutional infrastructure (…) and involved in the generation, diffusion and utilisation of technology"*. The TIS framework of Ortt & Kamp have adopted a company strategy, where the essential dimensions in technological innovation system have been conceptualised in a set of so-called TIS building blocks. These include*: (I) Product performance and quality; (II) Product price; (II) Production system; (IV) Complementary products and services; (V) Network formation and coordination; (VI) Customers; (VII) Innovation-specific institutions.* The TIS building block represent the main dimensions that are required to be, to a high extent, complete and compatible for large-scale diffusion of the innovation is enabled to take place. By investigating the completeness of TIS building blocks of the framework and assessing which influencing factors potentially will block large-scale diffusion of innovation, specific niche introduction strategies can be formulated. Especially in industries where product innovation is characterized by large-scale investments and powerful incumbents as in the aviation industry, it is of importance to take a firm perspective into consideration for steering the innovation system towards addressing sustainable challenges. Therefore, the TIS framework of Ortt & Kamp (2022) has been chosen as premise for analysing the sustainable aircraft technologies and practically formulating strategies for their deployment in this master thesis research.

## 2.3 METHODOLOGY OF TIS FRAMEWORK ORTT & KAMP (2022)

This section elaborates on the methodology of the TIS framework of Ortt & Kamp (2022). The TIS framework from Ortt & Kamp (2022) has its main objective to evaluate an innovation from a company perspective. By analysing two distinguished elements that play an important role, so-called TIS building blocks and influencing conditions, a methodology for companies to formulate niche introduction strategies for their innovations is proposed. In subsection 2.3.1, the concept of TIS building blocks will be elaborated on. In subsection 2.3.2, the influencing conditions that hamper TIS building block completeness will be explained. In subsection 2.3.3, the integration of these concepts into niche introduction strategies as proposed by the framework is described.

### 2.3.1 TIS BUILDING BLOCKS

The TIS framework as proposed by Ortt & Kamp (2022) represents a set of seven so-called TIS building blocks that are used as a reference to evaluate the different dimensions that are crucial to consider for the implementation of innovation. By differentiating whether the TIS building blocks are complete or not at the time of analysis, specific bottlenecks can be identified. These insights can subsequently help steering managerial decision making in how to overcome or mitigate these problems for an innovation to be implemented. An overview of the TIS building blocks including a small description is provided in Table 1.

TABLE 1: DESCRIPTION OF TIS BUILDING BLOCKS AS PROPOSED BY ORTT & KAMP (2022)

| TIS Building Blocks by Ortt & Kamp (2022) | Description |
|---|---|
| 1. Product performance and quality | The attraction of the product for the customer in terms of product performance and quality with reference to similar commercially available products. |
| 2. Product price | The financial and non-financial costs to acquire and use the product with reference to similar commercially available products. |
| 3. Production system | The availability and enhancement of the production system of the technological innovation, in terms of product quality and production costs. |
| 4. Complementary products and services | The availability of complementary products in services to support development, production, distribution, adoption, use, repair, maintenance, and disposal of the innovation. |
| 5. Network formation and coordination | The coordination and presence of a shared vision within the network of actors in the supply chain of the innovation. |
| 6. Customers | The potential customer segment that would largely benefit by using the innovation and their knowledge, means and willingness to acquire it. |
| 7. Innovation-specific institutions | The established set of formal and informal rules such as government policies, laws, standards and regulations and its long-term consistency. |

### 2.3.2 INFLUENCING CONDITIONS

After the identification of incomplete, or partly complete, TIS building blocks, an identification on the nature of the hampering to implementation is executed. The framework proposes seven so-called influencing conditions that could elaborate on the cause of the barrier. These influencing conditions can be present from across the value chain of aviation. This recognition is relevant for identifying which niche introduction strategy might be accurate to effectively position innovations for implementation. An overview of the influencing conditions including a small description is provided in Table 2.

TABLE 2: DESCRIPTION OF INFLUENCING CONDITIONS AS PROPOSED BY ORTT & KAMP (2022)

| Influencing conditions by Ortt & Kamp (2022) | Description |
|---|---|
| 1. Knowledge and awareness of technology | The fundamental and applied technological knowledge on the sustainable aircraft technologies, including on the aircraft itself, its production system, and its complementary infrastructure. |
| 2. Knowledge and awareness of application and market | The knowledge on market structure and the segments in which the sustainable aircraft technologies can potentially be implemented. This could be applicable for both potential customers and suppliers. |
| 3. Natural, human and financial resources | The availability of natural resources, human resources and financial resource for the implementation of the alternative. |
| 4. Competition | Competition of sustainable alternative with incumbent aircraft technology and competition among sustainable aircraft technologies in terms of different production systems, complementary infrastructure, and networks among companies. |
| 5. Macro-economic and strategic aspects | The status of economic system -regression or growth- and its influence on strategic policies of countries on the aviation industry. This includes |

| | |
|---|---|
| | availability of funds, conditions of market structure or the contemporary way of doing business. |
| 6. Socio-cultural aspects | The norms and values held by important customers and important stakeholders in the socio-technical system. Refers to the informal behaviour of actors in the TIS. |
| 7. Accidents and events | Accidents that occur both within and outside the TIS, referring to technological failure of the sustainable aircraft technologies or external events such as war or natural disasters. |

### 2.3.3 FORMULATING NICHE INTRODUCTION STRATEGIES

According to the output of the analyses from the formerly discussed dimensions, niche introduction strategies can be formulated. Here, the framework the adaptation phase of innovations between first introduction and initial stages of large-scale deployment. Ortt & Kamp (2022) state that when all TIS building blocks are complete, introduction strategies for large-scale deployment can be applied. Logically, when the TIS building blocks are incomplete, there is no viable option to implement the technology. In the case where some building blocks are incomplete, the identified influencing conditions causing these building blocks to be incomplete provides specification that can be used for the niche introduction strategy. The exact introduction strategy is specified on depending on which building blocks are incomplete and which influencing conditions play a role in this. A visualisation of the TIS framework of Ortt & Kamp (2022) is provided in Figure 1.

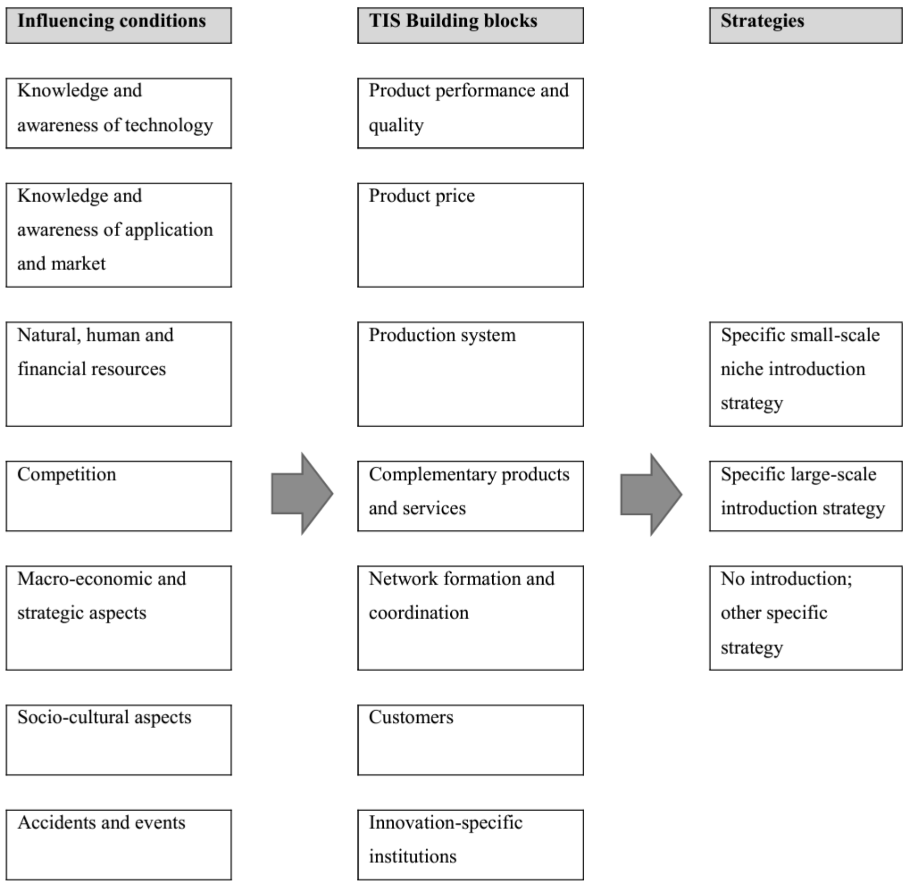


FIGURE 1: TECHNOLOGICAL INNOVATION SYSTEM FRAMEWORK ORTT & KAMP (2022)

## 2.4 APPLICATION OF TIS FRAMEWORK TO THE MASTER THESIS RESEARCH

As briefly stated before, the TIS analysis itself in framework of Ortt & Kamp (2022) will be extended for the objective of this Master Thesis research. While the framework of Ortt & Kamp (2022) provides essential insights in the implementation of innovation for technological transitions, it only examines the current situation without considering prospects of the development of an innovation in the short-term future. First, the influencing conditions present for incomplete and partially complete TIS building blocks will be analysed, where subsequently a prospect of completeness will be created. While this prospect of completeness is highly subject to uncertainties and other unknown dimensions that influence development, it does provide grip on orders of timeframes when a technology is considered ready for implementation. This will provide a dynamic dimension to the TIS framework where not only current situations and trends are considered, but a timeframe of when these trends are expected to be addressed as well.

Moreover, the framework focuses on one innovation and thereby lacks the opportunity to evaluate multiple solutions which can address sustainability challenges. Nevertheless, especially when addressing innovations under development for sustainability challenges, there is a range of different technologies that have the potential to be implemented. Also, for the sustainable transition of the aviation industry, an assessment of multiple technologies ranging is desirable. For large established industries, so-called drop-in technologies are necessary before the introduction of more radical, system changing novel innovations (Geels, 2002; Rye, 2010). Drop-in technologies are incremental innovations in the current socio-technical regime, which resemble currently deployed technologies and have a large area of reconciliation with the current socio-technical system, thus making it easier to implement the technology. As no broad changes are needed, incremental drop-in technologies such as deployment of SAF or focusing on enhancing efficiency of aircrafts, might be relevant for the short-term implementation of sustainable aircraft before a more system changing, radical innovation, such as hydrogen aircraft or electric aircraft, are ready to be implemented.

Furthermore, in some cases, the different technologies together with the deployed technology will participate in the race for becoming the established 'dominant design', as proposed by Utterback & Abernathy (1975). The dominant design refers to the technology that turned from one alternative next to a range of others to a technology that became the standard in the socio-technical regime. In other cases, however, the technologies should be deployed next to each other as technologies that complement each other in their positive contributions and shortcomings. For the aviation industry, the latter argument is applicable, leading to an evaluation of the sustainable aircraft technologies with the ambition to implement them both rather than comparing the sustainable aircraft technologies in an isolated manner and compare them to each other. As it is desired that implementation of either sustainable alternative is accomplished as soon as possible, it is desirable to consider a broad range of sustainable aircraft technologies and compare their individual TIS analyses in terms of compatibility to the socio-technical system.

The results of the TIS analyses on the proposed sustainable aircraft technologies and the dynamic dimension of the TIS framework enables insights under which timeframes it is desirable to introduce which technology to the industry. Rather than providing niche introduction strategies for each technology as proposed in the framework, the results will be translated into a higher-level understanding in the sequence of implementation of the sustainable aircraft technologies, and how sufficient support should be provided to incomplete TIS building blocks. This will grant industry and governments insights in what bottlenecks are currently present for the deployment of the sustainable aircraft technologies and in which sequence to address them.

## 2.5 CONCLUSION CHAPTER 2

Chapter 2 has elaborated on the theoretical context of this master thesis research. First, the broader literature on socio-technical transitions has been discussed. More specifically, the multi-level perspective and literature on strategic niche management have been elaborated on, including a justification why both frameworks are not sufficiently applicable for addressing the identified research gaps of this thesis. Furthermore, a technological innovation system perspective for analysing technological changes more practically has been proposed. Here, the framework of Ortt & Kamp (2022) has been discussed, including an explanation of TIS building blocks as main dimensions for evaluating crucial dimensions for the deployment of innovations. Furthermore, the methodology of the framework of Ortt & Kamp (2022) has been discussed, elaborating on the evaluation of TIS building blocks, the identification of influencing conditions that potentially pose bottlenecks for the implementation of the innovations, and the formulation of niche introduction strategies. Lastly, the application of the TIS framework of Ortt & Kamp (2022) to the master thesis research has been elaborated. Here, the formulation of a prospect of completeness for non-complete TIS building blocks has been introduced for providing a dynamic dimension to the TIS framework where not only current situations and trends are considered, but a timeframe of when these trends are expected to be addressed as well. Furthermore, a justification for the decision to focus on multiple innovations next to each other is granted for accelerating the sustainable transition of the aviation industry. Here, both incremental and more radical technologies will be addressed. Also, the decision to formulate a high-level deployment strategy in this master thesis opposed to a detailed niche introduction strategies from the Framework of Ortt & Kamp (2022) is justified.

# CHAPTER 3: METHODOLOGY

In this chapter, an outline of the conceptual framework that has been addressed in this research is presented. Section 3.1 addresses the research approach of this Master Thesis research. Section 3.2 addresses the conceptual framework developed for this Master Thesis. It should be noted that this conceptual framework is written in a general manner, where no focus has been laid specifically to the aviation industry. The application to the aviation industry can be found in Chapter 4. Section 3.3 elaborates on the data collection method applied for this study. Section 3.4 provides the main conclusions of Chapter 3.

## 3.1 RESEARCH APPROACH

This master thesis study used a qualitative research approach to investigate how the prospect of completeness of the TIS building blocks of the sustainable aircraft technologies guide incumbent companies on their deployment. A qualitative approach in terms of extensive literature study and interviews with relevant actors in the aviation industry was chosen for this research approach. Literature study is vital as large scale academic and industrial research is currently ongoing for sustainable aircraft technologies, making the state-of-the-art insights essential. This was obtained in the form of academic literature, company sustainability reports, white papers, and corporate news websites, including Airbus public knowledge. Moreover, as certain TIS building blocks and influencing conditions are shaped by other actors in the current socio-technical system, obtaining insights from experts from different angles was substantially relevant as well.

As stated before, a case study approach with Airbus' perspective was chosen since innovation and industrial specialisation of aircraft takes place at the OEM side. Airbus has set ambitious sustainability goals for researching on and developing sustainable aircraft in a short timeframe, making them a key actor in the pathway towards sustainable aircraft implementation in Europe (Dube & Nhamo, 2020; Modarress Fathi et al., 2023; Airbus, 2023b). By investigating which pathways towards sustainability would be most advantageous for Airbus, the opportunity of rapid adoption and implementation of sustainable aircraft within Europe is expected to be stimulated. Moreover, the objective of the analysis focused on sustainable aircraft implementation within Europe, with a specific focus on the Dutch/German ecosystem. In 2022, key players in the supply chain of the European aviation sector agreed to intensify cooperation to realise climate neutral aviation by 2050, also known as the *Flying Vision* initiative. Key players include airport Schiphol, airline KLM, aircraft producer Airbus and knowledge institutes TU Delft and NLR (TU Delft, 2022). As the Netherlands is particularly fixated towards sustainable flying, and the Airbus site located in Bremen specifically has close contacts with Dutch actors among the value chain of aviation, the delineation to the Dutch/German ecosystem is appropriate for the objective of this research. As the Netherlands is stated to have a leading position in airport innovation and aircraft maintenance within Europe (NAG, n.d.), introduction of novel aircraft technologies within its operational system in the Dutch/German ecosystem could influence broader changes within Europe.

## 3.2 CONCEPTUAL FRAMEWORK

This section presents the conceptual framework that was applied in the research, granting an overview of the steps that will be used for the analysis. Subsection 3.2.1 addresses the steps taken to adjust the framework to the industry under consideration. Subsection 3.2.2 establishes the scope of the research in terms of industry segment and thus a delineation of corresponding technologies. Subsection 3.2.3 elaborates on how to establish a baseline of reference for the completeness of the TIS building blocks of the technologies. Subsection 3.2.4 examines how prospects of completeness can be formulated for incomplete of partially complete indicators. An overall representation of the conceptual framework of this thesis can be found in Figure 2.

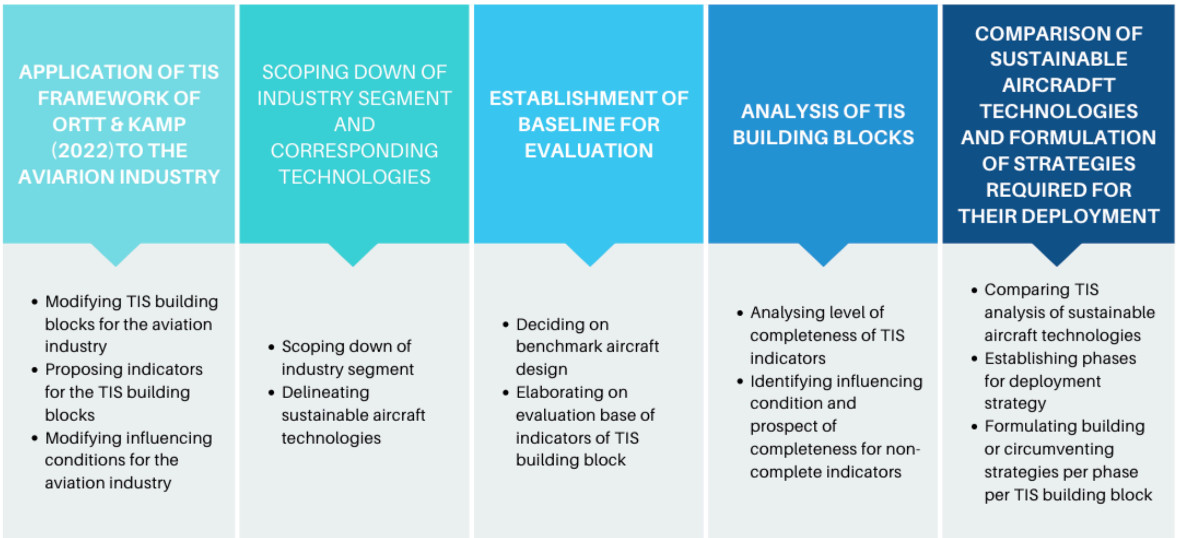


FIGURE 2: REPRESENTATION OF CONCEPTUAL FRAMEWORK OF THIS MASTER THESIS RESEARCH

### 3.2.1 APPLICATION OF THE TIS FRAMEWORK TO THE AVIATION INDUSTRY

The first step for creating the conceptual framework was to specify the framework of Ortt & Kamp (2022) on the industry under consideration. Hereby, the TIS building blocks and influencing conditions both needed to be carefully considered on a high-level basis and needed to be, where necessary, adjusted to the industry. By focusing and adjusting the framework on such industry- specific traits, it would be more suitable and reliable to evaluate a TIS within an industrial use case. Furthermore, the TIS building blocks were delineated into so-called 'indicators' which represent more specific elements to evaluate the completeness of TIS building block on. These indicators provide a more concrete basis on which dimensions the completeness of the TIS building blocks for an innovation can be analysed. For these steps, a high-level knowledge on the objectives and business-as-usual of the specific industry was required. Therefore, knowledge exchanges with business managers that have experience with industry traits and how business is conducted in the sector was essential for accurately grasping the industry-relevant traits. Chapter 4 presents the adjustments made to the framework for the aviation industry.

### 3.2.2 SCOPING DOWN OF INDUSTRY SEGMENT AND CORRESPONDING TECHNOLOGIES

As elaborated on before, it is interesting to evaluate a range of innovations as sustainable transitions in industry are often associated by a range of different technological solutions (Elzinga et al., 2023). To scope the range of sustainable aircraft technologies down, an industry segment was chosen to focus the analysis on. This focused industry segment delineated the range of sustainable aircraft technologies that are technologically feasible to implement. A reference of three sustainable aircraft technologies was most desirable to evaluate, since it would encompass a range of incremental and radical innovations. The options under considerations included hydrogen aircraft, ultra-efficient aircraft, and aircraft with 100% SAF deployment. Nevertheless, due to time constraints of this master thesis research, a reference of two alternatives, hydrogen aircraft and ultra-efficient aircraft, was chosen. This is elaborated upon in subsection 4.3.2.

### 3.2.3 ESTABLISHMENT OF A BASELINE FOR EVALUATION

The next step was to establish a baseline of evaluation for when the indicators of TIS building blocks of the sustainable aircraft technologies were considered complete. For this case study, an already established aircraft technology was chosen as a benchmark technology, which will be considered the reference for evaluating 'completeness' of the TIS analyses of the sustainable aircraft technologies. This is a conventional aircraft design with 50% SAF drop-in. Here, the indicators of the TIS building blocks of the sustainable aircraft technologies were evaluated on their completeness in terms of competitiveness to the indicator for the established aircraft technology. It is important to understand that an incomplete or partly complete building block does not mean that the alternative is subject to a permanent bad performance of the dimension. It rather shows that with the present performance, implementation of an alternative would potentially be hampered. After the indicators of the sustainable aircraft technology were evaluated according to the deployed technology, a higher-level conclusion on the completeness of the overall TIS building block was proposed. The performance of completeness of the overall TIS building block was considered equal to the mean of the performances of each separate TIS indicator. While there is a likelihood that some indicators may have proved to be of more relevance than others, this Master Thesis assumed that all indicators were equally important for the overall performance of the complementary TIS indicator. This was decided to limit complexity of analysis, making it more feasible for the short timeframe of this research.

### 3.2.4 ANALYSIS OF TIS BUILDING BLOCKS

As elaborated on in subsection 3.2.1, a set of indicators were proposed to represent the TIS building blocks. To evaluate the level of completeness of overall TIS building blocks with respect to the benchmark technology, the level of completeness for each indicator was assessed first. When an indicator was considered incomplete or partially complete, the main bottlenecks hampering completeness were identified by analysing which influencing condition or conditions are applicable for the situation, concurring to the methodology of Ortt & Kamp (2022). Subsequently, a prospect of completeness of the incomplete or partially complete indicator was provided, referring to a conception of a timeframe in which the indicator is considered to reach completeness. The prospect of completeness grants an insight in the timeframe in which each indicator and the overall TIS building blocks are considered complete and thus implementable. When this prospect of completeness shows a relatively late timeframe, this underpins the dimensions in the TIS which requires building on most in the short timeframe.

Here, a literature study was performed to formulate this prospect of completeness, using knowledge of e.g. expected technological developments or calculated price projections to formulate a timeframe in which the indicator is considered complete. When such knowledge was lacking in literature, interviews with knowledgeable experts were conducted in which such prospects were formulated by the experts. Here, input from a minimum of two experts were desirable for limiting subjectivity of the data. In the rare circumstance that no hard data was available for this formulation, insights of the researcher were used to establish a timeframe. These exceptions are elaborated on in subsection 4.4.2. After the analysis of each stand-alone indicator, the overall TIS building block was analysed based on the performance of the level of completeness of its indicators. Here, the average performance of the indicators was used to formulate the level of completeness for the overall TIS building block. Moreover, the latest prospect of completeness of its indicators were taken as a reference prospect of completeness for the overall TIS building block.

### 3.2.5 COMPARISON OF SUSTAINABLE AIRCRAFT TECHNOLOGIES AND FORMULATION OF STRATEGIES REQUIRED FOR THEIR DEPLOYMENT

Following the analyses on the indicators and the established level of completeness for TIS building blocks, the level of completeness of the overall TIS of the sustainable aircraft technologies was formulated as well. For both sustainable aircraft technologies, these results represented the compatibility of their TIS to the benchmark technology. These TIS analyses could be compared to each other, showing which technology was most compatible in the current socio-technical regime and could be considered the one where low hanging fruits in terms of time towards implementation could be picked. Here, the main rationale is that compatible technologies can be implemented more easily, thus accelerating the deployment of more sustainable aircraft technologies for the sustainable transition of the aviation industry. This did not detract from the necessity of the deployment of other alternatives as well, but rather proposed a method in which sequence to introduce them to the socio-technical system.

Subsequently, strategies for deployment were formulated. Here, the deployment strategies proposed in this thesis deviated partly from the formulation of niche introduction strategies as proposed by Ortt & Kamp (2022). The authors discuss formulating niche introduction strategies based on *(I) timing, (II) scale*, and *(III) type* of strategies. The last dimension was addressed as well in the study of Ortt et al. (2013), which proposed ten different types of niche strategies for the introduction of state-to-the-art technologies customized for certain market situations. Here, strategies were formulated to implementing technologies regardless of the bottlenecks that are present, by ensuring these are identified and circumvented. Nevertheless, the deployment strategies proposed in this master thesis research solely focus on the first two dimensions, *timing* and *scale*. Here, strategies for building on non-complete TIS building blocks of the sustainable aircraft technologies are key before deployment of either one is achievable. The decision not to focus on the *type* of niche introduction strategies was made to reduce the complexity of analysis within the short timeframe of this master thesis research and the time before implementation of either one is expected over a decade, leading the formulation of niche introduction strategies at this instance to be arbitrary by the time they should be applied.

A strategy focusing on deployment of all sustainable aircraft technologies was chosen as the largest improvement of sustainability within the aviation industry is expected from a range of different technological solutions (TU Delft & NLR, 2021). Here, the formulated prospect of completeness of the TIS analyses of both sustainable aircraft technologies were used as a reference timeframe in which deployment strategies were necessary. According to the current development of the sustainable aircraft technologies and the insights of the prospect of completeness, three distinguished phases were established. Here, the first phase represents the time required for maturing technological bricks, referring to the most relevant technological components of the sustainable aircraft technologies that distinguish them from conventional aircraft. This maturation is fundamental to be completed before robust design configurations could be proposed for certification. The second phase represents the time required before most compatible sustainable aircraft alternative could be deployed. The third phase represents the time required before the least compatible sustainable aircraft could be deployed. In all three phases, strategies for building on stand-alone incomplete or partially complete TIS building blocks were provided, as well as strategies for circumventing barriers for implementation where appropriate. These strategies were formulated according to the identified bottlenecks in the TIS analyses.

## 3.3 DATA COLLECTION METHOD

This section elaborates on the data collection method applied to this study is elaborated upon. Subsection 3.3.1 discusses the academic and grey literature that were reviewed for this study. Subsection 3.3.2 represents the stakeholder selection that was applied to obtain respondents, followed by an overview of the exploratory interviews that were conducted for this research. This includes a list of respondents as well as an explanation on how the interviews were executed.

### 3.3.1 ACADEMIC LITERATURE, POLICY DOCUMENTS AND GREY LITERATURE REVIEW

As stated before, qualitative data was mainly obtained in the form of academic literature, ranging from literature on socio-technical systems to literature from aerospace research groups on technological specifications of the sustainable aircraft technologies, to literature from energy research groups regarding the hydrogen supply chain. When academic literature on the current state of the TIS building blocks, the influencing conditions potentially forming bottlenecks and their prospect of completeness was lacking, other sources of literature were used. These include policy documents and white papers, and grey literature on company sustainability reports, technology road maps, and corporate news websites such as Aviation Weekly and Airbus public knowledge.

### 3.3.2 EXPLORATORY INTERVIEWS

The exploratory interviews served as a complementary collection of data next to the academic and grey literature study and primary governmental sources. A set of semi-structured interviews was conducted to obtain relevant insights from key actors in the aviation system, particularly for validating information and formulating prospects of completeness non-complete indicators of TIS building blocks. In this way, more cross organisational perspectives on how experts perceive the current and future development of the TIS building blocks were obtained. The semi-structured interviews granted optimal space for insights from the interviewees and provided clear viewpoints on certain problems regarding indicators of TIS building block of the sustainable aircraft technologies. One limitation of this approach was that there potentially is an excess of information that needs to be filtered upon (Queirós et al., 2017). Therefore, the interviews were kept short and to the point.

Respondents from all dimensions of the value chain of aviation were identified within Airbus' company network. These actors include aircraft OEMs, airlines as customers, airports, safety regulators, experts from universities and experts from knowledge institutes. Table 3 presents an overview of the interviewed respondents for the master thesis research. Most of the interviews were conducted in person, apart from few that were conducted within an online meeting setting. Each interview had the duration of 30 to 40 minutes, in which a set of ten to twenty questions were asked regarding indicators of TIS building blocks and their expected prospect of completeness from the perspective of the respondents. As every actor encompasses an expertise on a different area, the questions were customized to the actor to a large extent. Nevertheless, all respondents were asked the same question on their perspective towards collaboration among actors and the presence of a shared vision on sustainability within the aviation industry, as it is particularly interesting to obtain insights from different actors within the value chain of aviation. Moreover, each respondent was asked to elaborate on their perspectives regarding potentially missing regulations from industry and governments.

To ensure valid answers from respondents, the researcher stated that while the master research was being executed from an Airbus perspective, the study concerns a systematic overview of the TIS surrounding sustainable aircraft technologies in the beginning of the interview. This was done to mitigate the extent to which respondents would grant incomplete, strategic or biased information. On top of that, questions were formulated in a high-level manner to mitigate the extent of strategic answers from respondents. Furthermore, research ethics were considered by anonymising the respondents in this Master Thesis research to restrict chances of re-identification. This was executed by referring to the respondents by the type of stakeholder that is represented and their field of expertise. Moreover, the respondents were asked to sign an informed consent document in which all relevant details in data management have been addressed, which is included in Appendix D.

TABLE 3: OVERVIEW OF INTERVIEW RESPONDENTS

| Stakeholder type | Area of expertise | Date | Communication means | Coding |
|---|---|---|---|---|
| Airline | Innovation strategy | 12/09/2023 | Personal communication | Int. Airline |
| Airport | Airport Innovation | 18/09/2023 | Online communication (Teams) | Int. Airport 1 |
| | Sustainable Project Manager | 15/09/2023 | Personal communication | Int. Airport 2 |
| Knowledge institute | Future aviation fuels | 20/09/2023 | Online communication (Teams) | Int. Knowledge institute |
| OEM | Senior Manager Technology | 09/10/2023 | Personal communication | Int. OEM |
| Safety regulator | - | 27/09/2023 | Online communication (Teams) | Int. Safety regulator |
| Sustainable start-up | Strategy and business developer Hydrogen propulsion system | 14/09/2023 | Personal communication | Int. Start-up |
| University | Innovation strategy hydrogen | 13/09/2023 | Personal communication | Int. University |

## 3.4 CONCLUSION CHAPTER 3

Chapter 3 has elaborated on the methodology chosen for this master thesis research. First, a justification for the research approach was provided, elaborating on the qualitative data collection method used and explaining the argumentations for using a case study approach with Airbus' perspective and delineating the scope on the Dutch/German ecosystem. Second, the conceptual framework of the master thesis research was introduced. This includes an elaboration on how the TIS framework of Ortt & Kamp (2022) was applied to the aviation industry, most prominently by proposing a set of indicators for each TIS building block, followed by an explanation of how scoping down on an industry segment has delineated the focus on two sustainable aircraft technologies. The establishment of a benchmark technology for evaluating both technologies on with respect to the completeness of the indicators of TIS building blocks was discussed. After, the analysis of TIS building blocks was discussed, discussing how their indicators were evaluated based on their level of completeness and influencing conditions and a prospect of completeness was formulated for non-complete indicators. The overall level of completeness of the overall TIS building block was derived from the mean of the level of completeness of the separate indicators. The steps for comparing the overall TIS analyses of the sustainable aircraft technologies and the method for introducing deployment strategies were discussed. This step deviates from the formulation of niche introduction strategies proposed by Ortt &

Kamp (2022), by introducing a three phased deployment strategy for building on or circumventing non-complete TIS building blocks based on timing and scale of implementation. Third, the data collection method was determined, using academic literature, policy documents, grey literature and exploratory semi-structured interviews for obtaining relevant insights for the analysis from multiple dimensions of the value chain of aviation.

# CHAPTER 4: APPLICATION AND SCOPING OF TIS FRAMEWORK TO THE AVIATION INDUSTRY

In this chapter, important characteristics of the aviation industry are discussed, after which the TIS framework proposed by Ortt & Kamp (2022) is modified to the case study of the aviation industry. Section 4.1 grants an overview of essential industry-specific constraints and opportunities for transitioning towards green aviation. These insights steer the delineation for the focus of this study. Section 4.2 discusses which adjustments are deployed to the framework to be applied to the aviation industry. Section 4.3 introduces the sustainable aircraft technologies that will be addressed and scopes the industry segment down, resulting in the potential to have a focused analysis. Section 4.4 addresses the base of evaluation for the research, elaborating on the established aircraft design that will be used as reference model for evaluation and on how the established indicators will be evaluated next to this reference design. Section 4.5 provides the main conclusions of Chapter 4.

## 4.1 INDUSTRY-SPECIFIC CONSTRAINTS AND OPPORTUNITIES

The main objective of the Master Thesis research is evaluating the implementation of sustainable aircraft for the aviation industry. This evaluation, however, must be considered according to a set of aviation industry-specific constraints. The IATA (2018) has identified three main constraining variables for the implementation of sustainable technologies. First, aircraft are subject to a very long useful life. Aircraft are in service for 20-30 years, resulting in a long time to achieve total fleet renewal. This long depreciation period also means that investments in new aircrafts takes time to be paid back. Second, aircraft require extensive time for development. Since aircraft development is subject to strict certification requirements and rigid safety standards, incorporating novel technologies can take up to 10 years for implementation. Here, more radical sustainable aircraft technologies would bring relatively more technological uncertainty, while large-scale investments should be made. This may lead to incumbents becoming risk averse and a desirability to focus on a more incremental technological development trajectory. Third, aircraft operations require a large amount of energy. For operating an aircraft at a speed of approximately 1000 km/hour and at an altitude of more than 10 km, a significant amount of energy is needed, and up until this point the energy-to-weight ratio of novel energy carriers have not proven to be up to the competing level of fossil fuels.

To address these constraints, IATA (2018) also proposed three dimensions of action that the aviation industry can take towards sustainability. First, the energy use of aircraft could be reduced by focusing on aerodynamic efficiency in order to save energy. This refers to an incremental technological development pathway as discussed before and could be addressed by developing an ultra-efficient aircraft technology, which results into a significantly reduced fuel consumption. Second, kerosene used as fuel for aviation could be changed into an energy carrier that does not emit GHG or that is produced in a carbon neutral manner. This refers to a more radical technological development pathway and could be addressed by introducing hydrogen as fuel for propulsion. Here, SAF could also be introduced to propel aircraft with carbon neutral fuel, although this would be considered an incremental technological development pathway as well. Third, unavoidable CO2 emissions that are emitted during the transition phase from kerosine-fuelled aircraft propulsion to an aircraft propulsion with a novel energy carrier could be captured to reduce the level of CO2 emissions from aviation. These insights underline the importance to consider aviation specific dynamics when developing and applying a framework. Current analysis shows that several pathways to net zero are possible, and we still don't know which one will become dominant. Therefore, this thesis will address both incremental and radical sustainable aircraft technologies.

## 4.2 ADJUSTMENTS OF FRAMEWORK TO THE AVIATION INDUSTRY

In this section, the framework proposed by Ortt & Kamp (2022) is modified according to the industry logic of aviation. Subsection 4.2.1 elaborates on the modifications made on the TIS building blocks. Section 4.2.2 introduces the set of indicators that has been proposed for evaluating each TIS building block. Section 4.2.3 discusses the modifications made on the influencing conditions.

### 4.2.1 MODIFYING TIS BUILDING BLOCKS FOR THE AVIATION INDUSTRY

In this subsection, the TIS building blocks adjusted to the aviation industry will be broken down into several indicators which represent the performance of the TIS building block. These indicators will represent the most important high-level dimensions that are essential to consider in a TIS analysis of sustainable aircraft. In the TIS framework proposed by Ortt & Kamp, seven building blocks have been proposed which are illustrated in the left column of Table 4. For this Master Thesis research, two building blocks have been slightly altered to put specific focus on the case of sustainable aircraft innovation in the aviation industry. TIS building block four, *complementary products and services* has been replaced by the proposed building block *complementary infrastructure and services*. This had been chosen as sustainable transitions in aircraft are highly intertwined with the availability of such sustainable transitions in its complementary infrastructures (Hoelzen et al., 2022a). Without any base of complementariness with fuel supply infrastructure and modifications of the refuelling system at the airport, an aircraft with a novel energy carrier could still not be implemented for transportation, even when it has been developed and certified.

Furthermore, building block seven, *innovation-specific institutions*, is altered to *innovation-specific and industry-wide institutions* as it does not include the complexity of institutions specified for the aviation industry. As Williamson (1998) stated, industry is influenced and shaped by informal and formal institutions on a higher level. Here, the informal institution refers to the embeddedness of culture in terms of customs and norms, and the formal institutions refer to the rules that are formally implemented by means of the influence of this embeddedness. As the cultural perception of people is currently steered towards the notion of sustainability, the aviation industry, among others, is influenced by this external pressure. Formal institutions, influenced by informal institutions, are expected to change more towards sustainability in the coming decades (Scoones, 2016), making this important to be recognized when considering the institutional environment of the TIS.

It should be noted that in the framework proposed by Ortt & Kamp (2022), the influencing factor of *socio-cultural aspects* that might influence a TIS building block somewhat represents this dimension. Nevertheless, while understandable that this is considered an influencing factor opposed to a building block in a regular TIS, a TIS driven by a sustainability motive is inherently driven by a changing cultural perception in what is considered correct development of technology and industry. This makes the industry-relevant institutions from cultural conceptions of society a key TIS building block in system formation around the technological innovation of sustainable aircraft. An overview of the TIS building blocks that will be addressed in the research is provided in Table 4.

TABLE 4: MODIFICATIONS OF TIS BUILDING BLOCKS OF FRAMEWORK ORTT & KAMP (2022)

| TIS Building blocks framework Ortt & Kamp (2022) | TIS Building blocks framework Master Thesis |
|---|---|
| 1. Product performance and quality | Product performance and quality |
| 2. Product price | Product price |
| 3. Production system | Production system |
| 4. Complementary products and services | Complementary infrastructure and services |

| | |
|---|---|
| 5. Network formation and coordination | Network formation and coordination |
| 6. Customers | Customers |
| 7. Innovation-specific institutions | Innovation-specific and industry-wide regulations |

### 4.2.2 PROPOSING INDICATORS OF TIS BUILDING BLOCK FOR THE AVIATION INDUSTRY

For the assessment of the seven TIS building blocks, a set of indicators have been proposed per building block. These together form the basis of the analysis on the completeness of these building blocks. Here, for both sustainable aircraft technologies, the proposed indicators are evaluated against the performance of indicators of the benchmark technology, a conventional aircraft with 50% SAF deployment. The design that has been chosen is the Embraer 175, which is elaborated on in subsection 4.4.1. As a reference, the indicators benchmark technology are always considered complete. Table 5 provides an overview of the proposed indicators per building block, including the reference source consulted to obtain this information. An elaboration on each indicator is provided in Appendix B.

TABLE 5: PROPOSED SET OF INDICATORS OF TIS BUILDING BLOCKS

| TIS building block | Indicators | Source indicator |
|---|---|---|
| 1. Product performance and quality | CO2 emissions | Batteiger et al., 2022 |
| | NOx emissions | Batteiger et al., 2022 |
| | Contrail formation | Batteiger et al., 2022 |
| | Range | Zhang et al., 2013 |
| | Passenger capacity | Gössling & Lyle, 2021 |
| | Required fuel per seat | Int. Senior Manager Airbus technology (14/07/2023) |
| | Refuelling time | Fuel Cells and Hydrogen 2 Joint Undertaking, 2020 |
| | Noise emissions | Spakovszky, 2019 |
| | Passenger comfort | Hall et al., 2013 |
| | Passenger perspective on aircraft | Exchange with TU Delft Supervisors (22/08/2023) |
| | Operational safety | Bendarkar et al., 2022 |
| 2. Product price | Investment costs of aircraft | Karakaya & Sriwannawit, 2015; Airbus technology valuation training, 2023 |
| | Fuel costs | Fuel Cells and Hydrogen 2 Joint Undertaking, 2020; Hoelzen et al., 2022a |
| | Switching costs | Ortt & Kamp, 2022; Airbus technology valuation training, 2023 |
| | Transaction costs | Ortt & Kamp, 2022 |
| 3. Production system | Know-how on the principle of production | Exchange with Senior Manager Airbus technology (14/07/2023) |
| | Ramp-up ability of the production system | Exchange with Senior Manager Airbus technology (14/07/2023) |
| | Ability to produce a fleet in an appropriate time | Exchange with Senior Manager Airbus technology (14/07/2023) |

| | | |
|---|---|---|
| 4. Complementary infrastructure and services | Fuel production infrastructure | Ansell, 2022; Grim et al., 2022; Shahriar & Khanal, 2022 |
| | Fuel distribution infrastructure | Hoelzen et al., 2022a; Leal Filho et al., 2022; Pechstein et al., 2020 |
| | Fuel storage infrastructure at airport | Meindl et al., 2023; Grim et al., 2022 |
| | Refuelling infrastructure at airport | Timmons & Terwel, 2022 |
| | Maintenance Repair Overhaul (MRO) services | Interview with Senior Manager Airbus technology (14/07/2023) |
| 5. Network formation and coordination | Actor network | Hekkert et al., 2007; Alcouffe et al., 2008 |
| | Communication among actors and steps taken towards a similar vision | Mousavi & Bossink, 2017 |
| | Number of consortiums | Hekkert et al., 2007 |
| | Number of workshops and conferences | Hekkert et al., 2007 |
| | Number of publications on technical progress | Exchange with Senior Manager Airbus technology (14/07/2023) |
| | Media coverage on concepts of sustainable aircraft technology | Exchange with Senior Strategy and Business Development Lead Airbus (05/07/23) |
| 6. Customers | Customer type | Kamp et al., 2004; Rogers, 1983 |
| | Involvement of potential customer in innovation process | Ortt & Kamp, 2022; Geels, 2004 |
| | Awareness of benefit compared to incumbent aircraft designs | Ortt et al., 2013; Rogers, 1983 |
| | Financial means to acquire aircraft | Ortt et al., 2013 |
| | Willingness to acquire aircraft | Ortt et al., 2013 |
| 7. Innovation-specific and industry-wide regulations | Governmental policies and regulations (EU wide) | Köhler et al., 2019 |
| | Industry self-regulation | Gunningham et al., 1997 |
| | Subsidies and incentives | Köhler et al., 2019; Borrás & Edquist, 2013 |
| | Safety regulations | Blind, 2012 |
| | International and regional standards | Allen & Sriram, 2000 |

### 4.2.3 MODIFYING INFLUENCING CONDITIONS FOR THE AVIATION INDUSTRY

Furthermore, Ortt & Kamp (2022) have proposed seven influencing conditions as illustrated in the left column of Table 6. For this Master Thesis research, influencing condition three, *natural, human, and financial resources*, has been dismantled into three distinct influencing conditions as they refer to different dimensions that potentially have an impact on TIS building blocks. This has been inspired by the methodology of the Master Thesis of Dwisatyawati (2022), which dismantles the influencing condition into three separate ones too. By breaking this influencing condition down, it is expected that more specific insights in bottlenecks within TIS building blocks are presented, hence granting the opportunity to formulate more specific niche introduction recommendations. An overview of the influencing conditions that will be addressed in the research is provided in Table 6.

TABLE 6: MODIFICATION OF INFLUENCING CONDITIONS OF FRAMEWORK ORTT & KAMP (2022)

| Influencing conditions by Ortt & Kamp (2022) | Influencing conditions framework Master Thesis | Description |
|---|---|---|
| 1. Knowledge and awareness of technology | 1. Knowledge and awareness of technology | The fundamental and applied technological knowledge on the sustainable aircraft technologies, including on the aircraft itself, its production system, and its complementary infrastructure. |
| 2. Knowledge and awareness of application and market | 2. Knowledge and awareness of application and market | The knowledge on market structure and the segments in which the sustainable aircraft technologies can potentially be implemented. This could be applicable for both potential customers and suppliers. |
| 3. Natural, human, and financial resources | 3. Natural resources | The availability of natural resources in terms of raw materials and components needed for the implementation of the alternative. |
| | 4. Human resources | The availability of human resources in terms of competences of human capital needed for the implementation of the alternative. |
| | 5. Financial resources | The availability of financial resources for the implementation of the alternative. |
| 4. Competition | 6. Competition | Competition of sustainable alternative with incumbent aircraft technology and competition among sustainable aircraft technologies in terms of different production systems, complementary infrastructure, and networks among companies. |
| 5. Macro-economic and strategic aspects | 7. Macro-economic and strategic aspects | The status of economic system -regression or growth- and its influence on strategic policies of countries on the aviation industry. This includes availability of funds, conditions of market structure or the contemporary way of doing business. |
| 6. Socio-cultural aspects | 8. Socio-cultural aspects | The norms and values from important customers and other key stakeholders in the socio-technical system. Refers to the informal behaviour of actors in the TIS. |
| 7. Accidents and events | 9. Accidents and events | Accidents that occur both within and outside the TIS, referring to technological failure of the sustainable aircraft technologies or external events such as war or natural disasters. |

## 4.3 SCOPING OF INDUSTRY SEGMENT AND CORRESPONDING TECHNOLOGIES

This section introduces the sustainable aircraft technologies that will be addressed by scoping the industry down to one segment. Subsection 4.3.1 elaborates on the industry segment that has been chosen as focus of the analysis. Subsection 4.3.2 discusses the range of potential sustainable aircraft technologies that are present and how these have been scoped down in the industry segment into two alternatives.

### 4.3.1 SCOPING DOWN OF INDUSTRY SEGMENT

For scoping down into one market segment, the broad aviation industry needs to be considered first. The aviation industry is highly cost-driven and subject to many specific requirements for efficiencies and safety of operation. Aircraft development, certification, and production processes altogether normally lead to approximately 10 years of implementation. According to Fuel Cells and Hydrogen 2 Joint Undertaking (2020), aircraft development cycles typically take about every 15-20 years until a new aircraft design is offered. Therefore, an OEM needs to define which product to focus on and for which customer segment it is meant, being unable to know specifically what is desirable in 10-20 years from now. This implies that, a high level of certainty is desirable to start innovation on a novel aircraft. To ensure that the aircraft will be commercially interesting, a focus on an existing customer segment of an airline is a viable strategy. This focus does not exclude the presence of customers other than airlines that might already be interested in the innovation once established, but merely acts as a commercial hedge to ensure that the innovation will be interesting for the main consumer, namely the airlines that are already clients of the OEM. Therefore, the industry segment has been scoped by focusing on the main customer need, which would be the availability of desirable flight routes for an airline. Here, the deployment of the sustainable aircraft technologies is specified on a preferable connection of flight routes.

In line with this understanding, the focus in this Master Thesis research will be laid on a regional aircraft. With a 13% share of the global fleet that contributes to 3% of CO2 emissions from aviation (Fuel Cells and Hydrogen 2 Joint Undertaking, 2020), regional aircraft may not be the foremost important segment to reduce emissions. However, it does provide a feasible first step for the aviation industry to experiment with incremental and, more importantly, radical innovations. Focusing on smaller aircraft designs with a shorter required range will serve as a less risky steppingstone to develop novel alternatives on technological improvement and enables a learning-by-doing process which will enhance learning curves of innovation (Stein, 1997). This is particularly interesting for aircraft OEMs who are looking for the deployment of sustainable aircraft in the most cost-efficient manner over its R&D phase. Logically, smaller products are less costly than larger products making it appealing for an OEM. It should be noted, however, that a regional aircraft is still subject to a time and cost intensive certification process, which would not necessarily be less costly than larger designs.

This scope choice is also underscored by the interviews. Several respondents have indicated that the integration of sustainable aircraft technologies would logically start at a regional market-scale before sizing it up to the larger aircraft market sector, which is relied upon in the emission intensive long-haul flight routes (Int. Airline; Int. Start-up; Int. Airport 1; Int. Airport 2; Int. Safety Regulator). Regional airports are subject to less complex interdependencies making them more flexible for implementation of sustainable innovations. Moreover, when collaborating with local energy providers and regional aircraft, coherent experimentation of the technology can take place. One respondent has stated that considering the technology, regulations, ground infrastructure and the energy supply chain, the implementation of a smaller aircraft would make experimentation, technological learning curves, building the supply chain and improving business models a manageable process (Int. Start-up). Another respondent argues that less stringent certification requirements are present for smaller aircraft types (Int. Safety Regulator).

For Airbus as an OEM, in particular, the regional segment is interesting to invest in. Domestic economies in Asia are growing, with China's regional air traffic segment expected to be growing by 200% in 2039 (Treat et al., 2021). Furthermore, projections show that regional air traffic is expected to increase 4.5% at a yearly rate as opposed to 4% of total commercial aviation, leading to a market demand of 8200 new regional aircraft over the next 20 years, with a market value of €390 billion (Clean Aviation, n.d.). Also, Airbus has proposed a hybrid-hydrogen turboprop design in their ZEROe programme with a passenger capacity below 100 passengers (PAX) (Airbus, 2023c), making a focus on a regional design for the evaluation of the sustainable aircraft technologies a suitable one. Since Airbus is expected to act as a second mover in this market due to start-ups that have plans for earlier commercialisation, knowledge spill overs from these R&D projects of start-ups would be beneficial for its strategy.

### 4.3.2 DELINEATING SUSTAINABLE AIRCRAFT TECHNOLOGIES

For addressing sustainability in aircraft technology, several technological solutions are present. Batteiger et al. (2022) have proposed a wide range of sustainable energy carriers that can be used for aircraft propulsion besides kerosene. These include batteries, hydrogen, SAF in the form of synthetic fuels, and SAF in the form of biofuels. These technological options are currently most discussed options in roadmaps and state-of-the-art conference papers (IATA, 2018; ATAG, 2020; TU Delft & NLR, 2021; Brenner et al., 2023; Salgas et al., 2023) and have been investigated and argued for or against, as presented in Appendix C. In this master thesis research, the analytical focus will be laid on the hydrogen-fuelled aircraft and the ultra-efficient aircraft as basis of analysis. From an Airbus perspective, these two sustainable aircraft technologies require novel aircraft designs and certification processes, which makes the comparison of the two alternatives interesting to receive. Moreover, hydrogen and ultra-efficient aircraft are included in the R&D focus of Airbus, making them essential to consider (Airbus, n.d.). Also these technologies provide a different degree of novelty to incumbent aircraft technology, making them interesting to assess next to each other from a socio-technical systems perspective. SAF in the form of a synthetic fuel is also an interesting technology to consider, which will be elaborated on in section 4.4.1.

## 4.4 ESTABLISHMENT OF BASELINE FOR EVALUATION

In this section, the baseline for evaluation of the sustainable aircraft technologies is introduced. Section 4.4.1 presents the chosen employed regional kerosene aircraft design with 50% SAF drop-in to serve as a base of evaluation of the sustainable aircraft technologies. Section 4.4.2 elaborates on the evaluation base used to evaluate completeness of the sustainable aircraft technologies through the TIS building blocks and their corresponding indicators. Section 4.4.3 elaborates on indicators for which establishing a prospect of completeness was hard, and how this has been addressed in the Master Thesis.

### 4.4.1 DECIDING ON BENCHMARK AIRCRAFT DESIGN

Based on the argumentation of section 4.3, this Master Research will focus on the regional aircraft segment, with a specific focus on a 70-90 PAX design with a range of approximately 1.500 km. As the focus of analysis is on the Dutch/German ecosystem, the industry segment could be applied to the KLM City Hopper, a subsidiary of the Dutch national airline KLM. The reference aircraft chosen for evaluation is an Embraer 175 '*high density configuration'* which is the smallest aircraft type used by KLM airlines. This aircraft has a passenger capacity of 88 seats and reaches a maximum range of approximately 4.000 km (Embraer, n.d.). The aircraft has a low-wing design, two turbofan engines and a conventional-tailed body (GlobalAir, n.d.). The Embraer 175 serves as a regional aircraft and is responsible for flight routes from Amsterdam to e.g. Turin (818 km), Graz (968 km) and Stuttgart (611 km) (KLM, n.d.) within the KLM City Hopper segment. An illustration of the Embraet 175 model is provided in Figure 3 and its main technological specifications have been provided in Table 7.


FIGURE 3: EMBRAER 175 AIRCRAFT DESIGN (EMBRAER, N.D.)

TABLE 7: KEY TECHNOLOGICAL SPECIFICATIONS OF THE EMBRAER 175 (EMBRAER, N.D.; GLOBALAIR, N.D.)

| Technological specification | Performance Embraer 175 |
|---|---|
| Passenger capacity | 88 |
| Range (full passenger capacity) | 4.074 km |
| Length | 31,68 m |
| Height | 9,73 m |
| Wing span | 28,71 m |
| Maximum take-off weight | 40.370 kg |
| Maximum landing weight | 34.100 kg |
| Maximum payload | 10.084 kg |
| Max cruise speed | 0,82 Mach[1] |
| Time to climb to FL350[2] | 18 min |
| Take-off field length (full passenger capacity) | 1.244 m/4.153 ft |
| Take-off field length (full passenger capacity) | 1261 m/4.137 ft |

Furthermore, this reference aircraft will be considered with a 50% drop-in of SAF in the form of synthetic fuels through the Fischer-Tropsch synthesis[3]. From an OEM perspective, 50% drop-in of SAF next to kerosene does not require significant aircraft alterations and certification processes (CAAFI, 2023), meaning that this alternative could be regarded as system optimization technology from an OEM perspective. Therefore, this alternative is not chosen to focus analysis on, but rather as a business-as-usual baseline reference for the transition towards a sustainable aviation industry. The European ReFuelEU Aviation initiative has stated to oblige fuel suppliers to distribute SAF in order to increase the uptake of SAF by airlines (Think Tank European Parliament, 2023). By 2025, 2% of fuel supplied to EU airports should consist of SAF and by 2050 this should be 70% (Euronews, 2023a). This underlines that 50% SAF deployment in the incumbent regional aircraft model Embraer 175 makes a relevant reference technology for the two alternatives to be evaluated on.

[1] The Mach number is a dimensionless quantity representing the ratio of flow velocity tot he speed of sound in the medium (Schochet, 2005).
[2] FL350 refers to the altitude of 35.000 feet, equal to 10,7 km, above sea level.
[3] The Fischer-Tropsch Synthesis is a catalytic process where hydrogen and CO are converted into synfuels, such as SAF (Weststrate et al., 2016).

### 4.4.2 EVALUATION BASE OF INDICATORS OF TIS BUILDING BLOCK

The sustainable aircraft technologies are compared to 50% SAF drop-in deployment of the Embraer 175 aircraft type based on the TIS indicators proposed in subsection 4.2.2 and its technological characteristics elaborated on in section 4.4.1. While for most incomplete or partially complete TIS building block indicators the influencing conditions are identified and prospect of completeness is elaborated on, a few exceptions are present. First, due to time constraints within the Master Thesis research, several TIS building block indicators have not been analysed. Second, several TIS building blocks indicators represent elements that do not have a time dimension, thus cannot be related to an influencing condition or a prospect of completeness. Third, for other TIS building blocks indicators, a prospect of completeness was profoundly difficult to establish based on primary academic or grey literature and the semi-structured interviews. Therefore, reflections from the researcher obtained through the internship at Airbus and the Master Thesis process are provided. These reflections should not be considered as hard data, but rather as a proposition based on understanding of the researcher. All the exceptions of the analyses of the TIS building block indicators have been illustrated in Table 8.

TABLE 8: EXCEPTIONS ON EVALUATION BASE OF INDICATORS OF TIS BUILDING BLOCKS

| TIS building block | Indicators | Absence of analysis in this research | Absence of time dimension | Absence of hard data on prospect of completeness | Over reliance on one source for prospect of completeness |
|---|---|---|---|---|---|
| 1. Product performance and quality | $CO_2$ emissions | | | | |
| | NOx emissions | | | | |
| | Contrail formation | | | X *ultra-efficient aircraft* | |
| | Range | | | | |
| | Passenger capacity | | | | |
| | Required fuel per seat | | | | |
| | Refuelling time | | | | |
| | Noise emissions | | | | |
| | Passenger comfort | | | | |
| | Passenger perspective on aircraft | | | X *both aircraft* | |
| | Operational safety | | | | X *ultra-efficient aircraft* |
| 2. Product price | Investment costs of aircraft | | | | X *ultra-efficient aircraft* |
| | Fuel costs | | | | |
| | Switching costs | | X *both aircraft* | | |
| | Transaction costs | | X | | |

| | | | | | |
|---|---|---|---|---|---|
| | | | *both aircraft* | | |
| 3. Production system | Know-how on the principle of production | | | | X *ultra-efficient aircraft* |
| | Ramp-up ability of the production system | | | | |
| | Ability to produce a fleet in an appropriate time | | | | |
| 4. Complementary products and services | Fuel production infrastructure | | X *ultra-efficient aircraft* | | |
| | Fuel distribution infrastructure | | | | |
| | Fuel storage infrastructure at airport | | | X *hydrogen aircraft* | |
| | Refuelling infrastructure at airport | | | | |
| | Maintenance Repair Overhaul (MRO) services | | | | X *ultra-efficient aircraft* |
| 5. Network formation and coordination | Actor network | | | X *both aircraft* | |
| | Communication among actors and steps taken towards a similar vision | | X *both aircraft* | X *both aircraft* | |
| | Number of consortiums | X *both aircraft* | | | |
| | Number of workshops and conferences | X *both aircraft* | | | |
| | Number of publications on technical progress | X *both aircraft* | | | |
| | Media coverage on concepts of sustainable aircraft technology | X *both aircraft* | | | |
| 6. Customers | Customer type | | | | |
| | Involvement of potential | | | X *both aircraft* | |

| | | | | | |
|---|---|---|---|---|---|
| | customer in innovation process | | | | |
| | Awareness of benefit compared to incumbent aircraft designs | | | | |
| | Financial means to acquire aircraft | | | | |
| | Willingness to acquire aircraft | | | X<br>*both aircraft* | |
| 7. Innovation-specific and industry-wide regulations | Governmental policies and regulations (EU wide) | | | X<br>*both aircraft* | |
| | Industry self-regulation | | | X<br>*both aircraft* | |
| | Subsidies and incentives | | | | |
| | Safety regulations | | | | |
| | International and regional standards | | | | |

## 4.5 CONCLUSION CHAPTER 4

Chapter 4 has addressed SQ1, elaborating on the application and scoping of the TIS analysis framework from a company perspective to the aviation industry. First, relevant industry-specific constraints and opportunities have been identified. Second, the framework of Ortt & Kamp (2022) has been modified for the application to the aviation industry, by adjusting the TIS building blocks and influencing conditions. Here, TIS building block 4 has been reidentified as *Complementary infrastructure and services* and TIS building block 7 has been reidentified as *Innovation-specific and industry-wide regulations*. Also, influencing condition *natural, human and financial resources* has been split to have three distinctive influencing conditions for addressing potential bottlenecks. Furthermore, a set of 40 indicators have been formulated for analysing TIS building blocks more in-depth against the benchmark technology. Third, the industry segment has been scoped down to the regional market segment of aviation, focusing on a customer need of airlines to specify an aircraft design on certain flight routes. Focusing on smaller aircraft designs with a shorter required range will serve as a less risky steppingstone to develop novel alternatives on technological improvement and enables a learning-by-doing process which will enhance learning curves of innovation. Following from this scope, the hydrogen and ultra-efficient aircraft technology have been chosen as sustainable aircraft for assessment. Fourth, the baseline for evaluation has been established. A conventional aircraft design, the Embraer 175 aircraft design with a passenger capacity of 70-90 PAX, with 50% SAF drop-in fuel has been chosen as benchmark technology for evaluation the sustainable technologies on, representing a short-term business-as-usual reference. Moreover, an evaluation base of the proposed indicators has been provided, where Table 8 represents exceptions in the evaluation of certain ones. This includes an overall absence of the indicator in the analysis of this master thesis research, an absence of time dimension for the indicator, an absence of hard data on formulating the prospect of completeness or an over reliance on one source for formulating it.

# CHAPTER 5: ANALYSIS OF HYDROGEN AIRCRAFT TIS BUILDING BLOCKS

In this chapter, hydrogen aircraft are analysed according to the indicators proposed for the TIS building blocks in Table 5 after which main findings are concluded. The relevancy of each indicator is elaborated on in Appendix B. A hydrogen-fuelled aircraft design is a very promising sustainable alternative for aviation. The most viable option for producing hydrogen for aviation is through PEM electrolysis (Fuel Cells and Hydrogen 2 Joint Undertaking, 2020). Important here is that the electricity used for the electrolysis process should come from renewable energy sources (green) or from the reformation of natural gas, where carbon from the atmosphere through carbon capture technology is used as input, (blue) to retain the climate-friendly advantage of hydrogen over kerosene. An illustration of a conceptual hydrogen aircraft design is provided in Figure 4.


FIGURE 4: HYDROGEN AIRCRAFT CONCEPTUAL DESIGN. MODIFICATION OF ILLUSTRATIONS FROM FUEL CELLS AND HYDROGEN 2 JOINT UNDERTAKING (2020)

Hydrogen has a gravimetric energy density[4] which is three times higher than kerosine, making it interesting to deploy as fuel. Nevertheless, due to its relatively higher volume, hydrogen requires an approximately four times larger storage tank (Khandelwal et al., 2013). Hydrogen can be used in both pressurized gas and liquid form (LH2). Both options are currently under development, where the first option requires relatively larger on-board tanks than the second one as its volume is relatively high, and the latter option would require only half of the volume of a pressurized gas tank, resulting in a lighter tank and thus a higher fuel efficiency (Fuel Cells and Hydrogen 2 Joint Undertaking, 2020). This option also requires an insulation system to keep temperatures at 4K and minimise heat transfer (Gomez & Smith, 2019).

In line with the two states in which hydrogen can be deployed, there are two types of propulsion designs with hydrogen used as fuel input. The first option is a hydrogen combustion turbine in which hydrogen is directly burned to create thrust. The hydrogen combustion turbine can create a high level of power (Fuel Cells and Hydrogen 2 Joint Undertaking, 2020). As hydrogen contains no carbon whatsoever, the main combustion product is water. Due to the amount of nitrogen in air, however, the combustion of LH2 still leads to NOx formations in the atmosphere. While not a direct greenhouse gas, NOx contributes to the formation of ozone, therefore indirectly contributing to the greenhouse effect, and is an important source of air pollution. The second option is a fuel cell, which converts hydrogen into electricity that is used for driving an electric motor with a propeller. In this design no combustion is

[4] Gravimetric energy density refers to the energy available per unit of mass of a fuel (Züttel et al., 2010).

taking place, hence neither CO2 nor NOx is emitted. Once technology discussed to be promising is the polymer electrolyte membrane fuel cells (Schröder et al., 2021). Besides these two alternatives for propulsion, a hybrid option between hydrogen combustion and propulsion through fuel cells is possible as well, combining the high efficiencies and low number of emissions of the fuel cell with the high-power output of combustion turbines. Since hydrogen technology applied for aviation is still in its infancy, this thesis will not delineate on one specific hydrogen propulsion application but rather focus on both combustion and fuel cell application. Only in the cases where differences between the alternatives are present, a distinction will be visible in the evaluation.

Various academic research has focused on regional 40-70 PAX turboprop models for the assessments of hydrogen aircraft. Sparano et al. (2023), Pastra et al. (2022) and Palladino et al. (2021) evaluate hydrogen fuel cell deployment applied to these models and Adler & Martins (2023) and Boretti (2021) evaluate hydrogen combustion and hybrid configurations for turboprop aircraft. Moreover, start-ups such as Conscious Aerospace, Universal Hydrogen and ZeroAvia focus on the deployment of hydrogen-fuelled aircraft by rebuilding some type of a regional 40-70 PAX turboprop models (Futureflight, 2023; ZeroAvia, 2023). The German Aerospace Center, DLR, is working on the BALIS project for developing a fuel cell powertrain in a regional turboprop model (DLR, 2021). Universal Hydrogen has stated that an ATR 72 design would be the largest aircraft to fly a hydrogen-fuelled plane in the first phase of hydrogen deployment (Euronews, 2023b). This shows that the technological niche for hydrogen is focusing on this specific model. Even though this is not in line with the reference aircraft from 70-90 PAX for evaluation, this niche is currently the only one in which hydrogen aircraft are being developed, leading to information from this specific niche to be used for the hydrogen analysis.

## 5.1 PRODUCT PERFORMANCE AND QUALITY

### 5.1.1 CO2 EMISSIONS

The large advantage of hydrogen as fuel for aviation is that propulsion is obtained through a reaction between hydrogen and oxygen where only water is its by-product (Faye et al., 2022). Therefore, a hydrogen-fuelled aircraft will emit no CO2 whatsoever, as compared to the estimated 1.15 kg of CO2 that is emitted per kilogram of kerosine burnt in flight (Fuel Cells and Hydrogen 2 Joint Undertaking, 2020; Zhang et al., 2008). This is a very relevant advantage compared to conventional aircraft with 50% SAF drop-in, making the indicator considered complete.

### 5.1.2 NOX EMISSIONS

NOx emissions are significantly reduced as well with the deployment of hydrogen aircraft. The combustion of hydrogen could potentially reduce 86%-90% of NOx emissions as opposed to kerosene fuel (Khan et al., 2022; Agarwal et al., 2019). The Fuel Cells and Hydrogen 2 Joint Undertaking (2020) paper discusses that hydrogen turbines can be optimised further to reduce even more NOx emissions between five to ten years. Furthermore, an aircraft design with hydrogen fuel cells does not require combustion and thus does not emit NOx at all (Baroutaji et al., 2019). These reductions will lead to a net negative radiative forcing impact and will decrease the concentration of ozone in the atposhpere by up to 6% (Fuel Cells and Hydrogen 2 Joint Undertaking, 2020). Therefore, the indicator is considered complete.

### 5.1.3 CONTRAIL FORMATION

It is argued that contrail cirrus ice crystals are partially formed by exhaust soot particles (Voigt et al., 2021). As water is the only by-product of hydrogen combustion or propulsion through fuel cells, there is a factor of 4.3 increase in water vapour emission compared to using kerosene (Khan et al., 2022). The paper of Fuel Cells and Hydrogen 2 Joint Undertaking (2020) states that water vapor itself has a 10x lower climate impact than CO2 emissions. Moreover, the ice crystals that are formed in high-humidity regions are heavier, leading to faster precipitation and the creation of optically thinner contrails, which poses less effects on global warming. However, even though no soot particles are emitted by hydrogen-fuelled aircraft, impacts from these contrail and cirrus formation remain to be 50% to 70% of the current effective radiative forcing (ERF)[5] impact.

On the other hand, SAF produced as a synfuel contains fewer aromatics and its combustion causes less soot (Fuel Cells and Hydrogen 2 Joint Undertaking, 2020), leading to a decrease in ice crystal formation of 10%-40%. Bräuer et al. (2021) measured reductions up to 40% and also found that optical depths of contrails were reduced by 40% to 52%, where optically thinner contrails pose less effects on global warming. The study of Narciso & de Sousa (2021) states that contrail formation could even be reduced up to 76% with optical depth reduction up to 37%. Nevertheless, they also suggest that SAF combustion might lead to a possible increase in the frequency of contrail formation and more heavier ice crystals since higher amounts of water vapour is produced. As this Master Thesis considers the deployment of 50% SAF, the performance will roughly lead to half of the reductions mentioned above. Therefore, it is considered that a hydrogen-fuelled aircraft has a relatively lower effect of contrail formations than a conventional aircraft with SAF drop-in, making the indicator complete.

#### 5.1.4 RANGE

A key challenge of hydrogen aircraft design and integration is the relative heavy hydrogen fuel tanks and fuel cell systems required due to the lower volumetric energy density of hydrogen, when compared to conventional fuel tanks and engines (Smith & Mastorakos, 2023). This can be attributed to the insulation system that is needed to keep hydrogen in its liquid form (Int. Knowledge Institute; Gomez & Smith, 2019). With this extra weight, achievable flight ranges are lowered (Cipolla et al., 2022). The start-up Universal Hydrogen, which is converting ATR72-600 twin turboprop into a design propelled by a hydrogen fuel cell, estimates that their current model for regional flights can only fly 800 km as range (Euronews, 2023b). The study of Fuel Cells and Hydrogen 2 Joint Undertaking (2020) expects a regional 80 PAX hydrogen aircraft deployed by 2035 to have a range of 1.000 km. While both ranges are significantly lower compared to the conventional aircraft, the hydrogen aircraft would still be implementable for flights in the addressed customer market segment, making this indicator considered partially complete.

*Influencing condition and prospect of completeness*

As the relatively low range of hydrogen aircraft can be attributed to the hydrogen fuel tank and fuel cell systems, the influencing condition *knowledge and awareness of technology* is applicable for this situation. A respondent states that the current developments of the hydrogen tanks are still in an infancy phase and not optimally designed yet (Int. University). R&D over the coming decade could lead to a lighter and more compact hydrogen tank. For example, with the deployment of lighter-weight aluminium and composites, the weight of the tank could be significantly reduced. The respondent expects this R&D process to take 10-15 years, after which the tank requires certification of 5 years as well (Int. University). Therefore, the range is expected to be gradually increasing to an optimum within 15-20 years. Other respondents argue that these technological improvements go hand in hand with the development of regulations (Int. Safety regulator; Int. Start-up), where safety requirements could delineate the design space of the technology. Moreover, it is argued that the lack of fuel integration in the wings of the hydrogen aircraft could lead to improvements in the aerodynamics of the wings, which

[5] Effective radiative forcing measures an energy imbalance in the atmosphere caused by natural or anthropogenic activities, expressed in MW/m3 (Andrews et al., 2021).

could subsequently increase the aircraft range (Int. Knowledge institute). Therefore, not only the design of the tank should be considered, but the efficiency advancements made in other dimensions of the aircraft design should be acknowledged as well. Altogether, this indicator is expected to be complete between 15-20 years.

### 5.1.5 PASSENGER CAPACITY

Next to the weight constraint of the hydrogen fuel tank discussed in subsection 5.1.4, it will be significantly larger than a conventional fuel tank due to the low volumetric energy density of hydrogen (Khandelwal et al., 2013). Since the hydrogen-fuelled aircraft design is both constrained by the higher weight and the required space for the hydrogen tank, less overall weight and space is present for passengers and their luggage. The study of Smith & Mastorakos (2023) presents that the hydrogen aircraft under investigation could carry 84% of a conventional aircraft passenger demand at full range. Moreover, this reduction in passenger capacity is visible in the design plans of Conscious Aerospace, where a Dash 8-300 twin turboprop is converted into one propelled by a hydrogen fuel cell. The originally 50-seaters aircraft will have to reduce its passenger capacity to 37 to 40 seats (FutureFlight, 2023). Therefore, this indicator is considered partially complete.

*Influencing condition and prospect of completeness*

For this indicator, the same influencing condition on weight constraints discussed in subsection 5.1.4 applies. Furthermore, the influencing condition *knowledge and awareness of the technology* also applies to the size of the hydrogen tank which constraints passenger capacity. One respondent argues that hydrogen storage could potentially be integrated in the wing, thereby significantly enhancing the space utilization for passengers (Int. University) while another respondent contradicts this argument as the cylindric storage tank shape makes it more difficult to store hydrogen in wings (Int. Knowledge institute). Furthermore, it is argued that the storage tank could be integrated in the cargo hold, potentially posing problems for safety landings, or behind the luggage compartment which would lead to reduced luggage space (Int. University). Similar to the prospect of completeness of subsection 5.1.4, the hydrogen tank configurations are expected to be improved in terms of size and weight by 15-20 years.

### 5.1.6 REQUIRED FUEL PER SEAT

The study of Choi & Lee (2022) calculates that the Embraer 175 requires approximately 7.500 kg Jet A fuel. It is estimated that a hydrogen aircraft would require an increase in 9% of energy consumption for regional aircraft due to its larger H2 storage tank (Westenberger, 2003). Furthermore, it is stated that 0.36 kg LH2 was required to produce a fuel energy content similar to the one of 1 kg Jet A fuel (Choi & Lee, 2022). This would mean that 2.943 kg LH2 would be required for the propulsion of the hydrogen aircraft with similar ranges. With the estimation of Smith & Mastorakos (2023) where a hydrogen aircraft could carry 84% of the passengers of a kerosene aircraft, a hydrogen aircraft with reference to the Embraer 175 would carry 74 passengers. This means that the required fuel per seat would be approximately 34 kg hydrogen. For a conventional aircraft with 50% SAF drop-in, the required fuel per seat would be approximately 85 kg. Therefore, this indicator is considered complete.

### 5.1.7 REFUELLING TIME

According to several studies, the refuelling time of hydrogen aircraft is expected to be similar to the refuelling time of conventional aircraft. A report from the International Organization for Standardization (ISO/PAS, 2004) indicated that hydrogen boil-off procedures and storage requirements are potentially needed for safe refuelling operations and concluded that the refuelling time could be similar to conventional refuelling time. Fuel Cells and Hydrogen 2 Joint Undertaking (2020) state that the refuelling time of short-range aircraft would require a doubling of refuelling hoses, implying that a change in airport operations is necessary to achieve a similar refuelling time. Only a study of Brewer (1976) implied that the turnaround time of hydrogen aircraft would be increased by 20%. In this analysis, however, it is considered that only a single refuelling hose is used instead of two as proposed by the analysis of Fuel Cells and Hydrogen 2 Joint Undertaking (2020). Moreover, a respondent argues that the refuelling time is not expected to be quicker than conventional refuelling times (Int. Knowledge Institute). Nevertheless, the performance of this indicator remains unclear as the safety requirements for refuelling operations, such as safety radius for refuelling or the safety procedure for refuelling with passengers on the aircraft (Int. Airport 1). Therefore, this indicator is considered partially complete.

*Influencing condition and prospect of completeness*

Since no concrete safety requirements have been proposed for refuelling operations at airports, the influencing condition *knowledge and awareness of application and market* is applicable for this indicator. Currently, one respondent has stated to be investigating the refuelling time of a hydrogen aircraft (Int. Airport 1), which has not presented conclusions yet. The safety requirements on refuelling operations are analysed more in-depth in the TIS building block indicator *Safety regulations* in subsection 5.7.4, where a prospect of completeness of ten years is argued for. Therefore, the indicator is considered complete in ten years.

### 5.1.8 NOISE EMISSIONS

The indicator noise emissions has not been covered thoroughly by literature on hydrogen aircraft. In a study regarding a hydrogen fuel cells aircraft design, Guynn et al. (2004) expect an Effective Perceived Noise Level (EPNL) of 8 to 22 dB, however, a blended wing-body aircraft design is taken as reference. The study of Baharozu et al. (2017) states that hydrogen combustion engines emit the same noise as traditional aircraft. As this argumentation assumes similar noise emissions compared to conventional aircraft, this indicator is considered complete.

### 5.1.9 PASSENGER COMFORT

Passenger comfort of hydrogen aircraft has not been covered thoroughly by literature. Some research refers to the comfort of passengers as a dimension that needs to be taken into consideration when thinking about space utilization (Eissele et al., 2023), which is especially applicable for a hydrogen aircraft as the large tank size results either in less passengers in the aircraft or less passenger comfort. One respondent argues that comfort is expected to be maintained in their hydrogen aircraft design, regardless of it leading to a reduced passenger capacity (Int. Start-up). The potential economic loss of the reduced number of passenger seats could be compensated with other means, e.g. focusing on the deployment of the hydrogen aircraft in the business market segment (Int. Airline; Int. Start-up). This will be explained more thoroughly in Subsection 5.6.1. Therefore, this indicator is considered complete.

### 5.1.10 PASSENGER PERSPECTIVE ON AIRCRAFT

The passenger perspective on hydrogen aircraft is currently regarded negative. While the respondent from an airline perspective states that the sustainable character of hydrogen aircraft is relatively more apparent than the carbon-neutral supply chain for SAF deployment in aircraft (Int. Airlines), the safety of hydrogen technology is doubted. Gordon (2023) states that public concerns on hydrogen present are present related to safety and regulation over the whole supply chain and its end use in aircraft. It is argued that a large share of the public is still unaware of hydrogen used as an energy carrier for transportation. This assumption of a negative passenger perspective is underwritten by various respondents (Int. Airline; Int. Airport 1; Int. Airport 2, In. University). On the other hand, a survey study on the perception and the social acceptance regarding hydrogen deployment transportation systems in Spain has shown that respondents are overall aware of the favourable environmental performance and the suitability to apply this to the transportation system (Iribarren et al., 2016). Nevertheless, this indicator is considered incomplete.

*Influencing condition and prospect of completeness*

The most apparent influencing conditions present are *knowledge and awareness of technology* and *socio-cultural aspects*, as the current knowledge and norms of passengers are not including hydrogen technology applied for aviation at this moment. Another identified influencing condition is *accidents and events*, as the Hindenburg disaster of 1937, where a zeppelin propelled by hydrogen caught fire and crashed causing a great number of fatalities (DiLisi, 2017), is stated to be influencing the passenger perspective (Int. Airport 1). Various authors consider this public perception on hydrogen either to become a promoter or a barrier (Gordon, 2023; Michelmann et al., 2022; Derempouka et al., 2022; Bruce et al., 2018). To address this, hydrogen applications should be actively presented to the public to normalise its use in everyday life (Int. Airline; Int. Airport 1; Int. Start-up). Gordon (2023) proposes that the government should take a lead in organising demonstration projects of hydrogen applications. Bruce et al. (2020) underwrite this and propose hydrogen to be deployed first in ground support equipment to explicitly familiarize passengers with hydrogen deployment in transportation. For later steps, it is proposed to deploy hydrogen aircraft in popular flight paths, so that the demand to fly with the hydrogen aircraft will be taken up by overall demand of the flight path. As a number of applications of hydrogen have been deployed in society already, such as hydrogen tank stations for automotive and trucking industry (Int. Start-up) and plans have been established for hydrogen deployment in regional airports (Int. Airport 1; Int. Airport 2) and energy systems (European Commission, 2020a), this indicator is considered to be complete within 10 years from now.

### 5.1.11 OPERATIONAL SAFETY

The operational safety of hydrogen aircraft is currently challenging as hydrogen has different properties than conventional fuels, requiring safety requirements need to be changed accordingly. One example is the low boiling point of hydrogen, turning hydrogen rapidly into a gaseous state once leaked (Bose & Ohi, 1998; Schmidtchen et al., 1997), while kerosene would stay in liquid form in this situation. Moreover, the high pressures required for systems to keep hydrogen liquid also needs a standard on safety operation. It should be noted that this does not mean that hydrogen is per definition unsafe compared to kerosene, it is e.g. stated that the bursting into flames of hydrogen is more easily handled than kerosene (Khandelwal et al., 2004). This rather means that safety regulations have not yet adjusted to hydrogen aviation operations and is therefore considered incomplete.

*Influencing condition and prospect of completeness*

The influencing condition present for this indicator *is knowledge and awareness of technology*. One respondent argues that an established concept and design of hydrogen aircraft is currently lacking, which would be essential for safety regulations to be formulated upon (Int. Safety Regulator). Another respondent underwrites this by indicating that operational safety regulations will be established through the interaction and experimentation of technology learning curves from the OEM, ground infrastructure from the airport and the energy supply chain from energy providers (Int. Airport 1; Int. Start-up). In line with the prospect of completeness of subsection 5.1.7, derived from the prospect of completeness of subsection 5.7.4, the formulation of such safety requirements is expected to take approximately ten years.

### 5.1.12 CONCLUSION ON TIS BUILDING BLOCK 1

To conclude, the overall TIS building block *Product performance and quality* of hydrogen aircraft is considered partially complete. A strong basis of environmental performance is present, however, the performance of an aircraft from an industry perspective is relatively less compatible. Furthermore, safety standards for operating a hydrogen aircraft are currently lacking which should be established before commercialisation of the aircraft is possible. TIS building block 1 is expected to be complete within 20 years. The results of the analyses have been visualised in Table 9.

TABLE 9: EVALUATION OF COMPLETENESS OF TIS BUILDING BLOCK 1 OF HYDROGEN AIRCRAFT

| Indicator | Incomplete | Partially complete | Complete | Influencing condition |
|---|---|---|---|---|
| CO2 emissions | | | ■ | - |
| NOx emissions | | | ■ | - |
| Contrail formation | | | ■ | - |
| Range | | ■ | | Knowledge and awareness of technology |
| Passenger capacity | | ■ | | Knowledge and awareness of technology |
| Required fuel per seat | | | ■ | - |
| Refuelling time | | ■ | | Knowledge and awareness of application and market |
| Noise emissions | | | ■ | - |
| Passenger comfort | | | ■ | - |
| Passenger perspective on aircraft | ■ | | | Knowledge and awareness of technology; Socio-cultural aspects; Accidents and events |
| Operational safety | ■ | | | Knowledge and awareness of technology |
| Overall performance TIS building block 1 hydrogen aircraft | | ■ | | Prospect of completeness: 20 years |

## 5.2 PRODUCT PRICE

### 5.2.1 INVESTMENT COSTS OF AIRCRAFT

The investment cost of a regional hydrogen aircraft is expected to be 31% higher compared to a conventional aircraft adjusted by its forecasted technology in 2035. The extra costs are associated with an increased aircraft size, a relatively larger thus more expensive hydrogen tank structure and the increased complexity of fuel distribution (Fuel Cells and Hydrogen 2 Joint Undertaking, 2020). As this is a significant difference compared to conventional aircraft, the investment costs could potentially hamper diffusion. One respondent argues that overall cost reductions can be imposed by retrofitting an existing aircraft into a hydrogen one (Int. Start-up). While the technological building blocks and retrofitting procedure would be costly, retrofitting an aircraft would extend its life by reaching up to more than doubled flight cycles, making the overall aircraft cost-efficient. With these insights, this indicator is considered partially complete.

*Influencing condition and prospect of completeness*

The influencing condition present for this indicator is *knowledge and awareness of technology.* Ideally, when more R&D is spent on the hydrogen tank structure, volume and thus expenses on the hydrogen tank will reduce. Moreover, R&D could potentially increase modularity in the fuel distribution system, which could lead to a reduced demand for components. A more higher-level influencing condition present is *macro-economic and strategic aspects.* Strategic competition between large aircraft OEMs on hydrogen aircraft is currently lacking, since Boeing has not stated a clear vision on hydrogen as an alternative fuel for sustainably aviation (Boeing, n.d.). While various start-ups are focusing on the development of hydrogen-fuelled aircraft, the lack of competition on hydrogen aircraft between the two largest aircraft OEMs in the world (Flyingmag, 2022) hampers a strategic incentive which might reduce the speed of technological advances in the production of a hydrogen-fuelled aircraft (Correa & Ornaghi, 2014). As the higher investment costs are mainly related to the large hydrogen tank, the same prospect of completeness as Section 5.1.4 and Section 5.1.5, 15-20 years, has been taken as reference for the prospect of completeness of this indicator. Therefore, the indicator is considered complete within 15-20 years.

### 5.2.2 FUEL COSTS

The report of Fuel Cells and Hydrogen 2 Joint Undertaking (2020) states that hydrogen currently costs around 300 US dollars (USD) per MWh, while kerosene currently costs around 50 USD per MWh. The study by Gronau et al. (2023) concludes that hydrogen costs are four to six times more expensive as kerosine and Barcellona (2022) states that hydrogen costs are a factor of 5 higher than kerosene prices. Hydrogen costs are directly intertwined with the cost of renewable energy. Therefore, hydrogen prices directly correlate with the scale of implementation of RES, a market which currently is in its infancy considering its relatively low percentage (21.8%) of total energy consumption in the EU (Eurostat, 2023). It should be noted that most hydrogen price projections include distribution costs, which can be circumvented when producing hydrogen on site at airports.

When considering the effect of this high hydrogen cost for its application in aviation, Hoelzen et al. (2022a) state that for short-range aircraft, hydrogen fuel costs lead to a 12% increase of direct operating costs (DOC) of flights compared to that of conventional ones. When considering a 50% SAF drop-in in the reference aircraft, on the other hand, hydrogen costs are relatively less expensive. SAF in the form of synfuels is very expensive due to the current efficiencies and price of electrolysis and the Fischer-Tropsch synthesis process (Fuel Cells and Hydrogen 2 Joint Undertaking, 2020). The report states that SAF currently costs up to 450 USD per MWh. Balancing that with 50% kerosene, the costs of fuel for the reference aircraft are approximately 250 USD per MWh. As the current cost of hydrogen is comparable, but nevertheless more expensive to prices of kerosene with 50% SAF deployment, this indicator is considered partially complete.

*Influencing condition and prospect of completeness*

Currently, *competition* of the kerosene prices compared to hydrogen prices has the most negative influence on this indicator. Various studies, such as the ones by Hoelzen et al. (2023a; 2023b), show that hydrogen will soon be subject to economies of scale and learning rates as there will be a high demand of hydrogen by various hard-to-decarbonize sectors. A roadmap on measures for green hydrogen rollout in Europe, executed by IRENA and World Economic Forum (2022), has implied that between 2025 and 2030, demand for green hydrogen will rise and cost will decrease along the whole value chain. In the Netherlands specifically, an advisory report of the Dutch Electro Chemical Conversion & Materials has the ambitions to reach CO2 low hydrogen by 2 Euro per kg by 2030 and 1 Euro per kg by 2050 (ECCM, 2018). These projections, however, do not focus 100% on green hydrogen. On top of that, the analysis of Fuel Cells and Hydrogen 2 Joint Undertaking (2020) provides a longer-term perspective, estimating that hydrogen will reach a price near to 50 USD per MWh by 2050, as opposed to the projected kerosene price of 300 USD per MWh due to increasingly stringent EU tax regulations. These projections also included the expectation for SAF to be 2-3 times more costly than hydrogen from 2030 on. Therefore, the indicator is considered complete in 2030.

### 5.2.3 SWITCHING COSTS

The deployment of hydrogen in the aviation industry is associated with large-scale costs on various dimensions of its value chain. This includes investments for energy providers, grid network operators, airports, airlines, OEMs, companies that provide services within the supply chain and governments. As every actor is required to make investments in infrastructure or business operations for the deployment of a hydrogen-fuelled aircraft, the switching costs of hydrogen will be relatively high. With this knowledge, the indicator switching costs is considered incomplete.

It must be noted that this incompleteness simply is a result of the radical nature of hydrogen for the aviation industry, meaning the infrastructure requirements for hydrogen deployment diverge to such an extent from the established infrastructure of the socio-technical regime that the switching costs are inevitably high. The incompleteness of the indicator has a timeless dimension, where there is no influencing condition present that hampers the indicator, nor is there a prospect of completeness on when this will be considered complete.

### 5.2.4 TRANSACTION COSTS

For the deployment of hydrogen aircraft, novel materials that perform well under cryogenic circumstances need to be developed (Int. Knowledge Institute). As the hydrogen element is so small, it can diffuse through materials and embed inside materials which leads to hydrogen embrittlement and reduces the quality of the material properties (Int. Knowledge Institute). Therefore, the requirement of high-quality materials for a hydrogen aircraft are highlighted as well. Furthermore, extra safety technologies are needed, such as hydrogen monitoring sensors (Int. University). This means that for OEMs, relationships with other suppliers need to be established. Also, it is stated that hydrogen fuel cells will require scarce materials, which could potentially lead to industry dependencies (Int. University). Nevertheless, such materials are not expected to be scarce due to the formation of a market for the materials through high industry needs. Moreover, the Alliance for Zero-Emission Aviation (AZEA) is organising working groups on the introduction of hydrogen in aviation and are planning the requirements for new components of a hydrogen aircraft upfront in order to reduce transaction costs in terms of time (Int. University). Even though a hydrogen aircraft requires novel materials and components compared to conventional aircraft, this coordination process shows that efforts are made to minimize such transaction costs. Therefore, the indicator is considered partially complete.

As is the case with switching costs, the incompleteness of the indicator has a timeless dimension, where there is no influencing condition present that hampers the indicator, nor is there a prospect of completeness on when this will be considered complete.

### 5.2.5 CONCLUSION ON TIS BUILDING BLOCK 2

To conclude, the overall TIS building block *Product price* of hydrogen aircraft is considered partially complete. The investment costs of hydrogen aircraft are expected to be high but retrofitting an existing aircraft into a hydrogen one could lead to cost reductions through an extended lifespan. Hydrogen costs are currently higher than conventional fuels mixed with 50% SAF drop in, but this is expected to become less costly from 2030 on. The switching costs of hydrogen aircraft deployment are very high for all the whole value chain of aviation, as large-scale modifications in infrastructure and safety regulations need to be made. The transaction costs of changing business-as-usual into hydrogen aircraft deployment are also considered to be costly not only in financial terms, but also in terms of time needed for coordination with new component or raw material suppliers. TIS building block 2 is expected to be complete between 15-20 years, where the latest value is taken for the reference of the overall TIS building block. It should be noted that switching costs will remain high, and strategies need to be formulated to circumvent this incomplete building block. The results of the analyses have been visualised in Table 10.

TABLE 10: EVALUATION OF COMPLETENESS OF TIS BUILDING BLOCK 2 OF HYDROGEN AIRCRAFT

| Indicator | Incomplete | Partially complete | Complete | Influencing condition |
|---|---|---|---|---|
| Investment costs of aircraft | | | | Knowledge and awareness of technology; Macro-economic and strategic aspects |
| Fuel costs | | | | Competition |
| Switching costs | | | | X |
| Transaction costs | | | | X |
| | | | | |
| Overall performance TIS building block 2 hydrogen aircraft | | | | **Prospect of completeness: 20 years** |

## 5.3 PRODUCTION SYSTEM

### 5.3.1 KNOW-HOW ON THE PRINCIPLE OF PRODUCTION

Currently, there is an overall establishment of know-how present on the principles of production of a hydrogen aircraft. As mentioned more in-depth before, start-ups, incumbent OEMs and knowledge institutes are looking into various hydrogen configurations that could potentially lead to a well-functioning design. A range of technological bricks are currently taken into consideration, including the deployment of liquid or gaseous hydrogen and their complementary propulsion systems, as well as how to address robustness of thermal insulation properties from e.g. hydrogen tanks when operating under cryogenic conditions (Int. Knowledge Institute; Monkam et al., 2022). Moreover, as elaborated in subsection 5.1.5, the best way to integrate the hydrogen tank is under consideration (Int. University; Int. Start-up), as well as the design of the fuel system, which distributes fuel from storage to the propulsion system and is critical for the overall system (Int. Knowledge Institute). Furthermore, extra safety considerations as sensors for monitoring hydrogen leakage will be present within first phases of the design (Int. University). As innovation is ongoing but has not yet presented an established prototype from these technological bricks, the know-how on the principles of production is considered partially complete.

*Influencing condition and prospect of completeness*

For this indicator, the influencing condition *knowledge and awareness of technology* is present. Knowledge development on hydrogen aircraft could still take up to 9 years (Int. University). Taking the Clean Aviation Programme funded by the EU as example, three years are allocated to ground demonstrations of fuel cell powertrains, three years to test these powertrains in hybrid form in flight conditions and another three years to test the full hydrogen propulsion in flight (Int. University). Another respondent states that the technology know-how is already present, however, experimentation with the technology is needed for first phases (Int. Start-up). Instead of focusing on isolated R&D, the respondent states that knowledge should be obtained through learning-by-doing by deploying the product and experiment through cooperation between different types of actors in the value chain. By retrofitting an already established aircraft with a hydrogen propulsion system, it is argued that the certification process is relatively less challenging as a range of core technologies have been certified already. This would actively challenge the ecosystem to experiment, follow technological learning curves, and alter the supply chain and business models which will accelerate hydrogen deployment in aviation rather than "*waiting for the brand-new solutions to be developed*" (Int. Start-up).

Moreover, it is argued that the safety requirements for regional sized aircraft are usually less strict than for long-haul aircraft, making the regional segments an appropriate first step for experimentation (Int. Start-up). For novel hydrogen aircraft designs such as retrofitted aircraft configurations, implementation to the market is expected to be earlier than 2035. Another respondent expects the market deployment of hydrogen aircraft to take up to 14 years from now, when including the certification process (Int. University), which is elaborated on in subsection 5.7.5. Another respondent estimates regional hydrogen aircraft, operating in the lower end of the aircraft market will be deployed by the next 10-15 years (Int. Knowledge Institute). Currently, plans are present to execute R&D and certification at the same time to reduce extra time spent on the certification process (Int. University), which could reduce these projected timeframes. Altogether, this indicator is expected to be complete within 15 years.

### 5.3.2 RAMP-UP ABILITY OF THE PRODUCTION SYSTEM

Bruce et al. (2020) expect that the scaling up of hydrogen aircraft production could be consuming in the beginning phases of hydrogen aircraft introduction. As the know-how of the principles of production of a hydrogen aircraft has to be established first before the production system itself can be ramped up, and the radical nature of the technology makes it very likely that the production system needs radical alterations as well, this indicator is currently considered to be incomplete.

*Influencing condition and prospect of completeness*

As the know-how on the principles of production is not entirely present yet, the influencing condition *knowledge and awareness of technology* is also applicable for this indicator. Respondents argue that with the introduction of a relatively costly hydrogen aircraft, the production system and its ability to ramp-up should be well in place before commercialisation (Int OEM; Int. Start-up). Seven years before commercialisation is planned, the concept of the design needs to be delineated after which the production system can be established for the production of the aircraft (Int. OEM).

Furthermore, the influencing condition *macro-economic and strategic aspects* could negatively influence this indicator. A respondent argues that the current dynamics of aircraft acquirement for incumbent OEMs follows a cyclic procedure in which aircraft leasing companies acquire an aircraft over the coming 5 years and subsequently leases it to airlines (Int. Start-up). When a new aircraft has been introduced to the market, this procedure is repeated. The respondent is questioning whether leasing companies are willing to stop ordering a conventional aircraft type when a zero-emission model is expected to be commercialised in 5 years' time, as a radical new technology brings uncertainties (Int. Start-up). If the hydrogen aircraft will not be acquired in this period and leasing companies would rather wait for the new conventional aircraft to be introduced, this could lead to a dip in the production process which would pose issues on capital markets.

Furthermore, the production system is required to be able to deliver a reasonable order of magnitude for deploying hydrogen aircraft as an industrialised product to the market. Here, interactions with other incumbent aircraft OEMs as Boeing influences which orders of magnitude are required. As Boeing has not stated a clear vision on hydrogen as an alternative fuel for sustainably aviation (Boeing, n.d.), this could have negative impacts on hydrogen aircraft deployment in general, and thus also on the ramp-up of the production system. On the other hand, it is argued that hydrogen aircraft would be considered a niche product in which classical business does not necessarily apply, as it will not be able to earn its expenses back (Int. OEM). Therefore, classic product line perspective and competitive dynamics might not be appropriate, and a better driver to commercialise hydrogen aircraft could be developed for de-risking by cracking the market with the innovation, helping the technology mature while being implemented in the market and changing the rules of the game (Int. OEM).

At this point, it is uncertain to tell how these dynamics will unfold in the coming decades. This is argued not to completely take place before 2040 (Int. Start-up). On the other hand, the first working group of AZEA (2023) which focused on roll-out scenarios for hydrogen aircraft has proposed that under a conservative scenario, regional hydrogen turboprop designs will be ramped-up from zero deliveries in 2034 to 50 deliveries in 2043. This projection was based on a selection of aviation evolution scenarios and inputs from all WG1 members, including 50 OEMs, showing that the ramp-up of the production of hydrogen aircraft is considered to take place within this time range. Therefore, this indicator is considered complete in 20 years from now.

### 5.3.3 ABILITY TO PRODUCE A FLEET IN AN APPROPRIATE TIME

As this indicator is considered a next step of hydrogen aircraft deployment after the *know-how on the principle of production* of subsection 5.3.1 and is subject to the same problems identified in subsection 5.3.2, this indicator is considered incomplete as well.

*Influencing condition and prospect of completeness*

This indicator is dependent on the same macro-economic and strategic dynamics as described in subsection 5.3.2, making the indicators *knowledge and awareness of* technology and *macro-economic and strategic aspects* and their argumentations for the prospect of completeness applicable for this indicator as well. Therefore, this indicator is considered complete in 20 years from now.

### 5.3.4 CONCLUSION ON TIS BUILDING BLOCK 3

To conclude, the overall TIS building block *Production system* of hydrogen aircraft is considered incomplete. While the know-how on the principle of hydrogen aircraft production is present to an extent, this has not resulted in concrete designs configurations on which production systems could be altered. Subsequently, this results in an incomplete ramp-up ability of the production system and ability to produce a fleet in an appropriate time. TIS building block 3 is expected to be complete in 20 years. The results of the analyses have been visualised in Table 11.

TABLE 11: EVALUATION OF COMPLETENESS OF TIS BUILDING BLOCK 3 OF HYDROGEN AIRCRAFT

| Indicator | Incomplete | Partially complete | Complete | Influencing condition |
|---|---|---|---|---|
| Know-how on the principle of production | | | | Knowledge and awareness of technology |
| Ramp-up ability of the production system | | | | Knowledge and awareness of technology; macro-economic and strategic aspects |
| Ability to produce a fleet in an appropriate time | | | | Knowledge and awareness of technology; macro-economic and strategic aspects |
| | | | | |
| Overall performance TIS building block 3 hydrogen aircraft | | | | **Prospect of completeness: 20 years** |

## 5.4 COMPLEMENTARY INFRASTRUCTURE AND SERVICES

For TIS building block 4, the supply chain of hydrogen to airports is considered, as well as the presence of complementary services. A representation of the hydrogen supply chain is provided in Figure 5. As can be derived from the figure, multiple distribution options are present for supplying hydrogen to airports. This is discussed more in-depth in subsection 5.4.2.

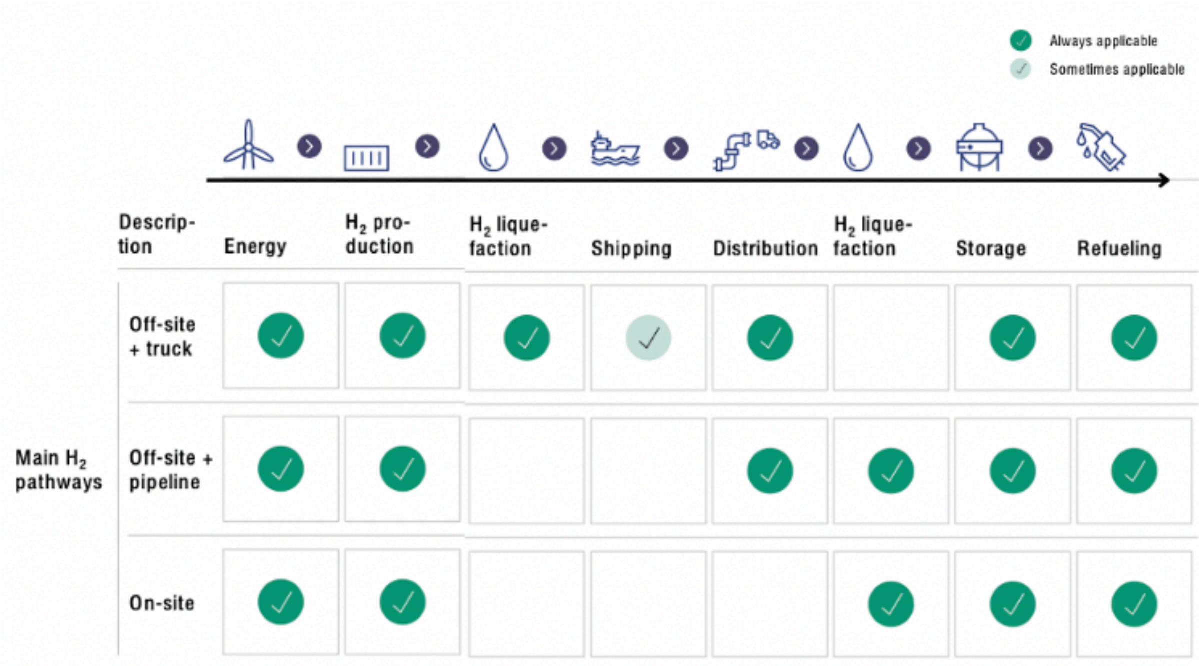


FIGURE 5: HYDROGEN SUPPLY CHAIN. MODIFICATION OF ILLUSTRATION FROM FUEL CELLS AND HYDROGEN 2 JOINT UNDERTAKING (2020)

### 5.4.1 FUEL PRODUCTION INFRASTRUCTURE

As stated before, the most viable option for producing hydrogen for aviation is through PEM electrolysis (Fuel Cells and Hydrogen 2 Joint Undertaking, 2020). The technological efficiency of hydrogen electrolysis and liquefication is 70% onsite and 58% when produced offside due to distribution (Fuel Cells and Hydrogen 2 Joint Undertaking, 2020). This shows that a high amount of renewable energy is demanded for the production of green hydrogen through electrolysis. It is stated that efficiencies higher than 70% can be reached, but that this would increase the capital costs of electrolysers (Int. Knowledge institute). Currently, around 95% of hydrogen is still produced through steam methane reforming without carbon capture, using natural gas and carbon as fuel input (IEA, n.d.). Only 4% of the hydrogen is produced with use of electrolysis (Starburst Aerospace, 2023), showing that the technology is mature but is currently still in need of scaling up before it can be used as fuel input for aviation. Therefore, the indicator is considered partially complete.

*Influencing condition and prospect of completeness*

The foremost influencing condition for this indicator is *knowledge and awareness of application and market*. Currently, the hydrogen market has not yet been developed to the size it needs to be for a cost reduction in electrolysers and hydrogen production (Taibi et al., 2020). The market requires responsive action for scaling-up, which currently is being addressed by the European Union as elaborated upon in subsection 5.7.3. Expectations are that by 2030, at least 40 GW of electrolysers will be installed within the EU to produce 10 million tonnes of renewable hydrogen (European Commission, 2020a). On top of that, another 10 million tonnes will be imported. A scenario in the report of Fuel Cells and Hydrogen 2 Joint Undertaking (2020) projects that 10 million tons of hydrogen for aviation would be required by 2040, which would be in-line with these strategies. Therefore, this indicator is considered complete by 2030.

### 5.4.2 FUEL DISTRIBUTION INFRASTRUCTURE

As can be seen in Figure 5, various alternatives for distributing hydrogen from production facilities towards airports are present. The paper of Fuel Cells and Hydrogen 2 Joint Undertaking (2020) discuss that both hydrogen trucks and pipelines can be deployed, where hydrogen can be distributed in liquid form. The advantage of hydrogen trucks is that it can be deployed in a short-time frame and is flexible in terms of travel route destinations. Currently, gaseous hydrogen trucks, also called tube trailers, are commercially available for distributing hydrogen. Cryogenic liquid trucks would transport hydrogen in liquid state, thereby transport more amount of hydrogen. Nevertheless, this technology has not yet been commercially deployed yet and distribution is relatively more costly due to the thermal insulation required and the boil-off of hydrogen (Faye et al., 2022). It should be noted that hydrogen production at the airport would be an option as well (Int. Airport 2; Fuel Cells and Hydrogen 2 Joint Undertaking, 2020), eliminating the need for fuel distribution infrastructure.

Hydrogen pipelines would be the most cost-effective option as it transports around 1000 metric tons of hydrogen per day (Reddi et al., 2016). The hydrogen pipelines could be constructed or obtained through retrofitting conventional gas pipelines. Currently, hydrogen pipelines have already been installed with over 4.300 km span globally, of which 90% is constructed in North America and Europe (RystadEnergy, 2023). Furthermore, Europe's first project of a hydrogen airport pipeline has been announced last year to be deployed in the UK (The Engineer, 2022). Furthermore, respondents have stated to be in contact with hydrogen providers for airport operations (Int. Airport 1 & 2). For both respondents, hydrogen is expected to be distributed through hydrogen trucks in initial phases, however, when enough hydrogen demand will be established at the airport, a respondent states that a hydrogen pipeline being deployed nearby could potentially be branched out towards the airport (Int.

Airport 2). Altogether, the current hydrogen distribution infrastructure is still inefficient, leading the indicator to be considered partially complete.

*Influencing condition and prospect of completeness*

Again, the influencing condition *knowledge and awareness of technology* plays a large role in the deployment of hydrogen distribution. Research on cryogenic liquid trucks is ongoing and Salzburg Aluminium Group states to be the first company developing one, expecting implementation in 2027 (H2 Bulletin, 2021). Furthermore, it is argued that the greatest barrier of hydrogen pipeline implementation is not the financial means but adjusting to the physical properties of hydrogen itself (RystadEnergy, 2023). As hydrogen requires cryogenic cooling down to 4K, pipeline system and compressors need to be developed to establish this and ensure boil-off or leakage of hydrogen is avoided (Fuel Cells and Hydrogen 2 Joint Undertaking, 2020). Furthermore, the influencing condition *knowledge and awareness of application and market* is identified. Gaseous hydrogen pipelines would already be feasible for implementation towards airports, but the establishment of the pipelines are not yet aligned with airport plans to deploy hydrogen. One respondent expects a first hydrogen pipeline to their airport to be established between 10 and 15 years (Int. Airport 2). Furthermore, the analysis of Fuel Cells and Hydrogen 2 Joint Undertaking (2020) expects sufficient hydrogen distribution infrastructure to be present between 2035-2040. Furthermore, incentives have been established to stimulate fuel distribution, elaborated on in subsection 5.7.3. Altogether, the indicator is expected to be complete between 15-20 years.

### 5.4.3 FUEL STORAGE INFRASTRUCTURE

Currently, three hydrogen storage infrastructure types are present, including compressed gaseous hydrogen storage, hydrogen storage and cryo-compressed hydrogen storage (Faye et al., 2022). The first two options are currently commercially available. As gaseous hydrogen storage has a disadvantage of having a low volumetric capacity, liquid hydrogen storage tanks are preferable. Here, both gaseous and liquid hydrogen storage trucks can be deployed, as well as gaseous and liquid hydrogen tank stations (Int. Airport 1; Int. Airport 2). The report of Fuel Cells and Hydrogen 2 Joint Undertaking (2020) states that hydrogen should be able to be stored for three days for the logistics of airport operations. As liquid hydrogen boils off when warming up slightly and currently leads to hydrogen leakage in storage infrastructure, improved heat control is necessary for meeting this requirement. As overall infrastructure deployment at aircrafts is currently low (Zhou, 2022), this indicator is considered incomplete.

*Influencing condition and prospect of completeness*

For this indicator, the influencing condition *knowledge and awareness of technology* is present. To mitigate energy losses of hydrogen storage, research is being conducted on cryogenic compress hydrogen storage technologies (Faye et al., 2022; Hassan et al., 2021). These have the potential to store hydrogen for up to seven days without losses, which would be in-line with airport needs addressed by Fuel Cells and Hydrogen 2 Joint Undertaking (2020). Currently, the technology is still in the prototyping stage and no research has presented an estimation when this technology will be commercially available. Furthermore, the deployment of hydrogen refuelling and storage infrastructure at airports is argued to be related to the demand of hydrogen at airports coming from airlines (Int. OEM). Moreover, no safety rules have been formulated specifically for hydrogen storage infrastructure at airports, which hampers deployment. This is elaborated upon more in subsection 5.7.4. Both subsections show that this is not expected to be established before entry of service of the hydrogen aircraft. Therefore, this indicator is considered complete between 2035-2040.

### 5.4.4 REFUELLING INFRASTRUCTURE AT AIRPORT

The options of refuelling infrastructure at airports include refuelling trucks, refuelling platforms linked to cryogenic hydrant refuelling pipelines and aircraft fuel lots away from boarding gates (Fuel Cells and Hydrogen 2 Joint Undertaking, 2020). While pipelines are more cost-efficient and enable safer and faster refuelling (Hoelzen et al., 2022b), the decision for either of these options depends on already implemented infrastructure and the daily fuel demand of athe airport (Mangold et al., 2022). Hoelzen et al. (2022b) state that trucks or fuel lots would be more viable for airports with an annual hydrogen demand lower than 125 kilo tonnes. Pipeline and hydrant systems, on the other hand, would be more beneficial for airports that pass that demand. One respondent has stated to be refuelling directly from the hydrogen storage tank by means of a hose initially, after refuelling by means of trainer trucks (Int. Airport 1). Another respondent has stated to be focusing on refuelling from trucks in initial stages already, however, with hydrogen in gaseous state (Int. Airport 2). For larger airports, it would be logistically too complex to deploy hydrogen trucks (Fuel Cells and Hydrogen 2 Joint Undertaking, 2020). As discussed in the indicator of 5.4.2, cryogenic liquid trucks and cryogenic hydrant refuelling pipelines have not been deployed yet. While initial refuelling infrastructure is being deployed on regional airports, this has not been established on a large scale. Therefore, this indicator is considered incomplete.

*Influencing condition and prospect of completeness*

As this indicator discusses similar technologies as subsection 5.4.2, the same influencing condition *knowledge and awareness of technology* and prospect of completeness of 15-20 years applies. Furthermore, the lack of specifications on safety requirements for hydrogen refuelling is hampering the implementation of refuelling infrastructure at airports. As the refuelling infrastructure of aircraft is a completely new technology with specification on the aviation industry, different safety requirements than for fuel storage technologies at airports need to be established (Int. Airport 1). An elaboration of these safety standards and their prospects of completeness of 10 years are provided in subsection 5.7.4. Altogether, the indicator is considered complete within 15-20 years.

### 5.4.5 MAINTENANCE REPAIR OVERHAUL (MRO) SERVICES

Overall, there is a well understanding present on which MRO services are needed for maintaining hydrogen aircraft. Meissner et al. (2023) discuss a range of 27 defined maintenance tasks that are needed for an on-board cryogenic hydrogen storage system. This include defined task description and intervals in which these tasks should be executed. Furthermore, Hoff et al. (2022) argue that extensive MRO is needed for the hydrogen fuel cell. As hydrogen fuel cells have already been deployed in the automotive sector, this experience can be built upon, assuming it to be manageable for the application in the aviation industry.

A disadvantage of MRO services of hydrogen systems in aircraft is that 48% of the maintenance tasks require removal of components for an in-shop maintenance, meaning the maintenance is not executed on the aircraft itself but requires a specialized facility. This is different from kerosene-based systems, which require 0% in-shop maintenance. Therefore, not only inherently different MRO operations are needed for the deployment of hydrogen aircraft, also the manner on which the maintenance is applied is deviating from the currently deployed MRO services. Furthermore, various respondents expect that alterations on the hangars, in which MRO services are executed, are necessary as well (Int. Airport 1; Int. Airport 2; Int University). These include the introduction of hydrogen detectors and sensors for addressing hydrogen boil-off, ventilation within hangars and procedures for addressing the chemical properties of hydrogen, including its explosiveness. Moreover, human capital is required to be educated for these alterations (Int. University). Altogether, this indicator is considered incomplete.

*Influencing condition and prospect of completeness*

According to the analysis of Hoff et al. (2022), *knowledge and awareness of technology* is currently hampering MRO services for hydrogen aircraft as resources related to hydrogen fuel cells MRO from the automotive industry have not yet been adapted accordingly to aviation applications. Moreover, *human resources* are influencing the indicator as human capital and competence is necessary for its deployment, which should be expanded more. Furthermore, a respondent has indicated that the AZEA is managing the alignment of different actors as MRO service providers for the deployment of hydrogen aircraft (Int. University). Nevertheless, the development of MRO services are expected to take between 5-10 years to optimise after the introduction of the aircraft (Int. OEM). Therefore, the indicator is considered complete between 2040-2045.

### 5.4.6 CONCLUSION ON TIS BUILDING BLOCK 4

To conclude, the overall TIS building block *Complementary infrastructure and services* of hydrogen aircraft is considered incomplete. While the fuel production infrastructure is currently being rolled out, the distribution infrastructure as well as the infrastructure required at the airport site are currently incomplete. On top of that, the MRO services are expected to undergo large-scale alterations, not only in terms of an increase in numbers of procedures but also in the alterations that are required to be applied to the in-shop maintenance as well as hangars. TIS building block 5 is expected to be complete before 2045. The results of the analyses have been visualised in Table 12.

TABLE 12: EVALUATION OF COMPLETENESS OF TIS BUILDING BLOCK 4 OF HYDROGEN AIRCRAFT

| Indicator | Incomplete | Partially complete | Complete | Influencing condition |
|---|---|---|---|---|
| Fuel production infrastructure | | | | Knowledge and awareness of application and market |
| Fuel distribution infrastructure | | | | Knowledge and awareness of technology; Knowledge and awareness of application and market |
| Fuel storage infrastructure at airport | | | | Knowledge and awareness of technology |
| Refuelling infrastructure at airport | | | | Knowledge and awareness of technology |
| Maintenance Repair Overhaul (MRO) services | | | | Knowledge and awareness of technology; Human resources |
| | | | | |
| Overall performance TIS building block 4 hydrogen aircraft | | | | **Prospect of completeness: 22 years** |

## 5.5 NETWORK FORMATION AND COORDINATION

### 5.5.1 ACTOR NETWORK

The actor network in the Dutch/German ecosystem of aviation includes a range of actors, including aircraft OEMs, airlines as customers, airports, energy providers, safety regulators, air traffic control, Universities, knowledge institutes, governments, and passengers. These actors are collaborating and exchanging knowledge with each other in a complex actor network, represented in Figure 6. Nevertheless, the extent to which this collaboration currently leads to the establishment of more sustainable aircraft technologies is disputable. An initiative is present in the Dutch/German ecosystem where key actors in the supply chain of the European aviation sector have agreed to intensify cooperation to realise climate neutral aviation by 2050, also known as the *Flying Vision* initiative. These actors include airport Schiphol, airline KLM, OEM Airbus and knowledge institutes TU Delft and NLR and want to collaborate with the Dutch government (FT, 2022). This initiative shows that a network for sustainable transitions within the Dutch/German ecosystem is being formalized. Therefore, this indicator is considered complete.

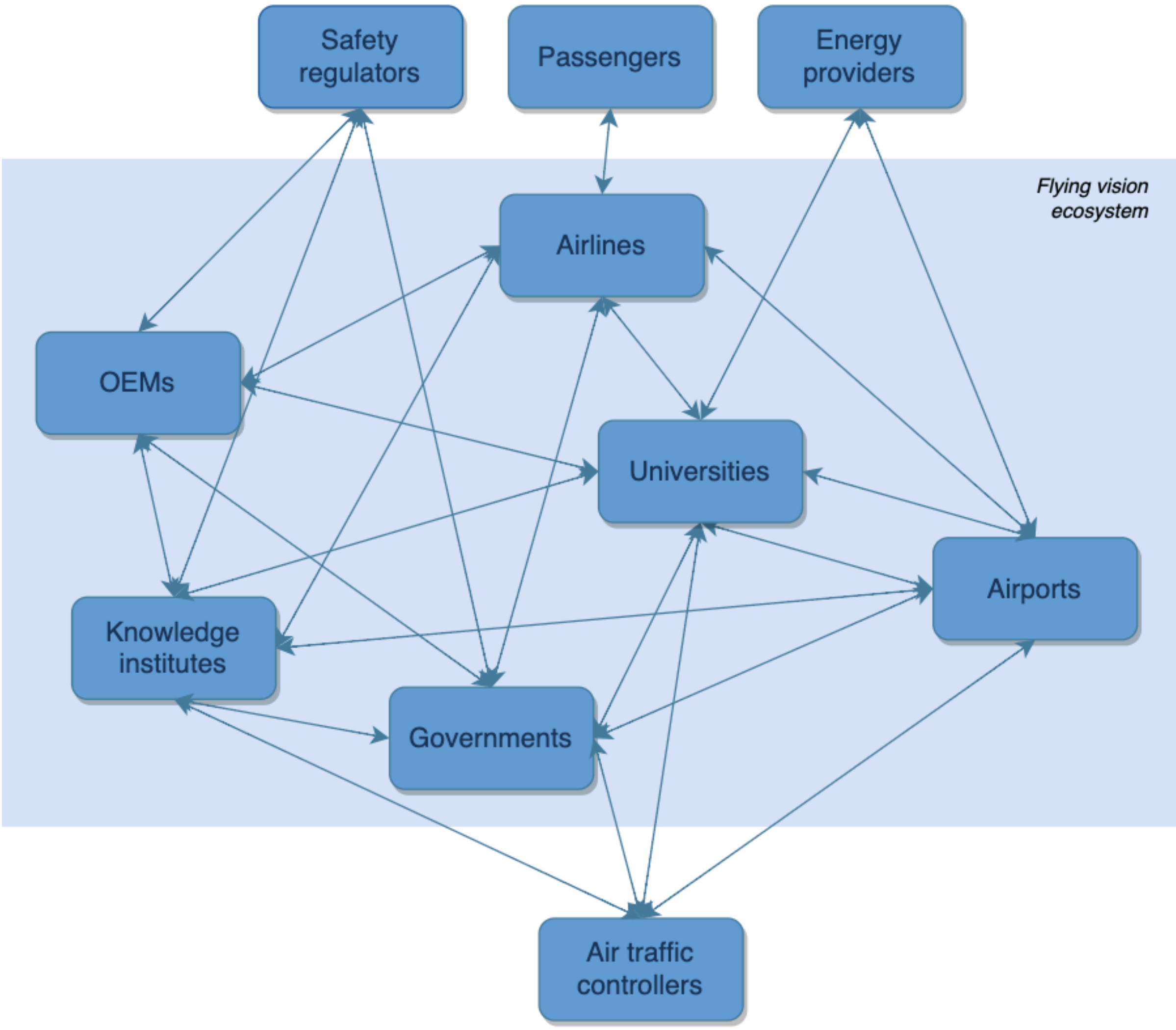


FIGURE 6: ACTOR NETWORK OF DUTCH/GERMAN ECOSYSTEM

### 5.5.2 COMMUNICATION AMONG ACTORS AND STEPS TAKEN TOWARDS A SIMILAR VISION

The perception of communication within the ecosystem and steps taken towards a similar vision on hydrogen aircraft deployment is diverse among the respondents. Respondents have been asked to provide a score on a Likert-Scale between 1 and 5, in which 1 represents very bad communication and vision alignment and 5 represents very good communication and vision alignment. A quantitative representation of these results is provided Figure 7.

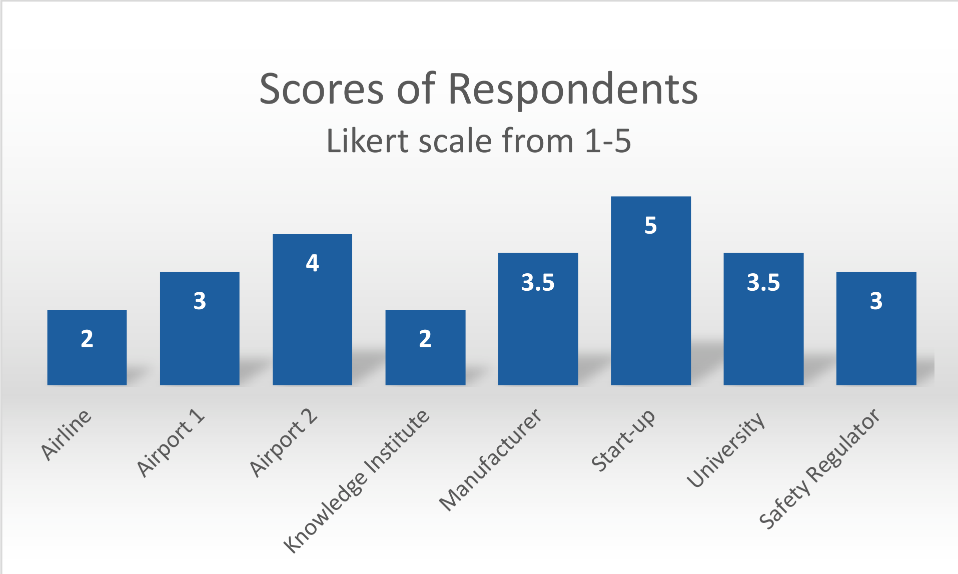


FIGURE 7: REPRESENTATION OF RESPONDENT SCORES ON HYDROGEN TECHNOLOGY

From Figure 7 can be derived that there is no uniform perspective on this indicator. An interesting observation is that respondents working within relatively smaller companies, such as the regional airports and the start-up, are relatively more positive on the communication and sense of a shared vision towards hydrogen for aviation. One respondent underwrites this by arguing that that thorough communication is present between OEMs, energy providers and the airport, regarding potential volumes of hydrogen and its complementary infrastructure required for hydrogen deployment (Int. Airport 2). Another respondent states that hydrogen is currently in a hype cycle where a perception of the potential is present which will expect to be attenuated later (Int. OEM). On the other hand, one respondent states that the current system is ready for SAF implementation, and that despite the overall impression that actors are focusing on hydrogen, most activities that are undertaking are on a relatively low maturity level as it is a radically different technology (Int. Knowledge Institute). Another respondent argues that it is difficult to aggregate all the activities of different actors in the aviation industry together (Int. Airline). This respondent proposes a hybrid configuration of a hydrogen propulsion in combination with a conventional SAF combustion is proposed as an intermediate step. As an average score of 3.3/5 is granted, this indicator is considered partially complete.

*Influencing condition and prospect of completeness*

For this indicator, the influencing condition *knowledge and awareness of technology* is applicable as the steps taken towards hydrogen deployment in aviation are still on a relatively low maturity level. It is challenging to formulate a prospect of completeness as this indicator represents subjective opinions of actors within the value chain of aviation which are all operating from a different perspective. Moreover, it could even be argued whether this indicator has the potential to become fully complete at all. Therefore, no prospect of completeness is formulated for this indicator.

### 5.5.3 CONCLUSION ON TIS BUILDING BLOCK 5

To conclude, the overall TIS building block *Network formation and coordination* of hydrogen aircraft is considered partially complete. With the introduction of the *Flying Vision* initiative in the Dutch/German ecosystem, a robust network for supporting sustainable transitions within the ecosystem is being formalized. While there is no uniform perspective on the perception of communication within the ecosystem and steps taken towards a similar vision on hydrogen aircraft deployment, the average score shows that a solid basis is currently present. The results of the analyses have been visualised in Table 13.

TABLE 13: EVALUATION OF COMPLETENESS OF TIS BUILDING BLOCK 5 OF HYDROGEN AIRCRAFT

| Indicator | Incomplete | Partially complete | Complete | Influencing condition |
|---|---|---|---|---|
| Actor network | | | | - |
| Communication among actors and steps taken towards a similar vision | | | | Knowledge and awareness of technology |
| Number of consortiums | X | X | X | X |
| Number of workshops and conferences | X | X | X | X |
| Number of publications on technical progress | X | X | X | X |
| Media coverage on concepts of sustainable aircraft technology | X | X | X | X |
| | | | | |
| Overall performance TIS building block 5 hydrogen aircraft | | | | Prospect of completeness: not applicable |

## 5.6 CUSTOMERS

### 5.6.1 CUSTOMER TYPE

The main classical customer type for the deployment of a regional hydrogen aircraft has been identified as the classical airline (Int. Airline; Int. Start-up). As the thesis focuses on the Dutch/German ecosystem, the KLM City Hopper would be a suitable customer for the introduction of the sustainable aircraft. Given that KLM is taking part in the *Flying Vision* initiative to accelerate a climate neutral aviation, it is expected that development and deployment of the hydrogen aircraft would be facilitated by the airline. Furthermore, a specific aim for the business segment within airline operations was considered for the deployment of hydrogen aircraft (Int. Airline; Int. Start-up). This segment consists of customers that need to fly regularly for business purposes and would be interested in paying more for a ticket to compensate their GHG emissions from flying regularly. As this market segment focuses specifically on regional flights, the Embraer 175 type aircraft would be applicable for the business market segment. Moreover, a start-up called EVIA AERO strives to become Europe's first sustainable airline by promoting sustainable regional flights (Airways, 2023). The company plans on connecting business regions within Europe and provide ticket prices that will be compatible to conventional ticket prices (EVIA AERO, n.d.). It is not unlikely that more airlines that focus on sustainable flights will be established in the near-term future.

Another respondent mentions that the charter segment might be interesting to address (Int. University), as there is a large demand for these flight routes which could stimulate hydrogen aircraft deployment. Furthermore, Bruce et al. (2020) have identified a strategy to implement hydrogen aircraft in the cargo segment first. In this way, pilots would receive appropriate time for training towards controlling hydrogen aircraft. Also, time is built in for scaling-up the aircraft production, which is expected to be time consuming in the beginning phases of hydrogen aircraft introduction (Bruce et al., 2020). As a customer segment within industry has been addressed already, but currently does not cover the range of customers present for conventional aircrafts, this indicator is considered partially complete.

*Influencing condition and prospect of completeness*

For this indicator, the influencing condition *competition* is present. As discussed, hydrogen aircrafts will be relatively more expensive than incumbent aircrafts, making a focus on the business segment for airlines an appropriate one to introduce hydrogen aircrafts to the market. Furthermore, a survey study indicated that people are more willing to travel 100 km to an airport to fly with a green/zero emission solution (90%) than to travel 50 km to a flight with a conventional aircraft (10%) (Int. Start-up). This shows that expected bottlenecks by industry might not be applicable. According to the respondent, these insights could help airlines to look at their network in a different way for the deployment of sustainable alternatives. Furthermore, the influencing condition *macro-economic and strategic aspects* influence this indicator as the state of the economy, being in regression or growth, impacts the types of customers that are interested in the novel sustainable alternative. The influencing condition is also presented by the lack of regulations for the deployment of hydrogen aircraft in aviation. By establishing strategic policies, more types of customers could be incentivised to adopt hydrogen aircraft. As no insights are currently present on the development of such regulations, this indicator is considered complete when hydrogen aircrafts will become cost competitive with conventional aircraft types as argued for in subsection 5.2.1. Therefore, the indicator is expected to be complete between 15-20 years.

### 5.6.2 INVOLVEMENT OF POTENTIAL CUSTOMER IN INNOVATION PROCESS

Currently, there is relatively low involvement of the potential customer in the innovation process. Knowledge exchanges regarding the developments in hydrogen aircraft are currently ongoing between aircraft OEMs and their customers, and it has been stated that both are eager to collaborate and have signed memoranda of understanding[6]. Nevertheless, specific actions towards collaboration within the innovation process have still not been taken (Int. Airline). It is argued that this process is just starting to open and still requires time to be established fully. This argumentation is also applicable for the *Flying Vision* initiative within the Dutch/German ecosystem, where an open innovative ecosystem is aimed for but has not been established fully yet. Another respondent considers the involvement of potential customers in the innovation process to be well established within their business context (Int. Start-up). As their focus is to retrofit an already existing aircraft model with a hydrogen propulsion system, the customer base that has already been established is addressed and involved in this process. Since both trends are visible within the Dutch/German ecosystem, this indicator is considered partially complete.

*Influencing condition and prospect of completeness*

The influencing condition present for this indicator is *socio-cultural aspects*. While one respondent argued that the airline and OEM clearly stated to want to cooperate, this has not been accomplished

[6] A memorandum of understanding is a non-binding agreement which state each party's intention to form a partnership together

yet (Int. Airline). This trend could suggest that the parties have not reached a base of trust between them yet, which requires more time to be build (Kazadi et al., 2016). Furthermore, the influencing condition *macro-economic and strategic aspects* play a role since the strategy timeline of an airline and an OEM are not considered to align (Int. OEM). An airline is stated to have a long-term strategic vision of approximately 10 years, while an OEM must have a strategy of over a decade. As stated in subsection 5.6.1, the state of the economy influences the strategic vision of customers which subsequently could shift quickly. Therefore, one respondent argues that collaboration involvement of the potential customer is not executed in the innovation process, but rather the subsequent phase where the technological base of the product has been established and particularly modifications on product performance level, deriving from specific requirements of the customer, can still be deployed (Int. OEM). Since the completeness of this indicator is based on the interaction between two firms, it is challenging to formulate a prospect of completeness. As the *Flying Vision* initiative has come up with key actors within the Dutch/German ecosystem of aviation, the involvement of the potential customer in the innovation process of sustainable aircraft is expected to be growing gradually over the coming years. Nevertheless, no specified prospect of completeness can be formulated for this indicator.

### 5.6.3 AWARENESS OF BENEFIT COMPARED TO INCUMBENT AIRCRAFT DESIGNS

A respondent has argued that the customer is currently aware of the benefits of hydrogen-fuelled flights over SAF-fuelled flights (Int. Airline). Next to the suitability advantage of hydrogen not emitting CO2 during flight, it is mentioned that a hydrogen aircraft would more easily be conceived as sustainable, and thereby encouraged, by the passenger than SAF would be. This is because the concept of net carbon-zero, operating with a net zero CO2 impact when taking the whole supply chain in consideration, is more problematic to perceive by the customer as CO2 is still a by-product of flying with an aircraft with 50% SAF drop-in fuel. Therefore, a positive attitude towards hydrogen aircraft is considered when assuming that the constraints of safety and a similar passenger capacity are being addressed. The latter one is especially important for aviation as a larger number of seats is more economic for airlines. Within the Dutch/German ecosystem specifically, Schiphol Airport is currently under restrictions to reduce the number of flights from March 2024 onwards (NRC, 2023), which could potentially put more demand on a high passenger capacity to sustain economically viable as an airline.

On the other hand, as addressed before in subsection 5.6.1, the potential loss of passenger seats in a hydrogen aircraft could be compensated by deploying more business class seats, which would bring relatively more revenue than economic class seats (Int. Start-up). Furthermore, the regional market segment of aviation is increasingly competing with other means of transportation for short-range distances, such as cars and trains due to sustainability considerations (Gunzinger et al., 2022; Int. Start-up). Therefore, it would be advantageous for airlines to focus on hydrogen aircraft deployment for their business case. A range of respondents argue that a retrofit design of a hydrogen aircraft would have a low threshold for implementation, making it an interesting design to consider for early phases of hydrogen aircraft deployment (Int. Airline; Int. Start-up; Int. Safety Regulator). With these insights, the indicator is considered complete.

### 5.6.4 FINANCIAL MEANS TO ACQUIRE AIRCRAFT

Respondents have stated that it is expected that customers have the financial means to acquire a hydrogen aircraft (Int. Airline). If the right customer market is addressed, the higher investment costs are expected to be balanced by the profits obtained from such flights. As mentioned in Subsection 5.6.1, various respondents mentioned that the business segment might be the right one to consider which correspondingly addresses this indicator as well. Furthermore, one respondent explained that flying is a price sensitive commodity, where a new balance in profitability needs to be found when deploying a relatively more expensive hydrogen aircraft (Int. Airline). This, on the other hand, was regarded as something that needs to be addressed rather than as a barrier for acquiring the innovation. When a retrofitted hydrogen aircraft design is acquired, the costs are expected to lead to approximately 10% increase in ticket prices (Int. Start-up). Passengers are expected to be willing to pay relatively more for a sustainable flight, as can be seen from the Scandinavian airline SAS who sold out a first-ever commercial regional electric flight scheduled in 2028 (Sasgroup, 2023) for a relative high price of 180 dollars (Aerospace Manufacturing and Design, 2023). Therefore, this indicator is considered complete.

### 5.6.5 WILLINGNESS TO ACQUIRE AIRCRAFT

As can be derived from the interview with an Airline, the willingness to acquire a hydrogen aircraft is stated to be present. Nevertheless, a defined plan to acquire hydrogen aircraft has not been established yet by the largest airlines in Europe (Airfrance KLM group, n.d.; Lufthansa Group, 2022; Ryanair, n.d.). In the corporate sustainability report of KLM, hydrogen propulsion systems have been stated as interesting but are still considered to be too far away (KLM, 2022). Moreover, Lufthansa (2022) has stated to do research on hydrogen aircrafts with research project *A320 Hydrogen Aviation Lab*, showing the interest of the airline to the technology. Nevertheless, as stated in subsection 5.6.1, the airline start-up EVIA AERO strives to be an airline operating with sustainable aircrafts only. EVIA AERO has partnered up with Cranfield Aerospace Solutions to develop a 19 PAX hydrogen aircraft by 2029 (Koenen, 2023), thereby showing that the willingness to acquire a hydrogen aircraft is present. To the knowledge of the researcher, this is the only airline clearly stating plans for early deployed hydrogen powered aircraft. As this shows that a willingness to acquire hydrogen aircraft is present, this is not equal to the willingness to acquire a conventional aircraft. Altogether, this indicator is considered partially complete.

*Influencing condition and prospect of completeness*

This indicator is influenced by *competition* with other aircraft types. Apart from competition in terms of investment costs, the uncertainties that come along with acquiring hydrogen aircraft deployment are high compared to that of conventional aircraft types. Incumbent companies tend to be avoiding risks, stemming from lock-in in the established company and way of doing business (Braganza et al., 2009). Conventional aircrafts have a better competing position in terms of the production system, complementary infrastructure, and networks among companies. Even including the deployment of 50% SAF, a conventional aircraft and its whole value chain would be relatively more reliable than the deployment of hydrogen aircraft would be.

Furthermore, the influencing condition *macro-economic and strategic aspects* has an impact on the indicator as well. As argued for in subsection 5.6.1 and 5.6.2, the state of the economy influences the business strategy and thus willingness to acquire hydrogen aircraft, for which large investments are needed. For the Dutch/German ecosystem specifically, the willingness of airlines to acquire the innovation might be hampered by the reduction in slots available for flights over Schiphol. This means that a reduced number of flights can be executed, where airlines foresee the need to deploy flights that are most economic to them. One respondent states that, on a higher level, this could lead to a substitution of regional aircraft to aircraft for long-range flights which would not be beneficial for the introduction of hydrogen aircraft on a regional flight level (Int. Airline). Furthermore, International Airlines Group (2022) has assumed hydrogen aircrafts to be taken in their fleet from 2040 onwards. As it is challenging to foresee how the willingness to acquire hydrogen aircraft will develop over the next decade, the indicator is acknowledged to be complete when uncertainties of hydrogen deployment will decrease, based on the prospect of completeness of TIS building block 2, 3, 4 and 5. Therefore, the prospect of completeness is considered 22 years.

### 5.6.6 CONCLUSION ON TIS BUILDING BLOCK 6

To conclude, the overall TIS building block *Customers* of hydrogen aircraft is considered partially complete. While customers state to be aware of the benefits of hydrogen aircrafts over incumbent aircraft designs and have argued to possess the financial means to acquire it, the willingness to acquire the innovation has not been stated in strategies of incumbent airlines. This can be accounted to the business cycles of customers that depend on the state of the economy. Moreover, while customer types have been identified for hydrogen aircraft deployment, this is on a relatively small scale compared to the whole offer in aviation. Furthermore, improvements in involving potential customers in the innovation process could be made. TIS building block 6 is expected to be complete within 22 years. The results of the analyses have been visualised in Table 14.

TABLE 14: EVALUATION OF COMPLETENESS OF TIS BUILDING BLOCK 6 OF HYDROGEN AIRCRAFT

| Indicator | Incomplete | Partially complete | Complete | Influencing condition |
|---|---|---|---|---|
| Customer type | | | | Competition; Macro-economic and strategic aspects |
| Involvement of potential customer in innovation process | | | | Socio-cultural aspects; Macro-economic and strategic aspects |
| Awareness of benefit compared to incumbent aircraft designs | | | | - |
| Financial means to acquire aircraft | | | | - |
| Willingness to acquire aircraft | | | | Competition; Macro-economic and strategic aspects |
| | | | | |
| Overall performance TIS building block 6 hydrogen aircraft | | | | **Prospect of completeness: 22 years** |

## 5.7 INNOVATION-SPECIFIC AND INDUSTRY-WIDE INSTITUTIONS

### 5.7.1 GOVERNMENTAL POLICIES AND REGULATIONS (EU WIDE)

Within Europe, the European Union has presented the EU Green Deal in 2019 in which ambitions to develop the continent towards climate neutral operation by 2050 are stated. Throughout the European Climate Law, this plan has become a binding EU legislation for all its member states in 2021 (European Parliament, 2023). Nevertheless, this legislation has not specified targets for the aviation industry, leading to the industry to set its own targets (see subsection 5.7.2). Furthermore, the EU has implemented the EU Emissions trading System (EU ETS), which is the world's first large-scale carbon market. This system works with a so-called 'cap-and-trade' principle in which the European Union has put a cap on the total amount of CO2 emissions that are allowed to be emitted by all operators within the European Union (European Commission, n.d.a). Here, operators can buy or receive emission allowances, which they are free to exchange among each other. The system covers approximately 40% of the GHG emissions within Europe. Since 2012, the aviation sector is included in this system, however, airlines currently receive free allowances for a certain amount of $CO_2$ emissions from their operations per year.

Furthermore, in July of 2021, the European Commission presented the 'fit for 55' package with the aim for aligning European climate policies with European climate laws and reducing emissions within Europe by 55% compared to 1990 levels (PBL, 2021). One objective is to progressively reduce the free allowances allocated to aircraft operators towards a system of full auctioning by 2027, applying for all European flights (European Commission, n.d.b). Moreover, the European Commission will apply CORSIA for International Aviation, which will be elaborated on in subsection 5.7.2, to extra-European flights that depart or arrive in countries where CORSIA applies. These regulations discourage the use of fossil fuels in aircraft operations, thereby indirectly supporting the deployment of hydrogen aircraft. To make this regulation tangible, the carbon price in the EU ETS has been on average €85 per tonne of $CO_2$ emitted in 2023 (Statista, 2023). Nevertheless, over the amount of $CO_2$ emitted by the aviation industry, this carbon price is considered rather low. Moreover, these costs are incomparable with the cost associated with the enrolment of the hydrogen infrastructure and its value chain. Therefore, it is also probable that this carbon price will encourage a focus on ultra-efficient aircraft and lead to the deployment of more SAF drop-in rather than on hydrogen aircraft. As overall policies and regulations are present within the EU, but do not target hydrogen aircraft specifically, this indicator is considered partially complete.

*Influencing condition and prospect of completeness*

It is argued that more top-down perspectives are needed from European perspective (Int. Safety Regulator). For the formation of policies and regulations, the influencing conditions *macro-economic and strategic aspects*, *socio-cultural aspects* and *accidents and events* apply to this indicator. Here, the first refers to the state of the economy, being in regression or growth, that serves as a premise for decision-making within the EU. The second represents the different norms and values that need to be aligned for the formation of such institutions. The third represents the external circumstances that might accelerate or hinder regulation. Compared to other regulatory instances, the European Union has a strong ambition to develop towards sustainability. Nevertheless, the EU consists of 27 member states, making it difficult to come to terms for the formulation of new regulations. Next year, the EU will vote for a new European Parliament, who have the influence to decide upon new regulations and alter already established ones (European Parliament, n.d.). As the political environment of the EU includes parties that desire to level off EU climate ambitions (NOS, 2023), the European Parliament of next year and its terms of policy will have a large impact in the enforcement and sharpening of sustainable policies and regulations. Moreover, it is suggested that a worldwide perspective and regulation on sustainable aviation should be considered (Int. Safety Regulator; Int. Start-up). As it is highly challenging to grasp how these trends will develop the coming years, no prospect of completeness is suggested for this indicator.

### 5.7.2 INDUSTRY SELF-REGULATION

The aviation industry is currently operating from a self-regulatory environment (Leal Filho et al., 2022). The International Civil Aviation Organization (ICAO) is an organisation from the UN to formulate principles and standards for international aviation. In 2016, their proposed plans for CORSIA were adopted by the aviation industry. The CORSIA is a market-based scheme addressed on a global level to restrict $CO_2$ emissions of international aviation (Prussi et al., 2021). Here, airlines need to disclose their $CO_2$ emissions every year and compensate for their emissions through financing a reduction in emissions from another airline (IATA, n.d.). CORSIA has been implemented in international aviation in 2019 and indirectly addresses the benefits of the implementation of a carbon-neutral fuel such as hydrogen. While the CORSIA carbon offsetting scheme imposes pressure on kerosene as a fuel for aviation, the industry focuses more on the deployment of SAF rather than implementing regulations to stimulate hydrogen as a fuel for aviation.

Moreover, the organisation International Air Transportation Association (IATA), which represents world's airlines and helps formulate industry policy on challenges for the aviation industry, has adopted three goals to mitigate CO2 emissions in 2009: *(I) annual improvements in fuel efficiency of 1.5%; (II) a cap on net aviation CO2 emissions from 2020* and *(III) the reduction of CO2 emissions of 50% by 2050 when compared to 2005 levels* (Kettler & Walls, 2022). Next to that, it has adopted four pillars to mitigate CO2 emissions, including *(I) improved technology and the deployment of SAF; (II) more efficient aircraft operations; (III) infrastructure improvements;* and *(IV) a single global market-based measure* (Leal Filho et al., 2022). Nevertheless, Kettle & Walls (2022) argue that these measures will be insufficient to meet Paris Agreement Goals. In the end of 2022, global governments, industry and civil society representatives have codified another international agreement on carbon reductions from aviation by 2050 (Mithal & Rutherford, 2023). This new goal reinforces commitment to the CORSIA, advocates the promotion of SAF and encourages states to develop action plans for themselves. Nevertheless, it is argued that such self-regulatory targets to decarbonise by 2050 represent an ambition rather than an established legislation towards sustainability (Int. Safety Regulator). Leal Filho et al. (2022) underwrite this argumentation and argue that voluntary alignment of the aviation industry and its commitment to long-term goals remain inconsistent. As self-regulation of the aviation industry has no specified focus on hydrogen aircraft deployment, this indicator is considered incomplete.

*Influencing condition and prospect of completeness*

This indicator is affected by the influencing condition *macro-economic and strategic aspects.* By focusing on increasing efficiency and the deployment of SAF as fuel, a large extent of the current way of doing business in the aviation industry would be maintained, which is strategically interesting for almost the entire value chain of aviation. On the other hand, the societal perception on the sustainability of the sector also requires the aviation industry to take more challenging actions towards sustainability. This currently affects companies, in terms of potential market loss (Int. Safety Regulator). Respondents argue that more governmental incentives are needed from a European perspective to help the aviation industry addressing the challenges it is facing (Int. Safety Regulator; Int. Start-up). The researcher considers it unlikely that the aviation industry will regulate itself towards hydrogen aircraft deployment without governmental support or incentives in the short-term. Similar to subsection 5.7.1, it is challenging to predict how self-regulation will organise within the aviation industry over the coming years. Therefore, no prospect of completeness is formulated for this indicator.

### 5.7.3 SUBSIDIES AND INCENTIVES

Currently, subsidies are present for the deployment of a hydrogen market within Europe. The EU has the ambition to deploy a total capacity of 350 GW of installed electrolysers by 2030, from only 500 MW in 2021. In the beginning of 2022, a roadmap was presented regarding which measures are required for green hydrogen rollout in Europe, executed by the International Renewable Energy Agency (IRENA) and World Economic Forum (2022). This roadmap states that for the coming five to ten years, the EU should focus on (I) formulating an additional rule for hydrogen production with increasing RES deployment; (II) easing such rules for first movers, and; (III) providing support to decrease investment costs of electrolysers. This would provide a basis to set up a hydrogen market in the short-term timeframe. This ambition will contribute to the ambition of the EU hydrogen strategy and Europe's REPowerEUplan to generate 10 million tonnes of green H2 by 2030. Also, these plans state that another 10 million tonnes of green H2 will be imported within that timeframe. In the Netherlands specifically, plans are set to install a 'Gigawatt Electrolyser' before 2030, which accounts for a hydrogen plant with thousands of electrolyser stacks which will lead to larger capacity that will be deployed centrally (GVNL, 2023). Therefore, appropriate incentives for producing cost competitive green hydrogen are present, which has been identified as a key bottleneck (Int. University).

The scenario of Fuel Cells and Hydrogen 2 Joint Undertaking (2020) shows that 10 million tons of hydrogen for aviation would be required by 2040, which would be in-line with EU strategies. However, it should be noted that this hydrogen production will not be allocated to the aviation industry completely. From 2030 onwards, the EU plans to deploy this green hydrogen at a large scale across so-called hard-to-abate sectors, referring to the industries that are highly reliant on fossil fuels and have a governmental priority to be allocated with green hydrogen (Paltsev et al., 2021). These include steel industry, cement industry, chemical industry, shipping industry and the aviation industry (European Commission, 2020b). Currently, no explicit strategy has been proposed yet to allocate the green hydrogen over these industries. One respondent argues that policy makers have the power to allocate this green hydrogen production capacity by themselves (Int. Safety Regulator). Green hydrogen might also be allocated through market-based mechanisms where a specific amount needs to be bought by the industries themselves.

Incentives are also present for the establishment of hydrogen distribution infrastructure. A directive on the internal market in hydrogen has been implemented and delivered by the first quarter of 2022 (European Commission, n.d.d). Plans for creating cross border pipelines to facilitate hydrogen distribution have been established in Germany, Spain, and France. By 2030, a length of 23.365 km of hydrogen pipelines have been dedicated over 28 European countries (RystadEnergy, 2023). Moreover, a European Hydrogen Backbone initiative, consisting of 32 energy infrastructure operators, has presented ambitions to repurpose 60% of existing gas networks in Europe and construct 40% new hydrogen pipelines by 2040 (European Hydrogen Backbone, 2022).

For hydrogen deployment in the aviation industry specifically, EU subsidies have been granted to the Clean Aviation Joint Undertaking programme, the leading research and innovation programme for carbon-neutral aviation. Here, €65 millions of EU funding is dedicated to hydrogen powered aircraft (Clean Aviation, 2023a). Moreover, the Horizon Europe which is an EU funding programme for research and innovation has been granted €20 millions for hydrogen airport ground infrastructures, refuelling technologies and new standards and certification procedures for hydrogen aircraft (Horizon Europe, 2023). In the Netherlands specifically, the government has supported the *Flying Vision* initiative which is expected to accelerate sustainable developments within the Dutch/German ecosystem. Even though the initiative is still in a set-up phase and no specific steps towards hydrogen aircraft in aviation have been made, this is expected to be attained over the coming years. Altogether, this indicator is considered complete.

### 5.7.4 SAFETY REGULATIONS

Currently, there is a lack of safety regulations available for the deployment of hydrogen in the aviation industry. Accurate safety regulations can be established only if there is a clear vision present on the technology itself (Int. Knowledge Institute; Int. Safety Regulator). As know-how of the production of a hydrogen aircraft is still under consideration, as argued for in subsection 5.3.1, regulation on the technological bricks of hydrogen aircraft and its operation is currently still not established properly.

For hydrogen storage at airports, the established safety regulations of hydrogen storage, e.g. tank stations, of industries can be applied to the airport as well (Int. Airport 1). The respondent argues that these safety regulations are established on regional level by municipalities, which have been translated from European guidelines. A safety radius for gaseous hydrogen tank stations have been established already, specified on 35m to other urban areas (Airport 1). Such a radius has not been established for liquid hydrogen storage, but these are expected within 5 years (Int. Airport 2). Furthermore, it is argued that the current established safety regulations for hydrogen storage are exceptionally strict. For a hydrogen storage facility in Ypenburg, for example, a safety radius has been established based on a worst-case scenario, where the amount of hydrogen being stored would explode in a stoichiometric manner (Int. University). According to the respondent this scenario would never happen under these specific conditions.

Furthermore, a lack of safety specifications regarding hydrogen refuelling is present. It is expected by respondents that the refuelling process will be similar to the refuelling process of conventional aircrafts propelled by kerosene. The energy provider is expected to manage the refuelling process while the airport monitors the installations (Int. Airport 1). Here, it is considered that an energy provider has the responsibility to come up with refuelling standards, including e.g. a specified safety radius around the fuel hose where no ignition spark is allowed to occur is currently lacking (Hoelzen et al., 2022a). This radius could potentially be set wider than the three meters set for kerosene refuelling (National Fire Protection Association, 2022), which could potentially lead to logistic problems at the airport. Moreover, a respondent argues that other interrelated procedures should be mentioned as well in the safety standard of refuelling, including whether passengers are allowed to board during the process and if extra safety considerations should be established for other ground operations. It is stated that these standards should come from industry through collaborations between the airport, aircraft OEM and energy provider (Int. Airport 1). As the safety requirements of conventional aircraft have been established and optimised over the past century and the ones for hydrogen aircraft operations still need to be formulated, this indicator is considered incomplete for hydrogen aircraft.

*Influencing condition and prospect of completeness*

For this indicator the influencing condition *knowledge and awareness of technology* is applicable as the formulation of safety requirements should develop in an evolutionary manner next to technological development (Int. OEM; Int. Safety Regulator). It should be noted that the safety requirements for kerosene-based aviation have been established by thorough experience from the automotive industry and have been subject to decades of feedback and refinery loops to get to the standards of today (Int. OEM; Int. Start-up; Int. University). Therefore, it is expected that this process of formulating safety standards will be time intensive as well. Another respondent argues that distinctive safety standards developed on local level will together undergo an interactive process where, as a result, one clearly defined standard will be formulated (Int. Airport 1). As this is an interactive process the respondent expects it to take longer to be established, but within a maximum of 10 years, when smaller hydrogen aircraft such as retrofit designs have been deployed. Furthermore, some collaborations are present to focus on the establishment of such safety regulations. The AZEA, for example, is organising working groups on the introduction of hydrogen in aviation, focusing on a range of different topics including the risks of hydrogen aircraft deployment and the establishment of safety requirements (Int. Airport 2; Int. Safety Regulator; Int. University). According to the projections that smaller retrofit hydrogen aircraft will be deployed in the coming years and safety requirements will start to be formulated, the indicator is considered complete in 10 years.

### 5.7.5 INTERNATIONAL AND REGIONAL STANDARDS

One international standard in the aviation industry is the certification process. Within Europe, EASA acts as the single point of reference for aircraft certification (Int. Safety Regulator; EASA, n.d.). When an aircraft OEM wants to certify a new aircraft model, a certification project of 5 years starts where the company should demonstrate the aircraft operating conform certification specifications through testing and analysis. As exceeding this timeframe would lead to a reconsideration on certification specifications and thus an increase of costs for the OEM, it is important to have established thorough experimentation with the innovation already before this process starts. One respondent highlights that for hydrogen technology specifically, no certification procedures have been established yet (Int. Safety Regulator). Apart from a range of high-level safety requirements that would remain applicable, including e.g. "*the probability of catastrophic failure"*, specified safety regulations for hydrogen aircraft need to be evolutionary composed according to the specific technological developments in industry. Thus, rather than establishing certification requirements before product development, these should be established during R&D phases of hydrogen aircraft developments. Therefore, it is highly important to involve the safety regulator in earlier R&D stages already, preferably within 5-10 years before the certification process starts. This could be done through European Research programmes such as Horizon Europe or the Clean Aviation Joint Undertaking. If EASA will be involved with the R&D of hydrogen aircraft now, the respondent expects the introduction of a hydrogen aircraft to be theoretically possible by 2035 (Int. Safety Regulator).

Furthermore, standards should be formulated for the refuelling of a hydrogen aircraft as well as in the European supply chain of hydrogen production and distribution to industry. As no safety radius has been specified around hydrogen refuelling, this refuelling standard is expected to be developing according to industry experimentation as discussed in subsections 5.4.4 and 5.7.4. Moreover, for the deployment of hydrogen distribution infrastructure, member states of the EU are currently expected to create their own rules and standards (European Commission, 2021). Transnational interconnections of pipeline systems are vital for the well-functioning of hydrogen markets and thus have a large influence on hydrogen prices and subsequently demand formation. Without a European-wide standard on hydrogen transportation rules and hydrogen quality, integration of cross-border hydrogen networks and markets could pose problems at later stages (European Commission, 2021), showing the relevance of establishing such requirements.

Moreover, in the Netherlands specifically, regional standards have been formulated to reduce the number of flights at Schiphol Airport from March 2024 onwards (NRC, 2023). As stated in subsection 5.6.3, this could lead to a focus on operations of large aircraft with a high passenger capacity, while the regional market segment is essential to address radical innovations such as a hydrogen aircraft. It is argued that this could be translated into a positive incentive for hydrogen deployment when exceptions would be granted to flights on hydrogen in such slots (Int. Airline). Altogether, the current international and regional standards for hydrogen as an innovation and hydrogen applied to aviation have not been addressed sufficiently, leading the indicator to be considered incomplete.

*Influencing condition and prospect of completeness*

The influencing condition *knowledge and awareness of application and market* currently hampers the indicator. As stated before, a wide range of standards are expected to be established within collaborations in industry itself. Here, standards formation is expected to take time and undergo similar interactive processes to define one clear standard for industry, as discussed in subsection 7.5.4. Currently, airports that are open for experimentation with hydrogen and want to facilitate developments such as the formation of refuelling standards are present (Int. Airport 1). The respondent argues that distinctive safety standards developed on local level will together undergo an interactive process where, as a result, one clearly defined standard will be formulated. As this is an interactive process the respondent expects it to take longer to be established, but within a maximum of 10 years (Int. Airport 1). Furthermore, the international standards on hydrogen pipeline infrastructure needs to be established at a higher level through coordination and collaboration of EU Member States. Taking the assumption in the report of Fuel Cells and Hydrogen 2 Joint Undertaking (2020) that sufficient hydrogen distribution infrastructure will be present between 2035 and 2040, it is expected that compatibility standards will be formulated within 15 years. Therefore, this indicator is considered complete within 15 years.

### 5.7.6 CONCLUSION ON TIS BUILDING BLOCK 7

To conclude, the overall TIS building block *Innovation-specific and industry-wide institutions* of hydrogen aircraft is considered partially complete. Currently, the self-regulation of the aviation industry is not incentivising itself towards hydrogen deployment in aviation. In Europe, the EU-wide governmental policies and regulations are considered reasonably aiming for overall sustainability in the continent, although more specific regulations on the aviation industry could be imposed. Safety regulations and international and regional standards are currently insufficient and are expected to be evolving within the next decade along with technological developments of hydrogen aircraft. Nevertheless, subsidies and incentives, which are expected to stimulate technological developments, are currently significantly present. TIS building block 7 is expected to be complete within 15 years. The results of the analyses have been visualised in Table 15.

TABLE 15: EVALUATION OF COMPLETENESS OF TIS BUILDING BLOCK 7 OF HYDROGEN AIRCRAFT

| Indicator | Incomplete | Partially complete | Complete | Influencing condition |
|---|---|---|---|---|
| Governmental policies and regulations (EU wide) | | ■ | | Macro-economic and strategic aspects |
| Industry self-regulation | ■ | | | Macro-economic and strategic aspects |
| Subsidies and incentives | | | ■ | - |
| Safety regulations | ■ | | | Knowledge and awareness of technology |
| International and regional standards | ■ | | | Knowledge and awareness of market |
| Overall performance TIS building block 7 hydrogen aircraft | | ■ | | **Prospect of completeness: 15 years** |

## 5.8 CONCLUSION CHAPTER 5

Chapter 5 has addressed SQ2, analysing the indicators of TIS building blocks of hydrogen aircraft technology on their level of completeness in comparison to the benchmark Embraer 175 aircraft design with 50% SAF drop-in fuel, which is considered to represent completeness. For incomplete indicators, influencing conditions potentially hampering developments have been identified and a prospect of completeness has been formulated according to academic and grey literature and insights from respondents of the interview. The level of completeness of the overall TIS building block has been derived from the mean of the level of completeness of the separate indicators. Also, the prospect of completeness of non-complete TIS building blocks has been derived from the longest formulated prospect of completeness of its indicators. Hydrogen aircraft developments within its TIS currently show to be incomplete in TIS building blocks *Production system* and *Complementary infrastructure and services*. Furthermore, the TIS building blocks *Product performance and* quality, *Product price*, *Customers* and *Innovation-specific and industry-wide* institutions are partially complete. Only TIS building block *Network formation and coordination* is considered complete for hydrogen aircraft.

# CHAPTER 6: ANALYSIS OF ULTRA-EFFICIENT AIRCRAFT TIS BUILDING BLOCKS

In this chapter, ultra-efficient aircraft are analysed according to the indicators proposed for the TIS building blocks in Table 5, after which main findings are concluded. The relevancy of each indicator is elaborated on in Appendix B. An ultra-efficiency aircraft design is another promising sustainable alternative for aviation. By establishing an aircraft design that is lighter, more aerodynamic, and more efficiently integrated, the amount of fuel required for operation could significantly drop. Even though the ultra-efficient alternative will use conventional kerosene for propulsion, this drop of required fuel per flight will lead to less climate impact of aviation.

The ultra-efficient aircraft technology is another promising sustainable alternative for aviation. Key performance drivers of incumbent aircraft have been improved significantly in this aircraft design, reaching optimisation towards the limit of physics while maintaining conventional so-called *tube and wing* design[7]. By establishing an aircraft design with less structural weight, less aerodynamic drag, and including engines with less specific fuel consumption that are integrated better on overall product level, the amount of fuel required for operation could significantly drop. These three dimensions are considered the technological bricks of ultra-efficient aircraft. Even though the ultra-efficient alternative will use conventional kerosene for propulsion, this drop of required fuel per flight will lead to less climate impact of aviation. An illustration of the ultra-efficient aircraft concept is provided in Figure 8.

FIGURE 8: ULTRA-EFFICIENT AIRCRAFT CONCEPTUAL DESIGN (AIRBUS, N.D.)

From the introduction of the first commercial aircraft onwards, half of the efficiency improvements are accounted by engine efficiency, showing the relevancy of addressing this technological brick for the ultra-efficient aircraft (Weinold et al., 2023). In this research, an open rotor propulsion engine has been chosen over a turbofan design. This engine design permits a significantly higher bypass ratio, referring to the proportion of mass flow rate of the bypass flow to the one going in the core of the engine which leads to reductions in fuel consumption (Mastropierro et al., 2020). The blades have a larger diameter which increases velocity at the blade tips. To ensure that this propulsive efficiency will not be affected in high cruise speed, e.g. by blade velocities in supersonic dimensions where drag and noise emissions are increased, the cruise flight altitude should be slightly lowered (Batteiger et al., 2022). For the deployment of the open rotor propulsion engine, a high position of the wing is required, as well and a

[7] A tube and wing design is the traditional aircraft design where the fuselage and the wings of the aircraft are not blended (Centracchio et al., 2018)

T-tail empennage arrangement as can be seen in Figure 8. While these could potentially lead to drawbacks, it is considered manageable in ultra-efficient aircraft to become neutral in drag and weight on overall aircraft level. Overall, it is expected that an advanced open rotor propulsion engine could reduce fuel consumption by 15% compared to conventional turbofan engines of an Embraer 175.

For the wing, an extreme high aspect-ratio wing is chosen to reduce lift-induced aerodynamic drag, thereby improving fuel consumption levels (Afonso et al., 2017). Compared to the Embraer 175 reference, its total wingspan will be approximately 9m larger. The total wing area would need to be kept constant to the reference, so wing chord[8] needs to be decreased. This could pose challenges for e.g. flight controls and high lift systems of the wing, which increase the amount of lift, however, with advanced solutions this impact is expected to be mitigated. A principal increase of wing weight resulting from the required higher bending moment from higher span is expected to be compensated by the use of advanced lightweight materials such as carbon fibre composites, which directly reduce the structural weight via its lower density at equal strength. Furthermore, load alleviation functions can counter the weight increase from the increased bending moment due to span (Nguysen et al., 2017), where active wing-moveable devices concepts can actively alleviate the load increase from manoeuvres and. Moreover, the design of the composite structure layout of the wing could enhance performance and stability for supporting the load alleviation further. The assumed drag reduction from the high aspect ratio wing is expected to be up to approximately 15%, without weight increase, resulting in an equivalent of reduction in fuel consumption.

Furthermore, the aerodynamic drag on the surface of the wing and empennage can be reduced by the application of a so-called *profile shape design*, which ensures a high portion of natural laminar flow. Improved natural laminar flow results in a drag reduction through lowering friction drag in the shear layer around the airframe, representing the region where airflow changes rapidly (Hollom & Qin, 2021; Sabater et al., 2022). To ensure this, it is essential that surface quality is very high, with a limited number of steps and waviness during manufacturing phase. With advanced material and surface protection technology, this is considered manageable. Natural laminarity on both the wing and wing tails could account for approximately 7% drag reduction.

Altogether, this ultra-efficient aircraft design composition is expected to reduce approximately 37% in fuel consumption. An uncertainty range of +/- 5% is estimated for this value, which depends on the maturity and performance of future technologies in real product application. As was the case in the hydrogen aircraft analysis, the TIS building block analysis of indicators is used as a reference on what the current performance of the indicators is, and which steps should be taken to enhance their development in the short-term future rather than focusing on the implementation possibilities of hydrogen-fuelled aircraft at this moment.

## 6.1 PRODUCT PERFORMANCE AND QUALITY

### 6.1.1 CO2 EMISSIONS

Even though ultra-efficient aircraft use fossil fuels for propulsion, the overall fuel consumption reduction of 37% would lead to the same percentage of reduced CO2 emissions. CO2 emissions of SAF-fuelled aircraft are net-carbon neutral by using carbon, obtained from Carbon Capture and Storage (CCS) technology[9], for the synthesis of the fuel (Colelli et al., 2023). As the CO2 emitted from SAF

[8] A wing chord represents the width of an aircraft's wing
[9] CCS technology can mitigate CO2 emissions by capturing it before or after combustion (Yadav & Mondal., 2022). The carbon could be used as resource for the production of synfuels such as SAF (Colelli et al., 2023).

combustion is carbon neutral (Fuel Cells and Hydrogen 2 Joint Undertaking, 2020) and a drop-in of 50% is considered for this research, the CO2 emissions from a conventional aircraft with SAF drop-in would be reduced by 50%. Since ultra-efficient aircraft still would emit 13% CO2 more compared to conventional aircraft with SAF drop-in, the indicator is considered incomplete.

*Influencing condition and prospect of completeness*

The influencing condition present is *knowledge and awareness of the technology.* Through R&D, there is a potential that more fuel consumption and thus CO2 emissions could be reduced by optimising aircraft configurations and using more light-weight materials. On the other hand, it is imperative to consider that efficiency improvements are subject to limits. Singh & Sharma (2015) argue that a slower increase in technological development in aerodynamics and engine designs and airframe materials has slowed down fuel efficiency improvements in the aviation industry the past four to five decades. Currently, overall efficiency improvements with conventional aircraft designs have reached an asymptote (Faggiano et al., 2017). Efficiency improvements are considered within the ranges of financial returns obtained from the improvements (Airbus technology valuation training, 2023). Also, materials for engines require suitable mechanical properties, densities, and corrosion resistance at high temperature, making the development of suitable aerospace materials challenging (Zhang et al., 2018). Therefore, efficiency gains should not impose too many costs which would make the purchase of ultra-efficient aircraft cost inefficient. Nevertheless, it is expected that efficiency improvements from the ultra-efficient aircraft design are possible in the future (Int. OEM). Altogether, the research estimates that more time is needed to reach a relatively larger amount of CO2 emission reduction, which is not expected to be present before 20 years from now.

### 6.1.2 NOX EMISSIONS

According to an analysis of Clean Sky 2 (2021) that investigates ultra-efficient aircraft design with a reduction of 34% of fuel consumption, NOx emissions could be reduced with 67% compared to the ATR72-500 design of 2014. This is beneficial when compared to the conventional aircraft with 50% SAF drop-in, as kerosene and SAF as fuels are combusted for aircraft propulsion and do not specifically address NOx emissions. Since improvements in ultra-efficiency aircraft lead to a significantly lower level of NOx emissions compared to a conventional aircraft with 50% SAF drop-in, this indicator is considered complete.

### 6.1.3 CONTRAIL FORMATION

Currently there is a lack of literature on exact numbers of contrail formation reduction of ultra-efficient aircraft. As stated before, it is argued that contrail cirrus ice crystals are partially formed by exhaust soot particles (Voigt et al., 2021). From this rationale, a lower fuel consumption would be expected to lead to relatively less soot particles and thus less contrail formation. Noppel & Singh (2007), on the other hand argue that the probability for contrail formation increases with higher engines efficiencies of open rotor technologies as water vapor saturation pressure is reached. As SAF as synfuel is expected to contain fewer aromatics in its composition (Fuel Cells and Hydrogen 2 Joint Undertaking, 2020), it is stated that flying on SAF could reduce 50%-70% of soot and ice concentrations (Voigt et al., 2021). Taking into consideration that SAF will be deployed for 50% next to conventional kerosene, this would account for a 25%-35% reduction of contrail formations. As it is inconclusive whether ultra-efficient aircraft will increase or decrease contrail formation of conventional aircrafts deploying kerosene, this indicator is considered incomplete.

*Influencing condition and prospect of completeness*

As there is a lack of hard data available on the contrail formation of ultra-efficient aircrafts, the influencing condition *knowledge and awareness of the technology* is present. Furthermore, the influencing condition *knowledge and awareness of application and market* is present. Research suggests that contrail formation from aircraft depend on altitude, temperature, and the relative humidity (Teoh et al., 2020; Xue et al., 2020). By adjusting flight altitudes, both fuel consumption and contrail formation can be reduced (Lán & Hospodka, 2022; Bräuer et al., 2021). This shows that flight operations should be altered according to environmental context of the flight route. Spinardi (2015) argues that the from a political and organisational perspective, changing the flight route coordination is challenging across the complex sociotechnical system of global aviation. Furthermore, Xue et al. (2020) state that changing altitudes potentially leads to conflicts with other aircraft, increases the workload of pilots and air traffic controllers and might lead to decreasing passenger comfort. Due to these complexities, a change towards different flight operations is not expected yet by the researcher within the coming 10 years.

### 6.1.4 RANGE

As the ultra-efficient aircraft encompasses state-of-the-art engines, and improved natural laminarity, the alternative is expected to reach similar or even larger ranges than a conventional Embraer 175 aircraft design. The wider wingspan could potentially increase weight of the aircraft, but this is expected to be nullified by making use of novel light-weight composite structures and load alleviation function (Int. OEM), which decreases structural load of the wing. The open rotor engine might impose extra weight to the aircraft, however, the integration of composites in e.g. fuselage would reduce overall aircraft weight. Therefore, weight is not expected to increase and thus would not affect the range of ultra-efficient aircraft. Furthermore, the study of Clean Sky 2 (2021) presents an ultra-efficient turboprop of 90 PAX that could reach a range of 1200 nautical miles opposed to the range of 100 nautical miles of the reference ATR turboprop design. Therefore, the indicator is considered complete.

### 6.1.5 PASSENGER CAPACITY

The novel technological bricks of ultra-efficient aircraft are not expected to have an influence on the interior of the aircraft design. As a lower speed might lead to a reduced number of flight cycles, which is economically less desirable, the passenger capacity could be increased to compensate for this. A study of Clean Sky 2 (2021) proposes an ultra-efficient aircraft design for the transportation of a total of 90. This passenger capacity would be in-line with the Embraer 175, which has a passenger capacity of 88 PAX. Therefore, this indicator is considered complete.

### 6.1.6 REQUIRED FUEL PER SEAT

The study of Choi & Lee (2022) calculates that the Embraer 175 requires approximately 7.500 kg Jet A fuel. Considering a fuel consumption reduction of 37%, this results in an ultra-efficient aircraft to require approximately 4.500 kg Jet A fuel. Taking the passenger capacity of 88 PAX of an Embraer 175, the required fuel per seat would be approximately 51 kg. This is beneficial compared to the 85 kg required fuel per seat for a conventional aircraft with 50% SAF drop-in. Therefore, this indicator is considered complete.

### 6.1.7 REFUELLING TIME

As the ultra-efficient aircraft uses kerosene for propulsion, the refuelling operation is assumed to be executed similar as to conventional aircraft. Furthermore, less fuel is required for ultra-efficient aircraft, leading to the expectation that refuelling time would decrease. Thus, the turn-around time of aircraft operations are not expected to be compromised with the introduction of ultra-efficient aircraft. Therefore, this indicator is considered complete.

### 6.1.8 NOISE EMISSIONS

For ultra-efficient aircraft, concerns are present over the noise levels of the open rotor engines (Smith et al., 2020). An open rotor engine has inherently high levels of noise emissions due to absence of a shielding benefit as a turbofan would have. Guo & Thomas (2015) describe how a surface liner treatment to mitigate noise emissions can be deployed in the vicinity of the engine installations. However, this technology would induce drag, showing that a trade-off is present between the efficiency of fuel consumption and noise emissions. Furthermore, the larger length of the blades leads the outer edges to have a relatively higher rotational speed, which as a result leads to relative higher noise emissions (Merino-Martínez et al., 2019). This could be mitigated when a lower rotational speed is exercised (Clean Sky 2, 2021). Moreover, Moshkov et al. (2018) propose a range of methods to reduce open rotor noise emissions. These include an optimization of the aeroacoustics of the blade shape to reduce approximately 2 dB and an increase in the number of blades used, which in turn leads to a higher weight of the engine. As noise regulations are present that need to be adhered to by aircraft designs, ultra-efficient aircraft are expected to optimise the trade-off between fuel consumption and noise emissions within the ranges of the regulation. Therefore, the indicator is considered complete.

### 6.1.9 PASSENGER COMFORT

Similar to subsection 5.1.9, the indicator regarding passenger comfort has not been covered thoroughly by literature. The study of Clean Sky 2 (2021) mentions that studies are ongoing on reducing cabin noise which would increase passenger comfort, showing that passenger comfort is being considered in the design plans of ultra-efficient aircraft. Moreover, as the novel technological bricks of ultra-efficient aircraft are not expected to affect the interior of the aircraft design, the cabin interior is assumed to be similar to established aircraft. Therefore, it is assumed that a minimal compliance to passenger comfort is adhered to, leading this indicator to be considered complete.

### 6.1.10 PASSENGER PERSPECTIVE ON AIRCRAFT

As ultra-efficient aircraft have a larger wingspan and a higher aspect ratio wing, the aircraft would have a different appearance than conventional aircraft, making it more visible for passengers to perceive how the aircraft would contribute to a more sustainable flight. One respondent argues that every step towards less emissions per flight would lead to positive reactions from passengers (Int. Airline). This perspective is argued against in the survey study of Chiambaretto et al. (2021), where results have shown that almost all respondents underestimate the fuel consumption reduction of the most recently introduced aircraft in their study on the recent developments of the phenomenon of *flight shame* within Europe. This shows that even though a share of fuel consumption reduction could be achieved by an ultra-efficient aircraft, these are not likely to be perceived like that by passengers. Therefore, this indicator is considered incomplete.

#### *Influencing condition and prospect of completeness*

The influencing condition apparent for this indicator is *socio-cultural aspects*. The concept of flight shame is related to negative feelings and having a bad conscience about flying from a passenger perspective (Doran & Ogunbode, 2021). Gössling et al. (2020) state that flight shame is already visible in declining passenger numbers in their study on changing perspectives on air travel behaviour in Germany. As flight shame is a relatively new phenomenon, introduced in its English variant in 2018 (Becken et al., 2021), it is challenging to grasp how this will develop in the coming decades and the influence it will have on the aviation industry. Therefore, instead of giving a prospect of completeness for this indicator, this dimension should be considered in the decision-making of the sustainable alternatives.

### 6.1.11 OPERATIONAL SAFETY

The operational safety of ultra-efficient aircraft is assumed to be similar to that of a conventional aircraft, since no alternative fuels are used for propulsion and thus no deviating regulations are required. Nevertheless, the novel aircraft will have features that have not been deployed yet, such as the open rotor engine. New safety requirements should be formulated for this technological brick, focusing e.g. on what would happen when an open rotor engine will break from the aircraft (Int. Safety Regulator). Seng et al. (2015) discuss that the loss of one or more fan blade should not lead to a dangerous situation for the aircraft and have investigated the introduction of a composite shield to protect passengers and critical systems of the aircraft. Furthermore, bird strikes in the open rotor engine should be evaluated (Chao & Zhaoguang, 2016). For high wing load structures, the operational safety is considered compliant, as it has been established before in conventional aircraft designs, e.g.in the Airbus A400M. Therefore, this indicator is considered partially complete.

#### *Influencing condition and prospect of completeness*

The influencing condition applicable for this indicator is *knowledge and awareness of technology*. It is expected that these safety requirements will be formulated within the certification process of the ultra-efficient aircraft (Int. Safety Regulator). For novel technological bricks, such as the open rotor engine designed for the ultra-efficient aircraft, a special condition procedure which is a safety proposal for a specific project in which certification specifications have not yet been established will be applied. Therefore, it is expected that this indicator will reach completeness during the certification process of the ultra-efficient aircraft, expected by 2035.

### 6.1.12 CONCLUSION

To conclude, the overall TIS building block *Product performance and quality* of ultra-efficient aircraft is considered partially complete. While NOx emissions are significantly reduced, there is a relatively lower environmental performance regarding $CO_2$ emissions and contrail formations, making overall environmental performance relatively moderate. In terms of aircraft performance from an industry perspective, the ultra-efficient aircraft is compatible with conventional aircraft. TIS building block 1 is expected to be complete within 20 years. The results of the analyses have been visualised in Table 16.

TABLE 16: EVALUATION OF COMPLETENESS OF TIS BUILDING BLOCK 1 OF ULTRA-EFFICIENT AIRCRAFT

| Indicator | Incomplete | Partially complete | Complete | Influencing condition |
|---|---|---|---|---|
| $CO_2$ emissions | ■ | | | Knowledge and awareness of technology |
| NOx emissions | | | ■ | - |
| Contrail formation | ■ | | | Knowledge and awareness of technology; Knowledge and awareness of application and market |
| Range | | | ■ | - |
| Passenger capacity | | | ■ | - |

| | | | | |
|---|---|---|---|---|
| Required fuel per seat | | | | |
| Refuelling time | | | | - |
| Noise emissions | | | | - |
| Passenger comfort | | | | - |
| Passenger perspective on aircraft | | | | Socio-cultural aspects |
| Operational safety | | | | Knowledge and awareness of technology |
| | | | | |
| Overall performance TIS building block 1 ultra-efficient aircraft | | | | **Prospect of completeness: 20 years** |

## 6.2 PRODUCT PRICE

### 6.2.1 INVESTMENT COSTS OF AIRCRAFT

The investment cost of an ultra-efficient aircraft is expected to be higher compared to conventional aircraft with adjusted technology. The extra costs can be assigned to the novel technological bricks of the aircraft. The high aspect ratio wing, open rotor engines and natural laminarity improvements on the wing and wing tail are stated to require further predevelopment maturation work before it can be implemented in an aircraft design (Int. OEM). The larger wingspan of the alternative leads to the requirement of more material for production and as state-of-the-art light-weight materials such as composites will be used, this will increase the overall costs of production (Devezas, 2020). Furthermore, the open rotor engine will be larger than conventional engines as it will encompass lengthy fans, posing more cost as well (Dorsey & Uranga, 2020). It should be noted that a conventional aircraft will require modifications as well for the commercialisation of a next generation fleet, which will also impose R&D expenditures and investments in state-of-the-art light-weight materials. Altogether, the relative higher investment cost of ultra-efficient aircraft is not expected to hamper its implementation as its relative low fuel consumption leads to cost efficiency of operations (Int. Airline). Therefore, this indicator is considered partially complete.

*Influencing condition and prospect of completeness*

The influencing condition addressing the higher investment costs of ultra-efficient aircraft is *Knowledge and awareness of technology.* Ideally, when more R&D is spent on the high aspect-ratio wings, open rotor engines and natural laminarity of the wings and wing tails, the technological bricks would undergo learning curves which could potentially result in lower costs. Furthermore, through R&D of the overall aircraft concept, the design could be optimised further and expenses on material and redundant components could potentially be reduced. Also, Hagnell et al. (2020) discuss that a clear trade-off is present between the lightweight performance of materials and the costs for producing these, meaning that the investment costs could also be reduced by compromising the sustainability performance of the aircraft design. As an overall ultra-efficient aircraft is expected to enter the market around 2035 (Int. OEM), such learning curves are expected to take another 5-10 years on top of that. Therefore, this indicator is considered complete within 20 years.

### 6.2.2 FUEL COSTS

For ultra-efficient aircraft, only conventional kerosene would be used as fuel, while the conventional reference aircraft would integrate 50% SAF drop-in fuel as well. SAF in the form of synfuels is very expensive due to the current efficiencies and price of electrolysis and the Fischer-Tropsch synthesis process. As mentioned in subsection 6.2.2, SAF currently costs up to 450 USD per MWh (Fuel Cells and Hydrogen 2 Joint Undertaking, 2020). Balancing that with 50% kerosene which currently costs around 50 USD per MWh (Fuel Cells and Hydrogen 2 Joint Undertaking, 2020), the fuel costs of the reference aircraft would account for approximately €250 per MWh as opposed to €50 per MWH for the ultra-efficient aircraft. Moreover, since the ultra-efficient aircraft consumes less fuel, the fuel costs considered over a flight naturally decreases as well. Therefore, this indicator is considered complete.

### 6.2.3 SWITCHING COSTS

As ultra-efficient aircraft use conventional kerosene as fuel for propulsion, its deployment in the incumbent socio-technical regime of the supply chain of aviation is overall in-line. While the wingspan of ultra-efficient aircraft will be relatively wider, it would still fit in Airport Code C, a categorisation on which aircraft is able to use which aerodrome (SkyBrary, n.d). Therefore, no alterations on airport ground operations such as refuelling are expected. Also, the sunk costs associated with infrastructure investments and optimising business operations have already been established before, meaning that no expenditures are regarding a switch from fuels production and distribution infrastructure or novel safety requirements. Costs imposed for the certification process of the novel aircraft concept will be present, however, since this is inherently related to the renewal of aircraft fleet in the aviation industry this is not considered to be hampering implementation. Therefore, this indicator is considered complete.

### 6.2.4 TRANSACTION COSTS

For the deployment of ultra-efficient aircraft, the established component providers are expected to supply the components required to produce the novel technological bricks to a large extent (Int. OEM). The introduction of ultra-efficient aircraft is perceived to be more evolutionary than revolutionary (Int. OEM; Int. Safety Regulator). Even though the ultra-efficient aircraft has a different design, the high aspect ratio wing is still building on similar state-of-the-art materials as used for novel conventional aircraft and consists of similar components, such moveable flaps used in conventional aircrafts. Therefore, it Is likely that the same range of providers will supply and co-develop the technological bricks of ultra-efficient aircraft. Therefore, this indicator is considered complete.

### 6.2.5 CONCLUSION

To conclude, the overall TIS building block *Product price* of ultra-efficient aircraft is considered complete. Even though the aircraft design is expected to be more costly than conventional aircraft, its lower fuel consumption ensures that it is still a cost-efficient aircraft. As the ultra-efficient aircraft makes use of conventional kerosene and its supply chain, the costs associated with fuel consumption, switching of technologies, and changing suppliers are not considered to hamper its deployment. The results of the analyses have been visualised in Table 17.

TABLE 17: EVALUATION OF COMPLETENESS OF TIS BUILDING BLOCK 2 OF ULTRA-EFFICIENT AIRCRAFT

| Indicator | Incomplete | Partially complete | Complete | Influencing condition |
|---|---|---|---|---|
| Investment costs of aircraft | | ■ | | Knowledge and awareness of technology |
| Fuel costs | | | ■ | - |
| Switching costs | | | ■ | X |
| Transaction costs | | | ■ | X |

| | | | | |
|---|---|---|---|---|
| Overall performance TIS building block 2 ultra-efficient aircraft | | | | Prospect of completeness: not applicable |

## 6.3 PRODUCTION SYSTEM

### 6.3.1 KNOW-HOW ON THE PRINCIPLE OF PRODUCTION

Currently, there is an overall know-how present on the principles of production of an ultra-efficient aircraft as the technological bricks to make an aircraft ultra-efficient are known (Int. OEM). The program of Clean Sky 2 (2021) aspires to introduce an ultra-efficient regional design with a high-aspect ratio wing and a turboprop engine by 2025 already. Furthermore, incumbent Boeing is working on a medium to large-range ultra-efficient aircraft together with NASA, which is expected to be implementable in the beginning of 2030 (NASA, 2023). For the ultra-efficient aircraft design proposed in this Master Thesis, the technological bricks are argued to require further predevelopment maturation work before it is eligible to be included in a future aircraft product (Int. OEM). The introduction of ultra-efficient aircraft is considered ambitious but not unrealistic by 2035, however, it should be balanced according to its affordability and robustness for a company to make the choice to invest in it. Altogether, these insights show that innovation is ongoing but still requires more developments, making this building block considered partially complete.

*Influencing condition and prospect of completeness*

Since the technologies of the ultra-efficient aircraft concept require further developments, the foremost influencing condition is *knowledge and awareness of technology*. One respondent argues that if the high aspect ratio wing, open rotor engine and natural laminarity of the wings and wing tails are subject to more developments in the coming four to five years, the overall technological concept of an ultra-efficient aircraft could be decided upon (Int. OEM). Consecutively, a development program for the overall aircraft concept could be established for five to seven years after which it is ready for entry to service. It should be noted that this procedure includes a certification process of the concept of the ultra-efficient aircraft. Therefore, an established know-how on the principle of production is expected before 2035.

### 6.3.2 RAMP-UP ABILITY OF THE PRODUCTION SYSTEM

As the know-how of the principles of production of a hydrogen aircraft must be established before the production system itself can be adjusted, the ramp-up ability of the production system is not present yet. Nevertheless, since the aircraft concept follows an evolutionary development from conventional aircraft, its complementary production system is also expected to be subject to evolutionary developments. Therefore, the basis of the production system and its ability to up has been established already and the modifications that need to be applied for including the novel technological bricks in the production system is not expected to be subject to risks. Therefore, this indicator is considered partially complete.

*Influencing condition and prospect of completeness*

As the know-how on the principles of hydrogen aircraft production is not entirely present yet, the influencing condition *knowledge and awareness of technology* is also applicable for this indicator. Similar to the production of hydrogen aircraft, it is argued that 7 years before its commercialisation, the concept of the design needs to be fixed after which the system will be set up for the production of the aircraft (Int. OEM). Within these 7 years, the production system is required to be able to deliver a reasonable order of magnitude to enrol the aircraft as an industrialised product to the market.

Furthermore, the influencing condition *macro-economic and strategic aspects* is significantly present. Nevertheless, the availability of the production system is very important to be in place before commercialisation (Int. Start-up) and is expected to be ready to deliver the novel aircraft in a reasonable order of magnitude, which depends on the market need and the business objective of the OEM (Int. OEM). Whereas hydrogen aircraft are expected to be developed as a niche product first, classical business dynamics for earning expenses back apply (Int. OEM). When the ultra-efficient aircraft would be the main business of an OEM, it is essential to establish a ramp-up of production capacity within three years after entry into service to compensate for the nonrecurring costs of investments of the production system (Int. OEM). Moreover, this would lead to a first mover advantage for the OEM to gain a high proportion of the market (Von Gleich et al., 2012). When the ultra-efficient aircraft is not considered to gain the main income of the business of the OEM, the company could still survive when performance problems arise and a ramp-up of production capacity is established within three years after entry into service.

Furthermore, it is argued that for a short-medium range sustainable aircraft, a market demand of 50-100 aircraft per month could be probable, while this ultimately depends on the competition dynamics of Airbus, Boeing, and smaller incumbent aircraft OEMs (Int. OEM). It is expected that this number of ultra-efficient aircraft could be produced by the production system within the before mentioned three years of the ramp-up of production capacity (Int. OEM). Without the presence of competition with other OEMs, it is stated that fewer incentives are present to ramp-up the production system in a short timeframe since the supply for the demand could be spread out over years for the to retain a stable income to the OEM (Von Gleich et al., 2012). As this scenario would be highly improbable, it is not examined further. Assuming that the production of ultra-efficient aircraft would be one of the main business activities of an OEM, competition among OEMs is present and the ultra-efficient aircraft concept is expected to be entering into service in 2035, the indicator is considered complete by 2038.

### 6.3.3 ABILITY TO PRODUCE A FLEET IN AN APPROPRIATE TIME

As this indicator is considered a next step of hydrogen aircraft deployment after the *know-how on the principle of production* of subsection 6.3.1 and is subject to the same established basis for production and problems identified in subsection 6.3.2, this indicator is considered partly complete as well.

#### *Influencing condition and prospect of completeness*

This indicator is dependent on the same macro-economic and strategic dynamics as described in subsection 6.3.2, making the indicators *knowledge and awareness of technology* and *macro-economic and strategic aspects* and their argumentations for the prospect of completeness applicable for this indicator as well. Therefore, the indicator is considered complete by 2038.

### 6.3.4 CONCLUSION

To conclude, the overall TIS building block *Production system* of ultra-efficient aircraft is considered partially complete. The know-how on the principle of hydrogen aircraft production is present to an extent and the technological bricks of an ultra-efficient aircraft are considered evolutionary to incumbent production systems. Therefore, alterations to the technological bricks are required but not expected to pose problems for its implementation. TIS building block 3 is expected to be complete within 15 years. The results of the analyses have been visualised in Table 18.

TABLE 18: EVALUATION OF COMPLETENESS OF TIS BUILDING BLOCK 3 OF ULTRA-EFFICIENT AIRCRAFT

| Indicator | Incomplete | Partially complete | Complete | Influencing condition |
|---|---|---|---|---|
| Know-how on the principle of production | | | | Knowledge and awareness of technology |
| Ramp-up ability of the production system | | | | Knowledge and awareness of technology; Macro-economic and strategic aspects |
| Ability to produce a fleet in an appropriate time | | | | Knowledge and awareness of technology; Macro-economic and strategic aspects |
| Overall performance TIS building block 3 ultra-efficient aircraft | | | | **Prospect of completeness: 15 years** |

## 6.4 COMPLEMENTARY INFRASTRUCTURE AND SERVICES

For TIS building block 4, the supply chain of kerosene to airports is considered, as well as the presence of complementary services. A representation of the kerosene supply chain is provided in Figure 9.


FIGURE 9: KEROSENE SUPPLY CHAIN. MODIFICATION OF ILLUSTRATION FROM KORONEOS ET AL. (2005)

### 6.4.1 FUEL PRODUCTION INFRASTRUCTURE

Ultra-efficient aircrafts are fuelled by conventional kerosene, which is extracted as crude oil through a process of fractional distillation (Koroneos et al., 2005). As can be seen in Figure 9, after extraction and its transportation towards a kerosene production plant, a range of process treatments can be applied to remove undesirable constituents in the fuel. As this infrastructure already is established and has undergone decades of learning curves, the process has been optimised and is not expected to hamper implementation of ultra-efficient aircraft. On the other hand, Metz et al. (2001) argue that oil reserves are finite, resulting in finite consumption possibilities as well. Compared to hydrogen or SAF used for propulsion, which can be produced from RES, this is a large disadvantage. As the production infrastructure is present but the availability of crude oil itself is limited, this indicator is considered partially complete.

*Influencing condition and prospect of completeness*

The influencing condition present for this indicator is *natural resources*. Metz et al. (2005) argue that technological advances could be made to extract non-conventional oils which could be processed into fuels, however, that this would be relatively more costly. These non-conventional sources of oil, on the other hand, are also subject to limited reserves. While the problem of the depletion of fossil fuels is not expected to be reached in the near-term future, it is important to consider and to start timely with finding strategic alternatives for kerosene as fuel. As the influencing condition refers to a resource that could be unavailable in the future, no prospect of completeness can be formulated.

### 6.4.2 FUEL DISTRIBUTION INFRASTRUCTURE

After the crude oil has been refined to kerosene, the fuel is being transported to logistic terminals by tankers, after which it is being transported to customers at airports by trucks (Koroneos, 2001). As this procedure has been established and maintained since the introduction of aviation, no alterations are required for the deployment of ultra-efficient aircraft. Therefore, this indicator is considered complete.

### 6.4.3 FUEL STORAGE INFRASTRUCTURE

For the storage of kerosene at airports, kerosene storage containers are used. These containers are different from general crude oil tanks due to the deviating properties of the fuels (Hou et al., 2019) and have been established for aviation specifically. Generally, horizontal tank designs are used for storage under 100 m3, while vertical tank designs are used for greater volumes. Similar to the argumentation of subsection 6.4.2, the fuel storage infrastructure for ultra-efficient aircraft already has been established and does not require alterations. Therefore, this indicator is considered complete.

### 6.4.4 REFUELLING INFRASTRUCTURE AT AIRPORT

For the ultra-efficient aircraft taken as reference in this Master Thesis, the wingspan would increase approximately 9m, potentially affecting gate sizing and ground operations at airports. The ultra-efficient aircraft design would have a wingspan 35 meters while the Embraer 175 has a wingspan of 26 meters. Nevertheless, this design would still fall in the range to Airport code C. Respondents from the airport perspective have indicated that there will be no operational differences to the refuelling infrastructure if the ultra-efficient aircraft would still be within the range of the Airport code of the conventional aircraft (Int. Airport 1; Int. Airport 2). As no alterations within the refuelling infrastructure of airports would be required, this indicator is considered complete.

### 6.4.5 MAINTENANCE REPAIR OVERHAUL (MRO) SERVICES

The MRO services for the technological bricks of an ultra-efficient aircraft have not been elaborated on sufficiently in literature. One respondent argues that MRO effort might go up, as different diagnostics, maintenance concepts and means for providing MRO services potentially are required for this alternative (Int. OEM). When established, this is expected to not necessarily lead to overall more MRO effort but rather to different activities within MRO effort. Since the technological bricks are evolutionary to conventional aircraft technology, the MRO services are expected to develop accordingly. As discussed in subsection 6.1.11, an open rotor engine is a novel technology for which safety requirements should be formulated (Int. Safety). This could potentially lead to more stringent MRO effort in the beginning phases of deployment. On the other hand, the wings manufactured with state-of-the-art composite materials such as carbon fibre reinforced polymers (CFRP) are expected to require less MRO services for investigating structural defects of the aircraft, as the strength of the components is very high (Séguin-Charbonneau et al., 2021). Altogether, this indicator is considered partially complete.

*Influencing condition and prospect of completeness*

The influencing condition applicable for this indicator is *knowledge and awareness of technology*. A study of Gillespie et al. (2020) shows how defects in CFRP materials can be found by a technique using transmission based on heat sources and contact sensors, where a thermal conduction profile is created that could indicate defects in the material. This is beneficial as it could reduce MRO efforts for estimating structural defects of the aircraft wings. Furthermore, a respondent argues that the overall development of MRO services is influenced by the market demand of the aircraft (Int. OEM). When it is economically interesting for the MRO provider to establish changes, MRO services will be developed according to the technological bricks of the aircraft. This is expected to take between 5-10 years to optimise after the introduction of the aircraft (Int. OEM). Therefore, this indicator is considered complete between 2040-2045.

## 6.4.6 CONCLUSION

To conclude, the overall TIS building block *Complementary infrastructure and services* of ultra-efficient aircraft is considered complete. While it should not be forgotten that fossil fuel resources are finite and current strategic alternatives for using kerosene as aircraft fuel should be further investigated, the incumbent socio-technical system is established for the deployment of kerosene in aviation. Only the MRO services are expected to require some time for adjusting to the novel technological bricks, however, as these are considered evolutionary compared to incumbent aircraft technologies, this is expected to pose barriers for implementation. The results of the analyses have been visualised in Table 19.

TABLE 19: EVALUATION OF COMPLETENESS OF TIS BUILDING BLOCK 4 OF ULTRA-EFFICIENT AIRCRAFT

| Indicator | Incomplete | Partially complete | Complete | Influencing condition |
|---|---|---|---|---|
| Fuel production infrastructure | | | | Natural resources |
| Fuel distribution infrastructure | | | | - |
| Fuel storage infrastructure at airport | | | | - |
| Refuelling infrastructure at airport | | | | - |
| Maintenance Repair Overhaul (MRO) services | | | | Knowledge and awareness of technology |
| | | | | |
| Overall performance TIS building block 4 ultra-efficient aircraft | | | | **Prospect of completeness: not applicable** |

## 6.5 NETWORK FORMATION AND COORDINATION

### 6.5.1 ACTOR NETWORK

For this indicator, the same actor network as described in subsection 5.5.1 and visualised in Figure 6 is present. As the *Flying Vision* initiative is present and represents the formation of an actor network that is robust for enhancing sustainability transitions in the Dutch/German ecosystem, the indicator is considered complete.

### 6.5.2 COMMUNICATION AMONG ACTORS AND STEPS TAKEN TOWARDS A SIMILAR VISION

The perception of communication within the ecosystem and steps taken towards a similar vision on hydrogen aircraft deployment is diverse among the respondents. Similar to subsection 5.5.2, respondents have been asked to provide a score on a Likert-Scale between 1 and 5, in which 1 represents very bad performance and 5 represents very good performance. A quantitative representation of these results is provided Figure 10.

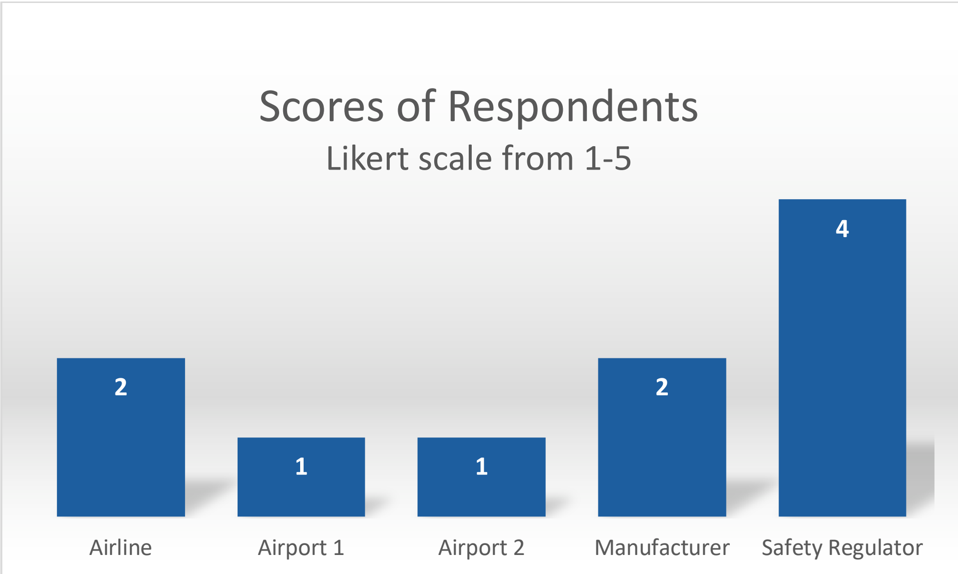


FIGURE 10: REPRESENTATION OF RESPONDENT SCORES ON ULTRA-EFFICIENT TECHNOLOGY

From Figure 10 can be derived that there is no uniform perspective on this indicator. Interesting to consider is that all respondents have provided a score based on a similar argumentation. An ultra-efficient aircraft is considered an evolutionary innovation (Int. Safety Operator), where less alterations from the ecosystem is required as the incumbent socio-technical system has been optimised for the implementation of such novel aircraft designs. This means that other actors within the value chain of aviation are not necessarily communicating about this technology (Int. Airport 1; Int. Airport 2). Another respondent argues that hydrogen technology is hyped at this moment while it would be a disruptive alternative, and the short-term contributions are not well understood (Int. OEM). Multiple respondents discuss how the ultra-efficient aircraft could be considered as a hybrid configuration with SAF drop-in (Int. Airline, Int. Safety Regulator). Furthermore, efficiency improvements could be applicable to future products such as hydrogen technology as well (Int. OEM). As an average score of 2/5 is granted, this indicator is considered partially complete.

*Influencing condition and prospect of completeness*

For this indicator, the influencing condition *knowledge and awareness of technology* is applicable as the communication on ultra-efficient aircraft currently is hardly present among key actors. Nevertheless, the rationale behind this is that the contemporary way of doing business is structured for this alternative already, hence not requiring further communication for its deployment. As it is challenging to predict how this communication will evolve over coming period, no prospect of completeness is formulated for this indicator.

#### 6.5.3 CONCLUSION

To conclude, the overall TIS building block *Network formation and coordination* of ultra-efficient aircraft is considered complete. While there is no uniform perspective on the perception of communication within the ecosystem and steps taken towards a similar vision on ultra-efficient aircraft deployment, the incumbent business structure within the aviation industry inherently leads to its deployment without requiring further coordination. The results of the analyses have been visualised in Table 20.

TABLE 20: EVALUATION OF COMPLETENESS OF TIS BUILDING BLOCK 5 OF ULTRA-EFFICIENT AIRCRAFT

| Indicator | Incomplete | Partially complete | Complete | Influencing condition |
|---|---|---|---|---|
| Actor network | | | | - |
| Communication among actors and steps taken towards a similar vision | | | | Knowledge and awareness of technology |
| Number of consortiums | X | X | X | X |
| Number of workshops and conferences | X | X | X | X |
| Number of publications on technical progress | X | X | X | X |
| Media coverage on concepts of sustainable aircraft technology | X | X | X | X |
| | | | | |
| Overall performance TIS building block 5 ultra-efficient aircraft | | | | **Prospect of completeness: not applicable** |

### 6.6 CUSTOMERS

#### 6.6.1 CUSTOMER TYPE

The main customer type for the deployment of a regional ultra-efficient aircraft has been identified as the classical airline. As ultra-efficient aircraft technology resembles conventional aircrafts and its relative high investment costs are expected to balance out against the cost efficiency of fuel consumption (Int. Airline), conventional airline operations would be applicable for the alternative. Here, it could potentially belong to many of the seven market segments identified in aviation, including traditional scheduled, low-cost, business, all-cargo and charter flights (Eurocontrol, 2022). These potential segments are equal to the target market of conventional Embraer 175 aircraft, leading the indicator to be considered complete.

#### 6.6.2 INVOLVEMENT OF POTENTIAL CUSTOMER IN INNOVATION PROCESS

The involvement of potential customers in the innovation process of ultra-efficient aircraft is similar to the customer involvement in the hydrogen aircraft innovation process. Therefore, the current state of the TIS building block is considered similar to the ones argued for in subsection 5.6.2. It should be noted that the low rate of involvement of the customer in the innovation process of an ultra-efficient aircraft could also be related to the relatively lower priority of having this exchange for the development of this aircraft as opposed to hydrogen aircraft. An important objective of an airline is to operate as efficiently as possible to reduce fuel consumption (Int. Airline), making an ultra-efficient aircraft fundamentally attractive for airlines. Nevertheless, a collaboration within the innovation process could enhance the knowledge base and align needs of the customer to the aircraft manufacturing (Kazadi et al., 2016). Altogether, this indicator is considered partially complete.

*Influencing condition and prospect of completeness*

For this indicator, the same influencing conditions *socio-cultural aspects* and *macro-economic and strategic aspects* as discussed in subsection 5.6.2 are applicable. Since the completeness of this indicator is based on the interaction between two firms, it is challenging to formulate a prospect of completeness. As the *Flying Vision* initiative has come up with key actors within the Dutch/German ecosystem of aviation, the involvement of the potential customer in the innovation process of sustainable aircraft is expected to be growing gradually over the coming years. Nevertheless, no specified prospect of completeness can be formulated for this indicator.

### 6.6.3 AWARENESS OF BENEFIT COMPARED TO INCUMBENT AIRCRAFT DESIGNS

Overall, airlines are aware of the benefits of ultra-efficient aircraft over designs of currently deployed aircraft (Int. Airline). Over the past decades, increasing fuel efficiency has been one of the main priorities in the aviation industry and is expected to remain a priority (Singh et al., 2018). From an airline perspective, a reduction in fuel consumption means a reduction in fuel price for the flight, which is economically beneficial and will therefore fundamentally be interesting for customers. Apart from that, an ultra-efficient aircraft is compatible with currently established infrastructure which is considered a good short-to-medium-term solution for sustainable aviation (Int. Airline). Moreover, the respondent has stated that ultra-efficient aircraft have the potential to be fuelled by SAF as well, mentioning that the comparison of an aircraft with 50% SAF drop-in is somewhat superfluous as the introduction of an ultra-efficient aircraft would lead to a hybrid configuration. Moreover, the respondent states that the establishment of an ultra-efficient aircraft should not lead to a hampering of R&D on the hydrogen aircraft, as this is considered a better alternative for the long-term (Int. Airline). The indicator is considered complete.

### 6.6.4 FINANCIAL MEANS TO ACQUIRE AIRCRAFT

As stated before, the ultra-efficient aircraft is predicted to be relatively more expensive than currently deployed aircraft, but this is expected to be compensated by the reduced operational cost due to the decreased required fuel needed. Moreover, when considering the integration of ultra-efficient aircraft with 50% SAF drop-in as proposed in subsection 6.6.3, the significantly higher SAF costs make a reduction in fuel consumption even more desirable for the customer (Int. Airline). Therefore, this indicator is considered complete.

### 6.6.5 WILLINGNESS TO ACQUIRE AIRCRAFT

As can be derived from the interview with an Airline, the willingness to acquire an ultra-efficient aircraft is stated to be present. The corporate sustainability report of Lufthansa Group (2022) states to be focusing on the deployment of the most fuel-efficient option on the market for achieving its climate goals, acquiring up to 180 new fuel-efficient aircraft by 2030. Also, International Airlines Group (2022) state to invest 13.5 billion USD for 192 efficient aircraft by 2030. This shows that an overall interest in fuel improvement and thus ultra-efficient aircraft is present. Nevertheless, the corporate sustainability reports of the largest airlines in Europe, including Air France KLM group (n.d.), International Airlines group (2022), Lufthansa Group (2022) and Ryanair (n.d.) discuss the deployment of SAF in conventional aircraft more than specifically stating an interest in ultra-efficient aircraft. Altogether, this indicator is considered partially complete.

*Influencing condition and prospect of completeness*

This indicator is influenced by *knowledge and awareness of the technology.* As ultra-efficient aircraft have not been promoted and implemented yet, the customers are not aware yet of the technology. Furthermore, as can be derived from the argumentation of the goals of Lufthansa Group and International Airlines group for 2030 and has been discussed in subsection 5.6.2, airlines tend to have a short-term business strategy horizon. As ultra-efficient aircraft are expected to have an entry into service by 2035, this is not included in business strategies from airlines yet. Nevertheless, from current decision-making of airlines to focus on more efficient aircrafts regardless of higher imposed costs, it can be derived that a willingness to acquire the ultra-efficient aircraft could be present when it is introduced to the market. Therefore, the indicator is considered complete by 2035.

### 6.6.6 CONCLUSION

To conclude, the overall TIS building block *Customers* of ultra-efficient aircraft is considered complete. As the customer type of ultra-efficient is compatible with current deployed aircrafts and its benefits to incumbent aircraft designs are considered, even with relatively higher investment costs, an overall positive customer attitude is present. Even if ultra-efficient aircraft have not specifically been mentioned in corporate sustainability reports, an overall focus of airlines on acquiring efficient aircraft is found. Furthermore, improvements in involving potential customers in the innovation process could be made. The results of the analysis have been visualised in Table 21.

TABLE 21: EVALUATION OF COMPLETENESS OF TIS BUILDING BLOCK 6 OF ULTRA-EFFICIENT AIRCRAFT

| Indicator | Incomplete | Partially complete | Complete | Influencing condition |
|---|---|---|---|---|
| Customer type | | | | - |
| Involvement of potential customer in innovation process | | | | Socio-cultural aspects; Macro-economic and strategic aspects |
| Awareness of benefit compared to incumbent aircraft designs | | | | - |
| Financial means to acquire aircraft | | | | - |
| Willingness to acquire aircraft | | | | Knowledge and awareness of technology |
| | | | | |
| Overall performance TIS building block 6 ultra-efficient aircraft | | | | **Prospect of completeness: not applicable** |

## 6.7 INNOVATION-SPECIFIC AND INDUSTRY-WIDE INSTITUTIONS

### 6.7.1 GOVERNMENTAL POLICIES AND REGULATIONS (EU WIDE)

As elaborated in subsection 5.7.1, governmental policies and regulations as the EU Green Deal, EU ETS, Fit For 55 package and CORSIA are present within Europe to reduce emissions from the aviation industry. As mentioned before, the EU Green Deal lacks specified targets for the aviation industry, thus imposing less guidance for taking steps towards sustainability. Furthermore, through the Fit For 55 package, the free allowances allocated to aircraft operators towards a system of full auctioning by 2027 (European Commission, n.d.b), meaning the aviation industry will be subject to the EU ETS system, enforcing airlines to surrender emission allowances for the GHG emitted by their flights. This policy promotes fuel consumption efficiency, thus stimulating the developments towards ultra-efficient aircraft. Moreover, CORSIA has a similar influence on the development of ultra-efficient aircraft. Nevertheless, while the alternative mitigates the costs imposed on emissions, it does not address the problem at its core. If CO2 prices would rise drastically the coming decades, ultra-efficient aircrafts will not show to be the most cost-efficient option in the long-term, as it relatively emits more CO2 than conventional aircraft with 50% SAF deployment does. Here, a focus on SAF or even hydrogen deployment would be relatively more desirable. Altogether, this indicator is considered partially complete.

*Influencing condition and prospect of completeness*

For this indicator, the same influencing condition *macro-economic and strategic aspects* as for subsection 5.7.1 applies.

### 6.7.2 INDUSTRY SELF-REGULATION

The self-regulation the aviation industry undertakes as discussed in subsection 5.7.2 apply to this indicator as well. The discussed three strategies and four pillars implemented by the IATA focus on efficiency improvements in aircraft technology and operations, showing interests that would be in-line for the deployment of an ultra-efficient aircraft. While the goals currently mainly tend to focus on the deployment of SAF as a fuel, this does not exclude the potential of deploying an ultra-efficient aircraft configuration as much as it does for the deployment of a hydrogen aircraft. Also, an intrinsic objective of OEMs has been focusing on increasing efficiency of aircrafts to reduce fuel consumption, as this appeals to airlines (Int. Airline). Here, the competitive market structure of aircraft production is based on efficiency optimisations. On the other hand, the implemented CORSIA offsetting carbon schedule leads to an increase of costs for the operation of aircrafts propelled by kerosene. While this stimulates the reduction in fuel consumption, it potentially also negatively influences a focus on ultra-efficient aircraft designs as they would still make use of kerosene for propulsion. Nevertheless, an overall focus on efficiency improvements is present in the aviation industry, leading this indicator to be considered complete.

### 6.7.3 SUBSIDIES AND INCENTIVES

As ultra-efficient aircraft technologies are evolutionary to conventional aircraft, they are less risky to be developed by OEMs. Therefore, the development of ultra-efficient aircraft is not demanding subsidies and incentives to the extent the development of hydrogen aircraft is. Furthermore, as the technology is more known to the incumbent socio-technical regime and thus more reliable than a revolutionary innovation such as hydrogen aircraft, it is expected that capital investments may be easier financed by shareholders (Stein & Stone, 2013). Furthermore, a range of subsidies within the EU are present for ultra-efficient aircraft. EU subsidies have been granted to the Clean Aviation Joint Undertaking programme, the leading research and innovation programme for carbon-neutral aviation.

Here, €40 millions of EU funding is dedicated to short and medium range aircraft for the deployment of a new highly efficient aircraft by 2035 (Clean Aviation, 2023a). This programme focuses on more efficient propulsion systems and novel wing designs among other technological bricks. In September 2023, another €33 million of EU funding were allocated for additional projects to accelerate highly efficient short-to-medium range aircraft by 2035 (Clean Aviation, 2023b). Furthermore, there are subsidies present for the deployment of ultra-efficient aircraft developments in the Netherlands. '*Luchtvaart in Transitie'* is a programme spanning over multiple years to make the Dutch/German aviation sector more sustainable. Projects of the program focus on Breakthrough technologies for ultra-efficient aircraft developments (Nationaal Groeifonds, n.d.). With this programme, the Netherlands serves as a frontrunner for innovating on ultra-efficient aircraft, e.g. by focusing on lightweight composites. The total investment in the project is €383 million, which is allocated over 12 different projects. Compared to EU's *ICAO – Capacity building and Training for Sustainable Aviation Fuels programme* which allocates €4 million to selected countries for increasing SAF production and feasibility studies (ICAO, n.d.), the subsidies in efficiency improvements of aircrafts are high. Therefore, this indicator is considered complete.

### 6.7.4 SAFETY REGULATIONS

As stated in subsection 6.1.11, the established safety requirements should be reconsidered with the introduction of ultra-efficient aircraft. Hereby, a focus on operating and safety procedures regarding the high aspect-ratio wings and open rotor engine should be considered. This is executed in the certification process of the aircraft. Since the main technological bricks of the ultra-efficient aircraft are novel innovations compared to conventional aircrafts, these elements are expected to be handled as a special condition within the certification process. The formulation of safety requirements is an interactive process with technological developments (Int. OEM; Int. Safety Regulator), however, since operation of ultra-efficient aircraft is expected to be compatible with currently deployed aircraft, mainly safety requirements for the production and maintenance of the aircraft are expected to be relevant. As ultra-efficient technology are in need of the establishment of safety requirements whereas conventional implemented aircraft are not, this indicator is considered partially complete.

#### *Influencing condition and prospect of completeness*

Similar to subsection 5.7.4, the influencing condition *knowledge and awareness of technology* is applicable as it is indicated that the formulation of safety requirements should develop in an evolutionary manner next to technological development (Int. OEM; Int. Safety Regulator). As these safety requirements will be established during the certification process of the ultra-efficient aircraft, the indicator is considered complete when the ultra-efficient aircraft is expected to enter service by 2035.

### 6.7.5 INTERNATIONAL AND REGIONAL STANDARDS

Within Europe, the international standard on the certification process is established through the safety regulator of the aviation industry EASA, where the certification process as elaborated on in subsection 5.7.5 applies for ultra-efficient aircraft as well. Furthermore, a performance standard of novel aircraft configurations has been implemented by ICAO in 2016, requiring 4% less fuel consumption in 2028 than in 2015 (Transport Policy, n.d.). It is expected that novel performance standards aiming for efficiency will be established after 2028. The standards do not necessarily provide strong incentives for deploying ultra-efficient aircraft, however, the deployment of the alternative is also not hampered for its implementation. Therefore, this indicator is considered complete.

### 6.7.6 CONCLUSION

To conclude, the overall TIS building block *Innovation-specific and industry-wide institutions* of the ultra-efficient aircraft is considered partially complete. The self-regulation of the aviation industry is incentivising itself towards more efficient aircraft designs in aviation. In Europe, the EU-wide governmental policies and regulations are considered reasonably working towards overall sustainability in the continent, although more specific regulations on the aviation industry could be imposed. Subsidies and incentives are sufficiently present for the developments of more efficient aircraft designs and safety regulations have currently not been formulated yet but are expected to evolve along with technological developments of ultra-efficient aircraft until its entry to service by 2035. Lastly, international, and regional standards neither promote nor hamper developments towards ultra-efficient technologies. TIS building block 7 is expected to be complete within 12 years. The results of the analyses have been visualised in Table 22.

TABLE 22: EVALUATION OF COMPLETENESS OF TIS BUILDING BLOCK 7 OF ULTRA-EFFICIENT AIRCRAFT

| Indicator | Incomplete | Partially complete | Complete | Influencing condition |
|---|---|---|---|---|
| Governmental policies and regulations (EU wide) | | | | Macro-economic and strategic aspects |
| Industry self-regulation | | | | - |
| Subsidies and incentives | | | | - |
| Safety regulations | | | | Knowledge and awareness of technology |
| International and regional standards | | | | - |
| | | | | |
| Overall performance TIS building block 7 ultra-efficient aircraft | | | | **Prospect of completeness: 12 years** |

## 6.8 CONCLUSION CHAPTER 6

Chapter 6 has addressed SQ3, analysing the indicators of TIS building blocks of ultra-efficient aircraft technology on their level of completeness in comparison to the benchmark Embraer 175 aircraft design with 50% SAF drop-in fuel, which is considered to represent completeness. For incomplete indicators, influencing conditions potentially hampering developments have been identified and a prospect of completeness has been formulated according to academic and grey literature and insights from respondents of the interview. The level of completeness of the overall TIS building block has been derived from the mean of the level of completeness of the separate indicators. Also, the prospect of completeness of non-complete TIS building blocks has been derived from the longest formulated prospect of completeness of its indicators. Ultra-efficient aircraft developments within its TIS currently show to be partially complete in TIS building blocks *Product performance and quality, Production system* and *innovation-specific and industry-wide institutions*. TIS building blocks *Product price, complementary infrastructure and services, network formation and coordination* and *customers* are currently considered complete.

# CHAPTER 7: COMPARISON OF SUSTAINABLE AIRCRAFT TECHNOLOGIES AND STRATEGIES REQUIRED FOR THEIR DEPLOYMENT

This Chapter presents the results of the analyses of Chapter 5 and Chapter 6 and integrates these insights in formulating strategies for the deployment of the alternatives. Section 7.1 provides a comparison of the completeness of the TIS analyses and the identified influencing conditions that hamper implementation of both hydrogen and ultra-efficient technologies. Section 7.2 translates these insights into strategies in terms of sequence of implementation of the alternatives, as well as an in-depth presentation of strategies to build on or circumvent indicators of TIS building blocks. This is essential for addressing bottlenecks of TIS building blocks based on which a strategy for deployment can be established. Section 7.3 provides the main conclusions of Chapter 7.

## 7.1 COMPARISON OF COMPLETENESS AND BOTTLENECKS OF ALTERNATIVES

In this subsection, the results of the hydrogen aircraft and ultra-efficient aircraft are compared in terms of completeness, prospect of completeness and the influencing conditions currently hampering deployment of the alternatives. Subsection 7.1.1 represents the results of the analysis on hydrogen aircraft. Subsection 7.1.2 represents the results of the analysis on ultra-efficient aircraft. Subsection 7.1.3 compares the alternatives to each other and draws high-level conclusions that serve as a base for deployment strategies.

### 7.1.1 OVERALL TIS HYDROGEN AIRCRAFT

The overall completeness of the TIS around hydrogen aircraft can be found in Table 23. Hydrogen aircraft developments within its TIS currently show to be incomplete in TIS building blocks *Production system* and *Complementary infrastructure and services*. Furthermore, the TIS building blocks *Product performance and* quality, *Product price*, *Customers* and *Innovation-specific and industry-wide* institutions are partially complete. Only TIS building block *Network formation and coordination* is considered complete for hydrogen aircraft. The prospect of completeness of the TIS building blocks vary between 15-22 years, of which the prospect of completeness of the whole TIS is 22 years. Furthermore, from a total of 36 analysed indicators for hydrogen aircraft, 10 are considered complete and 26 are hampered by one or more influencing conditions. Table 23 represents the influencing conditions on incomplete and partially complete indicators of TIS building blocks of hydrogen aircraft.

TABLE 23: OVERVIEW OF COMPLETENESS OF TIS HYDROGEN AIRCRAFT

| TIS building block | Incomplete | Partially complete | Complete | Prospect of completeness |
|---|---|---|---|---|
| 1. Product performance and quality | | | | 20 years |
| 2. Product price | | | | 20 years |
| 3. Production system | | | | 20 years |
| 4. Complementary | | | | 22 years |

| | | | | | |
|---|---|---|---|---|---|
| infrastructure and services | | | | | |
| 5. Network formation and coordination | | | | | - |
| 6. Customers | | | | | 22 years |
| 7. Innovation-specific and industry-wide institutions | | | | | 15 years |

TABLE 24: OVERVIEW OF INFLUENCING CONDITIONS HAMPERING HYDROGEN AIRCRAFT DEPLOYMENT

| Influencing conditions | TIS building blocks | TIS building blocks indicators |
|---|---|---|
| 1. Knowledge and awareness of technology | 1. Product performance and quality | Range<br>Passenger Capacity<br>Refuelling time<br>Passenger perspective on aircraft<br>Operational safety |
| | 2. Product price | Investment costs of aircraft |
| | 3. Production system | Know-how on the principle of production<br>Ramp-up ability of the production system<br>Ability to produce a fleet in an appropriate time |
| | 4. Complementary infrastructure and services | Fuel distribution infrastructure<br>Fuel storage infrastructure at airport<br>Refuelling infrastructure at airport<br>Maintenance Repair Overhaul (MRO) services |
| | 5. Network formation and coordination | Communication among actors and steps taken towards a similar vision |
| | 7. Innovation-specific and industry-wide regulations | Safety regulations |
| 2. Knowledge and awareness of application and market | 4. Complementary infrastructure and services | Fuel production infrastructure<br>Fuel distribution infra |
| | 7. Innovation-specific and industry-wide regulations | International and regional standards |
| 3. Natural resources | - | - |
| 4. Human resources | 4. Complementary infrastructure and services | Maintenance Repair Overhaul (MRO) services |
| 5. Financial resources | - | - |
| 6. Competition | 2. Product price | Fuel costs |
| | 3. Production system | Ramp-up ability of the production system<br>Ability to produce a fleet in an appropriate time |
| | 6. Customer | Customer type<br>Willingness to acquire aircraft |

| | | |
|---|---|---|
| 7. Macro-economic and strategic aspects | 2. Product price | Investment costs of aircraft |
| | 3. Production system | Ramp-up ability of the production system<br>Ability to produce a fleet in an appropriate time |
| | 6. Customer | Customer type<br>Involvement of potential customer in innovation process<br>Willingness to acquire aircraft |
| | 7. Innovation-specific and industry-wide regulations | Governmental policies and regulations (EU wide)<br>Industry self-regulation |
| 8. Socio-cultural aspects | 1. Product performance and quality | Passenger perspective on aircraft |
| | 6. Customer | Involvement of potential customer in innovation process |
| 9. Accidents and events | 1. Product performance and quality | Passenger perspective on aircraft |

### 7.1.2 OVERALL TIS ULTRA-EFFICIENT AIRCRAFT

The overall TIS performance of ultra-efficient aircraft can be found in Table 25. Ultra-efficient aircraft developments within its TIS currently show to be partially complete in TIS building blocks *Product performance and quality, Production system* and *innovation-specific and industry-wide institutions*. TIS building blocks *Product price, complementary infrastructure and services, network formation and coordination* and *customers* are currently considered complete. The prospect of completeness of the TIS building blocks vary between 10-20 years, of which the prospect of completeness of the whole TIS is considered 20 years. Furthermore, from a total of 36 analysed indicators for ultra-efficient aircraft, 20 are considered complete and 16 are hampered by one or more influencing conditions. Table 26 represents the influencing conditions on incomplete and partially complete indicators of TIS building blocks of ultra-efficient aircraft.

TABLE 25: OVERVIEW OF COMPLETENESS OF TIS ULTRA-EFFICIENT AIRCRAFT

| TIS building block | Incomplete | Partially complete | Complete | Prospect of completeness |
|---|---|---|---|---|
| 1. Product performance and quality | | ■ | | 20 years |
| 2. Product price | | | ■ | - |
| 3. Production system | | ■ | | 15 years |
| 4. Complementary infrastructure and services | | | ■ | - |
| 5. Network formation and coordination | | | ■ | - |
| 6. Customers | | | ■ | - |
| 7. Innovation-specific and industry-wide regulations | | ■ | | 12 years |

TABLE 26: OVERVIEW OF INFLUENCING CONDITIONS HAMPERING ULTRA-EFFICIENT AIRCRAFT DEPLOYMENT

| Influencing conditions | TIS BB | TIS BB indicators |
|---|---|---|
| 1. Knowledge and awareness of technology | 1. Product performance and quality | CO2 emissions<br>Contrail formation<br>Operational safety |
| | 2. Product price | Investment costs of aircraft |
| | 3. Production system | Know-how on the principle of production<br>Ramp-up ability of the production system<br>Ability to produce a fleet in an appropriate time |
| | 4. Complementary infrastructure and services | Maintenance Repair Overhaul (MRO) services |
| | 5. Network formation and coordination | Communication among actors and steps taken towards a similar vision |
| | 6. Customer | Willingness to acquire aircraft |
| | 7. Innovation-specific and industry-wide regulations | Safety regulations |
| 2. Knowledge and awareness of application and market | 1. Product performance and quality | Contrail formation |
| 3. Natural resources | 4. Complementary infrastructure and services | Fuel production infrastructure |
| 4. Human resources | - | - |
| 5. Financial resources | - | - |
| 6. Competition | 6. Customer | Customer type |
| 7. Macro-economic and strategic aspects | 3. Production system | Ramp-up ability of the production system<br>Ability to produce a fleet in an appropriate time |
| | 6. Customer | Involvement of potential customer in innovation process |
| | 7. Innovation-specific and industry-wide regulations | Governmental policies and regulations (EU wide) |
| 8. Socio-cultural aspects | 1. Product performance and quality | Passenger perspective on aircraft |
| | 6. Customer | Involvement of potential customer in innovation process |
| 9. Accidents and events | - | - |

### 7.1.3 COMPARISON OF SUSTAINABLE AIRCRAFT TECHNOLOGIES

As can be derived from both Tables 22 and 24, hydrogen aircraft developments within its TIS currently show to be incomplete in two TIS building blocks, partially complete in four TIS building blocks and complete in one TIS building block. Current ultra-efficient aircraft developments, on the other hand, show to be partially complete in three TIS building blocks and complete in four TIS building blocks. Table 24 and 26 show that both alternatives are hampered most by influencing condition *knowledge and awareness of technology*, hampering 6 TIS building blocks of hydrogen technology and 7 TIS building blocks of ultra-efficient technology. The technological bricks of both aircraft designs require more research before certification. For ultra-efficient aircraft, a focus on developing environmental performance would be required, as relatively more CO2 is emitted, and the formation of contrails of the alternative is not yet understood. Furthermore, the production system and MRO services need to be adjusted to the alternative, however, since the technological bricks are evolutionary to its counterparts deployed today this is not expected to require a profound amount of research. For hydrogen aircraft, research should improve the operational performance from industry, focusing e.g. on the range and passenger capacity of the aircraft. Furthermore, the ground operations at airports, hydrogen supply chain and regulations on certification requirements and operational safety need to be established, which all depend on the technological specifications of such hydrogen aircraft. Learning curves should bring overall costs of investment of both alternatives down.

Furthermore, the influencing condition *macro-economic and strategic aspects* is affecting several indicators of both alternatives as well. The establishment of the production system of hydrogen aircraft, the coordination between customers and OEMs and the formulation of regulations highly depends on its contextual trends. As large incumbent OEMs Airbus and Boeing are mainly competing among each other for a large size within market shares, a competition between these two on the alternatives would stimulate developments and experimentation. For ultra-efficient aircraft, which would be considered a focus of business for an OEM, this is expected to be present. This is not the case for hydrogen, which would be considered a niche technology, and on which Boeing has not presented a clear vision on. These competition dynamics also influence the demand and supply equilibrium that is reached which would affect the ability of the production system to ramp-up and produce a fleet in an appropriate time. Furthermore, a misalignment in business timelines of OEMs and customers hamper their coordination during the innovation phase of both alternatives. As ultra-efficient aircrafts would be an evolutionary change in the socio-technical regime, the alternative is expected to be hampered by these influencing conditions to the extent as hydrogen aircraft would be. The deployment of hydrogen aircraft would impose radical changes to the value chain of aviation, and thereby bring uncertainties, making it challenging to predict how the developments of these TIS building block indicators would unfold in the coming decades.

Following from this argumentation, several indicators of hydrogen aircraft specifically are hampered by the influencing condition *'competition'*. As hydrogen aircraft would impose large-scale changes to the incumbent socio-technical regime of aviation, the competition with a conventional aircraft with 50% SAF deployment, which only requires modification in fuel production infrastructure, is currently hampering hydrogen aircraft developments. Based on these results it can be concluded that both sustainable aircraft technologies currently do not prove to be fully ready for deployment. Nevertheless, an overall higher compatibility of ultra-efficient aircraft to the current socio-technical regime of aviation is present when compared to hydrogen aircraft. Therefore, the ultra-efficient aircraft is considered the sustainable technology where low hanging fruits could be picked.

## 7.2 DEPLOYMENT STRATEGY OF SUSTAINABLE AIRCRAFT TECHNOLOGIES

This section provides a strategy for the deployment of both sustainable alternatives. Since the largest improvement of sustainability within the aviation industry is expected from a range of different technological solutions (TU Delft & NLR, 2021), both alternatives are addressed for implementation. Furthermore, it is relevant to understand that every aircraft efficiency curve reaches an optimum, after which solely marginal improvements can be gained by industry. Also, potentially more stringent regulations for GHG emissions come up in the near-term future. While hydrogen aircraft require significant alterations to the incumbent socio-technical regime, the potential to gain from such a revolutionary innovation is promising as it is currently in the beginning of decades on learning curves.

Following from the insights of subsection 7.1.3, it is recommended to deploy ultra-efficient aircraft first and hydrogen aircraft in a later stage. Here, ultra-efficient aircraft should be presented as a main business product from first stages of deployment, competing with conventional aircraft types by presenting significant environmental and industrial benefits for operation. This would accelerate the sustainable transition of the aviation industry in first stages. Hydrogen aircraft, on the other hand, should be deployed as a niche product first for gradually building on interlinked technological, social, economic, and institutional developments in the socio-technical system of aviation. Here, the incumbent regime and hydrogen as a niche innovation could co-evolve, anticipated to be opening for the introduction of the sustainable alternative within the aviation industry. The presented sequence of deployment of the alternatives explicitly does not imply that this is executed consecutively to each other. Rather, it provides a dual strategy in which different methods should be deployed for the alternatives.

The deployment strategy is divided into three phases based on the developments on different levels that are required for building TIS building blocks of ultra-efficient aircraft and hydrogen aircraft. The timeframes of the phases have been determined according to development cycles operated in the aviation industry in combination with the insights in prospect of completeness of TIS building blocks around the sustainable aircraft technologies. The deployment strategy of this thesis represents one of more potential strategies that can be formulated following the insights of the analyses that are recommended to be implemented by the aviation industry. Logically, the phases build on each other, leading delays in a first phase to be influencing the second and third phase. The building or circumvention strategies of the TIS building blocks are then expected to be addressed in the subsequent phase as well.

### 7.2.1 PHASE 1: 2023-2028

This first phase has been identified by addressing the requirement of predevelopment of maturation work of both sustainable aircraft technologies as stated in subsections 5.3.1 and 6.3.1. A reference of five years has been taken as both technologies are aimed to be deployed by 2035, for which an establishment of the overall aircraft designs should be ready by 2028. For hydrogen aircraft technology specifically, the introduction of a retrofit design has also been stated as an essential first step for enabling the ecosystem of aviation to experiment, stimulating technological learning curves and alterations of supply chains of fuels and overall business models (subsection 5.3.1). Therefore, both strategies on building on technological bricks as well as building on the ecosystem through the deployment of retrofit designs are considered simultaneously.

#### 7.2.1.1 ULTRA-EFFICIENT AIRCRAFT

As can be derived from the analyses, it is required for ultra-efficient aircraft to undergo predevelopment maturation work of its technological building blocks the coming five years before their overall design concepts can be established (Int. OEM). This includes developments of the open rotor engine, extreme high aspect-ratio wing and its natural laminarity. To enter the alternative into service by 2035, its overall aircraft design configuration should be established by 2028.

#### 7.2.1.2 HYDROGEN AIRCRAFT

For hydrogen aircraft, it is required to undergo predevelopment maturation work of its technological building blocks the coming 5 years as well, before their overall design concepts can be established. This refers to the developments of the hydrogen tank and, if deviating from combustion for propulsion, developments of the fuel cell and its heat management. The safety regulator EASA should be involved early on in this process since a hydrogen aircraft is an entirely new aircraft for which new certification requirements should be devised (Int. Safety Regulator). To enter the alternative into service by 2035, its overall aircraft design configuration should be established by 2028.

Furthermore, as hydrogen retrofit designs are expected to enter the market already from 2025 onwards (ZeroAvia, 2023), experimentation should be facilitated for first hydrogen aircraft operations. This would establish a baseline for further developments within incomplete TIS building block 4 and partially complete TIS building blocks 6 and 7. Here, TIS building block 4 would be developing as the supply chain of hydrogen will have an increasing local demand coming from aviation. This will address the current lack of knowledge and awareness of technology by enhancing learning curves within hydrogen production and distribution technologies, as discussed in subsections 5.4.1 and 5.4.2. As elaborated on in subsection 5.7.3, it is yet unsure how the green hydrogen capacity, aimed for within EU strategies, will be allocated among other hard-to-abate sectors. Therefore, it is recommended that actors from the aviation industry lobby for the allocation of hydrogen to aviation.

Furthermore, as both a lack of knowledge on the technology and an absence of safety requirements have been identified in subsections 5.4.3 and 5.4.4, this phase of experimentation should focus on the establishment for hydrogen storage and refuelling processes and safety requirements. As this interplay between technological development and safety requirement formulation can be considered a chicken and egg problem, this experimentation phase is essential for the co-development of both dimensions. Both safety regulators and local authorities, which are identified to set safety standards in the before mentioned subsections, should be involved. These first steps would provide a cornerstone for further developments of the operational safety requirements of TIS building block 1 and the safety regulations of TIS building block 7 and thereby mitigate the risk that overregulation will hamper hydrogen aircraft deployment in later phases.

Moreover, by introducing hydrogen retrofit to the market in 2025, potential customers are made aware of the deployment of hydrogen aircraft and could communicate with start-ups. This could potentially broaden the current customer types that are identified in subsection 5.6.1 and enhance the current low customer involvement within the innovation process as discussed in subsection 5.6.2, thereby building on TIS building block 6.

### 7.2.2 PHASE 2: 2028-2038

As the performance of technological bricks has been improved and the overall design concepts of the sustainable aircraft technologies have been established, this second phase is considered a timeframe in which further incomplete or partially complete TIS building blocks are built on. A reference of ten years has been taken as both technologies are aimed to be deployed by 2035, and their complementary production systems are required to be ramped-up within three years after deployment, 2038, to compensate for the nonrecurring costs of investments of the production system (subsection 6.3.2). Here, ultra-efficient aircraft are expected to be deployed as a main business product, whereas hydrogen is expected to be deployed as a niche product. For both technologies, some TIS building blocks can be addressed by both building strategies and circumvention strategies. Here, circumvention strategies are deployed to provide short-term solutions for addressing bottlenecks within TIS building blocks, while these simultaneously require building strategies for being addressed in the long-term.

#### 7.2.2.1 ULTRA-EFFICIENT AIRCRAFT

In phase 2, the overall aircraft design of ultra-efficient aircraft has been established and should be tested and experimented with, building on partially complete TIS building blocks 3 and 7. For TIS building block 3, such experiments are relevant for setting a base design of how the production system should be designed and set up over seven years until entry to service is expected. As ultra-efficient aircraft are recommended to be deployed as a main business product, the production system should be able to deliver a reasonable order of magnitude, which depends on the demand of the market (subsection 6.3.2). Therefore, TIS building block 3 requires building by formulating business strategies for the deployment of the aircraft by 2035. These need to be aligned with operations to establish the capacity of the production system according to the demand of ultra-efficient aircraft.

In Phase 2 the certification process is starting, in which the technologies will be evaluated, and certification requirements will be formulated through a process of testing and experimentation (subsection 5.7.5). This is essential to the establishment of safety regulations of TIS building block 7. Moreover, the expected increasing cost for emitting CO2 by European-wide governmental policies and regulations, as identified in subsection 6.7.1, could be circumvented by the deployment of SAF in ultra-efficient aircraft. SAF is attributed as zero emissions under the EU ETS scheme, meaning the increasing CO2 prices will have less negative effect on ultra-efficient aircraft when a large share of SAF will be deployed as fuel. Together, these strategies would address the partially complete TIS building block 7 for the deployment of ultra-efficient aircraft.

For TIS building block 1, the established knowledge from Phase 1 together with the building of the safety regulations of TIS building block 7 of Phase 2 address the hampering indicator on the operational safety of the aircraft. Furthermore, the relatively worse environmental performance of ultra-efficient aircraft compared to a conventional one with 50% SAF drop-in is hampering TIS building block 1, setting the prospect of completeness for the whole indicator in 20 years. This hampering environmental performance could be circumvented by the deployment of SAF as well, as the environmental benefit from SAF with the relatively lower fuel consumption of ultra-efficient aircraft are combined and will enhance the environmental performance. Also, this could mitigate the negative passenger perspective on the sustainability of the technology as well. With this circumvention strategy, the prospect of completeness of TIS building block 1 is lowered to 12 years.

Since the prospect of completeness of TIS building block 1 is lowered to 12 years, the latest prospect of completeness of the overall TIS analysis is derived from TIS building block 3. This is expected to be complete by 2038. Therefore, the overall TIS of ultra-efficient analysis, thus its deployment, is expected to be fully established within Phase 2.

#### 7.2.2.2 HYDROGEN AIRCRAFT

Following from the predevelopment maturation work of its technological bricks in Phase 1, the overall aircraft design configuration of hydrogen aircraft is established at the beginning of Phase 2. This design could be processed further in the development of a niche product to be deployed by 2035. Further developments in technological bricks are necessary to undergo more learning curves for the development of hydrogen aircraft as a main product for business in later phases. Within Phase 1, first steps in building on TIS building blocks 4, 6 and 7 are taken. In Phase 2, these are built on more, as well as the remaining TIS building blocks.

For TIS building block 1, a relatively lower compliance of hydrogen aircraft with current operations in the aviation industry is present, referring to shorter range and lower passenger capacity due to relatively large and heavy hydrogen tank and fuel cell systems (subsections 5.1.4 and 5.1.5). This could be circumvented by focusing the deployment of the niche product on the business market segment, where the relatively higher costs induced by the lower compliance are balanced by the revenues generated from operation within this market. Simultaneously, more experimentation with these technological bricks should be done to enhance learning curves for reducing weight and size of hydrogen tank and fuel cell systems in hydrogen aircraft. Furthermore, successful results of experimentation through hydrogen projects in aviation should be marketed among the wide public, raising awareness of the ability to operate hydrogen aircraft safely and thereby improving the relatively negative passenger perspective on hydrogen deployment as discussed in subsection 5.1.10. It should be noted as well that TIS building block 1 is influenced by TIS building block 7, as the developments of formulating safety requirements will help building the operational safety and help optimizing the refuelling time of TIS building block 1.

For TIS building block 2, the relatively high investment costs of hydrogen aircraft can be circumvented in first stages as well by focusing on a business market segment for the niche product. The simultaneous improvement of the technological bricks would not only enhance the technological performance, but could also lower costs needed for their production. Furthermore, following from the learning curves of hydrogen production and distribution in Phase 1, fuel costs of hydrogen are considered 2-3 times lower than SAF by 2030, showing no stringency for further building on this indicator from 2030 on. Moreover, TIS building block 2 requires building in the alignment and allocation of switching costs and transaction costs that are imposed to the actors of the value chain. By stimulating actors within the value chain of aviation to establish well-defined roadmaps on implementation strategies and ensure thorough coordination between their business activities, these costs could be mitigated. The *Flying Vision* initiative could help with this cooperation between key stakeholders in the Dutch/German ecosystem. Nevertheless, it should be noted that an extent of these switching and transaction costs will inherently be present when shifting to hydrogen aircraft in aviation, as the transition from the incumbent socio-technical regime to one including hydrogen aircraft operations inherently is associated with large-scale costs.

For hydrogen aircraft as a niche product, the principles of production are known at the beginning of Phase 2. This serves as a baseline for adjusting production systems to hydrogen aircraft over seven years until entry to service is expected. Similar to TIS building block 3 of ultra-efficient aircraft, the production system should be able to deliver a reasonable order of magnitude, which depends on the demand of the market (subsection 6.3.2). Therefore, TIS building block 3 requires building by formulating business strategies for the deployment of the aircraft by 2035. Since the hydrogen aircraft is a revolutionary product which introduces a lot of uncertainty for all stakeholders, communication with potential customers is essential for OEMs in this phase for actively establishing demand of hydrogen aircraft. This illustrates the interdependencies between TIS building blocks 3 and 6.

For TIS building block 4, more experimentation is required as well, accelerating learning curves within hydrogen production, distribution technologies and hydrogen storage, as well as optimizing refuelling processes at airports. Here, the formulated safety standards need to undergo feedback loops of improvements, for which intensified coordination between airports, energy suppliers, safety regulators and local authorities is required. As discussed in Phase 1 of the deployment strategy of hydrogen aircraft, communication between industry and governments should be enhanced, which is essential for coordinating hydrogen allocation to the aviation industry. This illustrates the interdependencies present between TIS building block 4 and TIS building block 5. Moreover, TIS building block 4 requires building in the form of formulating and implementing MRO services for the established aircraft design configuration. This includes educating and training staff on new maintenance concepts as elaborated on in subsection 5.4.5.

For TIS building block 6, the enhancement of communication between start-ups or OEMs with potential customers as proposed for Phase 1 should be maintained and intensified. With the introduction of hydrogen aircraft as a niche technology by 2035, convincing potential customers of their willingness to acquire the aircraft is essential for its deployment. For the deployment of the niche product in the regional business market segment, it is essential to address regional airlines that perform in frequently operated business flight routes. For the Dutch/German ecosystem specifically, this could be KLM Cityhopper. As indicated before, building on TIS building block 6 is essential for building on TIS building block 3 in establishing a cost-efficient production system capacity of hydrogen aircraft.

For TIS building block 7, building further on safety regulations established in Phase 1 is essential for Phase 2. As hydrogen aircraft cannot be deployed without well-defined safety requirements for its operation, this directly influences developments in TIS building blocks 1 and 4 and indirectly influences TIS building blocks 2, 3 and 6. This demonstrates the necessity to intensify coordination between OEMs and safety regulators within Phase 2. If the formulation of appropriate safety regulations is hampered by any means, a circumvention strategy could be adopted to deploy the niche product for cargo transportation first before extending this to passenger transportation. Furthermore, EU-wide governmental policies and regulations and self-regulation of the aviation industry needs to be enhanced to favour developments towards hydrogen aircraft (subsection 5.7.1). Here, a continuous lobby for hydrogen aircraft to the EU is desirable to bring hydrogen aircraft technology on the agenda of EU-wide policy making. Moreover, with more initiatives such as *Flying Vision* within Europe, these industry self-regulation trends could be developed more towards hydrogen aircraft deployment.

In the end of Phase 2, hydrogen aircraft should be deployed as a niche product. TIS building block is expected to be complete, while TIS building blocks 1, 2, 3, 4 and 6 still require more building before reaching completeness. Due to the building strategies, these TIS building blocks are all considered partially complete at this point.

### 7.2.3 PHASE 3: 2038-2045

Phase 3 represents the timeframe where ultra-efficient aircraft have been deployed on a large scale and hydrogen aircraft have been deployed on a relatively smaller scale. The latter sustainable aircraft technology requires building more in TIS building blocks 1, 2, 3, 4 and 6. As the prospect of completeness of the overall TIS of hydrogen aircraft is set on 22 years, the deployment of hydrogen aircraft as a conventional business product is forecasted by 2045. In phase 3, only building strategies are deployed for the yet partially complete TIS building blocks.

#### 7.2.3.1 HYDROGEN AIRCRAFT

Following from the circumvention strategy of deploying hydrogen aircraft as a niche product in the business market segment or for cargo transportation in Phase 2, a focus on intensifying building on the TIS building blocks for large-scale implementation is performed in Phase 3. The strategies elaborated on in Phase 2 should be maintained for building on TIS building blocks 1, 2, 3, 4, and 6. Learning curves are expected to take five more years for TIS building blocks 1, 2, and 3, and seven more years for TIS building blocks 4 and 6. Entry into service of hydrogen aircraft as a conventional business product is expected by 2045, where hydrogen aircraft technology is expected to perform similar to conventional aircraft technologies in terms of range and passenger capacity. Moreover, the incumbent socio-technical regime of aviation is expected to have opened and integrated the changes in infrastructure, industrial networks and regulations in this timeframe. This novel configuration of the socio-technical system around aviation is essential for the deployment of hydrogen aircraft in this timeframe.

A rough representation of learning curves of both sustainable aircraft technologies, expressed in time invested in formulated building and circumvention strategies against the number of complete TIS building blocks of the sustainable aircraft technologies over time, is presented in Figure 11.

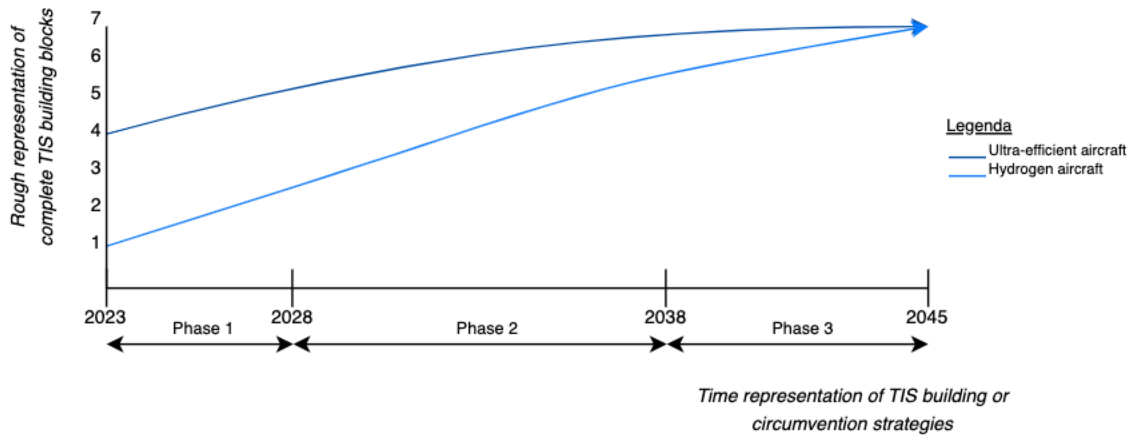


FIGURE 11: CONCEPTUAL REPRESENTATION OF TIS BUILDING OF BOTH SUSTAINABLE AIRCRAFT TECHNOLOGIES

## 7.3 CONCLUSION CHAPTER 7

Chapter 7 has addressed SQ4, elaborating on the results of the TIS analyses of hydrogen aircraft technologies and ultra-efficient aircraft technologies and the influencing conditions identified for each. Based on the comparison of these results, it has been concluded that both sustainable aircraft technologies currently do not prove to be fully ready for deployment, however, ultra-efficient aircraft would be relatively more compatible to the current socio-technical regime of aviation. Therefore, a focus on the deployment of ultra-efficient aircraft first, as the sustainable technology where hanging fruits could be picked, has been taken for accelerating the sustainable transition of the aviation industry in first stages. Hydrogen aircraft should be deployed as a niche product first for gradually building on interlinked technological, social, economic, and institutional developments in the socio-technical system of aviation before it can be introduced. Three Phases for deployment have been established according to the distinguishable stages of developments that are required for building TIS building blocks of ultra-efficient aircraft and hydrogen aircraft.

Phase 1 (2023-2028) represents the predevelopment of maturation work of technological bricks of both sustainable aircraft technologies. Also, the anticipated introduction of hydrogen retrofit aircraft by 2025 will challenge the incumbent socio-technical regime to experiment with hydrogen aircraft technology already. Phase 2 (2028-2038) represents the timeframe in which incomplete or partially complete TIS building blocks of both aircraft technologies are further built on or circumvented. By 2035, ultra-efficient aircraft are expected to be deployed as a main business product competing with conventional aircraft types. The overall TIS of ultra-efficient aircraft is expected complete by 2038. Hydrogen aircraft are expected to be deployed by 2035 as a niche product first, for gradually building on interlinked technological, social, economic, and institutional developments in the socio-technical regime of aviation for co-evolvement. Simultaneous with its deployment as a niche innovation, the yet non-complete TIS building blocks for hydrogen aircraft are built on further. Phase 3 (2038-2045) represents the timeframe in which last experimentations and learning curves with hydrogen aircraft are established. The overall TIS of hydrogen aircraft is expected complete by 2045, making entry into service as a conventional business possible. Here, the incumbent socio-technical regime of aviation is expected to have opened sufficiently for integrating changes in infrastructure, industrial networks, and regulations in this timeframe.

# CHAPTER 8: CONCLUSIONS AND RECOMMENDATIONS

In this chapter, the overall conclusions and recommendations of the master thesis research are provided. Section 8.1 elaborates on the overall conclusions of the master thesis. Section 8.2 represents the discussion of the master thesis. Section 8.3 elaborates on the practical implications for industry and policy making.

## 8.1 CONCLUSIONS

This section represents the conclusions of this master thesis research. Here, the steps taken in the research design are addressed, followed by an evaluation of the research questions. Subsection 8.1.1 provides a summary of the master thesis research. Subsection 8.1.2 formulates answers to the sub research questions and the overall research question of this master thesis.

### 8.1.1 SUMMARY OF MASTER THESIS RESEARCH

This master thesis research has addressed the sustainable transition within the aviation industry by evaluating two sustainable aircraft technologies in the context of their TIS. Here, the TIS framework from Ortt & Kamp (2022), taking a firm perspective as principle of analysis, has been modified and applied to the aviation industry. This has been done by adjusting the TIS building blocks and influencing conditions to specifically address important features of the aviation industry. Also, a set of 40 indicators have been established for the TIS building blocks, of which 36 have been analysed to enable a more in-depth analysis on the TIS building blocks. The regional market segment has been chosen as delineation of the research, as this industry segment is most suitable for providing a steppingstone for the deployment of the technologies. Following from this demarcation, hydrogen aircraft and ultra-efficient aircraft have been chosen as sustainable aircraft technologies for the objective of this master thesis research. Both technologies have been evaluated on their level of completeness in comparison to the benchmark technology, a conventional aircraft with 50% SAF deployment. For incomplete or partially complete indicators, influencing conditions and a prospect of completeness have been identified. From these analyses, an overall evaluation of the compatibility of the sustainable aircraft types, as well as how these compare to each other, has been formulated. These insights have been translated into a deployment strategy for the technologies, representing three distinctive phases to build on incomplete or partially complete building blocks. With these insights, recommendations for the aviation industry, policy makers and academics have been formulated.

### 8.1.2 ANSWERS TO THE RESEARCH QUESTIONS

*SQ1: How can the TIS framework of Ortt & Kamp (2022) be modified to be applied to the aviation industry?*

This thesis has modified the TIS framework of Ortt & Kamp (2022) to the aviation industry by altering the TIS building blocks to ones explicitly addressing industry-specifical traits of aviation. Furthermore, by dividing the TIS building blocks into 40 distinctive indicators, an extensive detailed analysis has been executed on the compatibility of TIS building blocks of the alternatives to the current socio-technical regime. This has ensured that critical insights in the performance of the sustainable innovations within their technological innovation systems have been granted, which subsequently has laid an essential foundation for addressing the overall research question of the thesis. Furthermore, by focusing on the regional market segment of aviation with a 70-90 PAX aircraft design, a well-scoped research design has been established where the novel sustainable innovations hydrogen aircraft and ultra-efficient aircraft could be evaluated against a conventional Embraer 175 aircraft with 50% SAF deployment as benchmark technology. The regional market segment has granted an appropriate steppingstone for developing and experimenting with sustainable aircraft designs.

*SQ2: To what extent are the TIS building blocks of hydrogen aircraft considered complete, and which influencing conditions and prospects for completeness are present?*

The thesis research has illustrated that hydrogen aircraft developments within its technological innovation system currently show to be incomplete in two TIS building blocks, partially complete in four TIS building blocks and complete in one TIS building block. From these insights can be derived that hydrogen aircraft are currently not ready for deployment and require more building in almost all TIS building blocks. The main influencing condition present was the *knowledge and awareness of technology*, which hampered indicators of almost all TIS building blocks. This illustrates how hydrogen aircraft require extensively more research on its technological bricks and overall aircraft design to improve performance from an industry perspective and to establish a basis for experimentation with operation and formulating safety requirements. The influencing conditions *macro-economic and strategic aspects* and *competition* were the second and third influencing condition currently hampering TIS building blocks. This shows that economic dynamics are highly influencing the establishment of the product and its production system, coordinating with potential customers, and formulating regulations in the EU.

*SQ3: To what extent are the TIS building blocks of ultra-efficient aircraft considered complete, and which influencing conditions and prospects for completeness are present?*

The thesis research has illustrated that ultra-efficient aircraft developments within its technological innovation system currently show to be partially complete in three TIS building blocks and complete in four TIS building blocks. From these insights can be derived that ultra-efficient aircraft are currently also not ready for deployment and require more building in three TIS building blocks. The main influencing condition present was the *knowledge and awareness of technology*, which hampered indicators of all TIS building blocks. Therefore, the alternative requires extensively more research on its technological bricks and overall aircraft design to improve environmental performance and adjustments within MRO services. Since the technological bricks are evolutionary to its counterparts over incumbent aircraft technologies, this is not expected to require a profound amount of research. Furthermore, *macro-economic and strategic aspects* was a second discernible influencing condition currently hampering TIS building blocks. Similar to the answer of SQ2, this shows that economic dynamics are highly influencing the establishment of the product and its production system and formulating regulations in the EU.

*SQ4: How do the TIS analyses compare to each other and how does it affect the deployment of the sustainable aircraft technologies in terms of building on or circumventing incomplete TIS building blocks?*

The insights of SQ2 and SQ3 show that both hydrogen aircraft as ultra-efficient aircraft are not fully ready for deployment at this point. Nevertheless, the TIS building blocks of ultra-efficient aircraft are relatively more complete and thus more compatible to incumbent aircraft and is therefore considered the alternative where low hanging fruit could be picked. As the largest improvement of sustainability within the aviation industry is expected from a range of different technological solutions, a dual strategy is proposed for the deployment of both alternatives. Here, three distinctive phases are devised. The first phase, representing the time frame between 2023-2028, delineates the time required for predevelopment maturation work of both alternatives. For hydrogen aircraft specifically, experimentation should be facilitated for the introduction of small retrofit aircraft designs by 2025. The second phase, representing the time frame between 2028-2038, portrays the building on incomplete and partially complete building blocks of the alternatives. For ultra-efficient aircraft, a circumvention strategy is proposed that enables entry into service by 2035, where the alternative would be deployed as a main business product, competing with conventional aircraft types by presenting significant environmental and industrial benefits for operation. A completion of all TIS building blocks would be reached by 2038. For hydrogen aircraft, entry into service as a niche product is expected by 2035, representing a gradual deployment rate of hydrogen aircraft which stimulates learning curves in yet incomplete TIS building blocks. The third phase, representing the time frame between 2038-2045, depicts the last building strategies required for completing all TIS building blocks of hydrogen aircraft by 2045. This represents entry into service of hydrogen aircraft as conventional business product.

*Main RQ: How can a TIS analysis from a firm perspective guide incumbent companies in taking steps towards the deployment of sustainable aircraft technologies over the next decades?*

The TIS analyses from a firm perspective on the sustainable aircraft technologies guide incumbent companies by providing essential insights in current shortcomings and their underlying bottlenecks for implementation. By dividing the TIS building blocks in a range of indicators, a detailed base for examination is provided for the sustainable aircraft technologies. A benchmark aircraft technology, in the form of a future business-as-usual scenario, grants a foundation of evaluation these technologies in terms of completeness to the current socio-technical regime. An evaluation of which influencing condition hampers incomplete or partially complete indicators and establishing a prospect of when these are considered complete are provided to create insights in the nature of the bottlenecks and a perspective of how these are expected to develop over the coming years or decades. These insights are crucial for formulating building or circumvention strategies that help overcome the bottlenecks for implementation of the sustainable aircraft technologies. Moreover, the insights support the evaluation and comparison of sustainable aircraft technologies in terms of compatibility of the TIS building blocks to the current socio-technical regime of aviation, thereby providing a tool for establishing a sequence of deployment which accelerates deployment of sustainable aircraft technologies over the next decades.

## 8.2 DISCUSSION

This section provides the discussion of the overall thesis design and its results. Here, the relevance of this master thesis study and its embeddedness in academic literature is addressed, as well as a discussion of the results. From these, the implications on academic literature as well as on future research is considered. Subsection 8.2.1 provides an overview of the scientific relevance of the thesis. Subsection 8.2.2 represents a discussion of the results, elaborating on observations made on the results and the limitations of the research design. Subsection 8.2.3 proposes recommendations for future research.

### 8.2.1 SCIENTIFIC RELEVANCE

This thesis contributes to the academic field by addressing several critical knowledge gaps in literature. First, while the largest improvement of sustainability within the aviation industry is expected from a range of different technological solutions, there is a lack of scientific research present on how various sustainable aircraft innovations relate to each other and how these can be developed and implemented simultaneously. This knowledge gap is addressed by focusing the TIS analysis on two sustainable aircraft technologies, hydrogen and ultra-efficient aircraft, which have been evaluated based on their compatibility to the benchmark aircraft technology, a conventional Embraer 175 with 50% SAF drop-in fuel. By focusing the TIS analyses on their compatibility to the incumbent socio-technical system and using these insights to formulate deployment strategies for both sustainable aircraft technologies, this thesis provides the tools for assessing the two sustainable aircraft technologies and how to deploy them next to each other while pursuing different technological trajectories.

Second, the involvement of firms in sustainable transitions is underexposed within literature on socio-technical transitions. As incumbent companies have the network and possess large key assets to invest in the development of new technology, their strategies could significantly drive system change and accelerate sustainable transitions. Involvement of companies is also crucial for ensuring implementations of sustainable technologies are successful as it prevents a potential resistance of the companies to change. As uncertainties associated with socio-technical transitions affects decision-making of firms, hesitation in making large-scale investments is present, which potentially hampers innovation. Especially within the aviation industry, where product innovation is characterized by large-scale investments and powerful incumbents, it is of importance to take a managerial perspective into consideration for steering the innovation system towards sustainable transitions. This research gap has been addressed by extending the TIS framework of Ortt & Kamp (2022), which has taken a firm perspective for evaluating TIS building blocks of innovations and proposing strategies to increase chances of successful implementation of innovation.

Third, the TIS framework proposed by Ortt & Kamp (2022) currently lacks application to a specific industry. This knowledge gap is addressed by applying the framework to the aviation industry, adjusting the formulation of TIS building blocks to specifically address essential dimensions of the aviation industry. Also, the proposed TIS building blocks in the framework have been extended by presenting a total of 40 indicators for each, which symbolize the most relevant dimensions of the TIS building block for the deployment of aircraft innovations within the aviation industry. Moreover, the influencing conditions have been altered to assess bottlenecks present for the sustainable aircraft technologies in more detail. As a result, this methodology provides an innovative approach for identifying current bottlenecks and how these should be addressed by industry, which has never been addressed so explicitly before in academic literature.

Fourth, the TIS framework proposed by Ortt & Kamp (2022) evaluates the current state of TIS building blocks, however, lacks an examination on how the dynamics of the developments of TIS building blocks are expected to unfold over time. Next to providing a set of indicators to evaluate the sustainable aircraft technologies, a prospect of completeness on incomplete or partially complete indicators of TIS building blocks is granted. Thereby, a more dynamic perspective on the development of TIS building blocks over the coming decades is provided, which is imperative for defining in-depth strategies for building on or circumventing incomplete or partially complete TIS building blocks. The engagement of the time dimension is crucial for the formulation of strategies over a longer timeframe and is a paramount contribution to academic literature on the deployment of novel innovations in socio-technical systems. Thereby, this thesis research has granted essential knowledge for firms on how to successfully develop the most important dimensions for the implementation of sustainable aircraft technologies, hence limiting uncertainties and considerably accelerating their deployment.

### 8.2.2 DISCUSSION AND LIMITATIONS OF RESULTS

A total of twelve points for discussion and limitations have been addressed for the master thesis. Subsection 8.2.2.1 represents the discussion of the results. Subsection 8.2.2.2 represent the limitations regarding the formulation and analysis of indicators of TIS building blocks. Subsection 8.2.2.3 elaborates on the limitations regarding the formulated prospect of completeness. Subsection 8.2.2.4 cover the limitations of the formulated deployment strategy.

#### 8.2.2.1 DISCUSSION OF RESULTS

- Altogether, this master thesis research has provided an in-depth analysis on the current level of completeness of the formulated TIS building blocks, the influencing conditions that provide barriers to the non-complete indictors and the expected timeframe in which they are considered complete. These insights show a high level of detail and complexity of interdependencies, which could only be used to an extent due to the time constraints of this master thesis research. Therefore, high-level deployment strategies for non-complete TIS building blocks have been formulated in this research. While this methodology has provided relevant knowledge for firms within the value chain of aviation and is therefore not particularly considered a limitation of this thesis, it shows that more in-depth deployment strategies could be created. Therefore, it would be interesting to focus future research on an approach to limit the complexity of the insights of the analyses and provide more practical means for companies to address building strategies for TIS building blocks on. Here, it would especially be interesting to design a practical tool that aggregates the detailed findings into a prioritization of key aspects to address in the formulation of deployment strategies.

- An interesting academic finding of the research is that TIS building blocks affect each other in their development, while the framework of Ortt & Kamp (2022) considers the TIS building blocks to be developing disconnected from each other. This is especially apparent in the analysis of hydrogen aircraft technology, as this alternative represents a radical innovation which requires building on the whole socio-technical system before implementation is possible. For example, the completeness of indicator *safety requirements* of TIS building block 7, influences the completeness of indicators *range, passenger capacity, refueling time* and *operational safety* in TIS building block 1, *know-how on the principle of production* in TIS building block 3, and *fuel storage infrastructure* and *refuelling infrastructure at airport* from TIS building block 4. Here, a chicken and egg problem regarding the influence of safety requirements on technological development and vice versa is evident, as these dimensions co-evolve with each other over time. Another example is that the indicator *fuel production infrastructure* of TIS building block 4 influences *fuel price* of TIS building block 2, since the scale of deployment of infrastructure will enhance learning curves of production, which would subsequently lead to a drop in fuel prices. Also, the indicators *actor network* and *communication among actors and steps taken towards a similar vision* of TIS building block 5 proves to be critical for almost all other indicators of TIS building blocks, since the coordination of business activities and investments is essential for the deployment of novel technologies.

  These insights show how indicators from different TIS building blocks are influencing each other or are interdependent on each other's development. Therefore, the master thesis research shows that the simplification in the framework of Ortt & Kamp (2022), stating that TIS building blocks can be evaluated separately from each other, does not accurately address the development of indicators and thereby TIS building blocks. It should be noted, though, that the framework of Ortt & Kamp (2022) addresses the adaptation phase of innovations between first introduction and initial stages of large-scale deployment, whereas hydrogen aircraft technology currently requires more building in its TIS building blocks. This could declare the interdependency of developments in safety regulations and technology. Nevertheless, removing the simplification that TIS building blocks develop in an isolated manner, a more thorough understanding of the dynamics between different dimensions within socio-technical systems could be provided. This could grant essential information in the order of relevancy to address building on TIS building blocks for accelerating the fortification of a TIS around a novel technology. Future research should address these findings with respect to the TIS framework of Ortt & Kamp (2022).

- Another interesting finding of this research with respect to the case study of the aviation industry is that the comparison of ultra-efficient aircraft to conventional aircraft with 50% SAF deployment is somewhat arbitrary as SAF could also be deployed for 50% in ultra-efficient aircraft without requiring any modifications of the technology. Therefore, the TIS analysis of ultra-efficient aircraft might have shown relatively more negative results compared to the conventional aircraft, while in practice the combination of these two technologies would be most preferred. Nevertheless, this observation has been included in the results of the master thesis already by proposing circumvention strategies with SAF deployment in ultra-efficient aircraft.

#### 8.2.2.2 LIMITATIONS REGARDING PROPOSED INDICATORS

- One limitation of the thesis is that not all indicators, proposed for the evaluation of sustainable aircraft technologies in Chapter 4, have been analysed due to time constraints of this thesis. Four of the six indicators of TIS building block 5 have not been addressed, including *number of consortiums, number of workshops and conferences, number of publications on technical progress* and *media coverage on concepts of sustainable aircraft technology*. As only two indicators have been assessed for concluding on the level of completeness of TIS building block 5, the evaluation could encompass a bias for both sustainable aircraft technologies. Since it is considered complete for both technologies, a more thorough analysis could potentially address more bottlenecks for which different deployment strategies should potentially be formulated. Future research should analyse all indicators to obtain more reliant results for the completeness of TIS building block 5.

- Furthermore, while the proposed indicators are considered to cover all relevant aspects for a TIS analysis within the context of the aviation industry, they are subject to several limitations. First, there is a slight bias present towards quantitative indicators over qualitative indicators. While using quantitative indicators has ensured the broad analysis was accessible within the timeframe of this thesis, this bias might have influenced the representation of the overall TIS building block, which indirectly has an influence on the results and strategies proposed in the thesis. Also, some indicators have been considered individually while the interaction with other indicators grants most insights. An example is *required fuel per seat* of TIS building block 1, which needs to be considered in combination with *passenger capacity* of TIS building block 1 and the *fuel price* of TIS building block 2 to be representing valuable information. Solely addressing *required fuel per seat* and evaluating this to the benchmark technology is rather arbitrary as fuels with different properties are compared to each other. Therefore, future research should focus on enhancing the list of indicators used for a TIS evaluation of sustainable aircraft designs in the aviation industry.

- Moreover, the proposed indicators are all considered equally relevant for the performance of the overall TIS building block. In practice, the indicators within a TIS building block vary in terms of importance and the depth of the aspects these represent. Since the completeness of overall TIS building blocks are evaluated based on the mean of the completeness of its indicators, this equal distribution of importance has influenced the overall results of the analysis. Moreover, a notion that all indicators need to be complete or circumvented before the overall TIS building block is considered complete has been maintained in this research. In practice, TIS building blocks could be complete enough for the deployment of the innovation while encompassing incomplete or partially complete TIS building blocks. In this line of argumentation, this thesis presumes that an overall TIS building block is only considered complete when the indicator with the longest prospect of completeness is considered complete. This has a significant influence on formulating the prospect of completeness for every indicator. Since the number of indicators formulated for every TIS building block varies among TIS building blocks, this potentially has resulted in a misalignment of prospect of completeness of TIS building blocks. Therefore, future research should focus on a ranking of importance of indicators of a TIS building block and on formulating a threshold for when TIS building blocks are considered complete while encompassing incomplete or partially complete indicators.

- Also, the level of completeness of the overall TIS building blocks has been based on the mean of the level of completeness of their indicators. While this method has provided a legitimate procedure for formulating the level of completeness of TIS building blocks, more credible procedures could possibly be used to represent these results. One example could be to determine the level of completeness of the TIS building block according to its least complete indicator, presuming that an overall barrier is imposed on a TIS building block when a bottleneck for one dimension is present. While this procedure would follow a reasonable logic, it inherently presumes that completeness of all indicators is essential for deploying a technology, which is debatable as elaborated on before. Moreover, this procedure would lead to a biased representation among TIS building blocks considering the unequal number of indicators proposed per building block. These implications should be addressed before using this procedure in practice.

#### 8.2.2.3 LIMITATIONS REGARDING PROSPECTS OF COMPLETENESS

- Another limitation of the study is that the formulation of a prospect of completeness in this master thesis research based on interviews with two or three experts could have led to subjective estimates of the timeframe. The outcomes of the expert interviews may be biased due to the working context of the respondent or due to the enthusiasm about a technology which inherently leads to a relatively more positive perspective on how future developments may evolve. Therefore, the quality of data input is inherently dependent on the experts interviewed, leading the formulated prospect of completeness to potentially be an arbitrary representation of how non-complete indicators will evolve the coming decades. Also, for some indicators the formulation of a prospect of completeness is over reliant on one source or even an overall absence of hard data was present. In the latter case, the researcher granted own insights. These exceptions are illustrated in Table 8. As the prospect of completeness has been used as a means for assessing completeness of TIS building blocks and how to address this in deployment strategies, this has large implications on the results of the thesis.

  For ultra-efficient aircraft specifically, this over reliance of data on one source could be attributed to the current business structure within the aviation industry. As ultra-efficient aircraft are considered evolutionary rather than revolutionary to conventional aircraft and are not expected to influence activities of other actors within the value chain, such as the fuel supply chain or the ground operations at airports, these actors are not aware of state-of-the-art developments of the attributes of the innovation. Therefore, mainly the OEM is aware of the technology and its developments in the coming few decades. These considerations show that the insights of this master thesis should be used as a guideline of the developments of sustainable aircraft technologies the coming decades rather than as a robust representation. Future research should address these issues by strengthening the method for data collection. This could be done by conducting more interviews with knowledgeable experts or through conducting a survey study for obtaining insights from a wide range of respondents that together provide a more representative timeframe of completeness.

- Furthermore, as the prospects of completeness are formulated based on expectations of certain developments, even when considering multiple primary sources, an overall uncertainty margin is present for all. Therefore, future research should not only strengthen the method for data collection, but also establish a margin of uncertainty around the formulated prospects of completeness. For example, the prospect of completeness of indicator *know-how on the principle of production* of TIS building block 3 from the hydrogen aircraft analysis has been formulated based on insights from three interviews. Here, the indicator is considered complete based on the following dimensions:

(I) Formulated assumptions of the respondents: between 10-15 years;
(II) The timeframe in which knowledge establishing programmes on hydrogen aircraft are finished, including the time to certify the resulting model by EASA: 14 years;
(III) The expected introduction of retrofit models, which could enhance learning curves of technological building bricks: before 2035, thus before 12 years.

While the robustness of the dimensions assessed for formulating the prospect of completeness could be debated, it has been set on 15 years. As it is evident that this value is not deriving from a unanimous interplay between the dimensions considered important for estimating the prospect of completeness, the uncertainty range can be established based on the latest expected prospect of completeness (15 years) minus the earliest expected prospect of completeness (10 years), which would come down to 5 years of uncertainty range. This uncertainty range should be applied to both 5 years before and after the set value. To lower this uncertainty, more data should be obtained for assessing expected developments of the indicator more in-depth. Future research should focus on establishing such a methodology for formulating an uncertainty range around the prospect of completeness of all non-complete indicators.

- Moreover, the research design focuses on formulating prospect of completeness while some indicators of TIS building blocks will never reach completeness. For example, radical innovation as hydrogen aircraft technology is inherently merged with switching costs, as the incumbent socio-technical regime requires large-scale modifications in the supply chain of fuels, airport operations, business models and regulations. While the level of costs can be reduced to an extent, these will inherently be present in modifying socio-technical systems. By representing such elements as indicators of TIS building blocks, being subject to the evaluation of its completeness, the research design embodies a slight bias towards the completeness of incremental innovations compared to the completeness of radical innovations as the latter one will never reach true TIS completeness.

#### 8.2.2.4 LIMITATIONS REGARDING DEPLOYMENT STRATEGY

- Another limitation of the study is that the formulated deployment strategy is one out of multiple strategies potentially executable where potentially different deployment strategies could have been formulated from the insights of the TIS analyses. One example would be to classify the phases of the deployment strategies according to the relevancy of TIS building blocks to be addressed, where incomplete TIS building blocks would have a priority over partially complete TIS building blocks. As the deployment strategy would still focus on the implementation of both sustainable aircraft technologies, the least complete TIS building blocks would be addressed in Phase 1. This would lead to the following distinguishable phases:

Phase 1: Incomplete TIS building blocks 3 and 4 from hydrogen aircraft technology and partially complete TIS building blocks 1, 3, and 7 of ultra-efficient aircraft.

Phase 2: Partially complete TIS building blocks 1, 2, 6, and 7 of hydrogen aircraft.

In practice, this delineation would be rather arbitrary since it inherently presumes that partially complete TIS building blocks require less time for building than incomplete TIS building blocks. As the level of completeness depends on the level of completeness of the indicators, and not on the time required for completion, this could prove to be problematic for this method. For example, incomplete TIS building block 4 and partially complete TIS building block 6 of hydrogen aircraft technology both entail a prospect of completeness of 22 years. When addressed in different phases, this could lead to a prolonged timeframe of implementation rather than an accelerated timeframe. Therefore, it might be interesting to consider the prospect of completeness of the TIS building blocks for distinguishing phases. Here, the shortest prospect of completeness could represent Phase 1, the following prospect of completeness could represent Phase 2, and so on. In practice, this would lead to the following distinguishable phases:

Phase 1: Partially complete TIS building block 7 of ultra-efficient aircraft (2023-2035).

Phase 2: Partially complete TIS building block 7 of hydrogen aircraft and partially complete TIS building block 3 of ultra-efficient aircraft (2023-2038).

Phase 3: Partially complete TIS building blocks 1, 2, and 3 of hydrogen aircraft and partially complete TIS building block 1 of ultra-efficient aircraft (2023-2043).

Phase 4: Incomplete TIS building block 4 and partially complete TIS building block 6 of hydrogen aircraft technology (2023-2045).

In practice, this delineation only discerns small timesteps and does not seem to serve a purpose for formulating deployment strategies. Since there is an interplay present between TIS building blocks, a necessity to address building strategies for multiple TIS building blocks is essential, which is not clearly addressed with this delineation. Therefore, future research should formulate a deployment strategy according to the integration of the highly detailed results on incomplete or partially complete indicators, their hampering influencing conditions, and their prospect of completeness. Here, not TIS building blocks, but their indicators and the identified influencing conditions should be used for formulating deployment strategies on. Here, the formulation of the three distinguishable phases for the deployment strategy as proposed in this master thesis could be maintained, as they represent development cycles in the aviation industry and the formulated prospect of completeness of TIS building blocks.

- Also, due to time constraints, deployment strategies are proposed based on *timing* and *scale* of deployment, rather than addressing which *type* of niche introduction strategy is used. Therefore, the deployment strategy has been formulated in a high-level manner, rather than using the extensive level of detail provided in the analyses of the sustainable aircraft technologies. While the deployment strategy addresses how to build on or circumvent TIS building blocks, it has not incorporated the more detailed insights from the non-complete indicators and the influencing conditions hampering them, which provides essential information on which specific types of niche introduction strategies could have been stipulated for this case study. On the other hand, an important finding of this thesis was that the technological bricks of both sustainable aircraft technologies require more technological developments before being ready for deployment. Therefore, a formulation of type of introduction strategy at this moment might end up being irrelevant by the time Phase two of the deployment strategy starts and further building or circumvention strategies for the TIS building blocks will be addressed. Nevertheless, future research should provide a method on how indicators and the insights obtained from the influencing conditions can be linked to the niche strategies proposed by Ortt et al. (2013), for ensuring that essential *types* of niche introduction strategies are addressed as well from Phase 2 on.

### 8.2.3 RECOMMENDATIONS FOR FUTURE RESEARCH

The points for discussion and the limitations that have been addressed for the master thesis show that the master thesis research has opened many opportunities for future research. These include recommendations regarding enhancing the case study and recommendations regarding broader opportunities of academics. Each has been identified and elaborated below. Subsection 8.2.3.1 addresses the recommendations for future research regarding enhancing the case study and Subsection 8.2.3.2 elaborates on the recommendations for future research regarding broader scientific contributions for academics.

#### 8.2.3.1 RECOMMENDATIONS FOR IMPROVING CASE STUDY

- The case study of this master thesis research could be improved by addressing the limitations discussed in subsection 8.2.4. Here, the four indicators proposed for TIS building block 5 that have not been addressed in the research should be analysed to obtain a more robust outcome for the evaluation. The indicators *number of consortiums* and *number of workshops and conferences* could be addressed by investigating how many partnerships among actors within the aviation industry are present and enumerating the workshops and conferences that are dedicated to the sustainable aircraft type. The indicator *number of publications on technical progress* could be investigated by making search strings on scientific search engines, such as Web of Science, with relevant keywords to obtain a representable scope of scientific literature on the sustainable aircraft type to be analysed on the quantity of publications. Also, the number of patents could be searched on a patent database, such as Espacenet. The indicator *media coverage on concepts of sustainable aircraft technology* could be investigated by making search strings on commercial search engines on aviation, such as Aviation Week, and analysing the quantity of publications as well.

- Furthermore, the overall proposed set of indicators should be enhanced, excluding arbitrary indicators and including more qualitative ones to reach a more realistic representation of the TIS building blocks. Here, it could be evaluated whether a more even distribution of indicators for each TIS building block would be preferable over the skewed distribution from this master thesis research. Also, redundancy among the formulated indicators should be critically evaluated, ensuring that every indicator represents a different element.

- Moreover, a hierarchy among indicators should be introduced, representing the importance and the depth of elements they symbolise, rather than considering the indicators equally relevant for the level of completeness of the overall TIS building block. This could be done by granting each a weight, representing its importance, which should be incorporated in the evaluation whether the TIS building block is considered complete. Here, the format of a Multi Criteria Analysis could be taken, where the indicators represent criteria which needs to be granted a weight to show their relative importance for the evaluation (Dodgson et al., 2009). This requires a quantification of what would be considered incomplete, partially complete, and complete in numerical terms, after which the indicators are granted a weight between 0 and 1, presenting the importance of the indicator in the analysis where the total of weight adds up to 1. An establishment of benchmarks on which score refers to an incomplete, partially complete, or complete evaluation of the TIS building block is necessary as well to establish results of the performance of indicators. Thereby, this method would provide a better representation of the importance of indicators in the evaluation of completeness of the TIS building block. Here, it should be considered whether a TIS building block is solely considered complete if all its indicators are complete as well, or whether a margin is provided to ensure that inherently non-complete indicators are not affecting the overall level of completeness of the TIS building block.

- Next to assessing the importance of indicators, this Multi Criteria Analysis could be used to create a Composite Indicator Index. This index would provide a simplified representation of the overall TIS building blocks by aggregating the data of its weighted indicators and their performance and prospect of completeness into one overall value (Mazziotta & Pareto, 2013). This would enable an easier comparison of TIS building blocks and thereby enhances the accessibility of the detailed data for formulating strategies by companies. Also, when creating such a Composite Indicator Index over time, the overall progress of building strategies on the level of completeness of TIS building blocks could be represented. This would not only show which TIS building blocks still require more building but would also grant insights in the effectiveness of preceding building strategies. Hereby, companies could track the performance of their actions.

- Another recommendation for future research would be to enhance the research design of the study by obtaining more data for evaluating the performance of the indicators, hampering influencing conditions and the prospect of completeness. This would enhance the robustness of the results and enables using a more structural research approach to identify influencing conditions and prospects of completeness. Here, more interviews could be conducted, preferably with three respondents per type of actor and an overall inclusion of more types of actors within the value chain of aviation. Especially for the formulation of prospects of completeness, input from different angles is needed to establish a more robust representation of a viable prospect of completeness. Another option for obtaining more insights could be to conduct a survey study, where both qualitative and quantitative data input could be obtained for evaluating the performance of the indicators of TIS building blocks and input from a wide range of actors in the value chain of aviation is ensured.

- Furthermore, future research should focus on designing a methodology for formulating an uncertainty range around the prospect of completeness of all non-complete indicators. This is essential for enhancing the robustness of the values since the prospects of completeness form the basis of the deployment strategies. The example provided in subsection 8.2.2.3 can be used as a reference, where three different steps that should be taken for all non-complete indicators can be distinguished. These include (I) an explanation of obtaining the prospect of completeness, (II) an indication of the level of certainty of the prospect of completeness, and (III) an elaboration on what is required for lowering this uncertainty. For the latter two steps, the insights in the influencing conditions forming bottlenecks could be used for establishing an uncertainty margin around its expected development and elaborating on what would be required for speeding up or lowering this uncertainty. Also, an identification of which indicators, hence TIS building blocks, never reach completeness should be established. Future research should address these points for the prospect of completeness of all non-complete indicators to enhance robustness of the case study.

- Another recommendation for future research is to execute the strategy formation of the case study with more details. Rather than formulating a high-level strategy for TIS building blocks, a detailed formulation on building or circumvention strategies for its indicators could be executed. Here, the identified influencing conditions should be incorporated, indicating a specific type of deployment strategy that is relevant for building on the indicator. As this would result in a very detailed representation on which strategies need to be deployed for each TIS indicator, and subsequently for the deployment of the sustainable aircraft technology, an orderly method needs to be established for structurally prioritizing this. Here, both the prospect of completeness of the indicator and the hierarchy of indicators, as discussed before, could be considered as a scale for prioritizing deployment strategies of indicators. A large prospect of completeness represents the urgency of the indicator to be addressed, whereas the prioritization of the indicators represents the relevance of the indicator to be addressed. By factoring both values, a structured prioritization method for formulating strategies in indicators is established, where a relatively higher score indicates relatively higher prioritization.

- A last recommendation for enhancing the case study in future research regards creating a practical tool from the methodology of this thesis for companies, which would enable them to track the completeness of the TIS building blocks over time. Following from the limitations of this thesis and other future recommendations provided before, a range of applications could be interesting for such a tool. One possibility of the tool would be to simplify the procedure of creating a Composite Indicator Index enabling easier tracking completeness of TIS building blocks, thereby representing which require more building. Especially for tracking TIS building blocks over time, having a user interface where companies solely need to input relevant data per time unit would enable companies to obtain relevant insights rapidly. Another application of the tool would be to help create heatmaps from the prospects of completeness, highlighting the timeframes in which indicators are considered complete through a traffic light colour scheme. This would put focus on which indicator has most relevancy for building on within its overall TIS building block. Here, the most important indicators could be addressed for deployment strategies, thereby creating a kind of ranking system which helps companies in prioritizing building or circumventing strategies that are needed for building on the overall TIS of a technology.

Furthermore, an application of the tool could be made to ensure refinement of the values of prospects of completeness in real time when external trends accelerate or hamper the development of indicators and thereby TIS building blocks. This is particularly interesting for developing innovations in a dynamic business environment where external trends are changing at a fast pace. Moreover, by changing the weight of importance for evaluation, companies could use the tool to perform a robustness analysis through what-if scenarios. By refining the weights of indicators to represent most importance given the business context the company is operating in, the tool can be used for companies to deviate on which deployment strategies are critical for building on or circumventing TIS building blocks, and which are less critical. Altogether, the creation of such a practical tool would be highly valuable for companies in tracking the completeness of TIS building blocks over time and evaluating relating deployment strategies for accelerating the introduction of their innovation.

#### 8.2.3.2 RECOMMENDATIONS FOR BROADER CONTRIBUTION TO ACADEMICS

- A different type of recommendations for future research addresses broader contribution to academics. Next to the method for incorporating the influencing conditions, prospect of completeness and hierarchy of indicators into strategy formulation, future research could address the influence of TIS building blocks on each other, elaborated on in the discussion of subsection 8.2.2.1. By investigating these dynamics among TIS building blocks, essential knowledge on which TIS building blocks have large influence over the development of others, and are therefore more relevant to address first, can be determined. This could clarify a sequence of addressing TIS building block to accelerate developments in the overall TIS around a novel technology. Here, the extended framework of Ortt & Kamp (2022) of this thesis could be used to identify the level of interplay between TIS building blocks. Here, three case studies of novel technologies from different sectors should be conducted to grant these insights in a generic manner. First, a set of more universal indicators which are applicable for multiple industries should be created per TIS building block. After an analysis of the completeness of the indicator, influencing conditions and prospect of completeness should be formulated for non-complete indicators, identifying dependencies of indicators from deviating TIS building blocks. The results of the three case studies should be evaluated structurally identifying which indicators are influencing others in more than two case studies. Next to an interesting contribution in academic literature on TIS, these insights could provide an extra dimension of prioritization that could be addressed for the deployment strategy addressed in the previous paragraph, prioritizing the sequence of addressing deployment strategies among TIS building blocks.

- Furthermore, this master thesis has shown the importance of building on multiple TIS building blocks for the implementation of more radical sustainable innovations, as these require large-scale investments. Future research could focus on using the TIS building blocks from the framework of Ortt & Kamp (2022) to formulate system building strategies necessary for the introduction of a radical innovation, rather than taking the innovation itself as focal point. For this research design, an industry perspective should be taken opposed to a firm or a policy-maker perspective, to retain focus on the socio-technical system within the dynamics of a chosen industry and to allocate the responsibility of deploying the strategy to multiple actors within the value chain of the industry rather than to one specific firm. This would especially be imperative for sustainable innovations, which often require changes in various dimensions of socio-technical regimes before being able to deploy them. Furthermore, this master thesis research has shown that sustainable innovations of costly products are even more dependent on changes in socio-technical regimes, as deployment encompasses significantly more risk for producers. Therefore, sustainable innovations in this case often do not even come close to reach the first adaptation phase that is considered in the framework of Ortt & Kamp (2022), demonstrating the necessity of a TIS analysis framework to address bottlenecks in TIS building blocks for formulating system building strategies for the deployment of an innovation.

- In line with this argumentation, a system building perspective could help addressing transition pathway literature more clearly in future research. As stated before, the framework of Ortt & Kamp (2022) has been proposed for the adaptation phase of innovations between first introduction and initial stages of large-scale deployment, in which the TIS analysis provides a snapshot of the current level of completeness of TIS buildings block. By shifting the focus from a firm analysis to an industrial one and addressing system building strategies instead of niche introduction strategies would provide a more dynamic assessment of the development of TIS building blocks over time. Here, system building strategies in a specific socio-technical regime should be translated into one practical roadmap for all firms within an industry. This roadmap should specify on important activities that need to be pursued by one or more firms and should translate strategies into industry milestones. This would provide practical means for an industry to align actors and stimulate collaboration towards a similar goal, potentially challenging socio-technical regimes actively and steering a socio-technical trajectory towards the deployment of sustainable technologies. Therefore, such a research design would be drawing on both transition pathways literature and constructive technology assessment within socio-technical scenario approach literature. A more evolutionary perspective of sustainable transitions and the implementation of novel innovations could be granted as well. Therefore, future research should focus on formulating a methodology to formulate system building strategies by creating roadmaps with intermediary milestones.

- When applying this to the case study of this master thesis research, this would be specifically interesting to accelerate sustainable transitions within the aviation industry. Here, the future development both sustainable aircraft technologies should be subsumed to one of the potential types of socio-technical transition pathways that new innovations can follow. The study of Geels & Schot (2007) has developed a typology of four transition pathways based on the timing and nature of interactions in the *landscape, regime*, and *niche* as proposed by Geels (2002). According to the insights of this master thesis research, ultra-efficient aircraft technology could potentially follow a *transformation pathway*, as incremental adjustments to existing aircraft technologies are made and the socio-technical regime is only challenged to a small extent. Furthermore, hydrogen aircraft technology could potentially follow a *reconfiguration pathway*, as technological and operational knowledge is proposed to be enhanced through deployment on niche scale first, after which further adjustments in the socio-technical regime are expected to be triggered. When the *landscape* will put increasingly more pressure on the socio-technical regime, it could be argued that hydrogen aircraft technologies would follow a *de-alignment and re-aligment pathway*. Nevertheless, this pathway represents a scenario in which incumbents will lose faith in e.g. regime rules, which is not expected to happen in the aviation industry due to the relevancy of its well-established and reliable safety procedures. As such an analysis was beyond the scope of this research, future research should establish an industrial-level analysis in which transition pathways for the sustainable aircraft technologies should be created through the development of roadmaps.

## 8.3 PRACTICAL IMPLICATIONS

In this section, the practical implications of the results of this master thesis research are discussed. Subsection 8.3.1 elaborates on the practical implications of the results for the aviation industry. Subsection 8.3.2 elaborates on the practical implications of the results for policy makers.

### 8.3.1 PRACTICAL IMPLICATIONS FOR THE AVIATION INDUSTRY

This master thesis research has proposed a deployment strategy of both hydrogen aircraft and ultra-efficient aircraft technologies. By analysing how the TIS around the sustainable aircraft technologies compare to the incumbent socio-technical regime in the aviation industry, an in-depth representation of current bottlenecks and how these are expected to evolve the coming decades is granted. From these insights, deployment strategies have been formulated, distinguishing three phases of development that are required for the implementation of both. This provides the appropriate tools for actors within the value chain of aviation to address the implementation of more sustainable aircraft technologies in the coming decades.

More specifically, the TIS analyses have presented that even though both technologies are not ready for deployment at this stage, ultra-efficient aircraft are more compatible to the current socio-technical regime and therefore desirable to be implemented as soon as possible to accelerate the sustainability transition within the aviation industry. It is recommended that ultra-efficient aircraft will be deployed with 50% SAF drop-in fuel to achieve the most effective environmental performance of the aircraft. Here, the aircraft should be deployed as a main business product, aiming to substitute a large share of conventional aircraft in the regional market segment within Europe. For Airbus specifically, this means that business models need to be established to ensure that the aircraft would be both attractive for customers and profitable for the OEM, since investment costs are expected to be relatively higher than conventional aircraft. Also, customers need to be made aware of the technology and should be involved in the latest phases of product development to increase chances of adoption.

Simultaneously, the TIS around hydrogen aircraft needs to be built on as well to reach sustainable transitions in the aviation industry most effectively. It is recommended to support experimentation with hydrogen aircraft from all dimensions of the value chain of aviation. Such experiments are essential for establishing safety procedures and ground operations, driving learning curves of hydrogen aircraft deployment. It is recommended that hydrogen aircraft are deployed as a niche technology first, allowing the socio-technical regime to adapt to the radical technology by adjusting infrastructure, industrial networks, institutions, and cultural perspectives on the technology. Depending on developments within safety regulations and potential negative passenger perspectives on flying with hydrogen aircraft, the cargo segment could be chosen first for deployment before the regional market segment is targeted. By 2045, hydrogen aircraft should be offered as a main business product as well. For Airbus specifically, this means that a focus on ZEROe aircraft technologies should be enhanced in the coming decades, offering them as a niche technology first before deploying them on a larger scale. For both deployment phases, it is crucial to coordinate with airlines and airports and to target a customer segment of which the flights are operating from and to airports with hydrogen refuelling infrastructure. Furthermore, business models need to be established for ensuring hydrogen aircraft is attractive for the customer as well as the OEM in both deployment phases.

### 8.3.2 IMPLICATIONS FOR POLICY MAKERS

The results of this master thesis have presented current bottlenecks in the TIS building blocks of the sustainable aircraft technologies that hamper implementation. Here, both analyses have addressed the suboptimal performance of EU wide policies and regulations to help the deployment of sustainable aircraft technologies. Furthermore, self-regulation within the aviation industry has formulated targets for the deployment of incremental sustainable innovations within the incumbent socio-technical regime. While this supports the deployment of ultra-efficient aircraft, hydrogen aircraft innovations are not targeted, representing a need for more top-down policies for the deployment of this sustainable aircraft technology. Furthermore, policy makers should understand the influence of global business dynamics in the aviation industry on the deployment of the alternatives. This includes the influence of competition between large incumbent OEMs on the development of sustainable aircraft alternatives. These trends should be backed by governments in order to ensure they are being enrolled. Also, as hydrogen aircraft deployment specifically is highly intertwined with the availability of hydrogen, policy makers should ensure enough RES capacity is present for its production and facilitate its allocation across hard-to-decarbonize industries. Also, hydrogen distribution infrastructure needs a European wide standard to mitigate potential problems with a misalignment of cross-border hydrogen networks.

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# APPENDIX A – LITERATURE RESEARCH ACADEMIC GAP

To find academic and peer-reviewed literature for the formulation of a research gap, a backward snowballing method of key theoretical frameworks have been applied and the database Scopus has been used. In Scopus, relevant articles have been obtained by (I) using appropriate key words and Booleans, (II) scoping down on English literature published >2015 and (III) scanning relevancy of the title and the abstract of the research. Here a focus has been laid on literature that examines holistic components next to technological and cost performances of sustainable aircraft designs. This methodology, depicted in Table A1 and A2, has resulted in the list of literature on sustainable aviation transition metrics represented in Table A3. Subsequently, the review of relevant sustainable aircraft innovation literature and theoretical literature can be found in Table A4 and A5.

*Table A1: Methodology for retrieving relevant case study literature*

| Key words Scopus | # Hits > 2015 | Steps | Article Chosen |
|---|---|---|---|
| Sustainable AND Aviation AND Economics | 200 | - Title scan of first 40 hits<br>→ 18 hits left<br>- Abstract scan | - Grim et al. (2022)<br>- Timmons & Terwel (2022)<br>- Shahriar & Khanal (2022)<br>- Hsu et al. (2022)<br>- Sharma et al. (2021)<br>- Jiang & Yang (2021) |
| Sustainable AND Aviation AND {holistic approach} | 10 | - Title scan | - Markatos & Pantelakis (2023)<br>- Pechstein et al. (2020) |
| Sustainable AND Aircraft AND Comparison | 79 | - Title scan of first 40 hits<br>→ 7 hits left<br>- Abstract scan | - Karpuk & Elham (2022)<br>- Proesmans & Vos (2022) |
| Commercial AND Aviation AND Sector AND Sustainability | 23 | - Title scan<br>→ 14 hits left<br>- Abstract scan | - Leal Filho et al. (2023)<br>- Guan et al. (2022)<br>- Ansell (2022)<br>- Kramer et al. (2022)<br>- Zaporozhets et al. (2020)<br>- Drünert et al. (2020)<br>- Hornung et al. (2019) |
| {Innovation System} AND Aircraft OR Aviation | 10 | Abstract scan | Meng et al. (2019)<br>Hartigh (2018)<br>Vértesy (2017) |
| Sustainability AND Niche AND Aircrafts OR Aviation | 9 | Abstract scan | Kim et al. (2019) |
| Aircraft AND Sustainable OR {Net Zero} AND Innovation | 64 | Abstract scan of first 20 articles | Bergero et al. (2023)<br>Yusaf et al. (2023)<br>Huete et al. (2022)<br>Dhara & Muruga Lal (2021) |

*Table A2: Overview of relevant case study literature*

| Title | Name | Date | Journal source |
|---|---|---|---|
| Hydrogen-Electric Aircraft Technologies and Integration: Enabling an environmentally sustainable aviation future. | Ansell | 2022 | IEEE Electrification Magazine, 10(2), 6-16. |
| Analysing the functional dynamics of technological innovation systems: A scheme of Analysis | Berget et al. | 2008 | Research policy, 37(3), 407-429 |
| Electrifying the production of sustainable aviation fuel: the risks, economics, and environmental benefits of emerging pathways including CO2. | Grim et al. | 2022 | Energy & Environmental Science, 15(11), 4798-4812. |
| Analysis of Carbon Emission Reduction in International Civil Aviation through the Lens of Shared Triple Bottom Line Value Creation. | Guan et al. | 2022 | Sustainability, 14(14), 8513. |
| Functions of innovation systems: A new approach for analysing technological change | Hekkert et al. | 2007 | Technological forecasting and social change, 74(4), 413-432. |
| Energy, economic and environmental (3E) analysis for the renewable jet fuel production process. | Hsu et al. | 2022 | Sustainable Production and Consumption, 33, 146-157. |
| Carbon tax or sustainable aviation fuel quota. | Jiang & Yang | 2021 | Energy Economics, 103, 105570. |
| Comparative study of hydrogen and kerosene commercial aircraft with advanced airframe and propulsion technologies for more sustainable aviation. | Karpuk & Elham | 2022 | Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, 09544100221144342. |
| Mission-oriented innovation policy and dynamic capabilities in the public sector | Kattel & Mazzucato | 2018 | Industrial and corporate change, 27(5), 787-801. |
| Global tourism, climate change and energy sustainability: assessing carbon reduction mitigating measures from the aviation industry. | Leal Filho et al. | 2022 | Sustainability Science, 1-14. |
| The technological innovation systems framework: Response to six criticisms | Markard et al. | 2015 | Environmental Innovation and Societal Transitions, 16, 76-86. |
| Implementation of a Holistic MCDM-Based Approach to Assess and Compare Aircraft, under the Prism of Sustainable Aviation. | Markatos & Pantelakis | 2023 | Aerospace, 10(3), 240. |
| A “book and Claim”-Approach to account for sustainable aviation fuels in the EU-ETS–Development of a basic concept. | Pechstein et al. | 2020 | Energy policy, 136, 111014. |

| | | | |
|---|---|---|---|
| Combining the technological innovation systems framework with the entrepreneurs' perspective on innovation. | Planko et al. | 2017 | Technology Analysis & Strategic Management, 29(6), 614-625. |
| Comparison of Future Aviation Fuels to Minimize the Climate Impact of Commercial Aircraft. | Proesmans & Vos | 2022 | In AIAA Aviation 2022 Forum (p. 3288). |
| Transition and strategic niche management: towards a competence kit for practitioners. | Raven et al. | 2010 | International Journal of Technology Management, 51(1), 57-74 |
| Technological change | Rip & Kemp | 1998 | Human choice and climate change, 2(2), 327-399. |
| More evolution than revolution: transition management in public policy. | Rotmans et al. | 2001 | Foresight, 3(1), 15-31. |
| The current techno-economic, environmental, policy status and perspectives of sustainable aviation fuel (SAF). | Shahriar & Khanal | 2022 | Fuel, 325, 124905. |
| Economic Analysis of Developing a Sustainable Aviation Fuel Supply Chain Incorporating With Carbon Credits: A Case Study of the Memphis International Airport. | Sharma et al. | 2021 | Frontiers in Energy Research, 802. |
| Economics of aviation fuel decarbonization: A preliminary assessment. | Timmons & Terwel | 2022 | Journal of Cleaner Production, 369, 133097. |

*Table A3: Review of relevant case study literature*

| Article | Aircraft Design | | | Holistic approach metrics for sustainability | | | | |
|---|---|---|---|---|---|---|---|---|
| | Hydrogen | SAF | Ultra-efficient | Comparison alternatives | Socio-technical analysis | Operation of flights | Complementary infrastructure | Regulation / policy |
| Grim et al. (2022) | | X | | | X | | X | |
| Timmons & Terwel (2022) | X | X | | X | | | | |
| Shahriar & Khanal (2022) | | X | | | X | | X | X |
| Hsu et al. (2022) | | X | | | | | | X |
| Sharma et al. (2021) | | X | | | X | | | X |
| Jiang & Yang (2021) | | X | | | | | | X |
| Markatos & Pantelakis (2023) | X | X | | X | | | | |
| Pechstein et al. (2020) | | X | | | | | X | X |
| Karpuk & Elham (2022) | X | | X | X | | X | | |
| Proesmans & Vos (2022) | X | X | | X | | | | |
| Leal Filho et al. (2022) | | X | | | X | X | X | X |
| Guan et al. (2022) | | | | | X | | | X |
| Ansell (2022) | X | | | | | | X | |
| Kim et al. (2019) | | X | | | X | | | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Bergero et al. (2023) | X | X | X | | X | | | |
| Yusaf et al. (2023) | X | | | | X | | | |
| Huete et al. (2022) | X | | | | X | | | |
| Dhara & Muruga Lal (2021) | | X | | | X | | | |

*Table A4: Methodology for retrieving relevant theoretical literature*

| Reference article | Backwards snowballing | Backwards snowballing |
|---|---|---|
| Ortt & Kamp (2022) | Rotmans et al. (2001) | Rip & Kemp (1998) |
| | Raven et al. (2010) | |
| | Markard et al. (2015) | |
| | Planko et al. (2017) | |
| Elzinga et al. (2023) | Hekkert et al. (2007) | |
| | Bergek et al. (2008) | |
| | Kattle & Mazzucato (2018) | |

*Table A5: Overview of relevant theoretical literature*

| Title | Name | Date | Journal source |
|---|---|---|---|
| Analyzing the functional dynamics of technological innovation systems: A scheme of analysis | Bergek et al. | 2008 | Research policy, 27(3), 407-429 |
| Assessing mission-specific innovation systems: Towards an analytical framework | Elzinga et al. | 2021 | Environmental Innovation and Societal Transitions, 48, 100745. |
| Functions of innovation systems: A new approach for analysing technological change | Hekkert et al. | 2007 | Technological forecasting and social change, 74(4), 413-432. |
| Mission-oriented innovation policy and dynamic capabilities in the public sector | Kattel & Mazzucato | 2018 | Industrial and corporate change, 27(5), 787-801. |
| Technological innovation systems in contexts: Conceptualizing contextual structures and interaction dynamics. | Markart et al. | 2015 | Environmental innovation and |

| | | | |
|---|---|---|---|
| | | | societal transitions, 16, 51-64. |
| A technological innovation system framework to formulate niche introduction strategies for companies prior to large-scale diffusion. | Ortt & Kamp | 2022 | Technological Forecasting and Social Change, 180, 121671. |
| Combining the technological innovation systems framework with the entrepreneurs' perspective on innovation. | Planko et al. | 2017 | Technology Analysis & Strategic Management, 29(6), 614-625. |
| Technological change | Rip & Kemp | 1998 | Human choice and climate change, 2(2), 327-399. |
| More evolution than revolution: transition management in public policy. | Rotmans et al. | 2001 | foresight, 3(1), 15-31. |

*Table A6: Review of relevant theoretical literature*

| Article | Innovation system perspective | Company perspective | Multiple technological trajectories | Time dimension in analysis |
|---|---|---|---|---|
| Rip & Kemp (1998) | | | X | X |
| Rotmans et al. (2001) | | | X | X |
| Hekkert et al. (2007) | X | | | |
| Bergek et al. (2008) | X | | | |
| Kattel & Mazzucato (2018) | X | | X | |
| Elzinga et al. (2023) | X | | X | |
| Markard et al. (2015) | X | X | | |
| Planko et al. (2017) | X | X | | |
| Ortt & Kamp (2022) | X | X | | |

# APPENDIX B – ELABORATION ON PROPOSED TIS INDICATORS

Appendix B provides an elaboration on the proposed TIS indicators for evaluation of the sustainable aircraft technologies. It should be noted that some indicators do not seem to provide concrete information when considered on its own, but together with the information of other indicators provide essential information. An example is required fuel per seat of TIS building block 1, which needs to be considered in combination with passenger capacity of TIS building block 1 and the fuel price of TIS building block 2 to be providing valuable information. Section B1 represents the indicators of TIS building block 1. Section B2 represents the indicators of TIS building block 2. Section B3 represents the indicators of TIS building block 3. Section B4 represents the indicators of TIS building block 4. Section B5 represents the indicators of TIS building block 5. Section B6 represents the indicators of TIS building block 6. Section B7 represents the indicators of TIS building block 7.

## B1 – PRODUCT PERFORMANCE AND QUALITY

The first building block refers to the quality and performance of the innovation compared to the competing products (Magnusson & Berggren, 2018). In the case of the aviation industry, predevelopment maturation work and certification processes take years (EASA, n.d.), while the potential technological building blocks and its performance have been identified already before. Therefore, these technologies can be evaluated on their performance already while they have not been entered into service yet. The indicators for this TIS building block include regular product performance of an aircraft, as well as its environmental performance.

### B1.1 CO2 EMISSIONS

As the objective of development of a sustainable aircraft is its environmental performance, this is considered the most important performance of the sustainable aircraft technologies. Environmental performance for aircraft could generally be addressed by the type of emissions they emit and life cycle environmental impacts such as sustainable material use, recyclability of components, emissions related to production and distribution (Rupcic et al., 2022; Krauklis et al., 2021; Vidal et al., 2018; Huang et al., 2016). For this research, it is assumed that the sustainable aircraft technologies will perform similar on the life cycle environmental impacts, while the type of emissions they emit will inherently differ. Therefore, only the emissions from operations will be included in the analysis of product performance and quality, where CO2 emissions are most common and best understood manner to measure climate impact of industry (Batteiger et al., 2022; Fuel Cells and Hydrogen 2 Joint Undertaking, 2020). Therefore, a focus in industry has shifted more towards reducing fossil-based CO2 emissions specifically (Fawzy et al., 2020). Member Airlines of IATA, for example, have committed to achieve net-zero-carbon emissions from their operations by 2050 (IATA, 2023). Moreover, Airbus has focused its objective to work towards net-zero carbon emissions by 2050 (Airbus, n.d.).

### B1.2 NOX EMISSIONS

A mere focus on reducing CO2 emission, however, will not solve the problem of the climate change effects induced by aviation on the environment. Aviation operation emits various types of GHG at high altitudes, including NOx emissions (Batteiger et al., 2022; Hoelzen et al., 2022a). NOx emissions emitted by aircraft enhance the formation of climate harming ozone in the upper troposphere and the lower stratosphere (Faber et al., 2008). This results in a climate warming with a relative higher ERF than CO2 emissions (Lee et al., 2021). Nevertheless, Lee et al. (2021) elaborate that NOx emissions from aviation also lead to cooling effects since long-term ozone, methane and stratospheric water vapor decrease.

Since this overall still leads to an increase of ERF, NOx emissions are included as indicator for the evaluation of environmental performance of the sustainable aircraft technologies.

## B1.3 CONTRAIL FORMATION

Moreover, aircraft operations lead to contrail formations at high altitudes (Batteiger et al., 2022). Contrails are created when soot particles and hot water vapour as exhaust products from the engine mix with the cool ambient air. In this process, soot particles and water droplets freeze into ice particles, which increases overall ERF in the environment (Teoh et al., 2020). It should be noted that a warming of the atmosphere mainly is caused by contrail formation during the night. During the day, contrail cirrus reflects solar radiation back into space, effectively cooling the atmosphere (Voigt et al., 2021). Nevertheless, results from the research of Lee et al. (2021) have concluded that overall, contrail cirrus is the actual largest contributor to ERF from aviation, making it an important indicator to assess the sustainable aircraft technologies on.

## B1.4 RANGE

Next to the environmental performance of the alternatives, it is most important to consider customer satisfaction on the aircraft. For an OEM, its main customers are airlines. The fundamental objectives of aircraft for these consumers are the technological performance indicators, of which most important is the range representing range (Zhang et al., 2013). A compliance with current practices in the aviation industry should be maintained to ensure smooth adoption of the sustainable aircraft types (Verstraete, 2015). If the range of sustainable aircraft technologies is lower than conventional aircraft, an increased number of flights is required for traveling similar distances, which would subsequently lead to an increase in emissions from operation, making this indicator relevant to address in this research.

## B1.5 PASSENGER CAPACITY

Furthermore, passenger capacity is a fundamental indicator for technological performance of aircraft. Together with the indicator range, the capacity of passengers that can be transported over a certain range is considered the overall passenger throughput of aircraft operations. Similar to B1.4, if the sustainable aircraft technology has a lower passenger capacity than a conventional aircraft, additional flights are required to transport the same number of passengers (Gössling & Lyle, 2021). Next to emission, this would affect staff requirements and slot availability, thus increasing DOC. Therefore, this indicator is essential for the assessment of a compliance of the sustainable aircraft technologies with current operations in the aviation industry.

## B1.6 REQUIRED FUEL PER SEAT

Another indicator for technological performance of the aircraft is the required fuel per seat needed for transportation (Int. Senior Manager Airbus technology, 14/07/2023). The fuel required for aircraft operations indicate how energy efficient the aircraft is operating (Yutko, 2011). Since the passenger capacity may vary among the sustainable aircraft technologies, the required fuel is assessed per passenger to establish an aligned evaluation base. Furthermore, the hydrogen sustainable aircraft technology makes use of a different fuel types than conventional kerosene, which has different properties. For this aircraft technology, the required fuel per seat of aircraft would influence the necessary size of the tank for fuel storage, which in its turn affects the performance of indicators B1.4 and B1.5. Also, this indicator is important for the overall assessment of fuel costs required for a flight with the sustainable aircraft technologies.

### B1.7 REFUELLING TIME

Moreover, an assessment of turnaround time is required for a compliance with current practices in the aviation industry. The most important aspect refers to refuelling of the aircraft. In general, short refuelling times could significantly reduce economic efficiency of operation (Fuel Cells and Hydrogen 2 Joint Undertaking, 2020); a loss of more than 10 minutes of turnaround time for three to four times a day could negatively impact revenues. This is especially important for regional aircraft rather than long-distance aircraft, since regional flights will encounter refuelling procedures more often which thus affects aircraft utilization (Mangold et al., 2022). Therefore, this indicator is essential for the evaluation of the performance of the sustainable aircraft technologies.

### B1.8 NOISE EMISSIONS

Also, noise emissions from aircraft are essential for the evaluation of performance of aircraft. Aircraft noise is identified as an inhibitor for growth in aviation due to nuisance to residents located near airports (Spakovszky, 2019). In the Dutch/German ecosystem specifically, airport Schiphol needs to reduce its number of flights from March 2024 on, as nuisance from noise emissions of the flights to and from the airport are currently very high (NRC, 2023). Therefore, the sustainable aircraft technologies should preferably emit less noise than conventional aircraft, or at least not emit more noise.

### B1.9 PASSENGER COMFORT

As the main customers making use of flight operations are passengers, the comfort of the interior of an aircraft is also an important indicator for product performance and quality. This refers to a minimum compliance towards comfort experience of the passenger (Hall et al., 2013). Next to elements such as comfortable seating and leg space, a trade-off in overall cabin space for passengers and space utilization for tank technologies of novel fuels is present, as these might require more space than conventional tank technologies (Eissele et al., 2023).

### B1.10 PASSENGER PERSPECTIVE ON TECHNOLOGY

Furthermore, it is important to include a passenger perspective on quality performance of the sustainable aircraft technologies as these in the end make use of the aircraft. This passenger perspective refers to various aspects, including opinions on the safety aspects as well as perceptions on the sustainable impact of the sustainable aircraft technologies (TU Delft supervisors, 22/08/23). The latter one is especially important in light of the recent trend of flight shame among potential passengers (Doran & Ogunbode, 2021).

### B1.11 OPERATIONAL SAFETY

Also, the operational safety of the sustainable aircraft technologies is essential for their overall evaluation of quality and performance. Novel aircraft technologies usually pose uncertainties as they deviate from incumbent aircraft types and thus traditional safety requirements (Bendarkar et al., 2022). This should be addressed before deployment of the sustainable aircraft technologies is possible, making this a crucial indicator for the evaluation of TIS building block 1. Here, safety requirements are considered ranging from the technological bricks of the sustainable aircraft to the type of fuels deployed in relation to airport operations and during flight.

## B2 – PRODUCT PRICE

The second building block refers to the price of the sustainable aircraft technology compared to the competing benchmark aircraft technology. A relatively higher price could potentially hamper diffusion (Kemp et al., 1998). Here, not only financial costs are considered, but non-financial costs such as time and effort as well.

### B2.1 INVESTMENT COSTS OF AIRCRAFT

The first indicator will represent the investment costs of the sustainable alternative technology, compared to that of conventional aircraft. This tightly interrelates with the attractiveness of the sustainable aircraft technology for customers, such as airlines, and thus with adoption of the technology. As high investment costs have been associated as barriers for adaptation of innovations (Karakaya & Sriwannawit, 2015), this indicator is essential for the deployment of sustainable aircraft technologies.

### B2.2 FUEL COSTS

Furthermore, the fuel cost of novel energy carriers is essential to consider as the main customers will encounter these costs in operation. Fuel costs is considered the second to third highest cost imposed on airlines (Efthymiou & Papatheodorou, 2020) and is considered the key driver of an aircraft's competitiveness (Fuel Cells and Hydrogen 2 Joint Undertaking, 2020). Fuel costs entails the annual energy consumption of an aircraft multiplied with the sum of costs related with production, processing, transportation, storage and refuelling per kilogram of fuel (Hoelzen et al., 2022a).

### B2.3 SWITCHING COSTS

The financial and non-financial costs associated with switching to another technology is important to evaluate as well (Ortt & Kamp, 2022), especially for evaluating more radical aircraft innovations that require changes in various dimensions of the incumbent socio-technical regime (Negro et al, 2012). From an industry perspective, this is represented by the non-recurring costs that need to be invested for the novel sustainable aircraft, referring to the one-time basis expenditures related with capital expenditures, design, development, investment, and legal costs (Airbus technology valuation training, 2023; Li et al., 2018). As it is infeasible within the time constraints of the master thesis research to get a precise indication of non-recurring costs per actor, the indicator will be assessed based on an overall overview of switching costs associated with the sustainable aircraft technologies. Since the switching costs are considered to be made once for the deployment of the technology, the indicator is considered time-dimensionless and will not be evaluated on its influencing condition and prospect of completeness.

### B2.4 TRANSACTION COSTS

Lastly, transaction costs are tightly intertwined to the supply chain of the firm (Short et al., 2016), associated with finding new material and component suppliers for the deployment of the sustainable aircraft technologies (Ortt & Kamp, 2022). For the deployment of novel sustainable aircraft technologies, this indicator is important to consider for the business operations of an OEM. Similar to switching costs, these costs are expressed in both financial and non-financial costs. Transaction costs are also assumed to be made once for the deployment of the technology, resulting in the indicator to be considered time-dimensionless and will not be evaluated on its influencing condition and prospect of completeness.

## B3 – PRODUCTION SYSTEM

The third building block refers to the availability of the production system to deliver the products in a high quality and in large quantities (Ortt & Kamp, 2022). Here, only the production system of OEMs for sustainable aircraft types will be evaluated, not the production system that is required to produce the fuel type complementary to the sustainable aircraft technologies.

### B3.1 KNOW-HOW ON THE PRINCIPLE OF PRODUCTION

First, it is relevant to establish the know-how of the technological bricks of the sustainable aircraft technologies and their overall aircraft design since the alternatives have not appropriately been developed yet today. This is indicated to be the essential knowledge base which is required for establishing production methods in an interview with the Senior Manager of Airbus Technology (14/07/23).

### B3.2 RAMP-UP ABILITY OF THE PRODUCTION SYSTEM

Subsequently, it is of importance to consider the ability to ramp the production system up. This refers to the ability of OEMs to alter and finetune the production system to the extent that it is able to deliver high quality aircraft in large quantities (Int. Senior Manager of Airbus Technology, 14/07/23), through a process of learning by doing (Ortt & Kamp, 2022). This capability is especially important for OEMs deploying novel sustainable aircraft technologies, as the aircraft industry is a highly competitive market. A first mover advantage of being able to produce novel technologies in a short amount of time could potentially lead to taking a large market share (Von Gleich et al., 2012). Since aircrafts have a lifetime of 20-30 years (IATA, 2018), and development cycles of OEMs occur every 15-20 years (Fuel Cells and Hydrogen 2 Joint Undertaking, 2020), a first mover advantage is desirable for generating a high level of income for OEMs. This indicator requires extensive knowledge coordination and the availability of human capital (Von Gleich et al., 2012).

### B3.2. ABILITY TO PRODUCE A FLEET IN AN APPROPRIATE TIME

Lastly, when the production system has ramped-up, it should reach an end state in which a whole aircraft fleet could be produced in an appropriate time (Int. Senior Manager of Airbus Technology, 14/07/23). This represents the overall performance of production capacity of the OEM (Timmis, 2020), and has been indicated as relevant to consider within the interview with the Senior Manager of Airbus Technology (14/07/23). This indicator is essential for evaluating the production system of the sustainable aircraft technologies.

## B4 – COMPLEMENTARY INFRASTRUCTURE AND SERVICES

The fourth building block refers to the availability of complementary infrastructure and services. Sustainable aircraft based on alternative fuels require new supply chains, including production and processing, distribution, storage and fuelling equipment (Hoelzen et al., 2022a). The current availability of such supply chains is evaluated within this TIS building block.

### B4.1 FUEL PRODUCTION INFRASTRUCTURE

First, infrastructure needs to be available to produce potential novel energy carriers for aircraft propulsion (Ansell, 2022; Grim et al., 2022; Shahriar & Khanal, 2022). The availability of fuel production capacity is essential for the operations of the sustainable aircraft technologies. An insufficient supply of fuel would have disastrous consequences for flight operations, potentially imposing large costs on airlines. As long as the fuel production infrastructure has not proved to supply enough fuel for the demand of these operations, investment in the complementary sustainable aircraft technologies could potentially be blocked, hampering overall deployment.

### B4.2 FUEL DISTRIBUTION INFRASTRUCTURE

Subsequently, facilities to process the produced fuel for distribution is essential for the supply chain of fuel as well. Specifically for sustainable aircraft technology using hydrogen as fuel, the availability of a well-established distribution system is essential (Hoelzen et al., 2022a). The fuels required for the sustainable aircraft technologies could be transported by means of truck, ship, train or pipelines (Yang & Ogden., 2007). Here, it is crucial that the distribution system is connected to airports (Leal Filho et al., 2022; Pechstein et al., 2020).

### B4.3 FUEL STORAGE INFRASTRUCTURE

Subsequently, airport infrastructure on fuel storage is required for keeping fuel at site until needed for aircraft operations (Meindl et al., 2023; Grim et al., 2022). This is required to ensure reliability of fuel supply for aircraft operations (Hoelzen et al., 2022a). Especially for sustainable aircraft technologies using hydrogen as fuel, such storage infrastructure is novel as well and might pose uncertainties on their performance, underwriting the importance of addressing this indicator.

### B4.4 REFUELLING INFRASTRUCTURE AT AIRPORT

Moreover, the refuelling system at airports needs to be aligned to the sustainable aircraft (Timmons & Terwel, 2022). This is closely related to the indicator *fuel storage infrastructure* and symbolizes the final infrastructure required for the supply chain of the fuel for aviation uses. Refuelling infrastructure that is coordinated to the complex logistics of airport operations are essential for reliable operations of the sustainable aircraft technologies.

### B4.5 MAINTENANCE REPAIR OVERHAUL (MRO) SERVICES

Furthermore, the availability of maintenance overhaul repair (MRO) services is an important indicator, argued for in an interview with Senior Manager Airbus technology (14/07/2023). MRO services encompass all maintenance required for safe operation of the aircraft within the high level of safety expected today (Vieira & Loures, 2016; Phillips et al., 2011). Moreover, it is essential for operational business in the aviation industry, as aircraft failure would lead to its outage for operation, which induces high costs for airlines (Int. OEM). The establishment of safe and reliable MRO concepts and time intervals of application is essential for the deployment of sustainable aircraft technologies within the established operational system of aviation.

## B5 – NETWORK FORMATION AND COORDINATION

The fifth building block refers to the level of coordination that is present between key actors in the supply chain of the innovation (Ortt & Kamp., 2022). Network formation and coordination is needed for the exchange of information in a heterogeneous context which potentially stimulates changes in R&D agendas (Hekkert et al., 2007) and an alignment of business activities towards the deployment of sustainable aircraft technologies.

### B5.1 ACTOR NETWORK

Within socio-technical systems, actor networks are a key dimension influencing the promotion of blocking of innovations. Hekkert et al. (2007) argue that network activity leads to a *learning by interacting* trend, which ensures knowledge diffusion regarding innovations. When a network is tightly connected, desirable innovations have higher chances to reach different types of actors and thus have higher chances of successful deployment (Alcouffe et al., 2008). For sustainable aircraft technologies, a network of actors with willingness to act towards sustainable transitions within the aviation industry is beneficial. This is especially the case for more radical technologies, which requires investments and motivation from different actors within the value chain of aviation. Therefore, the presence of a large and robust actor network is being evaluated in this indicator.

### B5.2 COMMUNICATION AMONG ACTORS AND STEPS TAKEN TOWARDS A SIMILAR VISION

For the deployment of sustainable aircraft technologies, cooperation between different actors is essential for coordinating activities and strategies for investments (Mousavi & Bossink, 2017). As a lot of stakeholders are involved in the transition of sustainable aviation and operate under their own interests, the proposed solutions from stakeholders could potentially conflict each other (Elzinga et al., 2023). Moreover, due to a limited number of resources, companies need a specific focus on what technologies to invest in (Hekkert et al., 2007). As a wide range of sustainable aircraft alternatives is present, a strong directionality of industry on a particular innovation is missing. Therefore, building towards a shared vision of which technology to focus is vital (Negro et al., 2012). Here, especially the coordination between OEMs, airlines, airports, and fuel providers are considered vital, but also challenging, for the implementation of sustainable aircraft technologies (Fuel Cells and Hydrogen 2 Joint Undertaking, 2020).

### B5.3 NUMBER OF CONSORTIUMS

The number of consortiums in the network represents joint ventures within an industry, being temporary or fixed. Hekkert et al. (2007) discuss that collaborations between universities and industries are a typical indicator to evaluate the structure of an innovation system. This is a quantitative indicator to enumerate cooperation of actors within a similar business project, providing key information in the performance of the overall TIS building block.

### B5.4 NUMBER OF WORKSHOPS AND CONFERENCES

Furthermore, the number of workshops and conferences on the sustainable alternatives are a good indicator of network formation. It is argued that the foremost function of networks is the diffusion of knowledge (Carlsson & Stankiewicz, 1991). As workshops and conferences bring people within industry physically together and educate them on novel sustainable aircraft innovations, thorough knowledge spill overs are obtained among actors. Hekkert et al. (2007) propose that this is a good indicator for assessing exchange of information within a network, which is required for coordination of actors on the sustainable aircraft technologies.

### B5.5 NUMBER OF PUBLICATIONS ON TECHNICAL PROGRESS

The number of publications on technical progress has been identified as an important indicator since it symbolizes the focus on knowledge creation of the sustainable aircraft technologies (Int. Senior Manager Airbus technology, 14/07/2023). This can be analysed by evaluating the hype cycle around the technologies, where a pattern of peak, disappointment and recovery of expectation stages are following each other successively of which the first represents a collective expectation on the technology (Dedehayir & Steinert, 2016). In first phases of innovation, firms are stated to compete based on expectations instead of competing on technological performance, and therefore considered a driver for technical development (Alkemade & Suurs., 2012). Thus, this indicator represents the extent to which expectations of a technology are shared among actors within an industry.

### B5.6 MEDIA COVERAGE ON CONCEPTS OF SUSTAINABLE AIRCRAFT TECHNOLOGY

Similar to the former indicator, the media coverage of topics and of the introduction of concepts of the sustainable aircraft technologies are interesting to consider, as it represents a focus on a particular technology by the industry (Int. Senior Strategy & Business Development Lead Airbus, 05/07/23). Borup et al. (2006) state how perceptions on sustainable aircraft technologies not only influence activities of engineers and scientist, but also stimulates changes in markets and infrastructure within the aviation industry. Next to scientific progress, changes within other dimensions of the socio-technical system are required, which can be derived from media coverage (Peeters et al., 2016).

## B6 – CUSTOMERS

The sixth building block refers to the potential customers that would be interested in the sustainable aircraft technologies (Ortt & Kamp, 2022). This TIS building block is essential to evaluate as it represents a potential demand formation which is essential for the deployment of the sustainable aircraft technologies.

### B6.1 CUSTOMER TYPE

Before the development of the sustainable aircraft technologies, it is key to distinguish which customer type are conceivably interested in the alternatives (Kamp et al., 2004). Rogers (1983) identified five groups of customer types that vary in perception on adoption of innovations, including (I) innovators, (II) early adopters, (III) early majority, (IV) late majority and (V) laggards. Next to the innovators, which introduce new innovations themselves, the identification of early adopters are vital to address for the deployment of novel technologies. Early adopters are associated with customers that have a positive attitude towards change and a willingness to try newly introduced innovations out and represent to a large extent opinion leaders of society (Orr, 2003). Here, both key market segments from airlines as a group of prosperous individuals that highly value novelty and sustainability, either as intrinsic incentive or as a status symbol, can be identified as early adopters.

### B6.2 INVOLVEMENT OF POTENTIAL CUSTOMER IN INNOVATION PROCESS

The involvement of potential customer in the innovation process is as a lack of knowledge of the sustainable aircraft technologies could potentially increase the perception of risk and uncertainty (Ortt & Kamp, 2022). Geels (2004) states that: *“users (..) have to integrate new technologies in their practices, organizations and routines, something which involves learning and adjustments. New technologies are sometimes said to be ‘tamed’ to fit in concrete routines and application contexts”* (p. 902). As sustainable aircraft innovations are associated with changing technological trajectories within the industry, this underlines the need for customers to be involved within their innovation process. Also, this relationship could enhance a competitive advantage over other OEMs and accelerate market deployment (Iglesias et al., 2020).

### B6.3 AWARENESS OF BENEFIT COMPARED TO INCUMBENT AIRCRAFT DESIGNS

Next to the involvement of the customer, it is essential that the customer is aware of the benefits of the sustainable aircraft technologies over conventional ones for their deployment (Ortt et al., 2013; Rogers, 1983) discuss, this includes an awareness of the new technology first, and subsequently seeing their value over current aircraft designs. Next to ensuring customers are attracted to the sustainable aircraft types, a study of Taghizadeh et al. (2018) found that customer knowledge on a product could also enhance the speed and quality of the innovation process.

### B6.4 FINANCIAL MEANS TO ACQUIRE AIRCRAFT

Moreover, it is important that customers are able to acquire the sustainable aircraft types financially (Ortt et al., 2013). As aircraft in general are associated with high investment costs, an increase in these costs with the introduction of the sustainable aircraft technologies should remain affordable for customers to be deployed.

### B6.5 WILLINGNESS TO ACQUIRE AIRCRAFT

Logically, altogether the customer must have a willingness to acquire the sustainable aircraft alternatives and use it for aircraft operations (Ortt et al., 2013). Independent of the reasoning behind this willingness, its absence would hamper the deployment of the sustainable aircraft technologies.

## B7 – INNOVATION-SPECIFIC AND INDUSTRY-WIDE REGULATION

The seventh building block refers to the formal regulations that either support or block the development and implementation of innovations (Ortt & Egyedi, 2014). Here, a focus on innovation policies to nurture the sustainable aircraft technologies is provided, as well as a focus on essential regulations within the aviation industry that hamper or support their deployment. These are evaluated on their supporting or hampering influence on the technologies (Ortt & Kamp, 2022), level of stringency (Altenburg & Pegels, 2017) and the long-term consistency of these regulations (Negro et al., 2012).

### B7.1 GOVERNMENTAL POLICIES AND REGULATIONS (EU WIDE)

According to Köhler et al. (2019), sustainability is a public good where public policy plays an important role in providing directionality of transitions through environmental legislations. Here, regulations set the limits in which society can operate, influencing the way in which socio-technical systems function. Within the EU, most important legislations on CO2 emissions are the Carbon Reduction and Offsetting Scheme (CORSIA) and European Union Emission Trading System (EU ETS) legislation, consecutively global and European-based measure to reduce carbon emissions and thus promote alternative fuels over kerosine (Guan et al., 2022; Leal Filho et al., 2022; Pechstein et al., 2020). While these CO2 legislations promote the introduction of sustainable aircraft technologies, the companies within the industries are key for their development and implementation.

### B7.2 INDUSTRY SELF-REGULATION

Industry self-regulation refers to the ability of an industry to set own ambitions and work towards them (Gunningham & Rees, 1997). Self-regulation provides an essential equilibrium between flexibility and certainty within industrial goals and enables a competitive climate for firms to operate in (Walters & Wiseman, 2023). When applied appropriately, effective initiatives can enhance the development and deployment of sustainable aircraft technologies. Gunningham & Rees (1997) discuss that effective self-regulation of an industry is expected when there is a public and private interest align.

## B7.3 SUBSIDIES AND INCENTIVES

For addressing the innovation of sustainable aircraft technologies specifically, more traditional policy instruments, in the form of subsidies and incentives, can be executed by governments (Edquist, 2013). Subsidies are economic policy instruments and could stimulate innovation by providing financial means for the supply side (Borrás & Edquist, 2013). Moreover, they provide a protected space for innovation to be experimented and developed in, which increases their chances of being deployed successfully (Köhler et al., 2019). As development and experimentation with the sustainable aircraft technologies pose high costs for OEMs, this indicator is essential to consider.

## B7.4 SAFETY REGULATIONS

Since aviation is subject to the transportation of many passengers, it is key for the well-functioning of the aviation industry. Safety within the aviation industry has significantly improved over the past decades, leading aviation to be one of the safest modes of commercial transportation (Oster et al., 2013). Safety regulations are crucial for the functioning of aviation, but could also hamper innovations, especially more radical ones compared to the current socio-technical regime. Radical sustainable aircraft technologies could be hampered by this indicator as the products are novel and there is a lack of experience present on their functioning (Blind, 2012). Safety requirements that are set too stringent could restrict experimentation with novel innovations, which is necessary for stimulating learning curves in the technology and their safety considerations. Nevertheless, when innovations are considered in-line with safety regulations, these could increase successful deployment as customers can rely on the reliability of the product. Therefore, safety regulations are key to evaluate for the deployment of sustainable aircraft technologies.

## B7.5 INTERNATIONAL AND REGIONAL STANDARDS

International and regional standards have an influence on innovation. Allen & Sriram (2000) define standards as *"documented agreements containing technical guidelines to ensure that materials, products, processes, representations, and services are fit for their purpose"* (p.172). Depending on the sector under consideration, standards could both limit and spur innovation. For the deployment of sustainable aircraft alternatives, this is assumed to have a hampering influence on innovation processes. The foremost important standard to evaluate is the certification process of aircrafts, followed by industrial standards for infrastructures used for operational functioning in aircrafts within the industry. Several other high-level standards are considered for this indicator.

# APPENDIX C – OVERVIEW OF POTENTIAL SUSTAINABLE AIRCRAFT TECHNOLOGIES

## BATTERY AIRCRAFT

Opposite to the other energy carriers, a battery aircraft does not use fuel but stored electricity for propulsion. When this electricity is generated in a green method, this would lead to zero GHG emissions during operation, making it an interesting alternative for addressing the sustainability challenge in the aviation industry. At this instance, however, batteries for aviation purposes have very low gravimetric energy densities, resulting in heavy batteries (Hepperle, 2012). A heavier battery means that the range of the aircraft is compromised, which is highly undesirable for aircraft operators. Moreover, the battery is accountable for a static weight throughout the whole duration of flight, as opposed to a continuous mass reduction by reduced fuel volume which increases range of flight (Faber et al., 2020). Due to these weight constraints in the current technological development of batteries, it is yet infeasible to deploy such an aircraft in commercial aviation. Therefore, battery aircraft will not be included in this research.

## BIOFUEL AIRCRAFT

Biofuels represent a range of various feedstock blends that have been processed into a fuel with resembling physical and chemical properties to conventional kerosine (Batteiger et al., 2022). Biofuels can also be considered SAF and can be distributed, stored and 'dropped-in' with existing infrastructure and kerosine as well. There are currently seven approved alternative fuel pathways, with more yet to be accepted. Similar to synthetic fuels, the overall sustainability dimension from the option is that the feedstock captured CO2 out of the air to grow, making its combustion carbon net zero. However, scepticism is present on how sustainable biofuels are as their production may lead to a low water footprint, eco-toxicity, and risks to biodiversity (Batteiger et al., 2022). Next to the potential land use changes, there is also finite land use present due to competition with crops cultivation (Pavlenko et al., 2019), and the other way around, using crops as input for biofuels potentially poses problems in the food industry (European Commission, n.d.e). Therefore, biofuels as an energy carrier for sustainable aviation will not be included in this research.

## HYDROGEN AIRCRAFT

Hydrogen is considered a crucial technology for the transition towards sustainability in the aviation industry. Hydrogen has a relatively high specific energy (33 kWh/kg) when compared to kerosine and other fuels and can be applied in both combustion systems and fuel cells (Batteiger et al., 2022). It can be stored in both pressurized gas and liquid form, where the gaseous option is unpreferable due to the low volumetric energy density of hydrogen, requiring larger and heavier tanks (Fuel Cells and Hydrogen 2 Joint Undertaking, 2020). As hydrogen as a fuel only emits water and no GHG, it is a promising energy carrier to consider for aviation. However, the extent to which hydrogen is considered sustainable derives from its production method. Preferably, hydrogen should be produced by electrolysis of water using electricity from renewable energy sources (Chi & Yu, 2018). The disadvantage of hydrogen as technology is that it requires large scale investments in novel aircraft design and complementary fuel production, supply and storage infrastructure (Hoelzen et al., 2022a). Hydrogen as an energy carrier for sustainable aviation will be considered in this research.

## SAF DROP-IN AIRCRAFT

Sustainable aviation fuels in the form of synthetic fuels are also considered an interesting technology for the transition towards sustainability. The idea of a synthetic fuel is that it is produced from water and captured $CO_2$ via a power-to-liquid conversions such as the Fischer-Tropsch process or a methanol process (Batteiger et al., 2022; Timmons & Terwel, 2020). The first conversion requires the input of hydrogen, making a green hydrogen production system important for this energy carrier as well. Here, so-called Sustainable Aviation Fuels (SAF) can be produced which can be distributed and stored making use of existing infrastructure, thus serving as a so-called drop-in fuel (Bauen et al., 2020). The sustainable advantage of synthetic fuels is that the required $CO_2$ input is captured, making its combustion carbon net zero. Other GHG emissions, however, are not eliminated by propelling aircraft with SAF (Bergero et al., 2023). Nevertheless, the aviation industry considers it a key technology for transitioning towards a sustainable aviation industry. Therefore, synthetic fuels in the form of SAF as an energy carrier for sustainable aviation will be considered in this research.

### ULTRA-EFFICIENT AIRCRAFT

The ultra-efficient aircraft technology is another promising sustainable alternative for aviation. Key performance drivers of incumbent aircraft have been improved significantly in this aircraft design, reaching optimisation towards the limit of physics while maintaining conventional tube and wing design. By establishing an aircraft design with less structural weight, less aerodynamic drag, and including engines with less specific fuel consumption that are integrated better on overall product level, the amount of fuel required for operation could significantly drop. Even though the ultra-efficient alternative will use conventional kerosene for propulsion, this drop of required fuel per flight will lead to less climate impact of aviation. This could be considered an incremental innovations within the aviation industry, leading to sustainable improvement of using existing knowledge of aircraft without requiring large-scale changes in the incumbent socio-technical system.

# APPENDIX D – INFORMED CONSENT DOCUMENT

Dear …….,

You are being invited to participate in a research study titled '*Developing effective strategies for the introduction of sustainable aircraft implementation in the aviation industry'.* This study is being executed by Charlotte Verdegaal from the TU Delft and is deployed from a Master Thesis internship position at Airbus, R&D department Bremen. Both TU Delft and Airbus employ a supervising role in this research.

The purpose of this study is to analyse at what stage of development different sustainable aircraft technologies (namely hydrogen-fuelled aircraft, SAF-fuelled aircraft in the form of synfuel, and ultra-efficient aircraft) are and when they are expected to be ready for implementation. By examining their current status and projected implementation timelines, the study aims to shed light on potential technological trajectories and highlight crucial bottlenecks that require attention within the aviation value chain in the forthcoming decade(s).

Your valued insights as a diverse array of aviation value chain actors -ranging from start-ups dedicated to sustainable alternatives, energy providers, safety regulators, airports, airlines, universities, to OEMs - are paramount to the study's success. An interview session of approximately 30 minutes is envisaged to facilitate this exploration. This engagement seeks to elicit your perspective on the development and future trajectories of various dimensions, known as 'TIS building blocks', delineated below:

*1) Aircraft performance and quality*
*2) Aircraft price*
*3) Production system*
*4) Complementary infrastructure and services (including hydrogen and SAF provision)*
*5) Stakeholder network formation and coordination*
*6) Customers*
*7) Innovation-specific and industry-wide regulation.*

**The data will be used for publication of the Thesis in the Thesis Repository of TU Delft and is expected to be distributed among interested employees of Airbus, as well as other interested stakeholders and respondents that have cooperated in the research.** We emphasize this point for your consideration, understanding that your insights contribute to a broader discourse. However, confidentially and anonymity are of utmost concern.

While the interview will not delve into sensitive organisational data, I acknowledge the risk of responses to inadvertently reveal your identity or organisation. To mitigate this risk, in the Thesis you will not be referred by the name or position/organisation. Instead, I will refer to you solely by your stakeholder type (e.g. 'OEM' or 'energy provider'), and area of expertise (e.g. 'hydrogen tank' or 'SAF production infrastructure'). This approach safeguards your privacy while ensuring the study's rigor. We shall define and agree upon the way you will be referred to in the thesis in the beginning of the interview.

To ensure transparency and rigor, the interview will be audio-recorded using a laptop and phone (as backup). The recordings will be stored temporarily on the TU Delft's and Microsoft OneDrive to facilitate transcription where only the responsible research and TU Delft supervisors have access to it. As in the final Thesis version, an anonymous summary of the transcript will only include the 'type' of stakeholder and field of expertise, to avoid the identification of respondents. Yet, your anonymous summary of the transcript will be shared with you, granting you the **opportunity to review and redact any data that could lead to personal identification**. Your accepted summary will be included in the final thesis version and thus publicly available, attributed to your stakeholder type and expertise, reinforcing transparency without compromising confidentially. Subsequently, all the recordings, full transcripts and this informed consent form will be securely deleted from OneDrive.

Your participation in this study is entirely voluntary **and you retain the prerogative to withdraw at any time.** You are free to omit any questions asked in the interview. Lastly, you **have the right to request access to and rectify or erase personal data** for the duration of the project.

Should there be complaints during and/or after the execution of the interview, particularly concerning the handling of personal data, you should communicate them to an email to both me, Charlotte Verdegaal (Master student, c.e.w.verdegaal@student.tudelft.nl), and my Responsible Researcher, Caetano Penna (Assistant Professor, c.c.r.penna@tudelft.nl). This correspondence should elaborate on the issue and indicate your preference for either (a) rectify the summary of the transcript or (b) withdraw from the study.

I hope that this letter clarifies the study's purpose, procedures, and data handling practices. Please do not hesitate to send me an email if you may have further questions.

With kind regards,

Charlotte Verdegaal

| PLEASE TICK THE APPROPRIATE BOXES | Yes | No |
|---|---|---|
| A: GENERAL AGREEMENT – RESEARCH GOALS, PARTICPANT TASKS AND VOLUNTARY PARTICIPATION | | |
| 1. I have read and understood the study information above, or it has been read to me. I have been informed about the goal of the interview to my satisfaction. | ☐ | ☐ |
| 2. I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason. | ☐ | ☐ |
| 3. I understand that taking part in the study involves:<br>• An audio-recorded interview by means of laptop and telephone, which will be stored in OneDrive of TU Delft and Microsoft Teams<br>• A transcription of the record in text form, of which an anonymized summary will be included in the Final Thesis version<br>• The audio-record of the interview, its full transcript and this informed consent form being destroyed, from laptop, telephone, and OneDrive after the end of this project, expected to be 30/11/2023. | ☐ | ☐ |
| B: POTENTIAL RISKS OF PARTICIPATING (INCLUDING DATA PROTECTION) | | |
| 4. I understand that taking part in the study also involves collecting your name, stakeholder type, and contact information as well as your field of expertise, with the potential risk of my identity being revealed. This refers to the situation where the respondent has a special position and perspective regarding one of the TIS building blocks under discussion, making him/her more likely to be re-identified | ☐ | ☐ |
| 5. I understand that the following steps will be taken to minimise the threat of a data breach, and protect my identity in the event of such a breach:<br>• The respondents will be referred to the type of stakeholder and his/her field of expertise, discussed upon in the interview<br>• This will be used as a reference both in the Thesis and the Transcript of the audio recording that will be stored<br>• The transcript of the audio recording will be stored in OneDrive of TU Delft where only the researcher has access to | ☐ | ☐ |
| 7. I understand that personal information collected about me that can identify me, such as my name or position within a company, will not be shared beyond the study team. | ☐ | ☐ |
| 8. I understand that all the recordings, full transcripts and this informed consent form will be destroyed after the duration of the project, expected to be 30/11/2023. | ☐ | ☐ |
| C: RESEARCH PUBLICATION, DISSEMINATION AND APPLICATION | | |
| 9. I understand that after the research study the anonymous summary I provide will be used for:<br>• Substantiation of assumptions/conclusion, potentially including quotes from the respondents<br>• Publication in the TU Delft online repository<br>• Distribution among employees of Airbus and other interested stakeholders<br>• Distribution among respondents that have contributed to the Thesis | ☐ | ☐ |

Signatures

______________________________ ____________________________ _________

Name of participant [printed] Signature Date

I, as researcher, have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

___________________________ ____________________ _________

Researcher name [printed] Signature Date

Study contact details for further information:

*Charlotte Verdegaal*

*[email address]*