Utrecht University

Ministry of Infrastructure and Water Management

PROPELLING SUSTAINABILITY: ACTOR-FOCUSED POLICIES FOR AVIATION

A Technical Innovation Systems Approach to Integrating Actors in Policy for Sustainable Energy Carriers

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Preface

This thesis is the result of a process that started nearly a year ago, in September 2023. For the final product of my master's education, I wished to achieve two things: To make a sustainable impact on the world around me and to challenge myself to produce the best thesis I could write.

Looking back, I am confident that I have achieved this. This thesis provides valuable contributions to literature to study sustainable innovations, while also recommending practical policy instruments to support sustainable aviation. Furthermore, this product reflects not only my recent education, but also the entirety of my academic experience. However, like every learning opportunity, this process has had its ups and downs. Therefore, I would like to acknowledge those who helped me.

First, I would like to thank Tom for his guidance and encouragement throughout my internship at IenW, Jan Willem for his supervision, and my colleagues for their support. Additionally, I would like to thank Joeri for enabling this thesis to achieve what I aspired to, as well as Anne for what we were able to accomplish these past two years. Finally, I would like to thank my friends and family for their encouragement whenever I needed it.

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Abstract

This research targets radical technological innovation to decarbonise the Dutch aviation industry with innovation policy provided by the Ministry of Infrastructure and Water Management (IenW). As most CO_2 emissions can be reduced using sustainable energy carriers (SEC), the study focuses on three focal technologies: sustainable aviation fuels, electric aircraft, and hydrogen aircraft.

A Technical Innovation System (TIS) approach is adopted from the perspective of actors, to study what drivers and barriers are experienced by two types of actors in the aircraft manufacturing industry: incumbents (established actors in the aviation industry) and new entrants (either start-ups or actors attracted from other systems). The research aimed to design policy instruments to better integrate these actors, fostering innovation. This study determined that an actor-oriented TIS approach, that differentiates between actors, benefits TIS research in certain cases. This approach has a solid foundation, but additional research is essential to fully realise its potential.

The research was conducted in four steps. First, a technological review identified distinct TISs for SEC, based on current literature and informal interviews with policy officers. This newfound analytical step examined activities and technologies in six separate value chains for SEC. It provided a useful overview of technologies, to scope a TIS analysis and understand how TISs are connected. The remainder of the research focused on hydrogen aircraft, which was identified as needing the most substantial innovation.

Second, a structural analysis identified twenty-one actors, by reviewing documents and thematically analysing fifteen 60-minute interviews with actors. It concluded that incumbents and new entrants contribute differently to the TIS, as they share different characteristics and perform different activities. These results partially support previous actor-oriented TIS research.

Third, a functional-structural analysis determined that the weakest systemic functions of hydrogen aircraft are guidance of the search, market formation, and mobilisation of resources. The findings confirmed that incumbents and new entrants experience distinctive drivers and barriers. This affected new entrants more than incumbents. However, most drivers and barriers were experienced by both actors.

Fourth, seven policy instruments were designed to improve the weakest systemic functions and address barriers experienced by incumbents and new entrants. This involved a tentative approach to establish a policy instrument toolbox, based on current literature.

IenW is advised to use these instruments to integrate specific actors into their innovation policy. Moreover, policy officers at IenW are recommended to utilise the insights each research step has provided to advance overall policy performance.

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Executive summary

The Dutch aviation industry accounts for approximately six percent of the country's CO_2 emissions and must decarbonise to help meet the global target of achieving net zero emissions in 2050. However, since incremental innovation cannot significantly reduce aviation emissions, there is a pressing need for radical technological innovation. Most CO_2 emissions can be reduced using sustainable energy carriers (SEC), which focus on three focal technologies: sustainable aviation fuels (SAF), electric aircraft, and hydrogen aircraft.

Technological innovation of these SEC takes place in systems, where actors and other components drive or delay the innovation process and determine the functioning of the system. One way to research this Technological Innovation System (TIS) is by studying what drivers and barriers are experienced by actors. This research studied two types of actors: incumbents that are established organisations in the aviation industry, and new entrants that are either start-ups or have been attracted to the industry from other systems. These actors are supported by innovation policies provided by the Ministry of Infrastructure and Water Management (IenW). IenW has set targets to reduce the CO_2 emissions of aviation and needs to support industry actors with policy instruments to achieve them.

Therefore, the key research question in this thesis is: *How can the Ministry of Infrastructure and Water Management integrate specific actors into their innovation policy for sustainable energy carriers in the aviation industry?* This question is researched through four sub-questions and subsequent research steps. First, a technological review identified distinct TISs for sustainable energy carriers and prioritised one for further research. This involved the collection and review of literature and informal interviews with policy officers at IenW. Second, actors within this TIS are identified and their contributions are assessed. To address this, an explorative search for actors was conducted, followed by fifteen 60-minute interviews with actors. Third, drivers and barriers to innovation experienced by these actors are determined, by further analysing the data collected in these interviews. Fourth, innovation policy instruments are designed through a literature review. These four steps outline the results and conclusions of this thesis.

Results and conclusions:

For sustainable energy carriers, what distinct TISs can be identified and which should be prioritised?
Six technological value chains for SEC could be identified, that are connected by some activities. SAF can either be bio-based or produced as synthetic SAF, by combining hydrogen and carbon. Both value chains require the most innovative development in their production methods. Hydrogen can either be combusted or consumed by fuel cells to power electric engines. These value chains require innovative production methods, as well as solutions for transport, distribution, and storage. Within the aircraft, new systems need to be developed to account for the additional weight, volume, and cooling of hydrogen. The final two value chains, for electric- and hybrid aircraft, require solutions to net congestion and infrastructure to store and supply electricity. The aircraft itself requires significant efficiency improvements. Furthermore, these value chains are connected, which indicates opportunities to develop products and systems that benefit multiple SEC. Based on this analysis, hydrogen aircraft should be prioritised due to its need for substantial innovation. Moreover, this TIS is well connected to other TISs and public-private collaborations are in place to develop hydrogen demonstrators.

For hydrogen aircraft, what specific actors can be identified and what are their contributions to the TIS?
The research identified twenty-one stakeholders, that contribute to the TIS of hydrogen aircraft in various ways. Half of the interviewed actors were incumbents. These are usually medium to large organisations and are more focused on supporting activities such as knowledge creation and ecosystem development. The other half, new entrants, are usually small organisations. They position themselves more often at the start or end of the supply chain and leverage experience from other industries. Both types of actors operate in a political context that influences their activities. This context is formed by four governmental institutions and provides regulatory oversight, financial support, and opportunities for collaboration.

For hydrogen aircraft, what are the drivers and barriers experienced by incumbents and new entrants?
The performance of a TIS can be measured by seven indicators, called systemic functions (SF). These include: Entrepreneurial activities (SF1), knowledge development (SF2), knowledge diffusion through networks (SF3), guidance of the search (SF4), market formation (SF5), mobilisation of resources (SF6), and creation of legitimacy (SF7). For each systemic function, drivers and barriers effect actors operating in the system. The analysis concluded that in general, SF2 and SF1 are the strongest-performing systemic functions, while SF4, SF5, and SF6 are most limited by barriers.

Distinct drivers and barriers for either incumbents or new entrants position them better or worse in the innovation system. Incumbents have unique drivers in entrepreneurial activities (SF1), knowledge diffusion (SF3), and legitimisation (SF7), mainly due to (international) collaborations in private consortia and with OEMs. Barriers for incumbents include limitations to international collaborations, affecting knowledge diffusion (SF3). As well as policy-influence, continuity, and consistency affecting activities (SF1) and guidance (SF4). Overall, incumbents benefit from these drivers, although they are adversely affected by policies. New entrants experience fewer unique drivers. Activities (SF1) and industrial legitimacy (SF7) are supported by their experience from other industries to develop technologies, driven by sustainable efforts. This experience enhances knowledge diffusion (SF3). Knowledge is

developed (SF2) by education programmes. Yet, new entrants struggle to utilise and influence existing policy. Limiting activities (SF1), knowledge diffusion (SF3), and guidance (SF4). Overall, they have limited access to financial resources and capacity (SF6) due to their size. Generally, new entrants are most restricted by policy integration and their limited size and are more affected by barriers than incumbents.

However, most drivers and barriers affected both types of actors, including three common barriers that concerned multiple systemic functions. These are the highly aviation-specific requirements for design and safety that affect the development and costs of hydrogen aircraft. As well as the long development times and lengthy returns on investments that create uncertainty. Finally, existing policy affects multiple functions through misalignment of policy, limited capabilities in policy designs, and limited direction. Addressing these is effective in improving multiple functions at once, including the weakest functions guidance of the search (SF4), market formation (SF5), and the mobilisation of resources (SF6).

For hydrogen aircraft, what policy instruments can effectively address and remove identified barriers?
Seven policy instruments can enable the three weakest functions to improve and target the main barriers for incumbents and new entrants. Guidance of the search (SF4) can be improved by technology standards, a roadmap, and policy evaluation procedures. Technology standards will reduce technical challenges and uncertainty of aviation-specific requirements. A roadmap will help to improve the continuity and consistency of policy for incumbents. This roadmap should consist of short-term targets and milestones to create assurance. Policy evaluation procedures allow new entrants to reach policy officers and ensure their representation. Evaluation procedures include a regular assessment of policy to determine if they support the desired actors. Market formation (SF5) can be strengthened with market-based scenarios and a roadmap. Market-based scenarios should be developed to reduce uncertainties limiting market formation. These scenarios aim to inform actors on the development of demand and costs. As well as to provide information on the return on investment. The roadmap designed for SF4 can also assure incumbents of the formation of the market. The mobilisation of resources (SF6) can be improved by loans and guarantees for innovative projects, grid access guarantee, and funds, loans, and subsidies. Loans and guarantees for innovative projects should improve the attraction of financial resources, as it reduces risks to attract investors. Grid access guarantee can assure the future availability of hydrogen. This regulating measure reduces the risks by ensuring access to resources. Finally, funds, loans, and subsidies should be extended to support new entrants to gain access to resources, as they were not always eligible for projects. Overall, these seven instruments can remove or reduce the effects of barriers limiting the innovative contributions of actors, by extending current policies and implementing new policy instruments.

Recommendations:
In summary, the Ministry of Infrastructure and Water Management (IenW) is advised to integrate specific actors into their innovation policy by addressing their barriers through the recommended seven policy instruments. These support the development of the weakest functions of the innovation system of hydrogen aircraft. Moreover, incumbents and new entrants identified by this research will be assisted in overcoming their distinct barriers through actor-focused policies.

The policy officers at IenW are also advised to utilise the insights each research step has provided. The technological assessment of different sustainable energy carriers (SEC) will allow policy officers to support multiple SEC at once. Likewise, drivers and barriers experienced in the hydrogen aircraft TIS may also be recognised in other TISs. Additionally, the identification of actors can be utilised in stakeholder management. Finally, the TIS framework can enable policy officers to verify if actors and the innovation system are supported by policy. This is possible by checking which functions are supported by a new or changed policy instrument. In conclusion, these recommendations will not only enhance the integration of both incumbents and new entrants into policy for hydrogen aircraft, but allow policy officers at IenW to leverage this research to advance overall policy performance.

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Terminology

Abbreviation:	Stands for:	Definition:
DLT	Sustainable Aviation Roundtable (Duurzame Luchtvaarttafel)	A public-private collaboration between industry organisations, government, and knowledge institutes.
EZ	Ministry of Economic Affairs (Ministerie van Economische Zaken)	A governmental organisation that addresses all matters relevant to economic affairs.
IenW	Ministry of Infrastructure and Water Management (Ministerie van Infrastructuur en Waterstaat)	A governmental organisation that addresses all matters relevant to infrastructure and water management.
ILT	Human Environment and Transport Inspectorate (Inspectie Leefomgeving en Transport)	An inspectorate of IenW. They regulate commercial and recreational aviation with authorisation and monitoring.
LiT	Aviation in Transition (Luchtvaart in Transitie)	A public-private programme that encompasses twelve projects with the objective of accelerating the progress of sustainable aviation.
NGF	National Growth Fund (Nationaal Groeifonds)	An investment fund to strengthen a sustainable earning potential by subsidising programmes.
OEM	Original Equipment Manufacturer	An organisation that manufacturers the aircraft. Assembled with products and systems from different tiers of suppliers.
RVO	Netherlands Enterprise Agency (Rijksdienst voor Ondernemend Nederland)	A government agency of EZ that directly stimulates entrepreneurship. They facilitate several subsidy instruments.
SAF	Sustainable Aviation Fuel	Type of aviation fuel that is considered to emit less carbon emissions during its lifetime.
SEC	Sustainable Energy Carrier	Term that encompasses several types of energy carriers that are more sustainable options to power an aircraft. The focal technologies include SAF, hydrogen and electricity.
TRL	Technological Readiness Level	Standardised method to determine the maturity of a technology. Ranges from TRL1 (basic principles) to TRL9 (operational).

1. Introduction

In 2015, by signing the Paris Agreement, 195 Parties including the European Union committed to reducing global greenhouse gas emissions to limit global temperature warming to well below 2°C degrees (United Nations, n.d.). By 2050, emissions should be net zero which implies that global emissions are balanced with removal or offsets to achieve no net increase. In 2018, passenger and freight aircraft accounted for 2.4% of global CO_2 emissions (Graver et al., 2019). Specifically, the Dutch aviation industry is, with 12 megatons in 2017, responsible for around 6% of the total Dutch CO_2 emissions (Uitbeijerse, 2020). It is therefore of importance to decarbonise. However, global emissions from the aviation industry are expected to increase as incremental innovation is unable to reduce emissions significantly (ICAO, 2019; Ministerie van Infrastructuur en Waterstaat, 2020a). Decarbonisation requires industries to transform using innovative technologies. Yet, the aviation sector is slow to change as the development of engines and other technical aspects are usually more incremental and take years to develop. Therefore, there is a pressing need to develop radical innovation.

§1.1 Problem introduction

Innovative development of new technologies can lead to more efficient use of resources and less stress on the environment (Hekkert et al., 2007). Innovation occurs through interconnected systems, and system characteristics can drive or delay the innovation process and should be controlled. Understanding how innovation systems function is therefore crucial to overcoming barriers and influencing the speed and direction of innovation. Hekkert et al. (2007) offer a framework for Technical Innovation Systems (TIS) to understand these functions.

This framework is relevant for sustainable aviation, which encompasses four technological innovation areas: aircraft design, sustainable energy carriers, airspace, and airports (ICAO, 2019; Ministerie van Infrastructuur en Waterstaat, 2023). CO_2 emissions can be reduced through each of these four innovation areas by for instance decreased wind drag (aircraft design), bio-based fuels (sustainable energy carriers), efficient flight routes (airspace), and electric ground operations (airports). However, most CO_2 emissions can be reduced through sustainable energy carriers, as current fossil fuels cause the most emissions. For sustainable energy carriers, three focal technologies are electricity, hydrogen, and Sustainable Aviation Fuels (SAF), each forming a TIS.

The technologies within these TISs are being developed by organisations within the aviation manufacturing industry, referred to as actors. These actors are either established organisations within the aviation industry (incumbents) or actors that have entered the industry (new entrants). These new entrants are start-ups, or are attracted from other TISs such as the fossil fuel- or automotive industry to develop TISs around sustainable aviation. By attracting actors, a TIS interacts with other TISs.

TIS interactions with other systems outside of the original technological domain should be identified by recognizing the context in which the TIS operates. This is described as TIS in context (Bergek et al., 2015), and it is important to understand if a TIS can be further developed by attracting new entrants from similar technological domains. However, research on contextual structures has been limited and has not been conducted for sustainable aviation. Nonetheless, scholars argue that the emergence of a new TIS influences other industries within its context (Markard, 2020; Ulmanen & Bergek, 2021). This research seeks to contribute to this literature gap by investigating actors previously operating in the surrounding context of the TISs for sustainable energy carriers and creating an understanding of the conditions to become active within the new TIS.

To enhance the innovative performance of the TISs of sustainable energy carriers, support is extended to actors through innovation policy. However, existing policy measures are deemed insufficient, necessitating a shift in policies to more effectively facilitate innovation (Gössling & Lyle, 2021). For instance, sustainable energy carriers face barriers such as increased costs, consequently warranting policy intervention (Larsson et al., 2019). Furthermore, current policy instruments are designed for incumbent actors and technologies, causing barriers to innovation (Foxon & Pearson, 2008). Therefore, there is a need to improve the current innovation policy to better facilitate actors.

§1.2 The case of Dutch Sustainable Aviation policy

National and international governmental organisations provide innovation policies and encounter the challenge of developing suitable policies for these actors. As previously stated, the Dutch aviation industry faces a significant challenge with a relatively high national share of CO_2 emissions. This is of concern to the Ministry of Infrastructure and Water Management (IenW), accountable for sustainable aviation policy in the Netherlands. In response, IenW developed the *Luchtvaartnota* and *Innovatiestrategie* (Ministerie van Infrastructuur en Waterstaat, 2020a, 2023). These documents have set targets for decarbonisation (Table 1), with the end goal of zero CO_2 emissions from aviation by 2070. In contrast, the annual CO_2 emissions were 4.6Mt in 1990, and 10.9Mt in 2005 (Uitbeijerse, 2020). Sustainability is one of four themes to innovate on, outlined in these documents. Flying more sustainably using sustainable energy carriers is expected to have the most impact in terms of CO_2 reductions (Ministerie van Infrastructuur en Waterstaat, 2020a).

Target	2030	2050	2070
Ground operations of civil aviation	CO_2 emissions are to be reduced by 100%		
Domestic civil aviation	CO_2 emissions are to be reduced by 15% to the emissions in 1990	CO_2 emissions are to be reduced by 100%	
International flights departing from the Netherlands	CO_2 emissions should be reduced to the emissions in 2005	CO_2 emissions should be halved to the emissions in 2005	CO_2 emissions are to be reduced by 100%

Table 1: Targets sustainable aviation (Ministerie van Infrastructuur en Waterstaat, 2020a)

By 2050, the Dutch Aviation industry should use a mix of different sustainable energy carriers for aircraft. These are Sustainable Aviation Fuels, electricity, and hydrogen. Each energy carrier serves a different strategic purpose in the short- and long-term, or flight distance. Sustainable Aviation Fuels (SAF) refers to two types of kerosine made from either biomass or synthetics. SAF can be blended in with fuels, replacing fossil fuels. SAF is applicable in the short-term for long-distance flights. However, the technologies of several production methods need to be further developed (Neuling & Kaltschmitt, 2018). Hydrogen can be applied to generate electricity during the flight with fuel cells, or fuel the aircraft's engines directly through hydrogen combustion (Ministerie van Infrastructuur en Waterstaat, 2023). The first hydrogen planes, with limited capacity and for flights up to 2.000km, are expected to enter the market around 2035 (Ministerie van Infrastructuur en Waterstaat, 2023). Hydrogen is the lightest element, which brings technological challenges for developing aircraft systems and infrastructure (Adler & Martins, 2023). Electric aircraft are expected to be suitable for short-distance flights up to 500km. Current ambitions are to use the first electric-hybrid planes with 20-50 passengers by 2030. By 2050, all short-distance flights should be fully electric (Ministerie van Infrastructuur en Waterstaat, 2020b). However, technologies for electric aircraft are not sufficiently developed. For instance, the energy density should be increased to make them economically viable (To70 & Unified International, 2023). Thus, for each TIS within sustainable energy carriers, there are technological challenges to be overcome to achieve the policy targets. To achieve these decarbonisation targets, IenW therefore needs to support industry actors with innovation policy.

§1.2 Research questions

The research aims to solve the defined innovation policy problem by first creating a technological contextual understanding of the different Technological Innovation Systems for sustainable energy carriers, highlighting technological challenges for each TIS. The TIS for hydrogen aircraft is selected as a case study for further investigation. Next, specific actors (incumbents and new entrants) active within this TIS are identified. Then, drivers and barriers to innovation for each type of actors are determined. Subsequently, innovation policy instruments for IenW are designed to overcome barriers with policy. Ultimately, this will allow IenW to enable actors to contribute to the development of necessary technologies for sustainable energy carriers, supporting the decarbonisation the Dutch aviation industry. Therefore, the key research question in this thesis is:

> *RQ: How can the Ministry of Infrastructure and Water Management integrate specific actors into their innovation policy for sustainable energy carriers in the aviation industry?*

This question is researched through four sub-questions, delineating the study into distinct steps:

> *SQ1: For sustainable energy carriers, what distinct Technical Innovation Systems can be identified and should be prioritised?*
> *SQ2: Within a selected TIS, what specific actors can be identified and what are their contributions to the innovation performance of the TIS?*
> *SQ3: Within a selected TIS, what are drivers and barriers to innovation experienced by incumbents and new entrants?*
> *SQ4: What innovation policy instruments can effectively address identified barriers, fostering innovation within the selected TIS?*

SQ1 provides a technological understanding of distinct TISs for sustainable energy carriers by identifying the state of different technologies across the value chain and analysing the interconnections between the TISs. This value chain is constructed through a combination of literature and interviews. By prioritising one TIS, a strategic focus can be established for the most impactful TIS, thereby maximising its potential impact. SQ2 identifies incumbents and new entrants within one TIS and assesses their contributions. This is done by mapping the actors through an exploratory search and identifying contributions from interviews. SQ3 assesses the functional performance of the TIS, by establishing distinct drivers and barriers to innovation faced by the two types of actors. This is accomplished by acquiring information from interviews with relevant actors and applying literature. SQ4 addresses the identified barriers by designing innovation policy instruments with which the innovation performance of the TIS can be improved. Policy instruments are identified from literature. Together, these sub-questions build a comprehensive understanding to allow the integration of specific actors into innovation policy.

§1.3 Relevance

With these research steps, the study contributes to current TIS-related literature. Studying the functional performance of the TIS from an actor-oriented perspective extends current literature which has been limited in its focus on actors (Planko et al., 2017). Additionally, the study distinguishes between incumbents and new entrants to determine if current TIS literature can benefit from this differentiated approach to the functional performance of actors when formulating effective policies. Furthermore, a complete overview of the value chains for sustainable energy carriers is established, extending existing literature. By reviewing this technological context, it can be determined how different TISs are connected and if policy can affect multiple TISs. Due to time constraints, this paper cannot provide a comprehensive analysis of all three TISs related to sustainable energy carriers. However, the methodological approach to researching one TIS offers a framework for further research on other TISs.

By designing policy instruments for specific actors and systemic functions, this study allows actors to be better integrated into current policies. This extends current knowledge on TIS-derived policy and enables actors to contribute to the TIS. Moreover, by offering insights into the policy needs of incumbents and new entrants, it can be determined if current policy instruments indeed support or hinder the development of the TIS (Foxon & Pearson, 2008). Finally, with sustainable energy carriers, the study targets the most carbon-heavy innovation area of sustainable aviation. The three focal technologies for sustainable energy carriers are not only used in the aviation industry but are also being developed for various modes of transport including road, rail, and maritime transport (Ministerie van Infrastructuur en Waterstaat, 2020b). Thus, developing innovation policies for a sustainable energy carrier in aviation can be important to target decarbonisation in other industries as well.

2. Theory

The main theory to be applied is the Technical Innovation Systems framework. TIS concepts to be introduced are structural elements, a functional-structural analysis, policy instruments, contextual structures, and actor-oriented TIS. These concepts will be applied to frame the research and interpret results.

§2.1 Technical Innovation Systems framework

2.1.1 TIS structural elements

From a structural perspective, TISs consist of four elements: actors, institutions, interactions, and infrastructure (Wieczorek & Hekkert, 2012). In some literature, the latter are combined and defined as networks. Actors can be categorised in various manners. In this research, they are defined by their role in the economic activity: civil society, government, NGOs, companies, multinationals, knowledge institutes, and other parties such as intermediaries (Wieczorek & Hekkert, 2012). Institutions are existing rules, norms and strategies created through habits, routines, and shared concepts (Crawford & Ostrom, 1995; Wieczorek & Hekkert, 2012). Interactions occur between actors within a network, or between individual contacts. Finally, infrastructure can be categorised in different ways, but this research takes the approach from Wieczorek & Hekkert (2012): physical (instruments, buildings etc.), knowledge (expertise, strategic information, etc.) and financial (subsidies, grants, etc.) infrastructure. By understanding these structural elements, a TIS can be thoroughly mapped providing an overview of the system's components. However, functional components need to be understood as well to provide insights into the functioning of a system.

2.1.2 TIS Functional–structural analysis

The innovation process can be categorised in terms of functions which describe an innovation system's performance (Wieczorek & Hekkert, 2012). Hekkert et al. (2007) distinguish seven systemic functions that positively or negatively affect the innovation system's performance. Table 2 contains an overview of these functions, their definitions and examples of how they can be mapped (Bergek et al., 2008; Hekkert et al., 2007).

Table 2: Systemic functions (SF) of Technical Innovation Systems

Systemic function:	Definition:	Examples of mapping this function:
Entrepreneurial activities (SF1)	Entrepreneurs perform activities to turn the potential of new knowledge, networks, and markets into concrete actions.	New entrants, diversification activities of incumbent actors, and experiments with the new technology.
Knowledge development (SF2)	Knowledge needs to be developed and facilitate learning by searching or doing.	R&D projects, patents, and investments in R&D.
Knowledge diffusion through networks (SF3)	Knowledge is diffused through network activity between different actors.	Workshops, conferences, network size and intensity over time.
Guidance of the search (SF4)	When various technological options exist and resources are limited, selection guides the development of a TIS.	Specific targets set by governments or industries, articles in professional journals, and the number of positive or negative articles regarding new technology developments.
Market formation (SF5)	Market conditions influence the development of a new niche market related to the technology.	Niche markets, specific tax regimes for new technologies, and new environmental standards that improve the technologies' chances.
Mobilisation of resources (SF6)	Resources are a necessary input to an innovation system's activities, determined by the access to resources.	Detect through interviews whether core actors perceive access to sufficient resources as problematic.
Creation of legitimacy (SF7)	Legitimacy is necessary for a new technology to function and develop over time.	Rise and growth of interest groups and their lobby actors.

According to Wieczorek & Hekkert (2012), a system's performance can be examined through a perspective of structural elements on the seven functions. Therefore, the functions and structural elements are closely related, and should both be examined to determine why a system performs as it does, and how the performance can be influenced. This coupled functional-structural analysis identifies drivers and barriers to innovation, which respectively positively and negatively influence the functioning of a TIS.

2.1.3 Technical Innovation System in Context

To better understand drivers and barriers, it is relevant to understand the context a TIS operates in. A TIS can be affected by other systems, through interactions with other systems, and influences from the landscape surrounding a technology (Bergek et al., 2008). These can be external links that influence a TIS but are not affected by internal processes from a TIS. Alternatively, they can be structural couplings, shared elements between a TIS and specific context structures (Bergek et al., 2015). Structural couplings arise when an element (e.g., an actor) operates in different contexts (e.g., different markets). Each context structure influences decision-making and affects different TISs. Bergek et al. (2015) identify four types of context structures: technological, sectorial, geographical, and political.

Table 3: Types of contextual structures (Bergek et al., 2015)

Type of contextual structure	Definition	Example of influence
Technological	Surrounding and related Technological Innovation Systems that influence the focal TIS.	Competition between similar technologies
Sectorial and geographical	Pre-existing infrastructures and institutions that an emerging technology must embed.	Different sectors of national contexts.
Political	Interactions with political systems	Political support for specific policies.

The contextual structures listed in Table 3 are relevant to understand what influences the performance of a TIS. As well as to understand what drives or prevents actors from other technologies or sectors to develop sustainable energy carriers.

2.1.4 Identifying policy instruments

Whilst drivers are advantageous in developing a TIS, barriers to the functioning of a TIS should be overcome. Through governance, this is possible using policy instruments. Policy instruments are implemented by governmental organisations and are necessary to advance technological development (Mickwitz et al., 2008). Policy instruments can target affecting the functioning of entire innovation systems (Wieczorek & Hekkert, 2012). In addition, they can be designed to target specific systemic functions (Kivimaa & Virkamäki, 2014). The research on policy instruments' impact on TIS functions has been limited (Reichardt et al., 2016).

To identify suitable policy instruments, the toolbox in Table 4 combines existing literature on policy instruments. Kivimaa & Virkamäki (2014) propose a framework that suggests policy instruments for specific functions. As this framework is built on a different set of systemic functions, it was adapted to fit the seven systemic functions by Hekkert et al. (2007). Likewise, Wieczorek & Hekkert (2012) list policy instruments that relate to the presence and quality of different systemic components. Instruments were selected and categorised into systemic functions. Finally, Rogge & Reichardt (2016) suggest instruments categorised in economic, regulating, or informative types. These were furthermore adapted for the toolbox to fit the systemic functions. This toolbox can be used to select suitable policy instruments for a specific systemic function.

Table 4: Policy instrument toolbox

Systemic function:	Kivimaa & Virkamäki (2014)	Wieczorek & Hekkert (2012)	Rogge & Reichardt (2016)
Entrepreneurial activities (SF1)	Policies stimulating new entrepreneurship and diversification of existing firms	Public-private partnerships, interactive stakeholder involvement, demonstration centres	Professional training and qualification, entrepreneurship training, training on new technologies
Knowledge development (SF2)	R&D funding schemes, educational policies, informational instruments	R&D Grants, loans/guarantees incentives for innovative projects, scientific workshops, training programmes, educational campaigns, public research labs	R&D Grants, professional training and qualification, scientific workshops, education system, cooperative R&D programs
Knowledge diffusion through networks (SF3)	R&D funding schemes, educational policies, informational instruments	Knowledge transfer mechanisms, thematic meetings, consultancy services	Thematic meetings, cooperative R&D programs
Guidance of the search (SF4)	Targets set in strategies, regulations, tax incentives, foresight exercises	Regulations, roadmaps, standards	Technology standards
Market formation (SF5)	Regulation-induced niche markets, tax exemptions, market-based policy instruments, public procurement, demand-side management,	Roadmaps, taxes, loans/guarantees incentives for innovative projects, regulations, agreements, scenarios, technology promotion programmes	Market design, environmental liability law
Mobilisation of resources (SF6)	Subsidies, educational policies, secondment of expertise	Grants, funds, loans, subsidies, loans/guarantees incentives for innovative projects, education campaigns	Grants, loans, tax incentives, state equity assistance, subsidies, feed-in tariffs taxes, grid access guarantee
Creation of legitimacy (SF7)	Problem and justification framing in policies, creating legitimacy, public participation	Regulations, norms, agreements, standards, prizes, technology promotion programmes, policy monitoring and evaluation, public debates, information campaigns	Public debates, public information campaigns, environmental liability law

These policy instruments should have three elements to be effective: a goal, type, and design features (Rogge & Reichardt, 2016). A goal describes the intended effect of the instrument and its contribution to general policy targets. The type indicates if the instrument is economic, regulating, or informative (Reichardt et al., 2016; Rogge & Reichardt, 2016). Finally, the design features incorporate several features such as the flexibility, level of support, and stringency of an instrument, although there is no standard list of features (Rogge & Reichardt, 2016). Incorporating these three elements ensures the design of a valid policy instrument.

§2.2 An actor-oriented perspective to TIS

By adopting the perspective of structural components, such as actors, a TIS can be analysed (Wieczorek & Hekkert, 2012). In recent years, there has been an increase in literature that has adopted an actor-oriented perspective on TIS (Gruenhagen et al., 2022; Jansma et al., 2018; Planko et al., 2017). Overall, three findings of these studies are relevant contributions to the theoretical framework. First, all three papers confirmed that TIS functions are suitable for analysing an actor's contributions to a system. Second, several functions could be interpreted differently by adopting an actor's perspective and a distinct difference could be found between governments and other actors (Planko et al., 2017). Third, one actor's drivers and barriers can relate to several functions (Gruenhagen et al., 2022). These findings in current literature confirm the relevance of the actor-oriented analysis of TIS and provide direction for interpreting the results.

However, existing TIS-related literature has not differentiated between certain types of actors, namely incumbents (actors with experience in a sector) and new entrants (actors attracted from other industries and start-ups founded within the TIS). This actor-oriented approach extends the theoretical framework by specifying the structural component of actors. With this, the functional-structural analysis can differentiate barriers and drivers for specific types of actors. Furthermore, these barriers can be better understood by a more specified view of the context that actors operate in or derive from. Finally, policy instruments can be designed to overcome these specific barriers. Thus, the established theoretical framework can both be leveraged and extended by a more specified approach to an actor-oriented TIS analysis.

3. Methodology

This study employs a qualitative research design to provide insights into specific actors. The research follows a single case study approach of hydrogen aircraft, which allows for a more in-depth exploration of the Dutch aircraft manufacturing industry (Clark et al., 2021). The focus on hydrogen aircraft was determined by defining the different TISs of sustainable energy carriers. The use of qualitative case studies to approach an actor-oriented TIS analysis is well-established in the literature (Gruenhagen et al., 2022; Planko et al., 2017). Being actor-oriented, the unit of analysis are individual actors contributing to the TISs. These are embedded units of analysis since they focus on a specific group of actors within a larger context (Clark et al., 2021). By approaching the TIS from an actor's micro-level, rather than a conventional meso-level, a more detailed understanding of an individual's contribution to the innovation system can be established. This includes identifying barriers and policy requirements. Furthermore, a meso-level perspective risks neglecting the role of certain actors (Gruenhagen et al., 2022). Finally, the research takes an inductive approach as the case-specific empirical data will extend the theory on designing innovation policy for specific actors. For these reasons, a qualitative case study approach is a suitable method to study this actor-oriented TIS.

Four research steps are undertaken to answer the research question, each focused on a specific sub-question (Figure 1). Concepts from the theoretical framework are incorporated in these steps. The first step is a technological review, to define distinct technologies within the TISs of sustainable energy carriers and the interconnections between them. The review incorporates a value chain, to highlight different technologies utilised across various activities. This is a novel research step in current TIS theory, added to this research to incorporate the contextual understanding of different technologies and how they are related. The remaining three steps are a modification of a five-step systemic innovation policy framework by Wieczorek & Hekkert (2012). This framework derives at policy instruments based on mapping structural elements and a functional-structural analysis. These steps are adapted to align them with an actor-oriented framework. Two steps of this original framework are excluded, which identify systemic problems and goals. Instead, this research adopted an approach that determines policy instruments for specific functions, rather than full systems. This has the added value of directing policy instruments at specific barriers that actors experience within a function. Each step requires a specific form of data collection. Collected data is then reviewed to identify key findings within the existing body of knowledge or analysed to interpret data.

Research Question						
Sub-question:	1: Define distinct TIS and interconnections		2: Identify specific actors and contributions		3: Identify drivers and barriers	4: Design innovation policy
Research steps:	Review of TIS technologies throughout the value chain		Mapping actors as structural elements		Functional-structural analysis on actors	Instrument design for actor-centric policy
Data collection:	Literature collection	Informal interviews	Document collection	Semi-Structured interviews	Semi-structured interviews	Literature collection
Data review and analysis:	Literature review	Record review	Document analysis	Thematic analysis	Thematic analysis	Literature review

Figure 1: Research design

§3.1 Data collection

SQ1 defines technologies within the different TISs for sustainable energy carriers using a value chain. Data is collected from literature and informal interviews with policy officers on sustainable aviation. Two types of data collection are used to triangulate the results and improve reliability and validity. To identify literature, queries designed for Google Scholar advanced search were applied, included in Appendix I. Additional literature was explored to complete the value chains. The informal interviews were conducted with nearly twenty members of the department of Sustainable Aviation, listed in Appendix I. These aimed to increase the understanding of the technologies, existing policies and current state of affairs within the industry. Often, (internal) policy documents were recommended and reviewed. After each interview, a record was created to consult for the technological review in SQ1. In addition, these records were utilised to construct an existing policy overview and increase the political contextual understanding.

SQ2 targets the identification of specific actors and their contributions to the TIS. SQ2 focused on the TIS for hydrogen application, as the analysis of SQ1 indicated this is most relevant for further research.
The population of relevant actors was determined by an exploratory search for actors using documents. This search followed several steps, described in the sampling strategy. The resulting list included both incumbents and new entrants and represents the population. To assess actors' contributions to the TIS, semi-structured interviews were conducted with a representative sample of actors. In semi-structured interviews, the researcher uses a list of guiding open-ended questions (Clark et al., 2021). This has the benefit of methodically formulating predetermined questions, thereby ensuring coverage of all topics, whilst retaining the flexibility to ask additional questions not listed in the interview guide. Fifteen interviews were conducted, with an average length of sixty minutes.

SQ3 assesses drivers and barriers through a functional-structural analysis of actors. Moreover, it differentiates between incumbents and new entrants. The semi-structured interviews are used to collect data on the drivers and barriers to innovation.

Finally, SQ4 designs policy instruments to recommend actor-centric policy. Literature is collected for the identification of policy instruments. This literature was sourced from academic papers and is incorporated into the theoretical framework in chapter two.

§3.2 Sampling strategy

The population of twenty-one actors is determined through the steps outlined in Figure 2. First, the Kamer van Koophandel (KVK) Business Register was consulted, which lists organisations that participate in economic transactions in the Netherlands (KVK, 2024). For this, relevant Standard Business Categories (SBI codes) were selected to identify organisations active in the Dutch aircraft manufacturing industry. Thirteen SBI codes were considered and three were further examined; 3030 manufacture of aircraft and components, 3040 manufacture of military fighting vehicles, 3316 repair and maintenance of airplanes. Second, additional websites that register company information were consulted to extend the list (Bedrijvenregister, 2024; Company.info, 2024). Each company's information was examined and relevant actors were chosen based on the following characteristics: 1) They are publicly active in the development of products and systems needed for hydrogen aircraft. 2) They have an office and/or production facility within the Netherlands. Fourth, the list was verified and extended by Peter Kortbeek from the industry organisation NAG, responsible for ecosystem identification. During the interviews, snowball sampling was used to ask respondents for additional contacts. This yielded no additional results but verified the existing list.

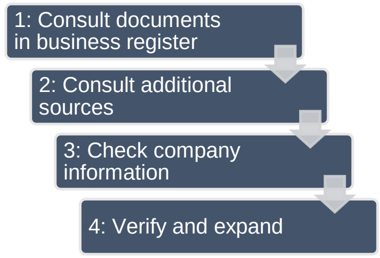

Figure 2: Steps in actor identification

The population was sampled, as there was insufficient time to interview all twenty-one actors. Therefore, the sampling ensures an adequate representation of a type of actor, type of activity, size, and main activity. As a result, some organisations that represented similar products such as composites were excluded after one interview had been secured. This method of sampling is known as maximum variation purposive sampling. It involves splitting up the population based on chosen characteristics (Clark et al., 2021). This is favourable as respondents are strategically chosen with the expectation that they provide new insights. Table 5 provides an overview of actors, those listed in bold have been interviewed.

Table 5: Organisations active with hydrogen in the Dutch aircraft manufacturing industry

Organisation	Type of actor	Type of activity	Size	Main activity	Contact	Function
ADSE	Incumbent	Intermediary	Medium	Consulting aircraft systems	Jan Verbeek	Senior Business Consultant Industrial Production Management
AeroDelft	New entrant	OEM	Small	Hydrogen aircraft	Hubert Blije	Team Manager AeroDelft
Aeronamic	Incumbent	Tier 2	Medium	Fuel cell propulsion system, Air Cycling System	Sido Kermans	Chief Technology Officer
Circonica	New entrant	Tier 3	Small	Fuel cells	Diederik Jaspers	Chief Technology Officer
Conscious Aerospace	New entrant	Tier 1	Small	Hydrogen aircraft system integrator	Bartjan Rietdijk	Engineering Lead
Fokker Next Gen	New entrant	OEM	Small	Hydrogen aircraft	Juriaan Kellerman	Chief Executive Officer

Fokker Services	Incumbent	Intermediary	Large	Consulting aircraft systems	Wilhem van Citters	Program Manager PMO
GKN Fokker	Incumbent	Tier 1	Large	Electrical systems and airframe	Arnt Offringa	Director Global Tech Center NL – Civil Airframe
					Johnny van Lugtenburg	Head of Technology – Electrical Systems
NAG	Incumbent	Intermediary	Medium	Ecosystem development	Peter Kortbeek	Manager Ecosystem and Valorisation
NLR	Incumbent	Knowledge Institute	Large	Knowledge development	Jan Terlingen	Business Developer Civil Aviation Industry
Saluqi Motors	New entrant	Tier 2	Small	Electric motors	Maarten Klomp	Chief Technology Officer
Toray Composites	New entrant	Tier 3	Large	Composites	Marc Huisman & Alberto Lario Cabello	Director R&D. Chief EU Tech. Center & Project Manager - Liquid Hydrogen Composites Technology
TU Delft	Incumbent	Knowledge Institute	Large	Knowledge development	Ingrid Houthuysen	Manager Strategic Partnerships Aerospace
Zepp Solutions	New entrant	Tier 2	Small	Hydrogen fuel cell systems	Antonio Scorccimarro	R&D Engineer Aerospace
Aerospace Innovation Hub	New entrant	Intermediary	Small	Ecosystem development		
Cryoworld	New entrant	Tier 2	Small	Cooling systems		
Futura Composites	New entrant	Tier 2	Medium	Composites		
Somni	New entrant	Tier 3	Small	Sensors		
Tejin Amrad	New entrant	Tier 3	Medium	Composites		
TNO	Incumbent	Knowledge Institute	Large	Knowledge development		
Xensor	New entrant	Tier 3	Small	Sensors		

The interviewed organisations cover a complete variety of chosen characteristics. The different Fokker organisations operate separately. GKN Fokker has been interviewed twice, as different participants provided necessary new insights with their experience and knowledge. The type of actors is differentiated between incumbents (experienced in the industry) and new entrants (start-ups and those attracted from other industries). The type of activity includes manufacturers, knowledge institutes and intermediaries developing products or systems for hydrogen aircraft. Manufacturing actors are further specified by different tiers that refer to their role in the supply chain. An OEM is an original equipment manufacturer and is responsible for assembling the aircraft. Typically, a tier 1 organisation assembles and supplies full systems to an OEM. Tier 2 organisations manufacture parts or subsystems. Tier 3 generally manufactures components. New entrants are considered to not have a background in aviation or have entered the industry as a recent start-up. This diverse range of characteristics provides a comprehensive perspective of actors in the case of hydrogen aircraft.

§3.3 Operationalisation

To both assess the actor's contributions to the innovation system and determine potential barriers, the interview guide in Table 6 is designed. This operationalises the theoretical concepts described in Chapter 2 into several themes. Prompts have been defined and allow for further questions. Both questions and prompts include a typology of questions according to Kvale's (1996) nine types of questions (Clark et al., 2021). This ensures a wide coverage of questions. To warrant validity, it was indicated at the start of the interview to provide additional context if the participant thought it necessary. This was again checked with the closing question. Most interviews were conducted in Dutch.

Table 6: Interview guide semi-structured interviews

Category	Theme	Question	Prompts
Introductory questions	Identity	Could you elaborate on your role and responsibilities within the organization? (Introducing) **Q1**	
TIS Involvement	SF1	What is the role of your organisation in relation to developing and dissemination	What are targets set for these technologies? (Specifying) **SF1.1**

and contributions		of technologies for hydrogen aircraft? (Introducing) **SF1**	What has let your company to become involved in this industry? (Follow-up) **SF1.2**
	SF2 & SF3	How does your organization contribute to knowledge development regarding this technology/product? (Introducing) **SF2**	How did your organisation share this knowledge? (Follow-up) **SF3.1**
	SF6	Do you have access to the resources to further develop business activities? (Introducing) **SF6**	What promotes or hinders access to these resources? (Specifying) **SF6.1**
			Has this situation changed since you entered this market? (Probing) **SF6.2**
	SF5 & SF4	How do you experience the prospect of realising this product in a future market? (Introducing) **SF5**	How do you consider the development of a future market? (Follow-up) **SF4**
			What are the obstacles to further developing marketable products? (Follow-up) **Q3.1**
	SF3	To stimulate cooperation, are you involved with other parties in the industry? (Introducing) **SF3**	How does this collaboration proceed? (Specifying) **SF3.2**
			If you have worked with the ministry, how has this gone? (Specifying) **SF3.3**
	SF7	To what extent do you experience recognition for the development and use of your product/hydrogen aircraft within society and industry? (Introducing) **SF7**	If not: What do you think needs to be done to improve this? (Probing) **SF7.1**
Innovation policy		Are you familiar with policy documents regarding sustainable aviation, for example the aviation memorandum and innovation strategy for aviation? (Introducing) **Q2**	If so, how has this affected your choices regarding business operations and innovation? (Specifying) **SF4.1**
		What are possible barriers for your organization regarding the existing policy of innovation of sustainable energy carriers? (Direct) **Q3**	How do you handle that? (Specifying) **Q3.2**
Closing questions	Validity check	Based on the topics we have discussed, is there anything you would like to add? (Direct)	
	Snowball sampling	Can you recommend others who can help me with my research? (Direct)	

§3.4 Data review and analysis

Collected literature for SQ1 and SQ4 was reviewed to identify key findings within the existing body of knowledge. For SQ1, this was done by scoping definitions and (sub)technologies until data was exhausted. Records taken for the informal interviews related to SQ1 were reviewed and triangulated to the collected literature. With SQ4, the literature review is focused on establishing a theoretical framework for policy instruments, relevant to the drivers and barriers found in SQ3. At first, current literature proved insufficient to propose systemic instruments. Therefore, additional literature was collected and information on policy instruments was adapted to increase its relevance. Documents collected for SQ2 were also reviewed on their contents, by categorising data (Clark et al., 2021).

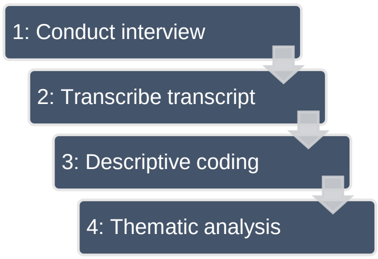

Figure 3: Analysis interviews

Interview data for SQ2 and SQ3 are processed and analysed according to the steps in Figure 3. After conducting the interviews and transcribing, the data requires coding to structure the data analysis and identify concepts such as functions. Coding is done through iterative steps between reading and memoing emerging ideas, describing codes, developing, interpreting the codes, and reporting results (Creswell & Poth, 2016). Descriptive coding is used, which summarises the data and mentions the topics (Saldaña, 2013). Through this type of coding, patterns and themes are identified. This is advantageous as the themes emerge from observations, generating theoretical insights. This supports the inductive approach of the research. A final advantage is that it retains the objectivity of the interview since the goal is to understand the innovation challenges. Additionally, supportive codes were added to structure the codes.

Several steps were undertaken to ensure a valid and reliable method of analysis. From 15 interviews, 1.110 codes were created, averaging 106 per interview. This included a total of 2.154 references. Each interview question was assigned a number, included in bold text in Table 6. This was used to structure the codes into categories related to the type of TIS functions (**SF**), with several overarching questions (**Q**). An answer to a question might refer to multiple functions. Therefore, the code was assigned according to the category deemed most appropriate. Appendix II includes an example of a coded function. Finally, coding structures were split to separately analyse incumbents and new entrants.

Codes were then interpreted using thematic analysis (Clark et al., 2021). This inductive method of analysis involves identifying patterns from data and creating and linking themes. It has the advantage of staying close to the coding process, which focuses on short clear descriptions. This is done through several steps which involve identifying, reviewing, defining, and evidencing themes (Braun & Clarke, 2006). Themes were identified by grouping similar codes and forming a structured overview by adding supportive codes. This was then reviewed after the initial coding process. In response, duplicate codes were merged and new themes were added. Themes were then defined to interpret the findings. Finally, evidencing involves using themes to argue the findings. It is a useful method of analysis for combining common barriers, by connecting findings. Appendix II includes the themes derived from the data.

§3.5 Research quality indicators

To ensure the validity and reliability of the research, several tactics are applied based on four quality indicators that are listed in Table 7 (Yin, 2009).

Table 7: Application of quality indicators by Yin (2009)

Indicator	Definition	Tactic	Application
Construct validity	Identifying correct operational methods for the concepts. (Yin, 2009) How well the measure conforms to theoretical expectations. (Clark et al., 2021)	Multiple sources of evidence (Triangulation)	Multiple methods of data collection and analysis were applied for each sub-question, to validate results.
			Interview findings are checked with available texts and documents and verified.
			Text and documents are tested on authenticity, credibility, representativeness and meaning.
		Establish a chain of evidence	The source's findings are connected through the data analysis.
Internal validity	Establish a causal relationship where certain conditions believed to lead to other conditions	Pattern matching	Recurring patterns/themes are identified through thematic analysis. This will establish a causal relationship between concepts, especially with the interviews.
		Explanation building	The theoretical framework is used to explain the findings from the thematic analysis.
External validity	Defining the domain to which findings can be generalised	Use theory	The theoretical framework is constructed, and sources are correctly referenced. Therefore, generalisation is done analytically by generalising a set of results to a broader theory.
Reliability	Operations of the study can be repeated with the same results	Use case study protocol	The methodology is extensively described and good practice in (social) research is upheld.

In addition, replicability is important as in the ministry's interest, the research might be replicated on the other two TISs not researched in depth after the first research phase. This is done by extensively describing the methodology and providing insights into primary data upon request.

Collected data was stored confidently on devices which only the author can access, following GDPR regulations. Agreements on data privacy have been made by signing a waiver provided by the ministry. Interviews were recorded with informed consent by respondents through email and again at the start of the interview. One interview was not recorded, but an agreement was made on taking and processing the minutes. Participants were given the option of reviewing their transcripts. The participants were made aware of the management of stored and shared data. Agreements have been made on the publication of the final thesis for the UU's thesis library.

4. Results – Defining technologies

The three main categories of sustainable energy carriers (SEC) can, combined with different technological applications, be split up into six types of SEC illustrated in Figure 4. Sustainable Aviation Fuels (SAF) are liquid fuels made from biological feedstock, or synthetic kerosene made from hydrogen and carbon. SAF can be blended with conventional fossil fuels. Hydrogen is an element that can be applied as a fuel for an aircraft's internal combustion engine, or applied to hydrogen fuel cells in-flight which generates electricity supplied to an electric engine. Electricity stored in batteries can power an aircraft with electric engines or be applied in hybrid with combustion engines to power the take-off of an aircraft, saving fossil fuels. By distinguishing different types of SEC and their technologies, an understanding is created of technological context structures surrounding each TIS.

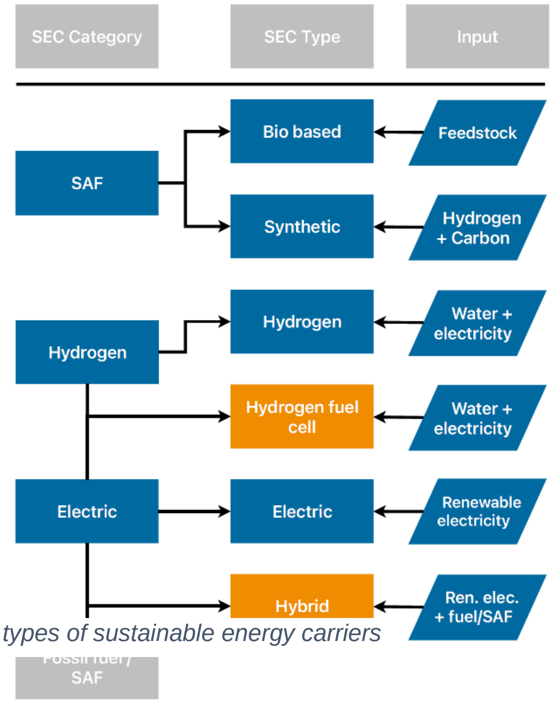

Figure 4: Six types of sustainable energy carriers

§4.1 Technological review

For these six types of SEC, value chains are identified and categorised by upstream logistics, airport infrastructure and aircraft operations (Figure 5). Appendix III contains an enlarged figure. GH_2 and LH_2 refer to gaseous and liquid hydrogen respectively. Hydrogen fuel cell and hybrid technologies follow the same value chain as hydrogen and electric respectively but differ in the final steps, these are hence marked orange. Activities within the value chain are described to create an understanding of different technologies, as each activity requires conventional or innovative technologies. Furthermore, interconnections between the different types of SEC can be determined based on this technological review.

4.1.1 Bio-based SAF

Bio-based

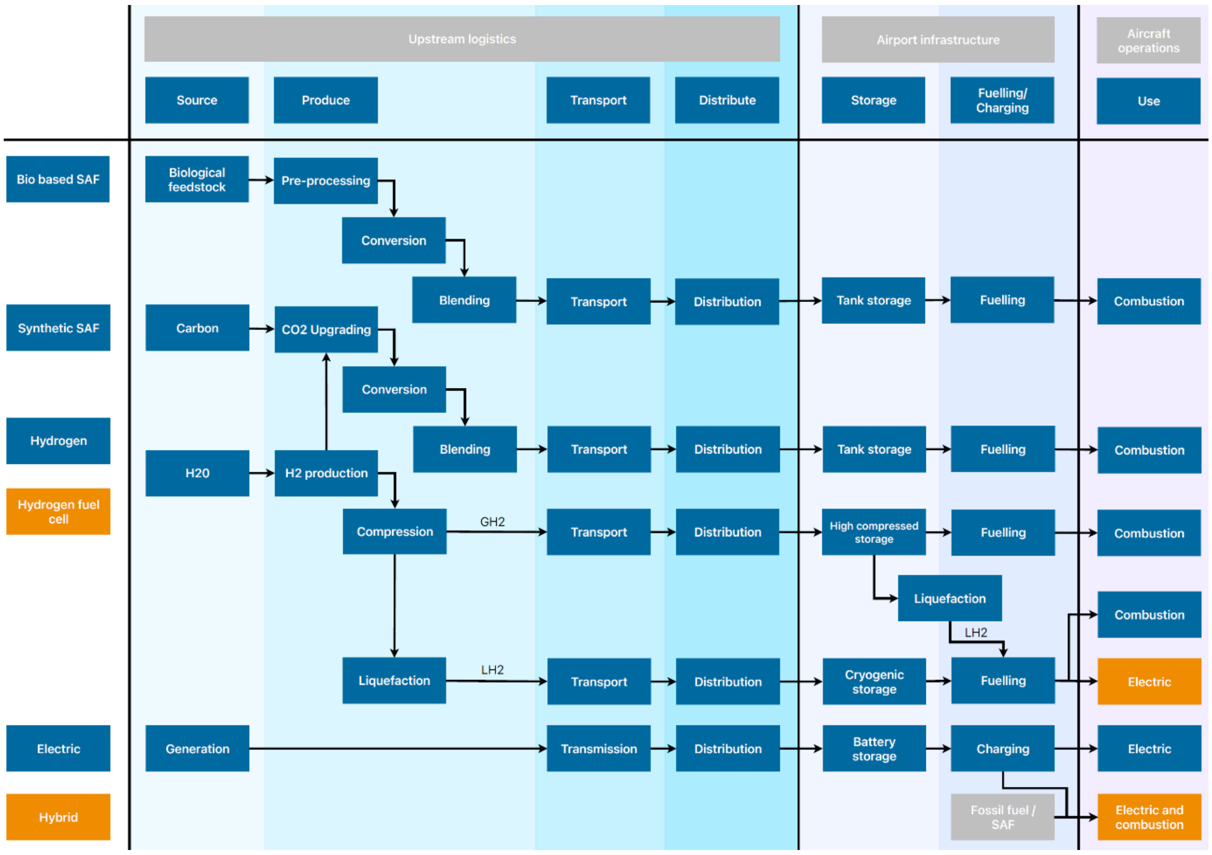

Figure 5: Value chain of sustainable energy carriers

Sustainable Aviation Fuels include all types of SAF sourced from biological feedstock. Different technologies are used to produce the fuel and the type of feedstock depends on the technology. Currently, waste streams based on fatty acids (e.g. grease) and oils (e.g. cooking oil) are the main source of feedstock (Davydenko & Hilbers, 2024; Oakleaf et al., 2022). Advancements in processing and conversion will allow other feedstocks such as forestry waste, municipal waste and algae to supply bio-based SAF (Ng et al., 2021). Technical challenges for these feedstocks lie in breaking down more advanced molecular structures. Seven production processes have been certified by ASTM, an organisation that provides standards for various industries (ASTM, n.d.). Of these, three processes are considered technologically ready to be applied in the short term: Hydroprocessed Esters and Fatty Acids (HEFA), Alcohol to Jet

(AtJ) and Biomass Gasification + Fischer-Tropsch (Gas+FT) (European Environmental Agency & European Union Aviation Safety Agency, 2023; Neuling & Kaltschmitt, 2018). HEFA is a technology that pre-processes waste streams from cooking oils, grease and similar products. This is then converted to hydrocarbon fuel components using small amounts of hydrogen, which make up the SAF (Holladay et al., 2020). AtJ utilises alcohols made from various feedstocks. Most applicable are methanol produced from biomass and ethanol produced from starches and sugars (Ansell, 2023). AtJ is processed by breaking down feedstocks and refining the product using various techniques (Petersen et al., 2021). Gas+FT produces biogas from various biological sources and municipal solid waste (European Environmental Agency & European Union Aviation Safety Agency, 2023). Feedstocks are converted to synthetic gas, which is then synthesised using a Fischer-Tropsch reactor to produce liquid fuel. Afterwards, the product is refined. Finally, the SAF produced through these three production processes is blended with conventional jet kerosene, typically Jet A1 Fuel (Holladay et al., 2020). The blended SAF is transported through conventional logistical routes, mainly pipelines, and road- and ship transport. Blended SAF will be supplied through the existing central pipeline network feeding into Schiphol and international airports in neighbouring countries, requiring all connected airports to use the blended fuel source (Ministry of Defence, n.d.). Distribution to other Dutch airports will be supplied through road- and ship transport (IvCB & Arcadis, 2024).

At airport infrastructure, SAF is stored in existing tank storage and fuelled with existing equipment, requiring no change in infrastructure or technology (Oakleaf et al., 2022).

Within the aircraft, SAF is used in existing combustion engines, which are certified for up to 50% blended SAF (Oakleaf et al., 2022). However, modifications must be made to increase certification for 100% SAF. The main barrier to using over 50% SAF is the reduced number of aromatics which reduces the swelling of seals within the engine, resulting in leakage (Anuar et al., 2021). However, Holladay et al. (2020) found that this problem only occurs in engines that were previously exposed to high amounts of aromatics. Overall, bio-based SAF's need for technological innovation is largest in the upstream logistics, mainly production.

4.1.2 Synthetic SAF

Synthetic SAF is created by combining carbon monoxide (CO) with hydrogen (H_2) (Ansell, 2023). H_2 is produced by splitting water (H_2O) into oxygen (O) and hydrogen (H_2), often through electrolysis (Ansell, 2023). The certified technology behind synthetic SAF is power-to-liquid (PtL) (European Environmental Agency & European Union Aviation Safety Agency, 2023; P. Schmidt et al., 2018). CO is combined with H_2 and then processed through a Fischer-Tropsch technology, similar to Gas+FT (Ramirez et al., 2020). The fuel is then blended with conventional jet fuel. Afterwards, the value chain for both types of SAF is identical (Barbosa, 2022). Again, the production of synthetic SAF requires the most significant technological innovation.

4.1.3 Hydrogen

Hydrogen is sourced from water and can be produced through various methods, either based on fossil fuels or renewable sources. Water splitting is considered most sustainable as it does not use fossil-based or biological resources, thus requiring little land use change and reduced carbon impacts (Kumar & Himabindu, 2019). Additionally, less water is consumed compared to fossil fuels (Beswick et al., 2021). However, water splitting is energy intensive. Water splitting is possible through thermolysis (water is heated to decompose water), photolysis (energy of light is absorbed and used to separate water) and electrolysis (water is split using electricity) (Nikolaidis & Poullikkas, 2017). Electrolysis is considered most suitable for producing hydrogen, as electrolysis is a proven technology and there are theoretically zero emissions (Kumar & Himabindu, 2019). Various methods exist to apply electrolysis, with PEM (Proton Exchange Membrane) considered the most efficient (Kumar & Himabindu, 2019). With PEM water electrolysis, water is split into hydrogen and oxygen using an electrical current passed through a PEM cell (Kumar & Himabindu, 2019). The produced H_2 is gaseous hydrogen (GH_2) which needs to be compressed to reduce the required volume. Without compression, the required volume would be 500 times as large as conventional fuel (Adler & Martins, 2023). However, pressure builds up in a tank due to temperature changes. Additionally, the GH_2 may be cooled down to below 20K (-253 °C) to liquid hydrogen (LH_2) in a process called liquefaction (Ansell, 2023; Hoelzen et al., 2022). This LH_2 would require about half of the required volume of GH_2 compressed to 700 bar (Adler & Martins, 2023). Gaseous hydrogen (GH_2) is transported using pipelines or trucks. By 2030, HyNetwork Services will have developed a hydrogen pipeline network that, with additional expansion, can supply larger airports such as Schiphol and Eindhoven (IvCB & Arcadis, 2024). However, until airports start requiring feasible amounts of hydrogen, trucks will be the main mode of transport for localised distribution. Liquid hydrogen (LH_2) is transported by trucks with cryogenic tanks, as it needs to stay cooled to below 20K. Short-distance distribution is possible with cryogenic pipes, but cooling requires a lot of energy (Hoelzen et al., 2022).

At the airport, hydrogen is stored on-site. GH_2 requires pressurized tanks (Adler & Martins, 2023). It can also be liquified on-site using cooling systems. Storing LH_2 requires cryogenic tanks. However, LH_2 boils at 20K resulting in a process called boil-off, which causes pressure inside the tank to build up (Ansell, 2023). Therefore, the resulting gas needs to be vented off and hydrogen is released to keep the pressure stable (Adler & Martins, 2023). This hydrogen leakage is an issue for long-term storage, particularly at airports with a high outside temperature. A lower surface area of a tank decreases the boil-off rate (Adler & Martins, 2023). Additionally, fuelling systems need to be redesigned to handle pressurised GH_2 or cryogenic LH_2 (Adler & Martins, 2023).

In aircraft, GH_2 or LH_2 can be directly combusted in hydrogen internal combustion engines (HICE), or supply hydrogen fuel cells that power electric engines (Adler & Martins, 2023; Oakleaf et al., 2022). HICE leverages existing technologies, redeveloped for hydrogen combustion (Adler & Martins, 2023). GH_2 and LH_2 have a lower energy density than conventional fuels. Therefore, both combustion and fuel cell hydrogen aircraft require redesigned tanks, fuel systems and aircraft reconfiguration to accommodate for the additional weight and volume of tanks and cooling systems (Adler & Martins, 2023). Hydrogen aircraft thus require significant innovations in different value chain activities. Most notable is the development of these systems and components, as they require many systems to change in the aircraft.

4.1.4 Hydrogen fuel cell

Hydrogen fuel cells produce electricity from hydrogen (H_2) and oxygen (O). The main advantage of fuel cells is that they only emit excess hydrogen, air, and water (Kumar & Himabindu, 2019). In any type of fuel cell, there are two electrodes, a negative (anode) and a positive (cathode). In a hydrogen fuel cell, electrodes from hydrogen break off at the anode and flow through a circuit causing an electric load (Adler & Martins, 2023). The oxygen enters at the cathode and produces water (H_2O). Depending on the type of fuel cell, this water forms at either the anode or cathode. Two main types are polymer electrolyte membrane fuel cells (PEMFC) and solid-oxide fuel cells (SOFC) (Kumar & Himabindu, 2019). An important distinction is that PEMFC operate at lower temperatures, whereas SOFC operate at high temperatures (Nikolaidis & Poullikkas, 2017). PEMFC activates quicker, which is beneficial. SOFC's high-temperature difference compared to the ambient air improves thermal management. To provide enough power, fuel cells are stacked in series. In addition to fuel cells, the aircraft requires an electric motor, a redesigned gearbox, a combustor, and a turbine (Adler & Martins, 2023). Additional aircraft reconfiguration needs to be made to accommodate tanks. Therefore, hydrogen fuel cell aircraft require more systems to change than hydrogen combustion.

4.1.5 Electric

For sustainable aviation, electricity to power electric or hybrid aircraft should be generated using renewable energy sources, for example, wind and solar energy. The generated electricity is transmitted through high-voltage systems. This is then converted into central power stations that distribute the electricity to the airports. Due to additional electrification of ground operations as well, the electricity needs for all airports will increase significantly (IvCB & Arcadis, 2024). This requires additional electricity capacity. However, the Dutch electricity network faces net congestion problems which could potentially hinder electrification (IvCB & Arcadis, 2024). Small airports will be the first to use electric aircraft for General Aviation (GA) activities such as flight lessons, recreational flights and gliding.

Electric aircraft require newly developed battery systems and electricity supply infrastructure to be installed at the airport (M. Schmidt et al., 2016). For aircraft, two options are battery plug-in chargers (BPC) and battery swapping stations (BSS) (Trainelli et al., 2021). BPC is currently certified for less than 100 kWh of power and needs to be scaled up for an estimated 3.5-7MWh to be able to supply larger aircraft (Trainelli et al., 2021). Standardised chargers are paramount for widespread adoption, especially for GA. For this, small electric aircraft manufacturers can use technologies from the electric car industry. BSS allow batteries to be swapped and charged externally. With this process, similar turnaround times (time to prepare an aircraft for departure after landing) can be achieved compared to current aircraft (M. Schmidt et al., 2016).

Within an operating aircraft, electricity is stored in batteries. Electricity has a low specific energy and energy density, meaning that a large amount of weight and volume is required to provide the aircraft with sufficient energy (Ansell, 2023). Therefore, current electrical aircraft are only designed for a small number of passengers. Existing lithium-ion batteries require further technological development to allow for weight reductions essential for larger aircraft. For example, Müller et al. (2022) estimate an increase in take-off weight of an Airbus A320 from 78 tons to 1293 tons based on current battery technology and 287 tons based on future technologies. These batteries require the most innovative development of the different technologies for electric aircraft.

4.1.6 Hybrid

Additionally, aircraft can be powered by both an electric motor and a combustion engine supplied with fossil fuels or SAF. Employing SAF in hybrid aircraft can potentially reduce GHG emissions by up to 90%, using combustion during take-off and landing and electricity during flight (Müller et al., 2022). This hybrid option reduces the required amount of battery weight while exhausting less emissions during critical parts of the flight. Different configurations of electric motors, combustion engines and propulsion systems can provide different energy efficiencies and complexity (Rendón et al., 2021). Hybrid aircraft can therefore be a solution to overcome the limited capacity of electrical aircraft due to current battery technology.

§4.2 Interconnections

Several interconnections can be found between the different value chains. These are relevant to understand how technological development is connected. Synthetic SAF and hydrogen are interconnected as they both require hydrogen to be produced. This offers an opportunity to develop the hydrogen production facilities for synthetic SAF, so that the technology is ready for larger-scale hydrogen production. A second interconnection is the combustion of both SAF and hydrogen. Both types require further development of conventional combustion engines, providing an opportunity to develop these for both fuels. Moreover, hydrogen fuel cell, electric-, and hybrid aircraft all require electric engines and battery systems. These can be co-developed for the same purpose. Another interconnection between these three is the development of new light-weight systems such as super conductive cables, as they all require significant weight reduction to become viable options for larger capacities and longer distance flights. These four interconnections indicate that it is important to develop systems in the context of other technologies and highlight opportunities to develop multiple systems at once.

§4.3 Prioritising a TIS

In addition to identifying interconnections, a TIS must be selected for further investigation. To be selected, this TIS should require significant technological innovation and opportunities for policy.

For both types of SAF, the main technological challenges occur within the initial steps of the value chain. For bio-based SAF this is the further development of feedstock processing techniques such as AtJ of Gas+FT. For synthetic SAF, it is the PtL technology, using similar technologies as Gas+FT. Since the value chain for SAF is the same as conventional jet fuel after blending, technological innovation should not be prioritised for the later parts of the value chain.

For hydrogen and hydrogen fuel cell technologies, significant innovation is required throughout the value chain. In particular, production technologies such as PEM (for hydrogen) or PEMFC/SOFC (for fuel cells) require further development as both technologies are considered early development (Adler & Martins, 2023; Kumar & Himabindu, 2019). Additionally, transport, distribution, and storage require new technological solutions that should be developed. Finally, the use of these technologies involves significant reconfigurations within an aircraft, and therefore additional research and development.

For electric and hybrid aircraft, upstream logistics in the value chain, such as the production and transport of renewable energy are primarily constrained by practical implications such as grid congestion. Therefore, the focus for technological innovation should be on airport infrastructure and aircraft operations. New infrastructure to store and supply electricity needs to be developed. Additionally, the aircraft requires significant efficiency improvements to enable longer travel distances for electric and hybrid aircraft.

Consequently, this research will prioritise the manufacturing of hydrogen combustion and hydrogen fuel cells as this SEC requires the most technological innovation, especially in aircraft operations. Specifically, on the development of fuel cell technologies and systems and products such as electric motors and tanks. In comparison, SAF's primary limitations lie in production technologies, while electric and hybrid aircraft are constrained by practical challenges and operational factors. Additionally, this TIS has several interconnections with other technologies, and its development can thus improve other TISs as well. Moreover, the Dutch aircraft manufacturing industry is focused on enabling hydrogen aircraft demonstrators together with the Ministry of Infrastructure and Water Management through Luchtvaart in Transitie, an eight-year programme focused on technological innovation. Thus, a TIS-based research to identify stakeholders and improve innovation with actor-centric policies is therefore beneficial for these parties, and the industry as a whole.

Utrecht University

Ministry of Infrastructure and Water Management

5. Results – TIS analysis for hydrogen aircraft

Actors active in the hydrogen aircraft manufacturing industry are analysed by identifying incumbents and new entrants and providing insights in their contributions to the TIS. Afterwards, the functional-structural analysis will determine drivers and barriers of innovation. These indicate the overall functioning of the innovation system, and the barriers should be removed by policy instruments.

§5.1 Mapping actors and contributions

5.1.1 Actor identification

Actors are identified and evaluated based on their contributions, following the exploratory search detailed in §3.2. This approach outlined the steps taken to select relevant actors from the hydrogen aircraft TIS.

The actors, listed in Table 5 cover a variety of organisational types and sizes. They supply materials (tier 3), develop (semi-finished) products (tier 2), design and integrate product systems (tier 1) and build demonstrators or prototypes for hydrogen planes (OEM). Specific products that are being developed are the thermoplastic fuel tank, fuel cell, fuel cell system, cable system, thermoplastic material, hydrogen propulsion system, electrical motor, air supply system, and an air cycling system. Some actors do not engage in product development directly, but rather contribute to the build-up of knowledge or provide consultation to other actors. These are the knowledge institutes and intermediaries. In addition, the actors perform business activities that cover the full process of developing a product or system covering design, engineering, integration, manufacturing, production, testing, and certification. It is not uncommon for actors to be active in multiple stages of the process, to enhance their value. Most activities are focused on system integration, design and engineering. Additionally, four organisations are actively involved in consultation. The broad spectrum of roles and activities undertaken by the actors ensures all necessary aspects of the TIS are covered.

Actors have different backgrounds and experiences. Of the interviewed actors, Aeronamic, Fokker Services, GKN Fokker, NAG and NLR have been engaged specifically in the civil aviation sector for an extended period, often with activities in the aerospace and defence industry as well. Similarly, ADSE and TU Delft have significant experience in the aviation sector but also focus on non-aviation industries. These seven organisations are therefore considered incumbents. AeroDelft, Circonica, Conscious Aerospace, Fokker Next Gen and Zepp Solutions are start-ups established for innovative hydrogen technologies. Toray Composites and Saluqi Motors are attracted from other industries for the need for respectively their composites and electric motors. Thus, these seven organisations are considered new entrants.

Differences between incumbents and new entrants are evident in their characteristics outlined in Table 5. Concerning the type of activity, incumbents are more often involved as an intermediary or knowledge institute. However, new entrants are more often an OEM or Tier 3 supplier. In terms of their size, incumbents are usually medium or large organisations, whereas new entrants are nearly all small organisations. The main activity for incumbents is to leverage their expertise for developing systems, consultancy services, knowledge-, and ecosystem development. However, for the development of the aircraft itself and separate products, they often rely on new entrants. Between the new entrants, it is noteworthy that the attracted organisations develop products that interconnected TISs use as well, and not just hydrogen aircraft. In contrast, the start-ups solely focus on products and systems for hydrogen aircraft. Thus, incumbents and new entrants position themselves differently in the TIS.

5.1.2 Governmental policy

The research itself is focused on manufacturers, knowledge institutes and intermediaries developing products or systems for hydrogen aircraft. Nonetheless, it is important to understand the policies that influence the political context in which these actors operate. Therefore, this section includes national governmental institutions to provide an overview of this political context.

<u>Ministry of Infrastructure and Water Management (IenW)</u>

In 2020, IenW and the aviation sector agreed to the *Akkoord Duurzame Luchtvaart* / *Sustainable Aviation Agreement* (Duurzame Luchtvaarttafel, 2020). This agreement outlined a roadmap and several targets to ultimately reduce CO_2 emissions of international flights departing from the Netherlands to zero by 2070. In 2020, this roadmap was detailed in the *Luchtvaartnota 2020-2050 / Innovation memorandum 2020-2050* (Ministerie van Infrastructuur en Waterstaat, 2020a). This document associated sustainable aviation with four public interests: safety, connectivity, liveability and sustainability. In 2023, IenW published the *Innovatiestrategie Luchtvaart* / *Innovation Strategy for Aviation* (Ministerie van Infrastructuur en Waterstaat, 2023). This policy document aligned the four public interests with four innovation areas: aircraft, sustainable energy carriers, airspace and airports. This document establishes a strategy for leveraging innovation to reach the targets. It outlined a long-term goal, necessary information and the role of IenW in reaching these goals.

IenW is responsible for policy regarding aviation. Within the Directorate Aviation resides the department of Sustainable Aviation. This department is focused on policy for sustainable aviation, including sustainable energy carriers. The department is structured around four main clusters: Sustainable Fuels, Goals, Standards and Pricing, Knowledge and Innovation, and International Affairs. Policy for hydrogen aircraft is distributed among these clusters.

For instance, Sustainable Fuels work on the availability of hydrogen and Knowledge and Innovation on the infrastructure. Besides these clusters, two policy officers work on stakeholder management. Most policies that the department works on focus on the prerequisites for the use and development of hydrogen aircraft. This department has worked on creating the *Innovatiestrategie Luchtvaart* and is currently developing a knowledge agenda that identifies the knowledge required for innovation by consulting actors. Finally, IenW subsidises innovation through the mobility fund. The mobility fund facilitates connectivity within the Netherlands through safe, innovative and sustainable mobility (Rijksoverheid, 2021).

The Human Environment and Transport Inspectorate (ILT) is part of IenW. The inspectorate focusses on multiple topics, including aviation. It regulates commercial and recreational aviation. ILT has two relevant branches: authorisation and monitoring. Authorisation approves permits to fly, or temporary exemptions for test flights. A hydrogen demonstrator will therefore have to gain authorisation from ILT. Monitoring is involved when an authorisation is granted and will inspect a future demonstrator to collect data. Currently, ILT is working on developing a protocol with which temporary exemptions can be given, and a process for approval once hydrogen aircraft enter the market.

<u>Ministry of Economic Affairs (EZ)</u>
EZ is concerned with the economic affairs of the Netherlands and therefore closely related to the manufacturing industries of the Netherlands. Within EZ, the Directorate Innovation and Knowledge is focused on developing these topics to strengthen economic growth and enable transitions. They work by mission-driven policy which aims to position and support the Dutch aviation manufacturing industry and knowledge institutes by funding R&D activities and partner countries and industries. They do not design dedicated policy but rather facilitate subsidies and (inter)national collaboration. Subsidy instruments which relate to aviation include the stepping stone fund, national growth fund, and research infrastructure investment fund. Other instruments are the national collective business plan, involvement in the Sustainable Aviation Roundtable and the facilitation of memorandums of understanding (MoU) with aircraft OEMs.

Netherlands Enterprise Agency (RVO) is a government agency of EZ that directly stimulates entrepreneurship. They facilitate several subsidy instruments offered by EZ that facilitate different types of innovations. These include TSH, TEI, DEI+ and RDM.

<u>Sustainable Aviation Roundtable (DLT)</u>
The Sustainable Aviation Roundtable (DLT) is a public-private collaboration between industry organisations, government and knowledge institutes. Representing the interests of both public and private parties, it has a unique position in the ecosystem. The DLT aim to realise the ambitions and targets set in the Akkoord Duurzame Luchtvaart through the use of focus groups. With a governance table, they monitor progress and adjust through consultation. IenW collaborates with the DLT and is involved in their governance.

<u>Luchtvaart in Transitie (LiT)</u>
LiT is an eight-year programme that encompasses twelve projects, supported until 2030. In this programme, IenW and industry organisations collaborate to accelerate sustainable aviation. LiT is funded by the National Growth Fund (NGF). The NGF is an investment fund to strengthen sustainable earning potential through subsidizing programmes that improve research and development of knowledge and innovation. The LiT programme is funded by approximately €750 million. The NGF supports LiT with €383 million and collaborating partners invest a similar amount. The programme is formally led under IenW and is supported by EZ.
The twelve projects are divided into three areas: Sustainable aircraft technology, sustainable knowledge, and sustainable ecosystem. Sustainable aircraft technology involves several projects aimed at improving the technology of aircraft. This includes demonstrators based on hydrogen combustion and hydrogen fuel cell technologies, innovative materials, and electrical and thermal systems. Projects related to sustainable knowledge support research, the development of roadmaps and a centre for researching and developing knowledge. The sustainable ecosystem projects focus on strengthening the ecosystem, international cooperation and a human-capital agenda.

These four governmental institutions and their subsidiaries interact with actors in various ways. IenW is the main institution to interact with actors, focused on the prerequisites for hydrogen aircraft. Through their policy officers, they execute their vision and supporting policy instruments. Additionally, their inspectorate ILT authorises and monitors the demonstrators the industry actors will develop. EZ focuses on the direct involvement of actors through RVO and executes most of the subsidy instruments available. The DLT and LiT support the industry with public-private collaboration, directly interacting with actors in various ways. Thus, by providing regulatory oversight, financial support and opportunities for collaboration these institutions form the political context in which the actors operate.

§5.2 Functional-structural analysis of actors

The functional-structural analysis provides insights into the drivers and barriers of incumbents and new entrants. With these, the functional performance of each systemic function (SF) can be determined. Appendix IV includes a complete overview of drivers and barriers for each systemic function.

5.2.1 Entrepreneurial activities (SF1)

Entrepreneurs carry out business activities within the TIS. The results describe these activities in terms of the positioning of the organisations, the pilot activities and the reasons for becoming active.

Positioning of organisations

It has been established in 5.1.1 that actors perform a wide variety of business activities and perform business activities throughout the supply chain. Both types of actors have set targets for these products to achieve lighter, more affordable and more sustainable products. More sustainable includes the removal of rare earth materials. Often the goal is to develop and demonstrate the new technologies and ensure safety. Scaling up was rarely mentioned as actors are often focused on lower Technological Readiness Level (TRL) technologies.

Both types of actors describe their role as enablers to the transition to more sustainable alternatives. Incumbents are more often interested in the development of an ecosystem and network within the industry, while new entrants prefer the development of technologies. Those attracted new entrants leveraged experience in other industries for this. They either have a background in the automobile sector which designs products for affordability and consumer preferences or the maritime sector which designs for cargo capacity. Incumbents operate more often in the military aviation sector, which is designed for high performance. In contrast to commercial aviation which is more targeted towards cost-effectiveness and reducing weight. Participants mentioned spreading risks, developing knowledge and an assurance of revenue as the reason to diversify their business activities. In addition, four organisations, mostly incumbents, are actively involved in developing business activities abroad.

Pilots

Actors undertake several activities to progress the development of a hydrogen aircraft, among which are several pilot projects aimed at launching demonstrators. Within the Luchtvaart in Transitie (LiT) programme, the HAPPS project aims to launch a demonstrator aircraft using hydrogen fuel cells in 2027. The project is led by Conscious Aerospace with other actors as partners. Another LiT project is the HOT project which aims to retrofit an existing aircraft for hydrogen combustion. However, this project is subject to change. The HOT project is led by FokkerNextGen. Furthermore, Project Phoenix is a demonstrator aircraft set to fly on hydrogen fuel cells by 2026. The project is led by student team AeroDelft.

International projects in which some actors are involved include H2Gear and Cavendish. H2Gear aims for a hydrogen combustion ground-based demonstrator by 2026, and a flying demonstrator by 2029. GKN Aerospace leads this project, and GKN Fokker is involved. Finally, a European programme called Cavendish aims to develop a hydrogen combustion engine including surrounding systems. Rolls-Royce runs this programme, and Fokker Services is involved. However, the programme is experiencing delays.

Becoming active

Incumbents and new entrants have different reasons to become involved in this industry. Incumbents see an opportunity to acquire or sustain an important role in the future. Especially as a first mover, there are advantages for a technological leadership and a solid position within the value chain. A second reason is the expected interest of current OEMs. If history repeats itself as it did with the introduction of composite parts instead of aluminium, this will result in new opportunities as the OEMs require sustainable products such as hydrogen aircraft. In contrast, new entrants are motivated by sustainability and the opportunity to contribute to a sustainable transition. This also motivates and attracts employees. Additionally, two factors drive both incumbents and new entrants. One is the future earning potential that is seen as significant due to large margins and expected revenue. The other is the desire to establish a niche market and explore the potential of a new business model based on more regional or remote areas.

For actors, there are also reasons not to become involved. Most commonly, the high requirements on safety, certification and technologies for aviation result in restrictions on business opportunities. Likewise, the high costs of developing and finally producing a product prevent actors from entering this industry. Incumbents more often have the willingness to invest, as new entrants often do not have the capacity to allocate those resources. Another barrier to entry is competition. The industry is described as a duopoly, with Airbus and Boeing controlling the market. This makes it more difficult to compete with established suppliers to the OEMs, which have access to long-term contracts and resources. A final reason is the competition with fossil-fuel-based technologies, as these have been further developed, are already certified and are considered cheaper. Both incumbents and new entrants encountered these barriers to become involved, but new entrants experienced them more often as they are more prone to risk.

The existence of innovation policy, or lack thereof, influences the undertaking of business activities. Both types of actors specifically mentioned the existence of the LiT projects as the main influence of policy to become active. Incumbents mention European and national targets and regulations, that require compliance or give reassurance. However, six incumbents and new entrants found that existing policy did not influence their choice to undertake entrepreneurial activities. Incumbents were often already active in projects. Some new entrants found that policies did not align with their business activities due to the limitation of current policies in terms of their scope and coverage. For example, there is a narrow focus on scaling up technologies and production.

Drivers and barriers

Table 8: Drivers and barriers of SF1. Drivers in black, barriers in red.

SF1 Entrepreneurial activities	Concerns
Activities occur throughout all steps of the product development process and within different tiers, from materials to aircraft development.	Both
Clear targets are set for developing improved products.	Both
Incumbents focus on ecosystem improvement and networks and operate internationally.	Incumbent
New entrants focus on the development of technologies, leveraging experience from other industries.	New entrant
Most actors are involved in several national and international programmes for hydrogen aircraft demonstrators.	Both
Incumbents become involved to sustain an important role in the future and interest of OEMs.	Incumbent
New entrants become involved to facilitate a sustainable transition.	New entrant
Both types of actors also become involved for earning potentials and new business models.	Both
The existence of the LiT programme and European projects enable business activities.	Both
Targets are often focused on demonstrating possibilities rather than complete development of marketable products.	Both
Some demonstrator programmes are subject to delays.	Both
Actors do not become involved due to high requirements for aviation, high costs of development, a controlled market, and competition with established technologies. This occurs more often with new entrants, as they are more prone to risk.	Both
Some incumbents were not influenced by policy as they were already active in projects.	Incumbent
Some new entrants were not influenced by policy as they the policy did not align with their business activities in terms of their scope and coverage.	New entrant

Several factors drive or restrict this systemic function and are summarised in Table 8, where drivers are highlighted in black and barriers in red. Overall, this function is well developed and driven by comprehensive and targeted involvement of both types of actors in the ecosystem and programmes for hydrogen demonstrators. They are motivated by various incentives to conduct activities, which differ depending on the type of actor. However, several barriers counteract these drivers and limit this systemic function leaving room for improvement. For all actors, these are the high requirements for aviation, costs, control and competition on the market. Policy influence is limited for incumbents who are already active, or for new entrants when it misaligns with business activities.

5.2.2 Knowledge development (SF2)

Knowledge development occurs in the process of learning. The analysis provided insights into the creation and acquisition of knowledge.

Actors indicate that knowledge is created in various manners, most commonly through research by incumbents. This is usually conducted by a Research and Development department, or by programmes based on a specific topic. Most research is conducted on system integration, followed by certification requirements.

All new entrants specifically emphasise collaboration on knowledge creation with other actors, in contrast to four incumbents. Collaboration on knowledge creation occurs most often with knowledge institutes. The main incentive is to acquire access to knowledge from specialised actors. Incumbents most often acquire knowledge through testing. This involves testing products, but also samples of materials and systems. The NLR specifically provides testing facilities that are utilised by other actors. These facilitate the testing of hydrogen systems, most commonly for powertrains.

Finally, knowledge is created through the education of students and the facilitation of PhD programmes. New entrants and the incumbent TU Delft included internships, dissertations, traineeships or providing experience as a way to create knowledge.

Drivers and barriers

Table 9: Drivers and barriers of SF2

SF2 Knowledge development	Concerns
Knowledge is created by incumbents through Research & Development and knowledge-specific programmes.	Incumbents
All new entrants and some incumbents collaborate to create knowledge together, with the intent to acquire specialised knowledge.	Both
Knowledge is developed by incumbents through testing, using facilities offered by other actors.	Incumbents
New entrants create knowledge by educating students and PhD programmes.	New entrants

Knowledge is actively being developed and is obtained from a variety of sources. Incumbents are most active in R&D and testing, whereas new entrants more often create knowledge collaboratively and provide education opportunities. This results in strong drivers unrestricted by barriers.

5.2.3 Knowledge diffusion through networks (SF3)

Created knowledge is then shared through a network. Different types of collaboration are mapped and these results are extended with the actors' view on sharing knowledge.

Industry collaboration

Most actors recognise that they are actively collaborating with sufficient organisations. The knowledge institutes TU Delft and NLR are most often mentioned, although other technological universities are involved as well. Incumbents indicate more formalised methods of collaboration as well, in which organisations work in private consortia to produce a product. Examples mentioned are a joint research centre and projects focused on developing composite tanks. However, actors have limited collaboration with airports, airlines and the industry organisation.

The larger Original Aircraft Manufacturers (OEMs) Boeing, Airbus and Embraer have limited business activities within the Netherlands. Nevertheless, about half of the organisations, mainly incumbents, mentioned working directly with these OEMs. Some have agreed on a memorandum of understanding (MOU), which establishes an outline agreement between the organisations. Others focused on actively communicating their business activities and possible concerns with the OEMs to increase their understanding and awareness. The participants are split on collaborating with international organisations, as some preferably focus on working with Dutch organisations but others rely on international suppliers.

Government collaboration

Various governmental institutions are actively involved with policy on hydrogen aircraft, or broader projects. Therefore, collaboration occurs with multiple organisations.

Collaboration with the Ministry of Infrastructure and Water Management (IenW), occurs on various policy instruments. Some actors worked with IenW on the initial proposal for Luchtvaart in Transitie, and others on projects related to the mobility fund. Various concerns are mentioned by participants, although none are mentioned often. Most important was IenW's inexperience with innovation projects, as they are often more focused on larger projects. This learning curve is acknowledged in limited knowledge, limited experience in designing policy instruments and the availability of these instruments. Both types of actors indicate the same concerns.

The Ministry of Economic Affairs (EZ) has a close collaboration with both incumbents and new entrants, especially through their government agency Netherlands Enterprise Agency (RVO). Actors collaborate for subsidy schemes such as TSH, TEI, DEI+ and RDM. Incumbents specifically collaborate with EZ for international innovation missions and to establish a strong international position for the Dutch aircraft manufacturing industry. Collaboration was generally viewed as positive, although some new entrants struggled with getting their subsidy applications approved for various reasons.

The two public-private collaborations include the Luchtvaart in Transitie (LiT) programme and the Sustainable Aviation Roundtable (DLT). Most actors collaborate with LiT and convey the recognition, collaboration, support, and financial resources brought by these projects as beneficial. For two new entrants, collaboration with LiT did not occur as they were not eligible or did not experience recognition. Surprisingly, only one incumbent mentioned collaborating with the DLT.

Collaboration also occurs internationally. Several incumbents are active in the Clean Aviation and Clean Sky programmes organised by EU project Horizon. This enables close collaboration with Airbus and broad partnerships. However, administrative burdens, political influences and lower-added values discourage actors. Instead, new entrants favour Dutch programmes for the focus on specific targets, higher TRL and the advantage of close collaboration. Finally, other collaborations involving governments occur through regional government and the innovation quarter, a regional economic development agency. These collaborations were rarely mentioned but allowed organisations to develop more locally.

Knowledge sharing

Throughout these collaborative efforts, knowledge is spread. This occurs most often by publishing research, white papers, lectures and meetings. The main driver for this is to enable partners to increase their knowledge, strengthening the ecosystem and improving appropriation. Furthermore, nearly half of the incumbents and new entrants viewed it as their role to share this knowledge. Some actors are cautious to share their knowledge, to protect their investments. Intellectual property protection measures are taken to avoid this. Besides, the NAG warned actors to be careful about sharing their knowledge.

Most knowledge sharing occurred within the LiT projects. Knowledge is also attracted from other mobilities and industries by new entrants. Of which some actors with a background in other mobilities opted to adapt their technological knowledge to the aviation sector. Incumbents do actively look for applications of sustainable energy carriers in other mobilities, such as electric vehicles, or other industries, such as the medical industry for the superconductivity of cables. However, it appears challenging to adapt these technologies, as aircraft require strict safety measures and different circumstances. Examples are a low-pressure environment, high energy density and low-weight components. This limits cooperation with actors in other TISs.

Drivers and barriers

Table 10: Drivers and barriers of SF3

SF3 Knowledge diffusion through networks	Concerns
Actors collaborate frequently, most often with knowledge institutes.	Both
Incumbents form private consortia and commit to long-term collaborations.	Incumbents
OEMs perform limited business activities within the Netherlands. Yet, they cooperate with a considerable amount of actors, often incumbents.	Incumbents
Government collaboration occurs with IenW, EZ (subsidies) and LiT (projects). Incumbents are more likely to leverage governmental organisations internationally. While new entrants prefer Dutch projects.	Both
Knowledge is actively diffused to strengthen the ecosystem and improve appropriation.	Both
Knowledge is brought from other mobilities and industries by new entrants.	New entrants
Incumbents seek knowledge from other mobilities and industries.	Incumbents
Actors have limited collaboration with airports, airlines and the industry organisation.	Both
Barriers to collaborate with governments occur due to the following factors: IenW's limited knowledge, policy design capabilities, and availability of policy instruments.	Both
New entrants struggled with EZ's subsidy applications and eligibility for LiT projects.	New entrants
Incumbents experience limitations in international collaboration with both industrial and governmental organisations due to administrative burdens, political influences and lower added values.	Incumbents
Regional collaboration is limited.	Both
Knowledge diffusion is barred by intellectual property protection.	Both
Knowledge attraction is constrained by aviation-specific requirements.	Both

Collaboration with the industry and governmental organisations are strong drivers for this function. However, the effect of this cooperation is restricted by a narrow collaboration within the sector and restricted capabilities within governmental organisations. New entrants specifically face barriers to eligibility for projects and subsidies. Incumbents struggle with disadvantages in international collaboration. Knowledge is actively diffused and new entrants and incumbents leverage knowledge from other mobilities and industries. However, diffusion is barred by IP protection and constrained by aviation-specific requirements. This systemic function is thus influenced by strong drivers and barriers.

5.2.4 Guidance of the search (SF4)

When various technological options exist, selection occurs. This selection process is dependent on the direction and priorities for activities, which in turn results in guidance. The study identified the effects of influences on business operations and the direction of innovation policy vision documents.

Influence on business operations

According to actors, hydrogen brings various technological challenges to developing a marketable product. The most pressing concern of using hydrogen aircraft is the added weight and required space of the tank and cooling systems. Hydrogen has a low energy density which requires a larger and thus heavier tank. The necessity to cool hydrogen to cryogenic temperatures adds additional weight. Unexpectedly, this concern was more often voiced by incumbents, even though new entrants will face the same challenges. Storing hydrogen brings additional challenges. Hydrogen is a light molecule and therefore requires specialised tanks which prevent leaks. In addition, new safety systems need to be developed for storing and fuelling hydrogen. These prerequisites prove difficult to design for aviation, as they require new systems and products that can be used in a confined, secure, and mobile space. This complicates adapting systems from other industries or mobilities.

The certification process entails aligning innovation activities with the relevant certification requirements, thereby influencing business operations. All aircraft components require certification. Type certificates (TC) are issued for specific aircraft systems, allowing multiple components to be certified concurrently. Systems are tested on certification standards such as safety and operational suitability and maintenance. Certification is issued by international authorities for aviation safety. In Europe and the United States, certification is respectively issued by the European Union Aviation Safety Agency (EASA) or the Federal Aviation Administration (FAA). A certification process for a type certificate can take around six years. If a TC is granted, the organisation must also be authorized with a Design Organisation Approval (DOA). This is an approval to create airworthy designs. The actors experience various barriers within the certification process. First, new certification standards need to be designed for hydrogen aircraft, lengthening the process. This also requires the safety authorities to be involved as early as possible. Therefore, EASA has created a pre-application process where actors are involved, that aims to speed up the process. However, actors indicated that EASA deals with a personnel shortage. Finally, a longer process increases complexity and new safety standards are complex to demonstrate early in the process. All of the reasons mentioned for developing a marketable product and certification concern both incumbents and new entrants, as they are inherent to the characteristics of the products and systems.

Direction of innovation policy

Business activities are guided by the direction taken in policy vision documents. All incumbents and half of the new entrants mentioned being informed of current innovation policy documents, although usually only partly. Awareness stemmed most often from being consulted and informed directly by the Ministry of Infrastructure and Water Management. Only incumbents indicated awareness of international policy. The remaining four new entrants are interested in policy but did not actively seek out current policy documents. While the actors were generally positive about the existence of policy documents such as the Innovation Strategy for Aviation, a minority of actors voiced some concerns. Most pressing is the balance of representation between different airlines, airports and the manufacturing industry, between incumbents and new entrants, and between different types of sustainable energy carriers. New entrants specifically expressed their need for a platform to ask questions and express their concerns. In addition, some actors found targets too generic and hoped for greater urgency to market innovation.

All incumbents and two new entrants voiced a need for long-term continuity and consistency of policy. Development of a new type of aircraft is expected to take over 10 years, which extends the duration of a political cabinet term. With the recent discontinuation of the national growth fund, actors anticipate a finiteness to the Luchtvaart in Transitie programme, which will last until 2030. Furthermore, uncertainty is voiced about the policy development after 2030. In the past, actors experienced an inconsistency of policy instruments. One actor specifically mentioned a switch in focus between cabinets from top sectors to key technologies to the national growth fund. Concerns are raised for suboptimal usage of policy instruments because of these inconsistencies.

Drivers and barriers

Table 11: Drivers and barriers of SF4

SF4 Guidance of the search	Concerns
Aviation safety authorities EASA and the FAA are actively involved in the certification process, improving direction.	Both
Policy innovation document are available and all incumbents and half of the new entrants are informed by the direction they provide.	Both
Incumbents are aware of international policy.	Incumbents
Technical challenges to using hydrogen limit development and business operations.	Both
Adapting products and systems is constrained by aviation-specific requirements.	Both
Certification is a complex, long-term process. This results in uncertainty and various challenges.	Both
The direction of policy vision documents is limited by the balance of representation.	Both
New entrants find it more difficult to reach policy officers for questions and concerns.	New entrants
Limits in long-term continuity and consistency of policy result in uncertainty.	Incumbents

This systemic function is subject to a limited number of drivers. The aviation safety authorities are actively involved in the certification process and policy vision documents exist to provide direction. However, the effectiveness of policy to provide direction is restricted by a balance of representation and lack of continuity and consistency. The latter is most often requested by incumbents. Other barriers originate from aviation-specific requirements and complexity which is unfavourable for the selection process within this systemic function. Lastly, new entrants find it difficult to reach policy officers. Notably, they also seem less concerned with technical challenges and policy direction, even though they are affected by them.

5.2.5 Market formation (SF5)

New technologies need a space in which to develop, provided by a niche market. Hydrogen aircraft do not yet exist in the market. Therefore, actors were asked about current developments and prospects of a future market.

Market developments

Both types of actors are generally optimistic about the development of a niche market, albeit limited to smaller planes and/or small distances. Actors expect the first aircraft to become available for short distances and limited passengers. These can serve regional markets and create new opportunities for areas where current aircraft would be less ideal due to pollution. Actors are split on the potential application within the Dutch industry, as some incumbents do not expect the Dutch industry to play a large role in building aircraft. However, the actors are confident in their products.

Optimistic estimates anticipate a hydrogen aircraft at the end of this decennium. Most actors expect market availability from 2035, with some anticipating 2040 or later. However, as aircraft are in service for over 20 years fleet renewal is expected to take a long time. Therefore, a significant carbon reduction from hydrogen aircraft is not expected until 2050 to 2070. The long development time is seen as a barrier to developing a marketable product, as uncertainty increases with time. Besides, the long service time of aircraft requires a more stringent development time to minimise possible implications 20 to 40 years from now. Notably, these concerns are more often indicated by incumbents than new entrants.

Market conditions such as time to market influence the development of technologies. Another is the long return on investments, mentioned by ten incumbents and new entrants. They expect at least five to ten years before revenue is generated. This requires investments over a long period, which impacts the availability of finances. Likewise, large investments are required for further development of the product and building the assembly line. The aforementioned factors influence the willingness to invest and the cost of entering the market. Most notable, however, is the affordability. Incumbents raise concerns over a sufficient business case as hydrogen aircraft are considered less profitable. This is largely due to their lower capacity passengers on board. New entrants share some of these concerns, but are more concerned about the financial risks.

Market prospects

The global aviation market is expected to grow significantly. This can be beneficial for market conditions, as the potential market will increase. However, it limits the impact of these more sustainable planes. The possibility of a future market is recognised by most actors. Although some view the affordability and operational restrictions as a nearly impossible factor to overcome. Operational restrictions from flying with hydrogen include cooling hydrogen, delayed acceleration and storing hydrogen planes.

The vision of both types of actors on different types of sustainable energy carriers, electric, SAF and hydrogen are aligned. Electric aircraft are expected for smaller distances and fewer passengers. Batteries prevent larger distances and carrying capacity but are considered the most efficient in transforming energy into power. SAF is applicable for long-range flights, with large amount of passengers. It has the potential to sustain the growth of the aviation sector and can be employed as a short-term solution. However, it is considered the least efficient by the participants. In addition, SAF is resource-intensive and global SAF production is considered to remain insufficient. Concerns were voiced that SAF might shift focus away from hydrogen development, as it is seen as a low-hanging fruit solution with limited impact.

Hydrogen is viewed to be able to bridge the gap between electric aircraft and SAF, as it will serve medium distances, with an average amount of passengers. At first, it will serve short distances during its development. The two types of hydrogen fuel cells are considered to be relatively efficient. As PEMFC is further developed, it is expected to be utilised first. However, SOFC promises to be a low-cost and highly efficient technology once advanced. Hydrogen combustion is considered to be more easily applicable, but less efficient. Due to their lower capacity, both types of fuel cells will require changes in the operational services of airlines.

Therefore, some actors expect other mobilities to become more significant if hydrogen planes cannot service enough passengers or distance. Nevertheless, a possible regional service might counteract this effect. Due to the previous experiences of actors, they expect that adopting a new technology brings uncertainty as the market might develop differently than expected. As the Dutch industry is relatively small, some incumbents find that it will be best to specialise their business activities.

Drivers and barriers

Table 12: Drivers and barriers of SF5

SF5 Market formation	Concerns
Actors expect a niche market to form. First for short distances and limited capacity, suitable for regional aircraft.	Both
The general global aviation market is expected to grow, improving the size of the market.	Both
The vision of different types of sustainable energy carriers is aligned.	Both
In the short term, the market is limited to short distances and limited capacity.	Both
While a commercial aircraft is expected sooner, incumbents expect a limited sustainable impact until 2050-2070.	Incumbents
Incumbents are split on the (limited) potential of the industry within the Netherlands.	Incumbents
Market formation is limited by several market conditions that limit development. This includes the uncertainty due to a long development time, long return on investments, and affordability.	Both
Actors expect SAF to attract greater attention than hydrogen, which can have an impact on market formation.	Both
Other modes of transport might be more favourable due to the limited application of hydrogen at first.	Both

Market formation is driven by a clear vision of the development of a market in the long term. However, barriers to market formation stem from unfavourable market conditions and increased uncertainty. Moreover, the application of hydrogen is limited in the short term and a significant sustainable impact is expected after 2050. This drives other sustainable energy carriers and modes of transport, resulting in increased competition and limited development for hydrogen aircraft. Finally, incumbents mention more concerns, whereas new entrants are more optimistic.

5.2.6 Mobilisation of resources (SF6)

Resources are key to enabling business activities and need to be accessed and allocated. Organisations should have sufficient access to these resources which can be restricted or improved. Furthermore, situational changes can indicate the access and allocation of resources over time.

Access to resources
Two incumbents and two new entrants mentioned having sufficient access to resources at the moment. Yet, most actors had limited access to certain types of resources. In order of times referenced, themes were found on finances, personnel, knowledge, capacity and resources from international sources.

Financial resources were most often described as a limiting factor. Incumbents were better equipped to allocate financial resources, compared to new entrants. Specifically, actors are uncertain about gaining access to money for scaling up in the long term. Early development of technologies requires investments without revenue, necessitating private investors. Some actors perceived difficulty in attracting these, as investors are more likely to invest in products with a shorter pay-back period. Or avoid risk due to high interest rates. The availability of subsidies is another influence on access to financial resources, as some new entrants are not able to gain access to national or EU projects and subsidy schemes. Reasons for this are a high amount of effort required or projects that do not align with their technology but focus on low- or higher TRL instead.

The availability of personnel also has a large influence on the actors. While some new entrants were able to find the right personnel, the shortage of suitably qualified personnel was widely recognised. Most commonly, due to competition from other industries focused on sustainable or high-tech technologies such as ASML. Another cause is the demographic ageing of personnel. To overcome these barriers, companies recruit international employees.

Most actors have access to at least some knowledge, either from a network or cooperation with other actors in the industry. When industry goals are aligned, this access improves. Yet, knowledge is spread among organisations and is therefore not always available. For example, non-disclosure agreements limit the access to knowledge. Interview participants themselves also bring knowledge and expertise. Nearly all participants were directors and managers, most often in charge of technologies. The knowledge areas of those who work for incumbents are most experienced in process management, engineering, thermoplastic materials and electrical systems. Most experience was gained by working at Fokker, an aircraft manufacturer until 1996. The new entrants are most experienced in certification, hydrogen, and engineering.

Capacity was a fourth theme among participants, which restricted their capacity to develop certain projects or allocate resources. Factors for incumbents are the inability to fully implement engineering or product development departments. New entrants mentioned the access to testing facilities and their small size as the limiting factor.

Resources may also come from international sources. Geopolitical tensions can influence the availability of resources, such as rare earth materials. Also, the Dutch aircraft manufacturing industry is limited in size compared to Germany, France and England. This can lead to competition for resources in Europe. These countries were also mentioned by most actors for financial resources. According to the participants, they have more available subsidies, attract EU investments more effectively and provide more state support for investments. For these reasons, they are considered by both types of actors to have a more established policy for aircraft manufacturing.

Changed situation
Some changes improve or limit the access to resources. In the past, incumbents recognise a period with limited financial instruments for aviation policy. This resulted in delays in development. This situation improved with the introduction of Luchtvaart in Transitie which provided an increased recognition of hydrogen aircraft, recognised by both types of actors. However, the policy instrument that allows funding of programmes like Luchtvaart In Transitie, the national growth fund, was recently discontinued. Incumbents indicated limited opportunities as no new projects are being taken on.

Positive trends were recognised after the Paris Agreement and the resulting policy led to increased global efforts and another push for hydrogen. This has improved the overall availability of resources, due to additional subsidies and focus from knowledge institutes. Current actors expect more new entrants to become attracted to this new industry that may originate from different mobilities and industries.

Future prospects pose concerns about sufficient access to materials and the availability of hydrogen. As other sustainable industries compete for these resources. Actors, often incumbents, are concerned about the availability of an infrastructure to supply hydrogen. In addition, net congestion may limit the production of hydrogen, which requires a large amount of electricity. Actors are dependent on solutions for these national infrastructural issues, where resources will have to be shared with other industries.

Drivers and barriers
Table 13: Drivers and barriers of SF6

SF6 Mobilisation of resources	Concerns
Some actors mention sufficient overall access to resources.	Both
Knowledge is accessible for most actors and both types of actors utilise previous experience to extend their knowledge.	Both

Innovation policy has limited incumbent's access to resources in the past. Yet, current access for actors is improved by the LiT programme.	Both
Global sustainability efforts increase the availability of resources and attract new entrants.	Both
Financial resources are limited due to restricted attraction of investments.	Both
Personnel is scarcely available and difficult to attract to this industry.	Both
The capacity to utilise resources limits the allocation of resources.	Both
New entrants are more likely limited to financial resources and sufficient capacity.	New entrants
Geopolitical tensions and competition within the EU restrict overall access to resources.	Both
The future availability of resources may be limited by competition from sustainable industries and the availability of infrastructure and electricity.	Both

Although some actors experience sufficient access to resources, especially knowledge. The access and allocation of resources is mostly limited by several barriers. Limited financial resources and personnel are most restricting. New entrants more often mention a limitation to financial resources and sufficient capacity. Additionally, actors expect threats to the overall access to resources in the future. Policy has positively and negatively impacted the mobilisation of resources.

5.2.7 Creation of legitimacy (SF7)

For new technologies to become established, they compete with the incumbent technology and resistance to change. Legitimacy needs to be created from public, institutional and industrial support, which reduces uncertainty and improves acceptance.

Public legitimacy

Both types of actors regarded public opinion to be favourable for the development of hydrogen aircraft. However, the public regards the aviation industry as polluting and slow to change. There is a drive for a more sustainable alternative to flight, which reduces the climate impacts. This is seen to improve the support, as the hydrogen aircraft offers a solution. Nevertheless, attention should be paid to noise pollution, as some hydrogen aircraft designs incorporate propellor engines which generate more sound. Some actors expect concerns over the safety of hydrogen, which can be overcome through valid communication.

Communication may also be key to legitimising a realistic increase in ticket prices, as hydrogen aircraft are expected to carry fewer passengers due to an increase in the required volume for tanks. The planned demonstrators offer an opportunity to increase public support. If communication is not sufficient, the fear of greenwashing may delegitimise these new technologies as an uninformed public may not view hydrogen as clean.

Institutional legitimacy

Political support and opinion influence the legitimisation of the new technology, especially when other technologies such as SAF and electric aircraft exist and might compete with hydrogen aircraft. Concerns are therefore voiced to continue to support hydrogen technologies or emphasize them further, such as what is done with Luchtvaart in Transitie. In the past, innovation missions led by EZ have also increased legitimisation. Some incumbents and new entrants are concerned about the continuation of current policy and present political support.

Additionally, both types of actors found uncertainties within current policy on a wide variety of topics. When uncertainties occur, the actors do not know if a certain obstacle will be resolved or what direction the government will take. The most significant concern is the availability of hydrogen infrastructure and the build-up of the value chain. Additionally, the regulation of hydrogen systems and the roadmap to adapting this regulation is of concern. Finally, it can be uncertain what sustainable energy carriers are governed by certain policy instruments and what government organization is involved.

Industrial legitimacy

The industrial opinion is described as cautiously optimistic. The interviewed actors are confident in the opportunities and have a clear vision. However, they do expect that other actors are hesitant to enter due to uncertainties about how the technology will develop. The long development time and profitability are other reasons to counteract legitimisation. New entrants are willing to take this risk and are more driven by their personnel's drive to work on sustainable technologies.

OEMs play a key role in legitimisation. Incumbents most often work with OEMs. They view Airbus as supportive as they have set a target for a commercial hydrogen aircraft by 2035. Boeing is more focused on SAF, but the incumbents have more recently noticed increased interest. However, their current issues with aircraft safety are assumed to reduce support for these new technologies.

Several characteristics of the aviation industry are also seen to counteract legitimacy. For example, the high safety standards required for hydrogen aircraft, and the fact that these systems do not yet exist in any industry. This creates uncertainty during the engineering phase. Liability is also a concern, due to the consequences when safety is not met. These factors increase uncertainty and risk and therefore reduce industrial support.

Drivers and barriers

Table 14: Drivers and barriers of SF7

SF7 Creation of legitimacy	Concerns
The public opinion is favourable and supported by a need for sustainable solutions.	Both
Communication is an opportunity to overcome concerns and increase public legitimacy.	Both
Clear political measures to promote hydrogen development increases institutional legitimacy.	Both
Industrial legitimacy is supported by new entrants willing to take risks, driven by support for sustainability.	New entrants
Incumbents that are active support industrial legitimacy and notice that OEMs boost legitimisation.	Incumbents
Public legitimacy is barred by concerns over noise and safety.	Both
A lack of communication can hinder public opinion.	Both
Uncertainties within current policies reduce institutional legitimacy. This includes the availability of hydrogen, a hydrogen value chain, regulations, policy scope and continuation of policy instruments.	Both
Industrial legitimacy is reduced by actors due to the long development time and concerns over safety, liability and profitability.	Both

The creation of legitimacy is equally affected by both drivers and barriers, as all types of legitimacy are balanced by both. Public legitimacy is driven by a clear support for sustainability, but barred by concerns over noise and safety. Institutional legitimacy is promoted by clear political measures for hydrogen. However, uncertainties within current policies reduce support. Finally, industrial legitimacy is influenced by actors, by becoming active and demonstrating possibilities. Nonetheless, aviation-specific characteristics and concerns over profitability limit the legitimacy. Overall, these barriers effect both incumbents and new entrants as they are inherent to external effects.

5.2.8 Functional performance

To determine the performance of a systemic function, the *drivers* and *barriers* are used to evaluate the functions in Table 15 on a five-point scale of very weak to very strong. This is determined by reviewing the impact of the drivers and barriers, rather than their quantity. This provides an overview of the worst- to best-performing systemic functions and the most important influences for each type of actor.

Table 15: Evaluating systemic functions

Systemic function:	Function evaluation:	The reason why the specific function is this way:
Entrepreneurial activities (SF1)	Strong	Actors drive this SF by a strong *targeted involvement* throughout the value chain and the presence of (inter)national *demonstrator* projects. Yet, activities are somewhat limited by *high requirements* and *costs* for aviation. Specifically, incumbents operate more *internationally* and focus on *ecosystem improvements* to sustain an important role in the industry. But, they are *less influenced by new policy* when they are already active. New entrants focus on *technological development*, leveraging their *experience* from other industries to facilitate a *sustainable* transition. Nonetheless, policy does not always *align* in terms of their *scope* and *coverage*. Yet, the effects of these barriers are limited.
Knowledge development (SF2)	Very strong	Strong involvement of actors in *knowledge creation*, especially knowledge institutes. Incumbents provide *R&D* and *testing facilities* and new entrants mainly facilitate *education opportunities*. This SF is unrestricted by barriers.
Knowledge diffusion through networks (SF3)	Moderate	Strong *collaboration* occurs between actors that actively diffuse knowledge. However, collaboration with governments is limited by *capabilities* and knowledge attraction is constrained by *IP protection* and *aviation-specific requirements*. Incumbents in particular cooperate with *OEMs* and seek knowledge from *other industries*. However, their international collaboration is limited by *constraints*. New entrants provide knowledge from *other industries*, but their *eligibility* for policy projects is limited. These barriers counteract knowledge diffusion, which is overall moderate.
Guidance of the search (SF4)	Very weak	Some *direction* is provided by policy and safety authorities. Nonetheless, stronger barriers emerge from *technological challenges*, constrained development due to *high requirements* and *complex certification*. The direction of policy is limited by *representation*. As well as *continuity and consistency* according to incumbents. New entrants struggle to *reach* policy officers.
Market formation (SF5)	Weak	The SF is driven by a *clear vision* of the development of the market and the opportunity of a *regional market*. Strong barriers originate from market conditions such as *aviation-specific requirements*, a *long return on investment*, and *affordability*. Other modes of *transport* are therefore favourable. Incumbents expect the market to form *later* due to *fleet renewal* and are therefore split on the *potential*.
Mobilisation of resources (SF6)	Very weak	The access to resources is improved by *sustainability efforts* and the *LiT programme*. *Knowledge* is accessible. Strong barriers emerge in the attraction of *financial resources, personnel* and *uncertainty* of the future *availability* of materials and hydrogen. New entrants are more likely limited to *financial resources* and *capacity* than incumbents.

Creation of legitimacy (SF7)	Moderate	Public and institutional legitimacy is created by a clear support for *sustainability* and *political measures*. Industrial legitimacy is provided by new entrants taking *risks* and *sustainability efforts*, and incumbents *diversifying* their activities. However, legitimacy is barred by *public concerns*, *uncertainties in policies* and concerns within the industry such as *liability* and *profitability*. Therefore, the legitimacy is moderate.

Table 15 shows that overall, SF2 and SF1 are the strongest functions and that SF4, SF5 and SF6 are the weakest. It is therefore important to prioritise the improvement of these functions with policy instruments. However, not every type of actor experiences the same drivers and barriers.

When focussing on drivers and barriers only experienced by incumbents, it can be determined that they benefit SF1, SF3 and SF7 with several drivers related to (international) collaborations in private consortia and with OEMs. In addition, their knowledge development (SF2) is stronger due to R&D and testing facilities. Barriers distinctive to incumbents relate to knowledge diffusion (SF3) with limitations to international collaborations. Moreover, entrepreneurial activities (SF1) and guidance (SF4) are affected by policy influence, continuity, and consistency. Finally, concerns over the market formation (SF5) post obstacles. Overall, the drivers position the incumbents better in the innovation system, whereas their barriers are mainly influenced by policy.

New entrants experience fewer unique drivers. Activities (SF1) and industrial legitimacy (SF7) are supported by the new entrants's willingness to take risks, drive for sustainability and development of technologies using their experience from other industries. Furthermore, they develop knowledge (SF2) through educational programmes and help diffuse knowledge (SF3) brought from other industries. However, new entrants more often struggle to utilise and influence existing policy, limiting their activities (SF1), knowledge diffusion (SF3), and guidance (SF4). Furthermore, their access to financial resources and capacity (SF6) is more likely limited due to their size. Generally, these drivers benefit the new entrants in some functions, although barriers are restricted by policy and their size. Still, incumbents and new entrants are mostly influenced by drivers and barriers that influence them both.

Three common barriers that influence both types of actors on multiple functions are identified in the analysis: First, the highly aviation-specific requirements for design and safety affect the development and costs of hydrogen aircraft. This resulted in actors to not conduct entrepreneurial activities (SF1), limit the attraction of knowledge (SF3), prioritise different developments (SF4), delay market formation (SF5), impede access to investments (SF6), and reduce industrial legitimacy (SF7). Second, the long development times and lengthy return on investments create uncertainty. This affected actor's entry to market (SF1), challenges in development (SF4), market conditions (SF5), investments (SF6) and industrial support (SF7). Third, existing policy has influenced functions by a misalignment of policy with actor's activities (SF1), limited capabilities in policy designs (SF3), limited direction of policy (SF4), and industrial legitimacy (SF7). Is it effective to target the resolution of these three common barriers, which relate to the three weakest systemic functions.

§5.3 Policy instruments

To improve these systemic functions, suitable policy instruments need to be identified. A policy instrument toolbox was established, introduced in the theoretical framework (Table 4). With this toolbox, instruments can be selected to effectively address and remove identified barriers. Instruments only focus on barriers to reduce restrictions in the development of functions, this is common practise in TIS literature (Wieczorek & Hekkert, 2012).

Effective policy instruments should have a goal, type, and design features (Rogge & Reichardt, 2016). The goals are determined by the barriers experienced by incumbents and new entrants and the barriers of the weakest systemic functions. Some of these barriers are common barriers that may indirectly effect other systemic functions as well. The type of instruments is either informative, regulating, or economic. The design features are added to ensure that the instrument supports the actor's needs.

Actors indicated in their interviews three sets of design features they expect from policy. First, the government should *create recognition*, *reduce risk* and *attract investors*. Recognition can be created by placing a spot on the horizon, which in turn reduces risk. Risk can likewise be reduced by creating policy needed for larger investments. Investments can be facilitated when a governmental organisation connect actors with investors and pension funds. Second, policy should *provide direction*, *set short-term targets* and *extend current policies* to cover more topics. Direction can be provided by vision documents that are extended with technology-specific roadmaps. Short-term targets are suggested to improve support. As policies do not cover all activities, it is suggested to extend these. Third, actors advise that policy should *have continuity*, *be flexible*, and *be available for input*. Continuity from long-term policy reduces risks and improves market conditions. Flexibility allows policy to adjust to the resolution of several uncertainties such as technical innovation. Lastly, government institutions are recommended to be contactable when ambiguities arise. These sets of features are included in Table 16 and help design and condition effective instruments.

Table 16: Policy instruments

Systemic function:	Goal:	Instrument:	Type:	Design features:	Indirectly effects:

Guidance of the search (SF4)	Reduce technical challenges and aviation-specific requirements	Technology standards	Regulating	Reduce risk, have continuity	SF1, SF3, SF5, SF6, SF7
	Improve continuity and consistency of policy for incumbents	Roadmap	Informative	Create recognition, provide direction, set short-term targets, have continuity	SF1
	Allow new entrants to reach policy officers	Policy evaluation procedures	Informative	Be flexible, available to input	SF1, SF3
Market formation (SF5)	Reduce uncertainties limiting market formation: long development time, return on investments and affordability	Market-based scenario's	Informative	Reduce risk, provide direction, be flexible,	SF1, SF4, SF6, SF7
	Assure incumbents on the formation of the market	Roadmap	Informative	Create recognition, provide direction, set short-term targets, have continuity	SF7
Mobilisation of resources (SF6)	Improve attraction of financial resources	Loans/guarantees for innovative projects	Economic	Extend current policies, reduce risk, attract investors	SF5
	Assure the future availability of hydrogen	Grid access guarantee	Regulating	Reduce risk, have continuity	SF7
	Support new entrants to gain access to resources, including the eligibility for projects	Funds, loans and subsidies	Economic	Extend current policies, be flexible	

Table 16 lists seven different policy instruments to improve the three weakest functions and aid incumbents and new entrants in overcoming their main barriers. These actor-focused policy instruments support a specific goal and fulfil the conditions set by actors and are therefore suitable policy instruments.

6. Conclusion

This thesis set out to provide innovation policy advice to the Ministry of Infrastructure and Water Management (IenW) to integrate actors into its innovation policy for sustainable aviation. This advice is based on several research steps which identified technologies, incumbents, and new entrants. To determine drivers and barriers to innovation and design suitable policy instruments.

SQ1 Identify and prioritise distinct TIS for sustainable energy carriers

Six types of sustainable energy carriers (SEC) could be identified. Their value chains included upstream logistics, airport infrastructure and aircraft operations and certain activities connect the separate value chains. For bio-based SAF and synthetic SAF, the largest challenges were found in the upstream logistics. Different production methods require further development to be technologically ready. Hydrogen combustion and hydrogen fuel cells also required innovative production methods. As well as other solutions for transport, distribution, and storage. Within the aircraft, new systems need to be developed to account for the additional weight, volume, and cooling of hydrogen. With electric and hybrid aircraft, the upstream logistics are most limited by practical implications such as net congestion. Aircraft operations require new infrastructure to store and supply electricity. The aircraft itself requires significant efficiency improvement to allow electric and hybrid aircraft to travel further. Moreover, interconnections were found between these different types of SEC, that indicate opportunities to develop products and systems that benefit multiple TISs. For instance, electric engines for hydrogen-, electric- and hybrid aircraft. Based on this analysis, hydrogen aircraft should be supported as its development requires the most technological innovation, specifically within the aircraft. Moreover, this TIS is well connected to other TISs and public-private collaborations are in place to develop hydrogen aircraft demonstrators.

SQ2 Identification of specific actors and their contributions

The research identified twenty-one stakeholders, covering a wide variety of organisational types and sizes. Actors contribute to the development of various products and systems, supply materials, and build demonstrators. Knowledge institutes and intermediaries provide knowledge creation and consultation. Half of the interviewed actors were incumbents with experience in the industry. These are usually medium to large organisations. They leverage their expertise to develop systems, consult, create knowledge, and develop the ecosystem. The other half are new entrants, start-ups or organisations attracted to the industry. They are usually smaller in size and develop demonstrators or supply products. The attracted organisations develop products that can be used in other TISs as well. Both types of actor position themselves differently and operate in a political context that influences their activities. This context is formed by four governmental institutions and provides regulatory oversight, financial support, and opportunities for collaboration.

SQ3 Drivers and barriers experienced by incumbents and new entrants

The analysis showed that for all actors, SF2 and SF1 are the strongest-performing systemic functions, while SF4, SF5, and SF6 are most limited by barriers. Distinct drivers and barriers for either incumbents or new entrants position them better or worse in the innovation system. Incumbents have unique drivers in entrepreneurial activities (SF1), knowledge diffusion (SF3), and legitimisation (SF7), mainly due to (international) collaborations in private consortia and with OEMs. However, distinctive barriers for incumbents include limitations to international collaborations, affecting knowledge diffusion (SF3). As well as policy- influence, continuity, and consistency affecting activities (SF1) and guidance (SF4). Overall, incumbents benefit from these drivers, although they are adversely affected by policies. New entrants experience fewer unique drivers. Activities (SF1) and industrial legitimacy (SF7) are supported by their experience from other industries to develop technologies, driven by sustainable efforts. This experience enhances knowledge diffusion (SF3). Knowledge is developed (SF2) by education programmes. Yet, new entrants struggle to utilise and influence existing policy. Limiting activities (SF1), knowledge diffusion (SF3), and guidance (SF4). Overall, they have limited access to financial resources and capacity (SF6) due to their size. Generally, new entrants are most restricted by policy integration and their limited size and are more affected by barriers than incumbents.

However, most drivers and barriers affected both types of actors, including three common barriers that concerned multiple systemic functions. These are the highly aviation-specific requirements for design and safety that affect the development and costs of hydrogen aircraft. As well as the long development times and lengthy returns on investments that create uncertainty. Finally, existing policy affects multiple functions through misalignment of policy, limited capabilities in policy designs, and limited direction. Addressing these is effective in improving multiple functions at once, including the weakest functions guidance of the search (SF4), market formation (SF5), and the mobilisation of resources (SF6).

SQ4 Innovation policy instruments

Seven policy instruments can enable the three weakest functions to improve and target the main barriers for incumbents and new entrants. Guidance of the search (SF4) can be improved by technology standards, a roadmap, and policy evaluation procedures. Technology standards will reduce technical challenges and uncertainty of aviation-specific requirements. A roadmap will help to improve the continuity and consistency of policy for incumbents. This roadmap should consist of short-term targets and milestones to create assurance. Policy evaluation procedures allow new entrants to reach policy officers and ensure their representation. Evaluation procedures include a regular assessment of policy to determine if they support the desired actors. Market formation (SF5) can be strengthened with market-based scenarios and a roadmap. Market-based scenarios should be developed to reduce uncertainties limiting market formation. These scenarios aim to inform actors on the development of demand and costs. As well as to provide information on the return on investment. The roadmap designed for SF4 can also assure incumbents of the formation of the market. The mobilisation of resources (SF6) can be improved by loans and guarantees for innovative projects, grid access guarantee, and funds, loans, and subsidies. Loans and guarantees for innovative projects should improve the attraction of financial resources, as it reduces risks to attract investors. Grid access guarantee can assure the future availability of hydrogen. This regulating measure reduces the risks by ensuring access to resources. Finally, funds, loans, and subsidies should be extended to support new entrants to gain access to resources, as they were not always eligible for projects. Overall, these seven instruments can remove or reduce the effects of barriers limiting the innovative contributions of actors, by extending current policies and implementing new policy instruments.

§6.1 Improve integration of actors

In summary, the Ministry of Infrastructure and Water Management (IenW) is advised to integrate specific actors into their innovation policy by addressing their barriers through the recommended seven policy instruments. These support the development of the weakest functions of the innovation system of hydrogen aircraft. Moreover, incumbents and new entrants identified by this research will be assisted in overcoming their distinct barriers through actor-focused policies.

The policy officers at IenW are also advised to utilise the insights each research step has provided. For instance, the technological assessment of different sustainable energy carriers (SEC) revealed that improvements in one TIS can benefit other interconnected TISs. This allows policy officers to support multiple SEC at once. For example, supporting electric engines will benefit hydrogen-, electric-, and hybrid aircraft. Additionally, the identification of actors in the hydrogen aircraft TIS provides a complete overview to be utilised in stakeholder management. Finally, the drivers and barriers that are experienced by actors in hydrogen aircraft TIS may also be recognised in other TISs. Policy officers concerned with other innovation systems may therefore recognise patterns and can adjust their policies.

Furthermore, IenW is advised to asses new or changed policy instruments using the systemic functions.
While this research set out to determine which barriers and drivers are experienced by actors and how the barriers can be removed by policy instruments. The TIS framework can also be used to determine if policies support the systemic functions that allow the innovation system to develop. This is possible by assessing a policy instrument and determining if it promotes entrepreneurial activities, knowledge development, et cetera. Therefore, this can be a beneficial method for IenW to verify if a policy instrument meets its intended goal. In conclusion, these three sets of recommendations will not only enhance the integration of both incumbents and new entrants into policy for hydrogen aircraft, but allow policy officers at IenW to leverage this research to advance overall policy performance.

7. Discussion

This thesis set out to contribute to current TIS-related literature by studying the functional performance and policy needs of specific actors in the TIS from an actor-oriented perspective. For this purpose, a framework was designed to approach this research through four distinct research steps. First, by reviewing technologies for sustainable energy carriers (SEC), to determine how TIS-related literature can benefit from the understanding of the technological context and how SEC are connected. Second, by distinguishing between incumbents and new entrants in the identification of actors. Third, to determine whether the TIS literature can benefit from a differentiated approach to the functional performance of these specific actors. Fourth, to extend existing knowledge on the design of actor-focused policy instruments to target specific functions. Additionally, the method of data collection and analysis is reflected upon.

The technological review was an innovative starting point for researching TIS. It provided a complete overview of technologies, that helped to understand how SEC are connected and to focus the research. Therefore, it can be a useful method to incorporate the technological context of TIS into the TIS framework. The results highlighted what activities in the value chain required innovative technologies. This supports the decision to target hydrogen aircraft and the aircraft manufacturing industry. The technological review also highlighted that results that relate to one SEC (e.g. the development of electrical systems), may also be generalised to other SEC as well (e.g. electric and hybrid aircraft). Therefore, the established value chain can be used as a starting point for further research of other SEC.

While some recent literature has adopted an actor-oriented perspective to research TIS, the distinguishment of actors between incumbents and new entrants deviated from current TIS research (Gruenhagen et al., 2022; Jansma et al., 2018; Planko et al., 2017). The review of the actor-oriented studies, included in the theory, concluded that several functions can be interpreted differently by adopting an actor's perspective. However, the results of this research did not indicate different interpretations of functions compared to studies that did not adopt an actor-oriented perspective. Yet, as the literature review suggested, the results did find barriers that relate to multiple functions. These include aviation-specific requirements, long development times, and return on investments. Thus, these results only partially support existing actor-oriented research. However, the study did provide new insights in comparing the contributions of incumbents and new entrants. Incumbents were found to be more focused on supporting activities such as knowledge creation and ecosystem development. In comparison, new entrants position themselves more often at the start- or end of the supply chain and leverage experience from other industries.

The functional-structural analysis provided additional insights into these two types of actors. This study did confirm that distinctive drivers and barriers place these incumbents and new entrants differently in the TIS. For example, it concluded that incumbents are better able to access resources than new entrants. However, most drivers and barriers were applicable to both types of actors. Therefore, the differentiation between incumbents and new entrants may not be necessary if a TIS aims to provide a more generalised overview of the current performance of an innovation system. Still, the distinct drivers and barriers that were found provided a useful specification for designing effective policy instruments. Further research could thus explore how to best leverage distinguished actors for actor-focused policy.

The final research step designed these policies for specific functions, using a policy toolbox and determining a goal, type and design features. Only select studies have previously adopted an approach to policy instruments for an individual function, as previous literature determined instruments based on the presence and capacity of structural components (Kivimaa & Virkamäki, 2014; Wieczorek & Hekkert, 2012). This study first attempted to design instruments based on the latter approach, but determined that not all barriers related to structural components and could therefore not be targeted by this approach. A notable example is a barrier of SF6 that is related to the availability of resources from competing technologies. This barrier is derived from the technological context and does not directly relate to the presence of capacity of actors, interactions, institutions or infrastructure. Therefore, an approach was chosen to select policy instruments for individual functions. The resulting policy instrument toolbox has provided a useful method to target the weakest-performing functions directly. Moreover, the goals, type, and design features adapted from Rogge & Reichardt (2016) ensured a valid instrument, which directly associated barriers and needs of actors to policy. For instance, a roadmap to assure incumbents of the formation of the market which creates recognition and provides direction. However, for some functions (e.g. SF4), only a limited amount of instruments could be determined. This tentative approach to establishing a policy instrument toolbox could therefore still benefit from further research.

The novel approach to research this case using these four research steps offered valuable insights. The technological review proved to be a useful starting point for TIS research, to scope and connect contextual technologies. Furthermore, distinguishing between actors provided insights into the different positioning of actors. However, few distinctive drivers and barriers were determined. Still, TIS literature can benefit from this differentiated approach to focus policy instruments. Finally, the adopted method to design policies is effective in connecting findings to address barriers. However, further research is needed to extend the policy instrument toolbox. Overall, this approach has established a solid foundation, but additional research is essential to fully realise its potential and further refine the undertaken steps.

§7.1 Data collection and analysis

The methods of data collection and resulting analysis provided various limitations and contributions. First, conducting informal interviews with experts on specific topics proved helpful in validating the results of the literature analysis. It also provided valuable perspectives for the rest of the research. Second, the research population consisted of just twenty-one actors with whom fifteen interviews were conducted. The analysis of these interviews resulted in sufficient data to determine drivers and barriers to innovation. Yet, the variance in answers was broad which can implicate the validity of the results as some valid answers were not mentioned often. The data collection could therefore have benefited from more interviews. Third, the descriptive coding and thematic analysis of the interviews proved to be a valuable method of inductively identifying different themes, listed in Appendix II. These themes were able to be used to systemically describe the drivers and barriers of a function. For instance, legitimacy (SF7) was categorised into public-, institutional-, and industrial legitimacy. Further research can use these themes, to more precisely measure drivers and barriers within a function. In conclusion, these approaches to data collection and analyses affected the research's validity and offered new insights.

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Appendix

Appendix I: Data collection sub-question one

To answer the first research sub-question, a literature review was performed and informal interviews were held to define the three TISs related to sustainable energy carriers: Sustainable Aviation Fuels, electric aircraft, and hydrogen aircraft.

Literature review

The literature review involved keywords found in existing literature that can be included in search queries, along with general keywords. Each keyword is adapted for a search term, to include variations of a certain word such as 'technology' and technologies'. An OR operator is included with a pipe '|', selecting one search term. This list is an iterative concept and will be expanded upon.

General:

Keyword	Search terms
Sustainable energy carriers	"Sustainable energy carriers"
Sustainable aviation	"Sustainable aviation"
Technical Innovation System	"Technical Innovation System"|"TIS"
Technologies	Technolo
Generation	Generat
Production	Produce|Production
Aircraft	Aircraft
Innovation	Innovati

Electric aircraft:

Keyword	Search terms
Power system	"Power system"
Electric power	"Electric power"
Engine	Engine
Aircraft Propulsion	"Aircraft propulsion"

Hydrogen:

Keyword	Search terms
Hydrogen	Hydrogen|"Sustainable hydrogen"|"Green hydrogen"
Engine	Engine
Fuel cell	"fuel cell"

Sustainable Aviation Fuels

Keyword	Search terms
Sustainable Aviation Fuels	"Sustainable Aviation Fuels"|SAF
Biofuels	Biofuel
Synthesized aviation fuel	"Synthesized aviation fuel"
Biokerosene	Biokerosene

These key terms can be combined using operators AND, OR, and – (not) to create search queries for Google Scholar. An example of this is: "Sustainable Aviation Fuels"|SAF AND generate AND technolo -biofuel. This results in a list of different SAF generation technologies excluding biofuels. Applied queries were recorded along with the amount of results and used articles. Queries were used until the analysed literature was found to be exhaustive.

Informal interviews

Informal interviews were conducted with 18 policy officers of the Ministry of Infrastructure and Water Management. These remain anonymous. Their cluster within the department of Sustainable Aviation and knowledge areas are listed below.

Nr.	Cluster	Knowledge areas
1	Doelen, Normeren en Beprijzen	CO2-plafond
2	Doelen, Normeren en Beprijzen	EU ETS, mondiale, Europese en nationale doelen, niet CO2-klimaateffecten
3	Doelen, Normeren en Beprijzen	CO2-plafond en niet-CO2-klimaateffecten
4	Doelen, Normeren en Beprijzen	Beprijzing, gedragsbeïnvloeding, privéjets
5	Duurzame Brandstoffen	Coördinator cluster

6	Duurzame Brandstoffen	ReFuelEU Aviation, DSL subsidie, Duurzame brandstoffen van de Duurzame Luchtvaarttafel
7	Duurzame Brandstoffen & Kennis en Innovatie	Renewable Energy Directive, Synthetische kerosine en waterstof, Infrastructuur voor duurzame energiedragers, Europese en nationale bijmengdoelen, biogrondstoffen
8	Gehele afdeling	Omgevingsmanager duurzame luchtvaart
9	Internationaal	State Action Plan
10	Kennis en Innovatie	Detachering ILT
11	Kennis en Innovatie	Coördinator
12	Kennis en Innovatie	Luchthavens, grondgebonden operaties, duurzame energiedragers. Alternative Fuels Infrastructure Directive
13	Kennis en Innovatie	General Aviation en Business Aviation, samenwerking met FR en DUI, duurzaam taxiën
14	Kennis en Innovatie	Innovatiebeleid, vliegtuigontwikkeling en -technologie, hybride en elektrisch vliegen, vlootvernieuwing
15	Luchtvaart in Transitie	Programmamanager
16	Luchtvaart in Transitie	Plaatsvervangend programmamanager, sustainable knowledge, staatssteuntraject
17	Luchtvaart in Transitie	Liaison tussen EZ en IenW, sustainable ecosystems en internationaal
18	Luchtvaart in Transitie	Sustainable technology, waterstof.

Utrecht University

Ministry of Infrastructure and Water Management

Appendix II: Descriptive coding and thematic analysis

Descriptive coding: (Codes with zero references are supportive codes or unique to one type of actor)

Incumbents:

Name	Files	Reference
SF2 Knowledge development	0	0
Onderzoek te doen	4	5
Kennis delen	3	4
Rol van verspreiden van kennis	3	4
Kennis ontwikkelt door steun van de overheid	2	4
IP beschermen, kennis behouden	2	4
Samen werken voor kennis	3	3
Kennis uit andere mobiliteiten en industrieën	2	3
Opleiden van kennis studenten en PhD'ers	1	2
Kennisinstellingen werken meer samen met bed	1	2
Context van vliegtuigen	1	1
Samenwerken kennisinstellingen	1	1
Waterstof kennis opbouwen breder dan Luchtva	1	1
Investeren	1	1
Grote bijdrage	1	1
Toepassen van kennis	1	1
Kennis uit het buitenland	1	1
Kennis op laag TRL	1	1
Benodigde kennis is complex	1	1
Inkopen van kennis	1	1
Specifieke kennis ontwikkeling	0	0
Touwtrekkersfunctie	0	0

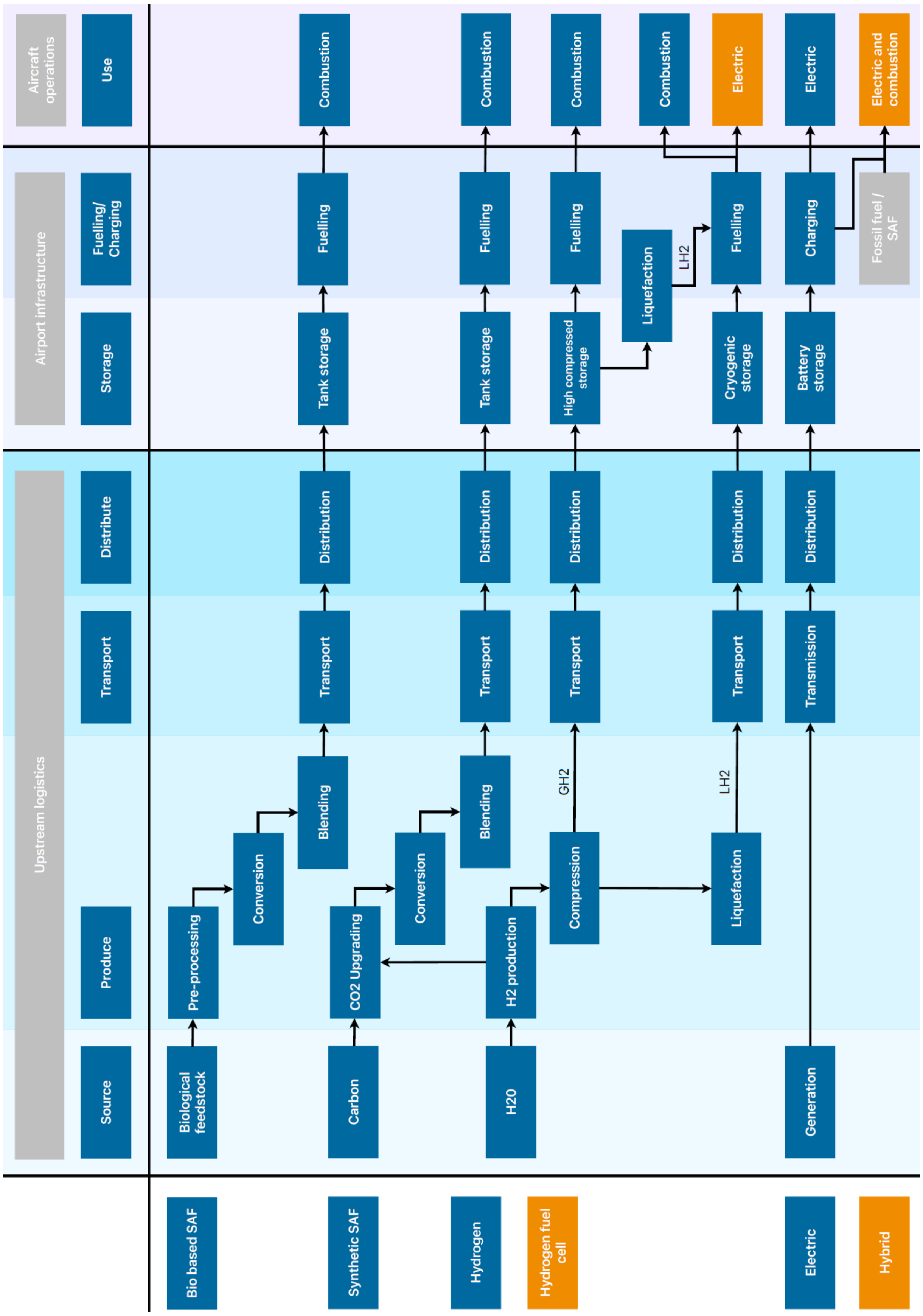
New entrants:

SF2 Knowledge development	0	0
Samenwerken kennisinstellingen	7	8
Samen werken voor kennis	6	8
Opleiden van kennis studenten en PhD'ers	4	7
Kennis uit andere mobiliteiten en industrieën	3	4
Kennis delen	2	5
Rol van verspreiden van kennis	2	2
Onderzoek te doen	2	4
Context van vliegtuigen	1	1
Kennis ontwikkelt door steun van de overheid	1	1
IP beschermen, kennis behouden	1	1
Kennis uit het buitenland	1	1
Touwtrekkersfunctie	1	1
Waterstof kennis opbouwen breder dan Luchtvaa	0	0
Investeren	0	0
Grote bijdrage	0	0
Toepassen van kennis	0	0
Specifieke kennis ontwikkeling	0	0
Kennis op laag TRL	0	0
Kennisinstellingen werken meer samen met bedri	0	0
Benodigde kennis is complex	0	0
Inkopen van kennis	0	0

Thematic analysis:

Systemic function:	Themes:
Entrepreneurial activities (SF1)	Positioning of organisations, Pilots, Becoming Active,
Knowledge development (SF2)	Creation of knowledge, Acquisition of knowledge
Knowledge diffusion through networks (SF3)	Industry collaboration, Government collaboration, Knowledge sharing
Guidance of the search (SF4)	Influence on business operations, Direction of innovation policy
Market formation (SF5)	Market developments, Market prospects
Mobilisation of resources (SF6)	Access to resources (Financial, Knowledge, Capacity, International), Changed situation
Creation of legitimacy (SF7)	Public legitimacy, Institutional legitimacy, Industrial legitimacy

Appendix III: Value chain



Appendix IV: List of drivers and barriers

Drivers in black, barriers in red. Drivers and barriers concern either new entrants or incumbents, or both.

SF1 Entrepreneurial activities	Concerns
Activities occur throughout all steps of the product development process and within different tiers, from materials to aircraft development.	Both
Clear targets are set for developing improved products.	Both
Incumbents focus on ecosystem improvement and networks and operate internationally.	Incumbent
New entrants focus on the development of technologies, leveraging experience from other industries.	New entrant
Most actors are involved in several national and international programmes for hydrogen aircraft demonstrators.	Both
Incumbents become involved to sustain an important role in the future and interest of OEMs.	Incumbent
New entrants become involved to facilitate a sustainable transition.	New entrant
Both types of actors also become involved for earning potentials and new business models.	Both
The existence of the LiT programme and European projects enable business activities.	Both
Targets are often focused on demonstrating possibilities rather than complete development of marketable products.	Both
Some demonstrator programmes are subject to delays.	Both
Actors do not become involved due to high requirements for aviation, high costs of development, a controlled market, and competition with established technologies. This occurs more often with new entrants, as they are more prone to risk.	Both
Some incumbents were not influenced by policy as they were already active in projects.	Incumbent
Some new entrants were not influenced by policy as they the policy did not align with their business activities in terms of their scope and coverage.	New entrant
SF2 Knowledge development	**Concerns**
Knowledge is created by incumbents through Research & Development and knowledge-specific programmes.	Incumbents
All new entrants and some incumbents collaborate to create knowledge together, with the intent to acquire specialised knowledge.	Both
Knowledge is developed by incumbents through testing, using facilities offered by other actors.	Incumbents
New entrants create knowledge by educating students and PhD programmes.	New entrants

SF3 Knowledge diffusion through networks	Concerns
Actors collaborate frequently, most often with knowledge institutes.	Both
Incumbents form private consortia and commit to long-term collaborations.	Incumbents
OEMs perform limited business activities within the Netherlands. Yet, they cooperate with a considerable amount of actors, often incumbents.	Incumbents
Government collaboration occurs with IenW, EZ (subsidies) and LiT (projects). Incumbents are more likely to leverage governmental organisations internationally. While new entrants prefer Dutch projects.	Both
Knowledge is actively diffused to strengthen the ecosystem and improve appropriation.	Both
Knowledge is brought from other mobilities and industries by new entrants.	New entrants
Incumbents seek knowledge from other mobilities and industries.	Incumbents
Actors have limited collaboration with airports, airlines and the industry organisation.	Both
Barriers to collaborate with governments occur due to the following factors: IenW's limited knowledge, policy design capabilities, and availability of policy instruments.	Both
New entrants struggled with EZ's subsidy applications and eligibility for LiT projects.	New entrants
Incumbents experience limitations in international collaboration with both industrial and governmental organisations due to administrative burdens, political influences and lower added values.	Incumbents
Regional collaboration is limited.	Both
Knowledge diffusion is barred by intellectual property protection.	Both
Knowledge attraction is constrained by aviation-specific requirements.	Both

SF4 Guidance of the search	Concerns
Aviation safety authorities EASA and the FAA are actively involved in the certification process, improving direction.	Both
Policy innovation document are available and all incumbents and half of the new entrants are informed by the direction they provide.	Both
Incumbents are aware of international policy.	Incumbents
Technical challenges to using hydrogen limit development and business operations.	Both
Adapting products and systems is constrained by aviation-specific requirements.	Both

Certification is a complex, long-term process. This results in uncertainty and various challenges.	Both
The direction of policy vision documents is limited by the balance of representation.	Both
New entrants find it more difficult to reach policy officers for questions and concerns.	New entrants
Limits in long-term continuity and consistency of policy result in uncertainty.	Incumbents

SF5 Market formation	Concerns
Actors expect a niche market to form. First for short distances and limited capacity, suitable for regional aircraft.	Both
The general global aviation market is expected to grow, improving the size of the market.	Both
The vision of different types of sustainable energy carriers is aligned.	Both
In the short term, the market is limited to short distances and limited capacity.	Both
While a commercial aircraft is expected sooner, incumbents expect a limited sustainable impact until 2050-2070.	Incumbents
Incumbents are split on the (limited) potential of the industry within the Netherlands.	Incumbents
Market formation is limited by several market conditions that limit development. This includes the uncertainty due to a long development time, long return on investments, and affordability.	Both
Actors expect SAF to attract greater attention than hydrogen, which can have an impact on market formation.	Both
Other modes of transport might be more favourable due to the limited application of hydrogen at first.	Both

SF6 Mobilisation of resources	Concerns
Some actors mention sufficient overall access to resources.	Both
Knowledge is accessible for most actors and both types of actors utilise previous experience to extend their knowledge.	Both
Innovation policy has limited incumbent's access to resources in the past. Yet, current access for actors is improved by the LiT programme.	Both
Global sustainability efforts increase the availability of resources and attract new entrants.	Both
Financial resources are limited due to restricted attraction of investments.	Both
Personnel is scarcely available and difficult to attract to this industry.	Both
The capacity to utilise resources limits the allocation of resources.	Both
New entrants are more likely limited to financial resources and sufficient capacity.	New entrants
Geopolitical tensions and competition within the EU restrict overall access to resources.	Both
The future availability of resources may be limited by competition from sustainable industries and the availability of infrastructure and electricity.	Both

SF7 Creation of legitimacy	Concerns
The public opinion is favourable and supported by a need for sustainable solutions.	Both
Communication is an opportunity to overcome concerns and increase public legitimacy.	Both
Clear political measures to promote hydrogen development increases institutional legitimacy.	Both
Industrial legitimacy is supported by new entrants willing to take risks, driven by support for sustainability.	New entrants
Incumbents that are active support industrial legitimacy and notice that OEMs boost legitimisation.	Incumbents
Public legitimacy is barred by concerns over noise and safety.	Both
A lack of communication can hinder public opinion.	Both
Uncertainties within current policies reduce institutional legitimacy. This includes the availability of hydrogen, a hydrogen value chain, regulations, policy scope and continuation of policy instruments.	Both
Industrial legitimacy is reduced by actors due to the long development time and concerns over safety, liability and profitability.	Both