Master's Thesis – Master Sustainable Business and Innovation

Identifying the Interactions between the Technological Innovation Systems of Bio-SAF and Synthetic SAF in the Randstad Cluster in the EU and Dutch Institutional Context

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Abstract

The aviation sector is a major contributor to environmental pollution, necessitating the urgent adoption of more sustainable fuel alternatives. Bio-sustainable aviation fuel (bio-SAF) and synthetic SAF are viable short- to medium-term solutions, particularly for medium- and long-haul flights, characterizing drop-in fuel compatibility. However, the sector faces significant challenges, including limited bio-SAF feedstock availability and synthetic SAF's current non-scalability. In response, blending mandates have been implemented in the EU institutional context. A comprehensive and integrated approach to developing and diffusion of both SAF types is essential to overcome these obstacles, advance the sector's transition towards sustainability, and reach the overarching sustainability goal.

This research examines the development of bio-SAF and synthetic SAF within the Randstad cluster, utilizing the Technological Innovation System (TIS) framework. This framework focuses on the performance of interactions between actors and associated "structural elements." Additionally, the EU and Dutch institutional contexts are analyzed for SAF development. Numerous scholars emphasize the significance of the interplay between multiple technologies within broader institutional contexts. Moreover, they underscore the importance of co-developing technologies and exploring how these technologies interact, referred to as "modes of interaction." This research aims to identify the role of institutional contexts in shaping the *"modes of interaction"* between bio-SAF and synthetic SAF within the Randstad cluster.

A qualitative case study comprising 17 interviews and desk research identifies various "modes of interaction" between the two technologies in the Randstad cluster. The findings reveal the presence of *"commensalism", "competition", "parasitism",* and *"neutralism",* while *"symbiosis"* and *"amensalism"* were notably absent. These findings contribute to understanding how institutional contexts influence TIS-TIS interactions in developing bio-SAF and synthetic SAF within the cluster, offering a foundation for the holistic advancement of bio-SAF and synthetic SAF in the cluster. Additionally, it provides a foundation for future studies seeking to explore understanding *"modes of interaction,"* allowing for studies to be compared at a higher level of aggregation and for long-term monitoring of case studies.

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Word count: 18.558

Abbreviations and Acronyms

EC European Commission
EU European Union
IPCC Intergovernmental Panel on Climate Change
IS Innovation System
NGO Non-governmental Organization
NIS National Innovation System
RHIA Rotterdam The Hague Innovation Airport
RTHA Rotterdam The Hague Airport
RIS Regional Innovation System
SAF Sustainable Aviation Fuel
SIS Sectoral Innovation System
TIS Technological Innovation System

1. Introduction

The development of alternative aviation fuels began in the United States in the 1970s. Due to rising fuel prices and uncertainties regarding supply, the focus was on producing cheaper alternatives. Today, alternative fuels are used to mitigate climate change. (Bauen et al., 2020). To achieve climate change mitigation, the 2015 Paris Agreement decided that global temperatures should not rise beyond 2 degrees Celsius and that efforts must be made to keep the rise below 1.5 degrees. (Delbecq et al., 2023). According to Shehab et al. (2023), the consequences of exceeding 1.5 degrees Celsius could have irreversible effects on the planet.

The aviation sector, a notable global emissions contributor, accounts for 2-3% of CO2 emissions, according to the Intergovernmental Panel on Climate Change (IPCC) (Shebab et al., 2023). Bauen et al. (2020) report a 140% rise in aviation activity from 2000 to 2019, with expected growth due to increased air travel access (Shehab et al., 2023). This growth escalates the industry's emissions and accountability. To mitigate this impact, Shehab et al. (2023) recommend prioritizing fuel-efficient aircraft, hydrogen and electric aviation technologies, and sustainable aviation fuels (SAFs), which are essential for the industry's sustainability and climate impact reduction.

Flying on hydrogen or electric aircraft could become a possibility to overcome the current barriers, but despite its potential, it has many obstacles. (Cabrera & Melo de Sousa, 2022; ICF, 2024). The current fleet of aircraft is designed for something other than this purpose, and the cost of renewing the current aircraft is high. So, these technologies are not viable in the short term but may be of long-term interest. (Cabrera & Melo de Sousa, 2022). In addition, flying on hydrogen and electric power is less suitable for medium—and long-haul flights (ICF, 2024). Figure 1 shows these two problems jointly.

	2020	2025	2030	2035	2040	2045	2050
Commuter » 9-50 seats » < 60 minute flights » <1% of industry CO_2	SAF	Electric and/or SAF	Electric and/or SAF	Electric and/or SAF	Electric and/or SAF	Electric and/or SAF	Electric and/or SAF
Regional » 50-100 seats » 30-90 minute flights » ~3% of industry CO_2	SAF	SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF
Short haul » 100-150 seats » 45-120 minute flights » ~24% of industry CO_2	SAF	SAF	SAF	SAF	Electric or Hydrogen combustion and/or SAF	Electric or Hydrogen combustion and/or SAF	Electric or Hydrogen combustion and/or SAF
Medium haul » 100-250 seats » 60-150 minute flights » ~43% of industry CO_2	SAF	SAF	SAF	SAF	SAF	SAF	SAF potentially some Hydrogen
Long haul » 250+ seats » 150 minute + flights » ~30% of industry CO_2	SAF	SAF	SAF	SAF	SAF	SAF	SAF

Figure 1. (Fuel) alternatives to kerosene in relation to flight type and timelines (ICF, 2024).

Drop-in fuels are a solution for short and medium-term (Cabrera & Melo de Sousa, 2022; Abrantes et al., 2021), as well as for medium and long-haul flights (ICF, 2024). These fuels can be used for existing infrastructure without the need for modifications to aircraft engines and fuel supply systems, as the fuel featuring the same quality and characteristics as conventional kerosine (Cabrera & Melo de Sousa, 2022; Abrantes et al., 2021; Arcadis, 2024; Chatrier & Van Dijk, 2024). These fuels can be categorized into bio-SAF and synthetic SAF (Su-ungkavatin et al., 2023). The distinction between the fuel alternatives is shown in Figure 2.

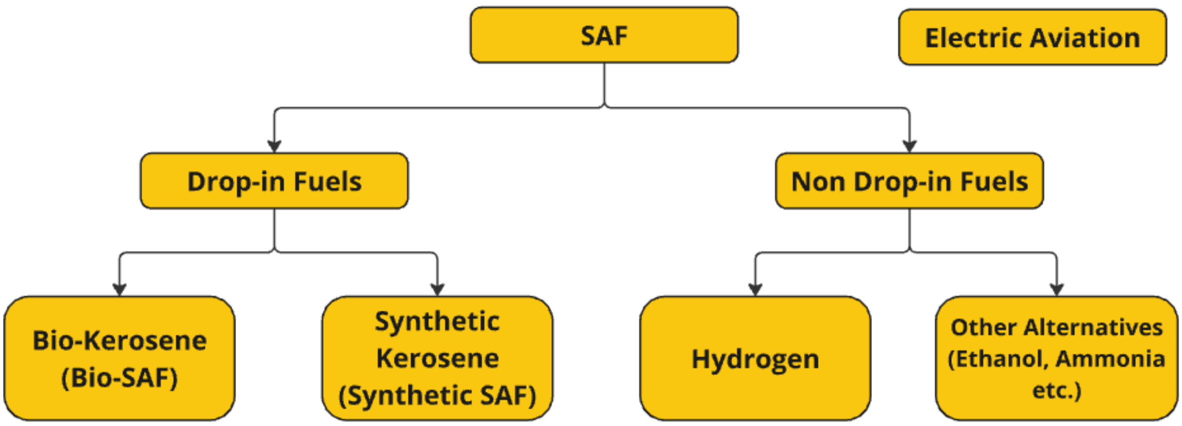

Figure 2. An overview of the categorization of various SAFs and the associated terminology. Adapted from Arcadis (2024).

According to Shahriar and Khanal (2022), bio-SAF is currently the leading industry of both fuels. However, Shebab et al. (2023) argue that the European Union (EU) has enough sustainable feedstocks to achieve enough SAF in the short term, but this is different in the long term. According to research, there is a biomass deficit equivalent to 1.35 Mt SAF in 2050. Regardless of feedstocks and processes, current technology will not be able to meet commercial demand in the future (Shebab et al., 2023), and the importance of encouraging the development of synthetic fuels is stressed (Scheelhaase et al., 2019; Chiaramonti et al., 2021; Shebab et al., 2023).

To accelerate the transition to SAF, the European Commission (EC) set a compulsory rate of incorporation for SAF over the years, including the sub-mandate of synthetic fuels. (Detsios et al., 2023), as shown in Figure 3.

	2025	2030	2032	2035	2040	2045	2050
Percentage of SAF used in air transport:	2%	6%	6%	20%	34%	42%	70%
Of which: sub-mandate Synthetic fuels (or e-fuels):	-	0.7%	1.2%	5%	10%	15%	35%

Figure 3. Total shares in fuel mix (EASA, 2024a).

The Port of Rotterdam supplies 24% of Europe's kerosene demand (Chatrier & Van Dijk, 2024). It is located near Europe's four largest airports, namely Heathrow, Paris, Schiphol, and Frankfurt (Stichting RHIA, 2021), making the port's transit function extremely important. In the Netherlands, five of the six refineries are located in the Port of Rotterdam, and almost all the terminals are in the Port of Rotterdam and the Port of Amsterdam (Arcadis, 2024). In this way, both ports are involved in developing the production, import, and export of bio-SAF and synthetic SAF, and the regional airports contribute (Chatrier & Van Dijk, 2024).

Schiphol, as one of the largest airports in Europe (RHIA Foundation, 2021), is involved in SAF developments (Arcadis, 2024), and Rotterdam The Hague Airport (RTHA) is considered an innovative airport in the region (Chatrier & Van Dijk, 2024), and has decided to start SAF blending in 2024 in cooperation with Shell. This ambitious goal continues to 14% SAF incorporation by 2030 (Huurman, 2023), an increase of 8% compared to the EU mandate. The abovementioned characteristics emphasize the relevance of Randstad as a cluster. Thereby, developments are taking place in the cluster that responds to fuel innovation.

According to the president of Shell Aviation, this is necessary to provide a robust and stable demand for scaling up the supply and use of SAF (Huurman, 2023). These ambitions are strengthened by the foundation of *“Rotterdam The Hague Innovation Airport”* (RHIA), where the aim is to develop the airport as an innovation partner, becoming the sustainable engine for the region (Stichting RHIA, 2022). Schneider et al. (2020) acknowledge the region's efforts to demonstrate projects attracting low-carbon industrial activities and related innovation. The study identifies industrial activities related to bio-SAF and synthetic SAF.
The theory will address the theory of technological innovation systems (TIS). Scientists regularly use this theory to map the current performance of technology. Some scholars use the theory to map TIS-TIS interactions (Markard et al., 2015; Bergek et al., 2015; Suurs & Hekkert, 2009; Johnson & Jacobsson, 2001; Sandén & Hillman, 2011). Also, the current theory needs to show the importance of an institutional context in influencing the interdependencies

of multiple TISs (Trencher & Wesseling, 2022; Azar & Sandén, 2011; Jacobsson & Sandén, 2021; Gawel et al., 2017).

As the TISs of bio-SAF and synthetic SAF interact in a cluster, which is affected by the EU and Dutch institutional context, the research will emphasize the importance of clusters for technology development and diffusion (Pérez-Alemán, 2005; Paraušić et al., 2017; Porter, 1998), and the role of institutional contexts are crucial for the development of both TISs individually, and in its entirety (Porter, 1998; Ketels et al., 2006; Pérez-Alemán, 2005; Paraušić et al., 2017).

The research will map out the interactions between the TIS of bio-SAF and synthetic SAF in the Randstad cluster. This will contribute to understanding the dynamics between two TISs and how this contributes to developing both technologies. Furthermore, this research will better uncover how the institutional contexts influence related TISs in a cluster with a similar sustainability purpose. Both insights could contribute to a more efficient approach to developing and diffusing both technologies and help to seek a foundation for efficient policy implications that contribute to the integral development of the two TISs and the overarching sustainability goal.

To achieve these insights, the study will answer the following research question:
What are the drivers and barriers to developing and diffusing bio-SAF and synthetic-SAF in the Randstad cluster in the EU and Dutch institutional context? This research question is answered with the help of two sub-questions:
(1) How do the technological innovation systems of bio-SAF and synthetic-SAF interact? (2) How do the EU institutional and Dutch institutional contexts affect the rate and direction of bio-SAF and synthetic-SAF in the Randstad cluster?

2. Theory

2.1. Innovation systems

According to Carlsson et al. (2002), innovation systems are frameworks that encompass knowledge creation, diffusion, and utilization. The concept emphasizes the importance of systemic interactions and the flow of knowledge and technology among the system's actors (Carlsson & Stankiewicz, 1991), which collaborate and compete to generate new technologies and innovations (Bergek et al., 2008). Innovation systems have developed over the past decades and evolved into various approaches within innovation systems linked to specified contexts such as national, regional, sectoral, or technological (Carlsson, 2002). These include the Regional Innovation System (RIS), which is limited to an innovation system within a specific region, and the National Innovation System (NIS), which is limited to country boundaries (Chung, 2002). Furthermore, a Sectoral Innovation System (SIS) focuses on a sector, and a Technological Innovation System focuses on a specific technology (TIS) (Hekkert et al., 2007).

2.2. Technological Innovation System

A TIS is characterized as a dynamic network. It operates through the interactions among various agents within a technological domain, facilitated by an institutional infrastructure that supports technology generation, diffusion, and utilization (Carlsson & Stankowiecz, 1991). It implies that there is a TIS for each technology, and each system is unique in its ability to develop and diffuse new technology (Negro & Hekkert, 2008). Because of a TIS's uniqueness is used as a descriptive framework to explore factors influencing an innovation process. It highlights the co-evolutionary relationship between technology maturation and the growth of a TIS, where each influences the other.

2.3. Structural-functional Analysis

Bergek et al. (2008) introduce a scheme of analysis to analyze an individual TIS. However, this research emphasizes the importance of the theories of TIS-TIS interactions and TISs in institutional contexts. It has incorporated these theories appropriately in the steps adjusted to this study. The scheme of analysis is shown in Figure 4. The grey and red circles are acquired from the original scheme of analysis, and the green-contoured components are adjusted from the original scheme of analysis or are added contributions.

The first step is to define the specific TIS under examination, focusing on a particular technology, sector, or area of knowledge; the second step is to identify the actors, networks, and institutions integral to the TIS. Wieczorek and Hekkert (2012) identify *"infrastructure"* as a fourth element. The TISs in context are identified, and the TISs are compared. The third step of the scheme of analysis involves evaluating the TIS's performance across seven critical functions (Bergek et al., 2008); the TISs in context are mapped, and the TISs are compared. In the fourth step, the systemic drivers and barriers of both TISs are uncovered and compared, mapping the TISs in context. Finally, the systemic drivers and barriers from the institutional contexts are related to the drivers and barriers of the cluster, resulting in a interaction, shown in Table 6. Eventually systemic drivers and problems are identified in a spaghetti diagram (Figure 5). Additionally, Bergek et al. (2008) stress the need for iterations in the analysis process.

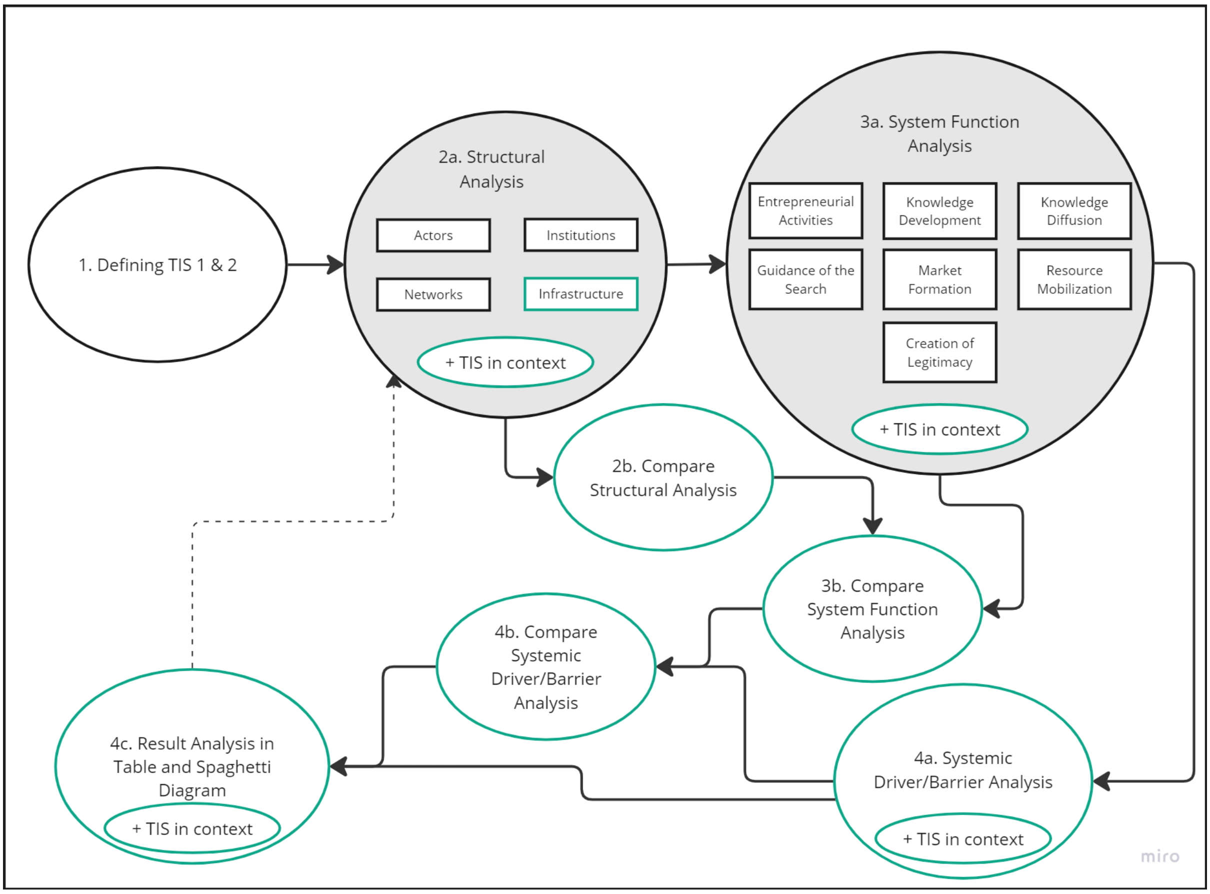

Figure 4. The scheme of analysis was adapted from Bergek et al.(2008) (Grey/Red) and the research contribution (Green).

2.3.1. Structural Elements

The TIS has structural and functional elements, with the structural elements highlighted in the structural analysis (Wieczorek & Hekkert, 2012). The first element is the 'actors,' which are the operating parts of a TIS (Carlson, 2002). Examples include involved parties, such as knowledge institutes, companies, governments, and non-governmental organizations (NGOs) (Wieczorek & Hekkert, 2012). The second element is composed of institutions, which can be both hard and soft. Complex institutions are laws and regulations, and soft institutions are norms, routines, or expectations (Hekkert et al., 2011). Jacobsson & Johnson (2000) describe the third structural element as networks, describing those cooperative relationships and links between actors. Wieczorek and Hekkert (2012) emphasize that these networks can also be bilateral, especially in the early stages of technology. The fourth element is described as the infrastructure and is divided into three parts by Wieczorek & Hekkert (2012), namely physical (machines, buildings, etc.), knowledge (expertise, know-how, etc.), and financial (subsidies, grants, etc.).

Hekkert et al. (2011) emphasize the significance of identifying structural elements, as this facilitates a comprehensive overview of the current presence or absence of these elements. These elements interact within the system to perform various functions such as generating and diffusing technology, developing, and sharing knowledge, forming markets, mobilizing resources, and guiding the direction of search and innovation efforts (Negro & Hekkert, 2008), which are elaborated in on in the next section.

2.3.2. System Functions

With the system functions (SFs), the current performance on development, diffusion, and use of technological innovation is mapped (Hekkert & Negro, 2009). Wesseling et al. (2022) argue that system functions are assessed to identify underlying system barriers, and according to Hekkert (2007), this approach contributes to understanding technological innovation systems. Eventually, system functions can serve as a foundation for policy formulation, allowing policymakers to intervene efficiently and foster innovations (Wesseling et al., 2022). The seven system functions are the following: Entrepreneurial activities, Knowledge development, Knowledge diffusion through networks, Guidance of the search, Market formation, Resource mobilization, and Creation of legitimacy (Hekkert & Negro, 2009; Hekkert et al., 2007), which are further explained in Table 1.

Table 1. System functions of a TIS, explanations adapted from Wesseling et al. (2022).

System Functions	Explanation
SF1: Knowledge Development	Learning by searching and by doing (e.g., R&D)
SF2: Entrepreneurial Activities	Entrepreneurial experimentation and commercialization of innovations (e.g., pilots)
SF3: Knowledge Diffusion	Exchange of tacit and codified knowledge in networks, including learning by interacting and using
SF4: Guidance of the Search	Providing directionality toward the focal technology and its different technological designs. (e.g., through positive expectations)
SF5. Market Formation	Activities that contribute to the demand and supply for SAF, notably through protected spaces (e.g., induced by regulations, policy, and standards)
SF6. Resource Mobilization	Allocation of financial, human, and physical resources to develop the technologies
SF7. Creation of Legitimacy	Create stakeholder support for the technologies and resources (e.g., through lobby)

2.3.3. Systemic Problems

A TIS framework describes developments and diffusion of new technologies in economic and societal contexts. However, these paths of innovation may also contain systemic problems that hinder the progression and integration of technological development (Negro et al., 2012). Wieczorek and Hekkert (2012) define these systemic problems as *"Problems that hinder the development of innovation systems."*

Negro et al. (2012) identify a series of systemic challenges inherent to the advancement of renewable energy technologies. The research delineates complex institutional challenges characterized by the misalignment and uncertainties in existing regulations and policies with the requirements of emergent technological innovations. In addition, it addresses soft institutional challenges, highlighting issues of legitimacy and societal acceptance concerning such technologies. Furthermore, the study extends to the shortcomings in essential capabilities, knowledge, interaction among stakeholders, integration of physical infrastructure, and the position of emerging technologies regarding regime technologies (Negro, et al., 2012).

The study by Trencher and Wesseling (2022) argues that barriers in emerging technologies regularly have a basis in regime technology, which can be identified from entrenched dynamics among actor networks of more developed system structures (Unruh, 2000). Unruh (2000) exemplifies a situation where regulatory uncertainties deter investment in an emerging technology, eventually exacerbating the systemic problem of the emerging technology. Hoffman (1999) emphasizes the case of institutional inertia in his research. Trencher and Wesseling (2022) also argue that barriers originate from other barriers within the development of a technology. Wesseling & Van der Vooren (2017) acknowledge both perceptions and argue that systemic problems can have implications for system functions and that these functions, in turn, trigger, maintain (case Hoffman, 1999), or reinforce (case Unruh, 2000) other systemic problems. Both perceptions are relevant, and Wesseling and Van der Vooren's (2017) research shows how the system functions and systemic problems are related.

2.3.4. System Interventions

System interventions are crucial in addressing systemic problems and fostering the transition towards sustainability and technological advancement, and to tackle systemic problems; it is crucial to understand the role of policy implications (Negro et al., 2012; Bergek et al., 2008). Jacobsson and Bergek (2004) emphasize the importance of policy implications in shaping the growth and direction of emerging technological fields, arguing that well-designed policies can mitigate risks and uncertainties inherent in technological innovation, in which the role of governments can be significant (Chaminade & Edquist, 2010). These policy implications include various actions, including financial support, regulatory adjustments, and stimulating collaboration and knowledge exchange (Edquist, 2001). Alkemade et al. (2011) emphasize the importance of a systematic approach in policy implications, as policies can influence one another. Therefore, this study also incorporates drivers in the results and data analysis, recognizing that drivers and barriers are interrelated rather than separate entities.

2.4. TIS-TIS Interactions

Markard et al. (2015) suggest that the TIS framework can extend beyond its initial scope, allowing for systemic comparisons across different TISs. Bergek et al. (2015) distinguish between vertical and horizontal TIS-TIS interactions. Herein, vertical TIS interactions are related to technology value chains, where the focal TIS is affected by changes in upstream TIS. For this study, the TIS-TIS interaction is horizontal. In this study, both TISs use the same inputs and complementary assets or generate the same outputs (Bergek et al., 2015). Bergek et al. (2015) look at the TIS-TIS interactions in the study from the perspective of one TIS influencing another. Other literature takes TIS-TIS interactions a step further.

Sandén and Hillman (2011) dive deeper and refer to technologies as *“socio-technical systems,”* stating that interaction between technologies is present the moment there is overlap in different dimensions of the *“socio-technical systems.”* These dimensions are observed as material, organizational, and conceptual (Sandén & Hillman, 2011), in which the different structural elements act (Bergek et al., 2008; Geels, 2004; Carlsson and Stankiewicz (1991).

Conceptual is described as follows: *"what actors and artifacts can do and what they ought to do, and this may be embedded in actors and physical artifacts, but they can also exist in symbolic systems. Two systems can overlap in a conceptual dimension without sharing physical artifacts or actors"* (Sandén & Hillman, 2011).

Bergek et al. (2015) highlight the concept of TIS-TIS *"running in packs,"* implying the collaborative advancements necessary for a robust shift towards sustainable practices. These interactions facilitate the emergence and development of new technologies and ensure a more effective and comprehensive approach to sustainability transitions (Sandén & Hillman, 2011). In this regard, Bergek et al. (2013) point to the relatedness of multiple TIS, where there is overlap between structural elements such as actors, networks, and institutions. Strengthening these elements means creating a more extensive and robust market and network formation, institutional support, and knowledge spillovers, which are crucial to this research.

Interactions between TISs are crucial in shaping the pathways to innovation and market acceptance of new technologies. Learning and knowledge diffusion processes are central to these interactions, where exchanges of insights and expertise can significantly accelerate technological development (Bergek et al., 2013). Carlsson and Stankiewicz (1991) underscore the role of knowledge sharing in the evolution of technological systems, highlighting its importance in overcoming technical hurdles and improving system efficiency. This vision is exemplified in the article of Jacobsson and Lauber (2006), which states that multiple technologies have a complementary nature. The study of Johnson & Jacobsson (2001) explored how an innovation hub fostered local renewable energy sectors, highlighting TIS-TIS interactions.

However, interactions can also occur in negative cases. In the article by Suurs & Hekkert (2009), the TIS-TIS interaction is about a matured and emerging technology competing to become dominant. The essence of the overlap between technologies is also further endorsed by Sandén and Hilman (2011). In doing so, Sandén & Hillman (2011) state that interactions do not simply lead to positive or negative externalities. The research identifies multiple modes of interactions between two technologies, as further described in Table 2. With this, the theory endorses the importance of the nature of the TIS-TIS interaction

Table 2. Two-technology interaction, adapted from Sandén and Hillman (2011).

Mode of Interaction	The Effect	Description
Competition	(-) & (-)	Inhibition (e.g., a shared resource or market is short in supply)
Symbiosis	(+) & (+)	Interaction favorable to both

Neutralism	(0) & (0)	Neither technology affects the other
Parasitism	(+) & (-)	Technology 1 is benefited, and 2 is inhibited.
Commensalism	(+) & (0)	Technology 1 is benefited, and 2 is not affected
Amensalism	(-) & (0)	Technology 1 is inhibited, and 2 is not affected

Furthermore, misalignments or conflicts may arise when technologies lobby for policy attention, potentially hampering the development of one technology in favor of another. Trencher and Wesseling (2022) discuss how fuel cell electric vehicles (FCEVs) face systemic barriers compared to the more advanced and widespread battery electric vehicles (BEVs), worsening FCEVs' relative barriers. This highlights the importance of examining the interactions between technologies when studying their development. (Trencher & Wesseling, 2022).

Multiple scholars criticize the so-called *"technology-neutral policy,"* in which no distinction is made in policies for different technologies. Azar and Sandén (2011) argue that mature technologies can be taken *"from the shelf,"* and new technologies still have to be developed and *"put on the shelf."* The industrial capacity has to be developed to become competitive, which requires market access before even reaching cost competitiveness (Jacobsson & Sandén, 2021). Gawel et al. (2017) further advocates for the financial advantages of technology-specific policies. He posits that insufficient investment in climate-friendly technologies can hinder the long-term potential for cost reduction. Scholars thus indicate the importance of the role of institutional context in developing related technologies.

The study by Borrás & Edquist (2013) distinguishes between regulatory, financial, and soft instruments for policy implications, and they argue that a policy mix is an ideal solution to counter problems in the innovation system. Soft instruments ensure that the government assumes the role of coordinator and facilitator rather than regulator. Scholars such as McCann and Ortega-Argilés (2015) even highlight the importance of EU policies in fostering the development of technologies, offering crucial support that facilitates the development and diffusion of technology across regions, which is strongly related to this study.

The regulations and strategies in the field of SAF in the Randstad cluster are influenced at the European and Dutch institutional levels. For example, the European government's *"ReFuelEU Aviation"* regulatory initiative is linked to the *"Fit for 55"* package, which is part of the *"European Green Deal"* (EASA, 2024a). The EU also looks at projects, such as Horizon Europe, the EU's critical funding program for research and innovation, which supports projects related to SAFs, among other green technologies (European Commission, 2022). At the national level, direction is given to support innovations. The government determines the extent of support given to knowledge and physical infrastructures, strategies, and regulations. The Ministry of Infrastructure and Water Management (I&W) is responsible for innovations in sustainable aviation in the Dutch institutional context (Rijksoverheid, 2024).

The theory above underscores the relevance of TIS-TIS interactions. Various scholars highlight the relevance of the interplay between two technologies within broader institutional contexts. Actions arising from these institutional contexts impact the technologies individually and necessitate consideration of their interactions. This research seeks to integrate these theoretical perspectives to enhance the understanding of how institutional contexts influence

TIS-TIS interactions. By establishing this interrelated framework, the study aims to lay the groundwork for effective policy implications that support the holistic development of the two TISs, ultimately contributing to an overarching goal of sustainability.

2.5. TISs in Cluster

The *"geography of innovation"* literature explores how the physical location of economic activities influences the innovation process. It argues that innovation does not occur in isolation but is significantly affected by the geographical context in which it is embedded. This includes factors such as the proximity of firms to one another, the presence of research institutions, and the availability of skilled labor and infrastructure (Malecki, 2021; Asheim et al., 2011).

Scholars also focus specifically on the cluster level, which builds on the geography of innovation by focusing on the benefits and dynamics of firms and institutions concentrated in a geographical area, often referred to as a *"cluster"* (Pérez-Alemán, 2005; Paraušić et al., 2017). Clusters provide a supportive ecosystem that includes companies, government agencies, research institutions, and other organizations contributing to innovation (Porter, 2007), which is the case for bio-SAF and synthetic SAF. Porter (1998) highlights how such concentrations can increase productivity, drive innovation, and stimulate new business formation. Bergek et al. (2015) describe this contextual structure as based on "surrounding or related" TISs. In the Randstad cluster, the geographical concentration of industries related to aviation, energy, and technology (Schneider et al., 2020) creates a fertile ground for innovation in bio-SAF and synthetic-SAF.

Thus, in addition to the concluding paragraph from the previous section, the study will include an extra dimension that considers the technologies' geographical interaction.

3. Methodology

3.1. Research Design and Analytical Approach

The design of this study was well-aligned with the case study methodology, which Bryman (2016) highlights for its ability to explore real-world contexts in-depth, matching the objectives of this research. Moreover, case studies are commonly employed in TIS analysis (Wesseling et al., 2022; Suurs & Hekkert, 2009). The research followed four analytical steps from the adjusted analysis scheme, incorporating *"TIS-TIS interactions"* and *"TIS in context,"* with detailed operationalization of each step. The first analytical step, the case delineation, is outlined in this section. Steps 2 to 4 involve a structural-functional approach and are described in this section.

3.1.1. Structural Functional Approach

Integration of TIS-TIS Interactions & TIS in Context

The theory explains the importance of TIS-TIS interactions and describes its role in cluster development. The steps of comparison in the methodology observe the TIS-TIS interactions according to the concepts described in the theory (Bergek et al., 2013; Sandén & Hillman, 2011). The findings of the comparisons were categorized. The theory also explained the importance of TIS in context, with the EU and Dutch institutional context in this study impacting the development of the TISs individually and in its entirety. To understand the role of the institutional contexts on these TISs, the EU and Dutch institutional contexts were highlighted in the structural analysis, system function analysis, and systemic problem analysis. Ultimately, the systemic drivers and barriers of the system functions were categorized and related to a *"mode of interaction"* and presented per system function.

Step 1: Defining the TISs (Case study delineation)
This first step defines the unit of analysis of both TISs or, in other words, the delineation of the case study. This section defines the nature, 'level of aggregation,' and 'range of applications. Lastly, the spatial domain is defined geographically and in terms of the contexts in which the TISs operate.

The study's nature referred to the TISs being studied as knowledge fields or products. The research questions indicated that this study looked at knowledge fields. Holmén and Jacobbson (2000) argue that the knowledge fields approach exposes knowledge around the development and use of technology, which was the case in this research. The product focuses on development regarding the materials used for a specific technology, which is also partly focused on in this research.

The 'level of aggregation' concerns the choice of including 'much' to research a broader TIS or, more specifically, define a TIS more in-depth. The 'range of applications' describes the application, product, or industry to which the analysis is limited. This concept distinguishes between broad TIS and specific TIS and between individual and related knowledge fields. For this study, the latter was relevant. In the broad sense of sustainable aviation fuels, the related knowledge fields of bio-SAF and synthetic SAF were considered. The second choice, 'range of application,' can be traced back to the choice of aviation fuels. Bio and synthetic fuels are applicable in several industries, but this research focused on their application in aviation.

As mentioned, there was a difference in spatial domain based on geography and context. For this study, the Randstad cluster was the spatial domain considered geographically. Both investigated TISs are then put in the context of European and Dutch institutional policies and strategies for SAFs.

In short, this research studied the knowledge and product fields of two related TISs, namely the TIS of biofuels and synthetic fuels in aviation. The study researched these two forms of SAF in the geographical context of the Randstad cluster and has placed both in the context of European and Dutch institutional policies and strategy.

Steps 2, 3, and 4abc: System functions analysis, comparisons, and systemic driver and problem analysis
Structure
The seven system functions were delineated from the perspective of institutional contexts and the activities within the Randstad cluster. For each perspective, the results were presented in a consistent structure. Initially, the perspectives were mapped out. Following this, a

comparison was conducted between bio-SAF and synthetic SAF within the context of the given perspective and specific system function, thereby facilitating an understanding of the interactions between the TISs. Subsequently, the drivers and barriers were analyzed from that perspective. It served as a comprehensive framework for both structural and system function analyses. Note that system functions overlap and are interrelated. To remain as concise as possible, the study attempts to avoid repetition. For this reason, data is positioned at the system function, where it is best for clarity. The data analysis further expands on the interactions between system functions and the identified TIS-TIS problems and drivers.

Execution

The research consisted of desk research and interviews. The interview data were coded following the steps detailed in Appendix D. Positive and negative statements were separated to identify drivers and barriers from each perspective for each system function. Bio-SAF and synthetic SAF overlaps were identified during the data analysis to highlight TIS-TIS interactions. Appendix E presents the drivers, while Appendix F outlines the barriers within the institutional contexts related to the corresponding TIS-TIS *"mode of interaction."* Appendix G illustrates the interdependencies between bio-SAF and synthetic SAF within the cluster, which are also associated with the TIS-TIS *"mode of interaction."*

The data analysis integrates the information from Appendices E, F, and G. The drivers and barriers identified within the institutional context and the cluster are grouped and linked. This entire interaction is related to the *"mode of interaction,"* as depicted in Table 6. This table details which drivers and barriers from the institutional context influence those from the cluster and how these relationships lead to a TIS-TIS *"mode of interaction,"* categorized by system function.

Since the same overarching drivers and barriers apply to different system functions, and the same "mode of interaction" occurs between the TISs, they are consolidated in a spaghetti diagram, shown in Figure 5. This diagram allows a deeper understanding of the interlinked system functions, systemic drivers and problems, and their *"mode of interaction."* The influence of institutional contexts on the cluster is therefore analyzed at a higher level of aggregation, serving as the foundation for effective policy implications aimed at providing comprehensive support for the development of both SAFs.

3.2. Data Collection

Data was collected through desk research and interviews. The steps incorporated results from desk research and 17 cluster experts' interviews, with an average of 45 minutes spent on the questions related to the system functions (Appendix A). In doing so, the interviews generated a comprehensive overview of both TISs. Respondents were asked to assess whether and how they perceived the EU and Dutch institutional contexts as influencing system functions at the local level for each TIS and whether they observed any interactions between both TISs. Respondents were also asked to relate the EU and Dutch institutional contexts to the identified drivers and barriers. The responses concerning the EU and Dutch institutional contexts, along with the comparisons of the TISs, were systematically categorized under the relevant system functions, further described in the data analysis. Furthermore, Appendix B indicates the structural elements that each respondent discussed, and Appendix C shows how respondents rated the different system functions, further providing insights into the interviews.

As a sampling strategy, actors in the Randstad cluster were identified by consulting experts in the field and during the desk research. A purposive sampling strategy was carried out depending on the number of actors involved (Campbell et al., 2020). The author sought to interview an equal distribution of the available actors and their expertise, as displayed in Table 3. Based on the interviews held through snowball sampling, new interviewees could also be found. Table 3 shows an overview of the respondents for this research. All respondents provided data on both bio-SAF and synthetic SAF, and no difference in quality was noted in the data obtained.

Table 3. Overview of the Respondents

Type of Organization	Respondent
Airline	R14
Airport	R1
Airport	R2
Airport	R4
Consultancy	R5
Consultancy	R12
Consultancy	R15
Environmental Organization	R9
Fuel Supplier	R3
Fuel Supplier	R6
Fuel Supplier	R8
Governmental Organization	R10
Governmental Organization	R16
Knowledge Institute	R7
Knowledge Institute	R11
Knowledge Institute	R17
Port	R13

As indicated, desk research complemented the interviews to supplement missing or strengthen particular data. Academic literature, public documents, and reports were used for desk research. Publications were retrieved from the following sources: Google Scholar, Nexis Uni, and governmental and public websites. The research aimed to map the current status of both TISs and the EU and Dutch institutional context, and the combination of search terms, which were extensive hits from 2023 onwards, are considered suitable for the research. The search terms used during the desk research are visible in Table 4. The interviews used a semi-structured interview guide with open-ended questions, which are attached in Appendix A. Interviews were recorded and were transcribed later. Finally, transcripts were coded via Condens.io. The coding scheme is in Appendix D, as mentioned before.

Table 4. Search terms desk research.

Search Terms

(Sustainable Aviation Fuel, SAF) *OR* (Bio-SAF) *OR* (Synthetic SAF, E-SAF) *OR* (EU, *EU policies*, *EU regulations*, *EU strategies*) *OR* (Dutch Government, *Dutch policies*, *Dutch regulations*, *Dutch strategies*) *AND* (Rotterdam The Hague Airport, Rotterdam The Hague Innovation Airport, RHIA, Rotterdam, Rotterdam Airport, Port of Rotterdam)
(Sustainable Aviation Fuel, SAF) *OR* (Bio-SAF) *OR* (Synthetic SAF, E-SAF) *OR* (EU, *EU policies*, *EU regulations*, *EU strategies*) *OR* (Dutch Government, *Dutch policies*, *Dutch regulations*, *Dutch strategies*) *AND* (Schiphol, Amsterdam, Port of Amsterdam)
(Sustainable Aviation Fuel, SAF) *OR* (Bio-SAF) *OR* (Synthetic SAF, E-SAF) *OR* (Rotterdam The Hague Airport, Rotterdam The Hague Innovation Airport, RHIA Rotterdam, Rotterdam Airport, Port of Rotterdam) *OR* (Schiphol, Amsterdam, Port of Amsterdam) *OR* (*names of actors* or *names of organizations* or *names of institutions* or *names of associations*) AND (EU, *EU SAF policies*, *EU SAF regulations*, *EU SAF strategies*)
(Sustainable Aviation Fuel, SAF) *OR* (Bio-SAF) *OR* (Synthetic SAF, E-SAF) *OR* (Rotterdam The Hague Airport, Rotterdam The Hague Innovation Airport, RHIA Rotterdam, Rotterdam Airport, Port of Rotterdam) *OR* (Schiphol, Amsterdam, Port of Amsterdam) *OR* (*names of actors* or *names of organizations* or *names of institutions* or *names of associations*) *AND* (Dutch Government, *Dutch policies*, *Dutch regulations*, *Dutch strategies*)
(Sustainable Aviation Fuel, SAF) *OR* (Bio-SAF) *OR* (Synthetic SAF, E-SAF) *OR* (EU, *EU SAF policies*, *EU SAF regulations*, *EU SAF strategies*) *OR* (Dutch Government, *Dutch policies*, *Dutch regulations*, *Dutch strategies*) *AND* (*names of actors* or *names of organizations* or *names of institutions* or *names of associations*)

3.3. Data Analysis

Thematic analysis was appropriate for this exploratory research. Braun and Clarke (2006) argue that thematic analysis is suitable for processing vast amounts of data into a structured and sorted overview. In this research, it was essential to adopt this approach as data from transcripts were coded among system functions and their related barriers. Braun & Clarke (2006) and Verhoeven (2020) identify three phases and six steps for a thematic analysis described in Table 5.

Table 5. Phases, steps, and description for the thematic analysis.

Phases & Steps	Description
Exploration phase **1. Familiarization** **2. Initial coding creation of categories**	1. This involves diving into the data through reading and re-reading the data and noting initial ideas.

	2. Systematically code the data set in a wide-ranging manner, tagging data snippets with codes that summarize their essential content or meaning
Reduction phase **3. Search for themes** **4. Review and refinement of themes**	3. Assemble codes into potential themes (system functions/systemic drivers and barriers), gathering all data relevant to each system function. 4. Check if the system functions/systemic drivers and barriers work to the coded extracts and the entire data set.
Reflection phase **5. Definition and naming of themes** **6. Reporting**	5. This involves developing a detailed analysis of each system function/systemic driver and barrier. 6. Systemic function/systemic driver and barrier analysis

3.4. Reliability and Validity

Bryman (2016) emphasizes the importance of reliability and validity when conducting a qualitative study. External reliability is the extent to which the study is replicable. Because this study used interviews with open-ended questions, it is almost impossible to replicate the study exactly. To ensure that someone cannot conduct a similar study, documentation of recordings is made through transcripts. Bryman (2016) also emphasizes internal reliability, which is about whether more than one observer is involved in the study. Member validation has occurred to avoid biases (Bryman, 2016). Interview outcomes were shared with the interviewees, creating control.

Member validation also played a vital role in internal validity. This deals with the alignment between the observations and the theoretical concepts. The alignment between data and theoretical concepts was checked by sharing the outcomes with the interviewees. Finally, external validation was necessary (Bryman, 2016). This involves the extent to which findings can be generalized to other situations. This research is a case study of two TISs in the Randstad cluster in two contexts.
For this reason, it is not possible to directly transfer results to another situation. Findings for this cluster cannot fully be transferred to another situation. However, theoretical findings from this study can be further explored.

3.5. Ethical Issues

Ethical issues were included in this research. Before an interview, the interviewee was asked if he or she agreed to have the audio recorded. In addition, the confidentiality of the (unused) data is added, meaning that interviewees were mentioned anonymously in the research, and company names were not linked to any statements. Finally, the data used was reviewed with the supervisor before the research was publicly available.

4. Technology Description

Bio-SAF is aviation fuels produced from renewable organic materials, such as vegetable oils (including used cooking oils) (R1; R2; R4; R5; R6; R7; R9; R10; R12; R13; R14; R16; Arcadis, 2024; Chatrier & Van Dijk, 2024), algae, waste fats, and plant residues (Hileman et al., 2009;

EASA, 2024c). These materials are converted into liquid fuels (Arcadis, 2024). Hydrogen is often required to produce these fuels (R8; R11; Arcadis, 2024). The most common production pathway for bio-SAF is the Hydroprocessed Esters and Fatty Acids (HEFA) process, which involves hydroprocessing oils and fats to produce jet fuel (Hileman et al., 2009; EASA, 2024c). Other pathways include the Alcohol-to-Jet process, where alcohols such as ethanol or butanol, derived from biomass, are converted into jet fuel, and the Fischer-Tropsch process, which gasifies biomass to produce syngas, later converted into liquid hydrocarbons (Klein-Marcuschamer et al., 2013; EASA, 2024c). The production processes are illustrated in Figure 5.

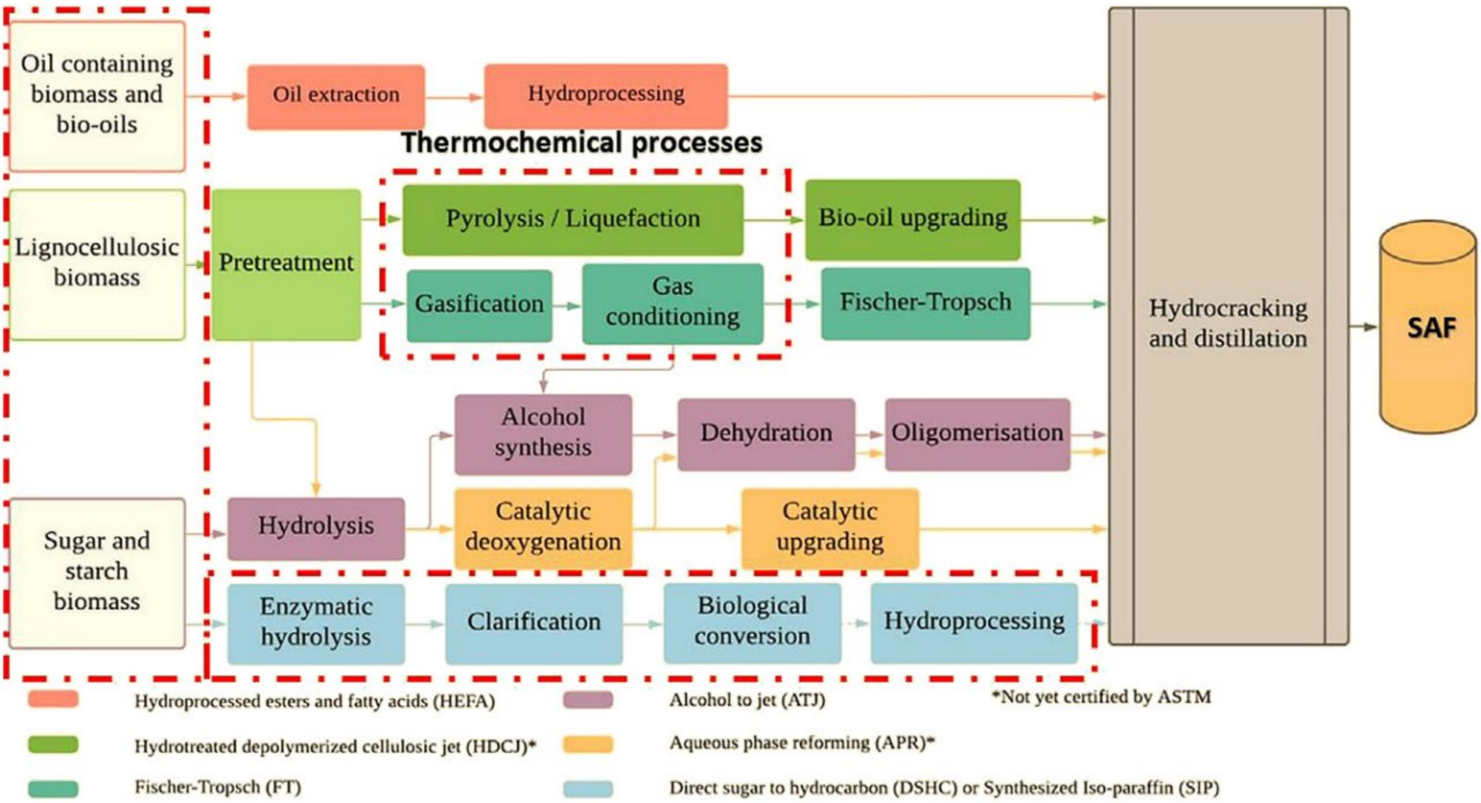

Figure 5. The production processes of HEFA, FT, and AtJ (Okolie et al., 2023)

Synthetic SAF is produced by converting (green) hydrogen (R8; R11; Arcadis, 2024) and CO2 (R8; R10; R16; Arcadis, 2024) into liquid fuels using renewable electricity. This process involves electrolysis to produce hydrogen and CO2 to create synthetic hydrocarbon fuels. These fuels are also classified as Renewable Fuels of Non-Biological Origin (RFNBOs) (Arcadis, 2024). The power-to-liquid process is the most notable pathway for synthetic SAF production, as shown in Figure 6. In this process, renewable electricity is used to split water into hydrogen via electrolysis. This hydrogen is then combined with CO2, captured either from industrial emissions or directly from the atmosphere, to synthesize hydrocarbons through the Fischer-Tropsch, ethanol, or methanol synthesis process (R11; Brynolf et al., 2018; EASA, 2024c). The Fischer-Tropsch process is used for bio-SAF and synthetic SAF.

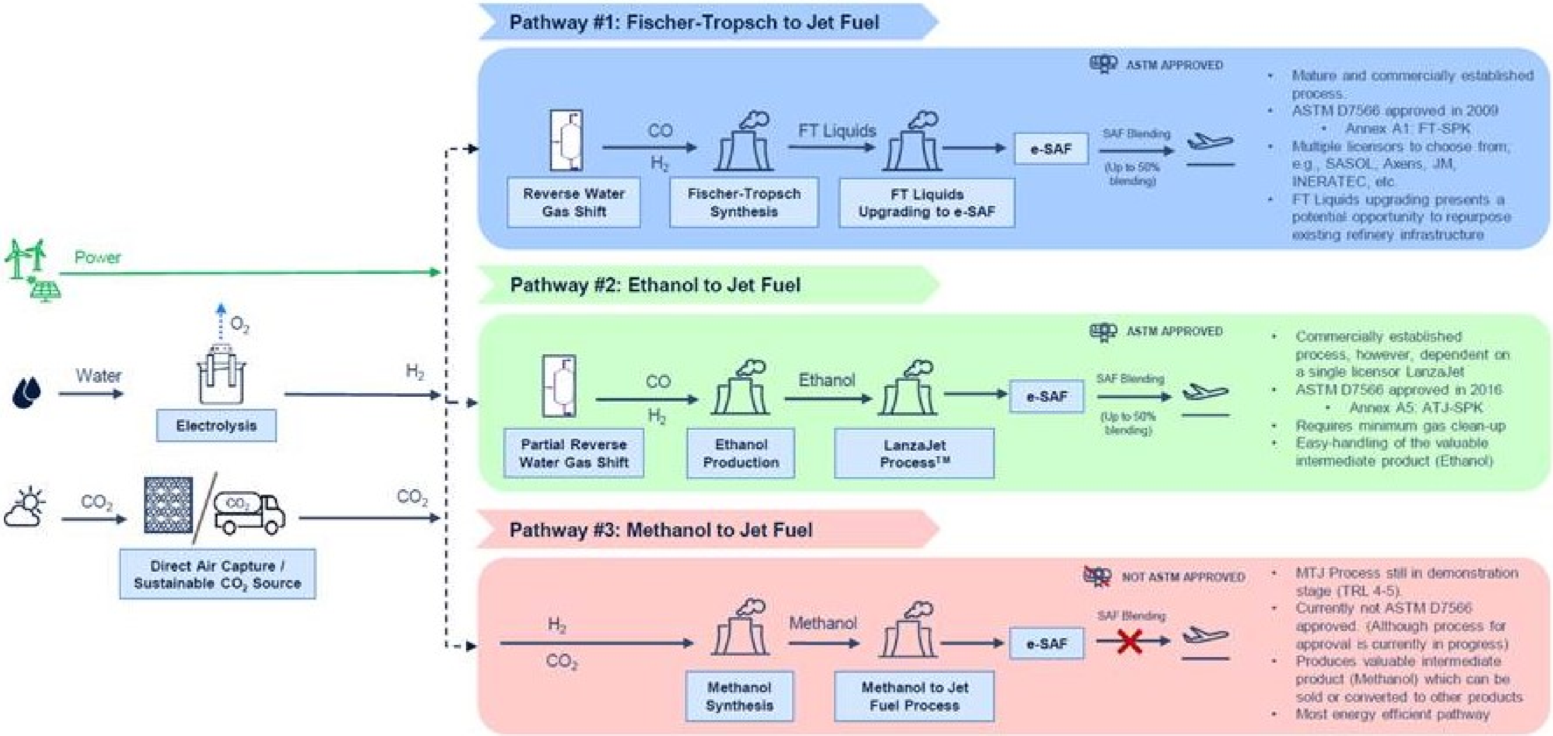

Figure 6. Production processes voor synthetic SAF (R11).

Potential and Perspective

Figure 7 depicts the timelines associated with the expected SAF production in Europe. It shows that HEFA is currently the only fuel option, with Alcohol-to-Jet and Fischer-Tropsch expected to develop rapidly. The large-scale development of Power-to-Liquid is expected to occur later. Figure 7 also illustrates the expected production scale for the various European processes.

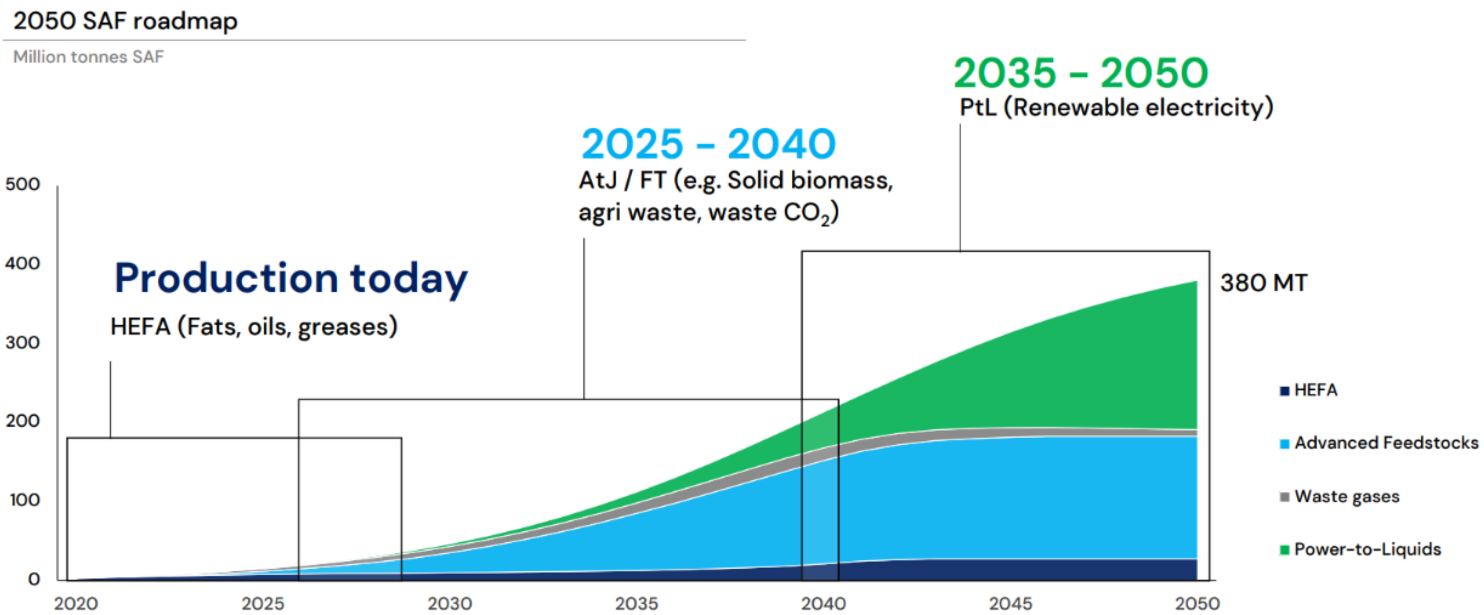

Figure 7. The production pathways and their timelines for Europe (ICF, 2024)

5. Results

The results are structured per system function; each function is first described from the EU and Dutch institutional context perspective and then from the cluster perspective. From these perspectives, the associated structural elements, drivers, and barriers are discussed for each function, and a comparison between bio-SAF and synthetic SAF is made. The drivers and barriers from the institutional contexts are further distinguished in Appendices E and F, with the corresponding *"mode of interaction."* The TIS-TIS interactions in the cluster, with the corresponding *"mode of interaction,"* are described in Appendix G.

5.1. Knowledge Development (SF1)

The roles of the EU and Dutch institutional contexts in the R&D of bio-SAF and synthetic SAF were examined to map this system function and the performance of R&D projects within the cluster.

5.1.1. The EU & Dutch Context

Europe supports R&D efforts (R1; R2; R3; R5; R8), with subsidies allocated for them through the Horizon Innovation Fund (R1; R2; R6; R8; R12), such as the Tulips project (R1; R2; R3; R4; R5; R6; R7). However, the REDIII regulation poses challenges for scaling up R&D efforts, particularly for synthetic SAF (R9).

The Dutch government contributes to the R&D of bio-SAF and synthetic SAF (R1; R2; R7; R10; R12; R17). Funding is made available for the development of new forms of SAF (R2; R16; R17), including those based on alcohol (R2; R16) as well as synthetic SAF (R16; R17). In recent years, there has been significant financial support in knowledge development aimed at sustainable innovation in aviation (R1; R2; R10), exemplified by initiatives like the National Growth Fund (R2; R5; R6; R7; R16; R17) and DEI+ (R16) through the RVO (R10; R16; R17). Additionally, knowledge development is fostered within the Sustainable Aviation Table (R2; R10; R16).

However, the Dutch government has faced a shortage of scientific personnel for many years, which has resulted in insufficient policy attention to barriers within R&D (R9; R11). Therefore, the Dutch government frequently commissions external companies to conduct studies, even when the knowledge already exists within the sector (R1; R2). In addition, the high costs of investing in R&D make it hard to support a technology successfully (R16).

5.1.1.1. Comparison of Bio-SAF & Synthetic SAF

The Tulips project supports the R&D of bio-SAF and the R&D on synthetic SAF in (R4). Also, the Dutch government holds initiatives that support the R&D bio-SAF and synthetic SAF, like the National Growth Fund (R2; R5; R6; R7; R16;) and DEI+ (R16). The Dutch government maintains a technology-neutral stance regarding investments and support (R16). Overall, R&D is a barrier to scalability (R1; R2; R3; R4; R5; R6; R7; R8; R9; R10; R11; R14; R16).

5.1.2. The Cluster

The Randstad is making good progress in R&D development (R1; R2; R6; R10), but more R&D efforts are needed (R1; R11; R12; R14). Respondents indicate that the fundamental R&D phase of SAF is completed (R1; R2; R3; R4; R5; R6; R7; R8; R9; R14; R16). Several projects contribute to the R&D efforts of bio-SAF and synthetic SAF within the cluster (R1; R2; R3; R7). The Tulips project, led by Schiphol (R1; R2; R3; R4; R5; R6; R7; R14), contributes to scalability of SAF (R4). The Zenid project, initiated by RHIA, has previously contributed to the R&D efforts (R1; R2; R4; R14; R16; R17), and currently, Synkero is continuing this work (R1; R2; R3; R4; R5). Shell has a laboratory in Amsterdam (R6). Additionally, some companies are investing in the (knowledge) development of hydrogen and electrolyzers (R3).

European projects funded by Horizon also involve knowledge institutes (R1; R2; R8; R9; R10; R16; R17), such as NLR (R2), TU Delft (R1; R2; R8; R9; R16; R17), and Utrecht University (R1). TU Delft, in particular, is a key institution for R&D (R8; R16; R17). Despite the involvement of universities, R&D progress can be improved (R1).

5.1.2.1. Comparison of Bio-SAF & Synthetic SAF

The technical R&D for both bio-SAF and synthetic SAF has been established already (R1; R2; R3; R4; R5; R6; R7; R8; R9; R10; R11; R12; R13; R14; R16; R17). In terms of R&D development phases, the HEFA technology is a frontrunner (R1; R2; R3; R4; R5; R6; R7; R10; R12; R13; R14; R16). The HEFA technology is significantly more advanced in bio-SAF than the alcohol-to-jet technology (R3; R10; R14; R16). Bio-SAF technologies are relatively ahead of synthetic SAF (R1; R2; R3; R4; R5; R6; R7; R9; R10; R12; R13; R14; R17). To successfully develop synthetic SAF, many different R&D components must be integrated and scaled up (R11).

The development depends on the same institutions and stakeholders, such as certification and blending (R2; R8). Despite the sector's and knowledge institutions' contributions, R&D is needed to enable scale-up of bio-SAF and synthetic SAF (R1; R2; R3; R4; R5; R6; R8).

5.2. Entrepreneurial Activities (SF2)

To map this system's function, the support from the EU and Dutch institutional contexts to entrepreneurial experimentation and commercialization of innovations such as pilots and scaling up of SAF was examined. Additionally, the activities within the cluster were described.

5.2.1. The EU and Dutch Context

European projects contribute to developing activities such as pilots (R1; R2; R3; R5; R11; R12). Horizon finances the Tulips project (R1; R2; R3; R4; R5; R6; R7), which conducts pilots on the scalability of SAF (R4), including increasing bio-SAF uptake through incentives (R1; R4; R5; R8; R16). These SAF incentives have made a positive impression (R4). Scaling up bio-SAF expectations is positive with Tulips and the combined SAF incentive (R4; R8). While synthetic SAF is still behind, initial reports are promising (R4).

Startups can approach the European Innovation Fund for financing needed for production and scaling up (R5). This fund is financed through the EU ETS mechanism (R5). The Net-Zero Industry Act, an initiative from the Green Deal, focuses on scaling up sustainable energy production (R16), including electricity, hydrogen, carbon capture, grid technologies, and biogas (European Commission, 2024a). The act aims to attract investments and create better market conditions (European Commission, 2024a).

The Dutch government contributes to pilots through subsidies (R3; R7; R10; R11; R16; R17), such as the National Growth Fund (R2; R5; R6; R7; R10; R16; R17) and the DEI+ program managed by the RVO (R10; R16; R17). Sometimes pilots progress to the project phase (R3; R7; R16). The National Growth Fund allocates around 350 million euros to innovation, but only a tiny portion is directed towards SAF (R9; R17), and the industry is required to contribute to national developments (R11). The sector experiences challenges in acquiring specific necessities for a project's initiation from the Dutch institutional context (R1; R3; R4; R6; R8; R12).

5.2.1.1. Comparison of Bio-SAF & Synthetic SAF

Horizon invests in the development of bio-SAF and synthetic SAF (R1; R4; R5; R8), as seen in the Tulips project (R4). The European Innovation Fund (R5; R10) also supports the development of bio-SAF and synthetic SAF (R5; R10). The Dutch government subsidizes pilots (R3; R7; R10; R11; R16; R17). However, the Dutch government maintains a technology-neutral stance regarding investments and support (R16).

The EU and Dutch institutional contexts must do more to initiate demonstration projects and scale-up efforts (R11; R14). Ten pilots running annually on synthetic SAF (R11) should be established to achieve effective scaling. This effort should involve large companies and startups (R14). Significant funding and support are still required for the development and scaling up of synthetic SAF (R2; R3; R4; R6; R9; R10; R11; R14; R16; Mutrelle, 2024), and to a certain extent for advanced bio-fuels as well (R8; R14; R16). Investment timelines for both types of SAF are behind (R7; R9; R10; R14), particularly for synthetic SAF (R1; R4; R9; R10; R11; R14; Mutrelle, 2024).

5.2.2. The Cluster

The cluster holds a strong position in the fuel industry, providing a solid foundation for the trade and production of SAF (R6; R8; R11; R12). Nearly 20 years ago, SkyNRG, KLM, and Schiphol were crucial pioneers in the SAF sector, and now Neste has joined them (R8). Commercialization and production are areas where the cluster traditionally excels (R8).

The Port of Rotterdam is a crucial hub in fuel production, storage, and transportation (R6; R8: R11: R12; R13; R14; R16, R17; Chatrier & Van Dijk, 2024). Five of the six refineries in the Netherlands are in the Port of Rotterdam (Arcadis, 2024), and almost all terminals are in the Port of Rotterdam and Port of Amsterdam (R3; R17; Arcadis, 2024). The area of Rotterdam aims to play the same supply role with SAF as it has with kerosene, accelerating the production of bio-SAF and synthetic SAF in the region (Chatrier & Van Dijk, 2024). The cluster, therefore, holds the infrastructures and facilities for conducting pilots, demonstrations, and other activities (R11; R12; R13). The Port of Rotterdam supplies 24% of Europe's kerosene demand (R12; R16; Chatrier & Van Dijk, 2024) and is located near Europe's four largest airports, namely Heathrow, Paris, Schiphol, and Frankfurt (Stichting RHIA, 2021), making the port's transit function extremely important (R13; R16). The ambition is to continue fulfilling this role for bio-SAF and synthetic SAF (R13).

In the cluster, RTHA is seen as an innovative airport (R1; R2; R3; R4; R8; R13; Chatrier & Van Dijk, 2024), exemplified by the synthetic SAF pilot with Zenid (R1; R2; R3; R4; R5; R16; R17), which had potential (R1; R2; R4; R5; R16) but lacked sufficient financial support (R1; R2; R3; R4; R5). The Zenid project also involved the Port of Rotterdam (R3). Since 2023, bio-SAF has been blended at RTHA and delivered by a tanker truck from Shell (Arcadis, 2024; Chatrier & Van Dijk, 2024).

Schiphol is primarily supplied with sustainable kerosene from the EVOS Oost terminal in the Port of Amsterdam (Arcadis, 2024) and is connected to the Rotterdam port area through pipelines (Chatrier & Van Dijk, 2024). Schiphol is also involved in pilots (R1; R2; R3; R4; R8; R13), including the Tulips project (R1; R2; R3; R4; R5; R6; R7), the synthetic SAF project Synkero (R1; R2; R3; R4; R5; R17), and the bio-SAF plant named DSL01 in Delfzijl, both of which are managed by SkyNRG (R3; R4). If the mandates remain, Synkero will hopefully deliver by 2030 (R3; R4; Arcadis, 2024). The Port of Amsterdam is involved in the Synkero project (R3).

Furthermore, SkyNRG is collaborating with Europe to scale SAF production (R4; R5). However, securing a grid connection and providing wind energy for the Synkero project is challenging due to the Dutch government's lack of help (R3; R5). Tulips focus on both bio-SAF and synthetic SAF (R4), including the SAF incentive program to increase bio-SAF uptake (R1; R2; R4; R8; R13; R14) and to promote synthetic SAF (R4). Developments in synthetic SAF production are currently underway in the Port of Rotterdam, with serious consideration being given to commercial scale (R13). Start-ups are now scaling up efforts (R6) and seeking collaborations with airports (R1).

Primarily, the major oil companies in the region are taking steps to scale up bio-SAF production (R3; R9; R12; R13), as it requires investments ranging from tens of millions (R14) to billions (R1; R10). Neste is the largest bio-SAF supplier in the Randstad (R4; R5; R13; R14; Arcadis, 2024). Neste's biofuel plant operates in Rotterdam (R5; R8; R12; R16; Chatrier & Van Dijk, 2024) and is set to expand in 2026 (Neste, 2024). Additionally, SkyNRG's plants in Delfzijl (R1; R2; R3; R5; R9; R12; R13; R14; R16; Arcadis, 2024) and Shell's plant in Rotterdam are under construction (R1; R2; R6; R8; R12; R13; R14; R16; Chatrier & Van Dijk, 2024). However, Shell's bio-SAF plant was halted in July 2024 for commercial reasons (R10; R12; R13; R16; R17).

"Shell Nederland Raffinaderij B.V., a subsidiary of Shell plc, is to temporarily pause on-site construction work at its 820,000 tonnes a year biofuels facility at the Shell Energy and Chemicals Park Rotterdam in the Netherlands to address project delivery and ensure future competitiveness given current market conditions" (Shell, 2024).

The recently announced plants are solely focused on HEFA production (R1; R2; R4; R6; R7; R9; R10; R12; R13; R14; R16), and HEFA is already commercially scalable (R1; R2; R3; R4; R5; R6; R9; R10; R12; R13; R14; R16). The first synthetic SAF plant, by SkyNRG, is scheduled for 2030 (R3; R4; R7; R13; Arcadis, 2024). SkyNRG, as a minor player, is actively scaling up bio-SAF and synthetic SAF (R3; R4; R5; R12; R14), including collaborations with Europe (R5).

5.2.2.1. Comparison of Bio-SAF & Synthetic SAF

The cluster has a favorable environment for developing SAF activities (R6; R8; R11; R12; R13; R14; R16). The Tulips project led at Schiphol, supports the development of bio-SAF and synthetic SAF (R1; R4; R5; R8; R16). Bio-SAF and synthetic SAF should have progressed further in their respective developments (R7), particularly synthetic SAF. Significant funding and support are still required for scaling up synthetic SAF (R1; R2; R3; R4; R6; R9; R10; R12; R14) and, to a certain extent, for advanced biofuels (R8; R14). The challenge for synthetic SAF lies in creating a network of partners, collectively taking the steps towards commercial scaling (R6; R10; R11), and securing the necessary financing (R6; R10; R11; R15). There is limited activity in synthetic SAF (R6; R7; R9; R10), which is used to achieve effective scaling (R11; R14).

The region provides various examples of business cases encountering multiple barriers (R1; R2; R5; R9; R10; R12). Investments in production facilities, such as a SAF plant, are risky (R1; R2; R6; R12; R17; Arcadis, 2024), which causes delays. Realizing these facilities takes a long time (R1; R2; R4), and there must be certainty that a plant will continue operating (R1; R4; R12; R13; R17). This requires several factors, including sourcing (R1), feedstock (R1; R13), transport (R1), and engineering (R1). It is challenging for small entities to make a transition from the R&D/pilot phase to commercial production (R1; R2; R3; R4; R14; R17; Mutrelle, 2024), and the task is often left to large companies (R14; R17; Mutrelle, 2024).

5.3. Knowledge Diffusion (SF3)

The analysis focused on how actors exchange knowledge in networks to map this system's function. This is considered for the EU, the Dutch institutional context, and the cluster.

5.3.1. The EU and Dutch Context

European funding facilitates collaborations that involve knowledge sharing (R1; R2; R3; R4; R5; R17), such as the Horizon program with the Tulips project (R1; R2; R3; R4; R5; R6; R7), led by Schiphol (R1; R2; R3; R4). As part of this initiative, the EU Clearing House is being established (R4, Tulips, 2024) to support startups in bringing SAF technologies to market (R4).

The EU recently introduced the Renewable and Low-Carbon Fuels Value Chain Industrial Alliance, which focuses on SAFs (and fuels for water transport) (R16). This alliance aims to foster collaboration and networking and influence industry initiatives regarding value chains for sustainable fuel supply (European Commission, 2024b). The Dutch government also aims to join this alliance (R16).

The Dutch government actively encourages knowledge diffusion (R2; R4; R7; R8; R10; R12; R13; R16). The Ministry of Infrastructure and Water Management (I&W) is open to engagement with stakeholders from the aviation sector (R2; R4; R7; R10; R12; R13; R16). The ministry contacts airlines, fuel suppliers, airports, knowledge institutes, NGOs, and other societal actors (R2; R7; R8; R9; R10; R12; R13; R16). However, the communication between the government and airlines (R14) and between the Dutch Ministries of I&W and Economic Affairs and Climate Policy (R10) could be improved.

The Ministry of I&W holds biannual informational meetings with sector parties to discuss new regulations and the implementation of existing policies (R2; R7; R10; R12; R13; R16), such as the execution of ReFuelEU in conjunction with EU ETS (R7; R10; R12) and subsidies (R10). These meetings also ensure that the sector is meaningfully involved (R12). Additionally, the Sustainable Aviation Table, an initiative of the Ministry of I&W, has established various working groups with key actors from the aviation sector (R2; R7; R9; R10). However, coordination between the Ministry of I&W and Economic Affairs and Climate Policy could be more cohesive (R10).

5.3.1.1. Comparison of Bio-SAF & Synthetic SAF

European projects, such as Horizon with Tulips (R1; R2; R3; R4; R5; R6; R7) and the Renewable and Low-Carbon Fuels Value Chain Industrial Alliance (R16), focus on knowledge sharing and the development of both bio-SAF and synthetic SAF. Similarly, meetings organized by the Dutch government address the overarching importance of SAF (R2; R3; R4; R5; R7; R12), including those held by the Ministry of Infrastructure and Water Management (I&W) (R2; R7; R9; R12).

5.3.2. The Cluster

Parties within the sector are well-connected, with multiple platforms, networks, and conferences available (R1; R2; R3; R4; R6; R7; R8; R11), especially in the early stages of development (R3; R5; R8; R11). SkyNRG began building a network within the sector ten years ago, which has since expanded to include airlines and airports (R5). However, connections with fuel suppliers are generally weaker (R5). Within the cluster, knowledge is further shared through initiatives like RHIA (R1; R2; R3; R5; R13; R14; R16), Tulips (R1; R2; R3; R5; R7), the Sustainable Aviation Table (R2; R4; R5; R6; R16), and the recent collaboration between the Port of Rotterdam and RTHA (R1; R2; Chatrier & Van Dijk, 2024). Additionally, regular commercial SAF meetings involve fuel suppliers, banks, consultants, and airlines (R6).

As the industry grows, it becomes more challenging for parties to connect (R3; R8). Additionally, the sector's commercialization and growth have decreased centralized knowledge sharing (R1; R3; R4; R5; R6; R7; R8; R10; R12; R13). This includes details on how they supply, the quantities they deliver, costs (R1; R5), and their production methods (R7; R10; R13). Political sensitivities also impact knowledge sharing, as seen in the conflict between Schiphol and KLM (R10). As long as knowledge sharing between the government and the market remains strong, competition among companies is beneficial (R1; R6; R8; R10).

5.3.2.1. Comparison of Bio-SAF & Synthetic SAF

Bio-SAF and synthetic SAF are discussed at multiple meetings (R1; R2; R3; R4; R5; R6; R7). During the meetings organized by the Ministry of Infrastructure and Water Management (I&W), the potential for integrating synthetic SAF into the cluster's industry was also discussed (R12). However, communication between the government and various sector stakeholders, such as resource providers, technological and scientific entities, and industry players, is fragmented (R11; R17). This fragmentation hinders the cohesive integration of all necessary elements for development (R11; R17).

5.4. Guidance of the Search (SF4)

To map this system function, respondents were asked to what extent directionality toward the technologies is provided. The analysis distinguishes between the EU, the Dutch context, and the cluster.

5.4.1. The EU and Dutch Context

As SAFs are the most feasible alternative fuels for reducing emissions in the short term, the ReFuelEU Aviation initiative was established to stimulate the production of these fuels (Soone, 2021). Overall, European policies, particularly the ReFuelEU mandate, have been met with a positive response (R1; R2; R3; R4; R5; R6; R7; R8; R9; R10; R12; R13; R14). The blending targets outlined within ReFuelEU are perceived as robust and distinctive (R1; R2; R4; R5; R10), considered achievable in the near term (R1; R5; R16), yet ambitious in the longer term (R16). To achieve these targets, substantial emphasis must be placed on advancing other SAF technologies (R16). ReFuelEU establishes a uniform regulatory environment across Europe (R7; R10; R12; R14; Hernieuwbare Brandstoffen, 2024), mandating that airlines refuel at their departure airports (R7; R12), with blending targets standardized across all countries (R16). ReFuelEU also requires reporting fuel compositions, making this information publicly available (R7). This consistency enables SAF to gain momentum across Europe, including the Randstad, as the market adapts to these mandated requirements, fostering increased confidence (R2; R4; R8). The ReFuelEU targets are subject to revision every three years (R4; R10), presenting opportunities and uncertainties (R4; R10).

The free allowances under the EU ETS for airlines are being gradually phased out, with airlines required to fully cover these costs by 2026 (R1; R2; R7; R12; R17; Hernieuwbare Brandstoffen, 2024). This policy is anticipated to narrow the price gap between kerosene and sustainable aviation fuel (SAF) over time (R1; R2; R7; Mutrelle, 2024). The European Innovation Fund is directing revenues from the EU ETS system towards fostering advancements in various sectors, including SAF (R5; Hernieuwbare Brandstoffen, 2024). Startups can seek financial support from the European Innovation Fund to aid in production and scaling efforts, as discussed in the Entrepreneurial Activities section (R5). Moreover, investments are being channeled through Horizon (R2; R4; R5; R6), such as the Tulips project (R1; R2; R3; R4; R5; R6; R7), which is dedicated to scaling up SAF through pilot projects and experimental initiatives (Tulips, 2024).

However, the EU strategy and policies have faced criticism (R1; R4; R5; R6; R8; R9; R16). A significant concern is that Europe's approach predominantly emphasizes stimulating fundamental research (R8; R17) and creating demand through initiatives like ReFuelEU (R8), while the investment subsidies necessary for large-scale implementation are deemed inadequate (R6; R8; R9; R17). Some critics argue that the blending targets set by ReFuelEU could have been more ambitious, particularly during the initial years (R1; R2; R4; R5; R9; R13). Additionally, the scaling up of synthetic SAF is not projected to occur gradually; instead, it requires a substantial increase after 2030 (R1; R6; R5; R12; R16), a target considered by many to be nearly unattainable (R5; R6; R12; R16).

A perceived gap exists between the established targets and the broader climate ambitions (R1; R2; R4; R5; R6; R9). The ReFuelEU mandate and associated policies primarily focus on fuel suppliers (R1; R5; R6; R7), leaving a noticeable lack of legislation directed at airlines and consumers (R5; Mutrelle, 2024). Currently, airlines are predominantly linked to policies centered on production (R6). To support fuel suppliers more effectively, incentives such as guaranteed income (R6; R17) or price certainty (R8) could be introduced. This lack of incentives is particularly evident for synthetic SAF, which faces challenges in achieving supply before 2030 (Mutrelle, 2024). Furthermore, the REDIII regulation exempts the aviation sector from specific sustainability measures, complicating the efforts of SAF producers to scale up research and development and establish a viable business model (R9; R17). Since SAF is more expensive than emissions credits, the EU ETS is unlikely to significantly drive SAF development (R9). Additionally, the ability to offset emissions through the EU ETS in other sectors raises the risk that actual SAF blending may progress slowly (R9; R16).

In addition to criticisms of the policies, uncertainties in regulations and strategy have caused stakeholders to hesitate, making it challenging to develop a coherent strategy and viable business case (R1; R4; R6; R9; R10; R12; R15; R17; SkyNRG, 2024). This hesitation contributes to a reluctance to commit to long-term contracts, creating a vicious cycle (R12; Arcadis, 2024). Furthermore, uncertainty surrounds the flexibility mechanism (R4; R6; R12; R16), exacerbated by fluctuating regulations between European and national policies (R6). Additionally, the Directorate-General for Climate Action and the Directorate-General for Mobility and Transport often fail to coordinate effectively (R6; R12; R16). As a result, one department may implement the flexibility mechanism, while another mandates that SAF be supplied to specific airports (R6; R12). There is also ambiguity regarding the linkage between REDIII and ReFuelEU, as their objectives are not fully aligned (R12). Companies find it challenging to understand the interconnections between these policy frameworks (R12). Airlines, in particular, are concerned about the costs associated with the EU ETS and the availability of SAF (R12).

The Dutch government provides various subsidies to support projects, including those funded through the National Growth Fund (R2; R5; R6; R7; R9; R10; R14; R16; R17). However, there is criticism regarding the Dutch strategy and the policy uncertainty surrounding the development of sustainable aviation fuels (SAFs) (R1; R2; R3; R4; R5; R6; R8; R9; R14; R17; Arcadis, 2024). Consequently, the Dutch government is not prioritizing the production side of SAF development (R1; R2; R4; R5; R8; R9), a situation highlighted by rejecting a National Growth Fund application (R5). Additionally, subsidies from the National Growth Fund tend to favor established oil companies rather than startups despite the potentially significant impact that startups could make (R14; R17). The limited duration of support from the National Growth Fund further exacerbates this issue (R5; R7; R16; R17).

Overall, subsidies from the Dutch government are characterized by high uncertainty (R1; R2; R5; R6; R7; R9; R14; R17), with lengthy application processes and complex regulations (R1; R3). The Renewable Fuel Units subsidies are allocated annually (R1), which adds uncertainty to the business cases (R1; R9; R10; R17). Moreover, although the revenue generated from the aviation tax is supposed to be reinvested in SAF development, as mandated by the EU, this reinvestment is not being implemented (R1; R9; R14).

The absence of clear policy is evident in the insufficient support provided by the Dutch government for scaling up SAF production (R1; R2; R3; R4; R5; R6; R8; R9; R10; R11; R14; R17; Arcadis, 2024). This issue is compounded by slow application processes and regulatory approvals, particularly in critical areas such as factory construction (R1; R3; R8), securing adequate wind energy (R3; R5), and establishing grid connections (R3; R10; R12; R13; R14; R17), as exemplified by the challenges faced in the Synkero project (R3; R5). Specifically, support for synthetic SAF is notably lacking (R10; R11; R12), especially regarding resource allocation (R17). To stimulate market development, it is suggested that the Dutch government prioritize the production of a certain amount of synthetic SAF (R3; R10; R11), irrespective of the associated costs (R11).

Internal barriers also persist due to regulatory uncertainties, particularly concerning compliance with reporting requirements (R12; R14). A comprehensive documentation package must guide companies through these processes (R12). Furthermore, the Renewable Fuel Unit subsidies must be better aligned with the Renewable Energy Directive (RED) and other relevant regulations (Arcadis, 2024). The interaction between EU and Dutch regulations and strategies is often misaligned, leading to confusion and inefficiencies (R16; R17).

5.4.1.1. Comparison of Bio-SAF & Synthetic SAF

Policy-wise, the scaling up of bio-SAF and synthetic SAF is being addressed comprehensively through ReFuelEU (R1; R2; R4; R5; R10; R12), with blending percentages in ReFuelEU targeting both bio-SAF and synthetic SAF (R1; R2; R3; R4; R5; R7; R8; R10; R12). Additionally, there is a higher incentive under the EU ETS for advanced bio-fuels (SkyNRG, 2024) and synthetic SAF (R1; Mutrelle, 2024; SkyNRG, 2024), reflecting its higher cost. The blending targets within ReFuelEU are solid, but they could have been set higher, especially in the early years (R1; R2; R4; R5; R9; R13), as there is a gap between these targets and the broader climate ambitions (R1; R2; R4; R5; R6; R9).

There is a significant overlap between bio-SAF and synthetic SAF. Both rely on the same European and national projects and funds (R8), such as Horizon (Tulips), the Sustainable Aviation Table, and the National Growth Fund. Therefore, both types of SAF depend on the same governmental and institutional support (R6; R8; R10).

5.4.2. The Cluster

The market aligns with the ReFuelEU mandate, which boosts confidence (R2; R4; R8; R17). Technically, the cluster has significant potential and ambition (R1; R2; R3; R5). As discussed in the last three system functions, the previously mentioned R&D projects, pilots, production facilities, networks, platforms, and regional collaborations contribute to confidence in technological developments. However, confidence in synthetic SAF is shallow because significant technological improvements are still needed before scaling up can become a reality (R14).

Knowledge gained from various aspects of the Zenid project has been carried forward to the Synkero project, enhancing confidence in its development (R4).

It is crucial to consider how decisions are made regarding available technologies and feedstocks (R3; R5; R16). It is essential not only to follow the interests of established fuel suppliers (R5; R14) but also to prioritize companies like Neste (R5; R13) and SkyNRG (R5). Fuel suppliers should take more initiative (R4; R10). Within the cluster, however, Shell has halted the construction of the bio-SAF plant in Rotterdam (R10; R12; R13; R16) (Shell, 2024). Industry stakeholders fear that SAF shortages may arise relative to the targets (R7; R14), as current assumptions about sufficient resources, robust technologies, and scalability may need to be more optimistic (R7). General confidence in the availability of feedstocks within the Randstad cluster for bio-SAF and synthetic SAF is not strong (R1; R2; R3; R4; R5; R6; R7).

5.4.2.1. Comparison of Bio-SAF & Synthetic SAF

Confidence is higher in bio-SAF development than synthetic SAF (R1; R2; R3; R4; R6; R9; R10). This is primarily because bio-SAF is more advanced in its development (R1; R2; R3; R4; R6; R9; R10; R12; R13; R16), particularly with the HEFA technology (R1; R2; R3; R10; R12; R16), which is already commercially scalable (R1; R2; R3; R6; R7; R10; R12; R13; R16). Efforts must focus on more than just developing bio-SAF (R12); both bio-SAF and synthetic SAF should be developed in parallel (R12; R16).

The advancements in bio-SAF have already addressed some of the initial questions for synthetic SAF, as both rely on the same governmental and institutional frameworks (R2; R6; R7; R8; R10), such as for subsidies (R7), blending mandates (R2), and certification processes (R2).

5.5. Market Formation (SF5)

Activities that contribute to the demand and supply for SAF are examined to map this system function. This includes describing policies and regulations from the EU and the Dutch government and regional activities stimulating SAF demand.

5.5.1. The EU & Dutch Context

ReFuelEU is widely regarded as an effective political measure (R1; R2; R3; R4; R6; R7; R8; R9; R12; R13) for bridging the gap between market demand and production costs (R1; R2; R3; R4; R7; R8; R12; R13) while also providing certainty of demand (R8; R12; R13; R16), which in turn positively influences investments in production facilities (R8). The current design of the mandate preserves market freedom while incentivizing the production side (R1; R7; R16). However, despite the mandate, the gap between the price and demand for SAF remains significant (R1; R2; R16). Additionally, EU ETS regulations contribute to forming the SAF market (R1; R2; R5; R7; Mutrelle, 2024). Regulation plays a decisive role in determining which technologies and approaches succeed, underscoring the critical importance of policy in shaping market developments (R1; R2; R3; R4; R6; R7; R8; R9; R13).

Within the European institutional context, uncertainties persist regarding the implementation of REDII and REDIII (R1; R9; R12), as well as ambiguities surrounding the practical application of ReFuelEU (R1; R4; R12; R16). For instance, questions remain about the supply mechanism for feedstocks to production facilities (R4). The interdependence between stimulating supply and demand is a critical factor that deeply influences market dynamics (R2; R17).

Given the absence of an existing market for synthetic SAF, the private sector's role in establishing this market is crucial. The Dutch government's uncertainty in policy and strategy (R1; R2; R3; R4; R5; R6; R8; R9; R11; R14; R17) hinders its potential to become a hub for sustainable aviation fuels (SAF) (R9; R10). However, with the right strategies and active involvement, the Dutch government has the potential to lead in the establishment of a market for synthetic SAF. The government must actively create this market (R11; R17; Arcadis, 2024). Although the Dutch government is exploring increasing its involvement, these efforts remain primarily confined to the legal domain (R9).

Nationally, the Sustainable Aviation Table has set a target of 14% SAF blending by 2030, which exceeds the EU's target (R1; R2; R3; R4; R7; R9; R10; R12; R13; R14; R16; R17; Chatrier & Van Dijk, 2024). However, this target is not legally binding, as the European regulation mandates only a 6% blending requirement by 2030 (R1; R2; R3; R4; R7; R12; R16; R17). The discrepancy between the national target of 14% and the EU's 6% is estimated to cost approximately 500 million euros (R1). This national mandate has both advantages and disadvantages. On the one hand, it may lead to higher ticket prices in the Netherlands (R14) and can be perceived as an attempt to generate goodwill (R7; R17). It might be more effective for the Dutch government to advocate for higher European blending percentages (R14; R17). On the other hand, leading countries in SAF adoption could attract the production of more affordable SAFs (R12). Additionally, while the current aviation tax generates 200 million euros annually, this revenue is not reinvested in making aviation more sustainable; instead, it is allocated to the general state budget (R1; R9; R14), despite EU requirements that such funds be used for sustainability efforts (R1; R9).

5.5.1. Comparison of Bio-SAF & Synthetic SAF

The blending percentages set by ReFuelEU (R1; R2; R3; R4; R6; R7; R8; R9; R12; R13), EU ETS (R1; R2; R5; R7; Mutrelle, 2024), and the national mandate (R1; R2; R3; R4; R7; R12; R13; R14; R16) are focused on both bio-SAF and synthetic SAF.

5.5.2. The Cluster

Various initiatives are currently underway within the cluster to boost demand for SAFs. At RTHA, airlines have committed to meeting the national target of 14% SAF blending by 2030 (R1; R2; R12; R13). Similarly, Schiphol Airport has agreed with KLM to aim for a 10% blending target by 2030 (R1; R2; R4; R12) and has introduced an airline incentive program to encourage this transition (R4). The Dutch aviation cluster has already prepared to meet the 14% national target, positioning the sector favorably to achieve the 2030 goals (R12). However, some argue that the national mandate has also introduced additional uncertainties within the sector (R16; R17).

The Randstad cluster is strategically positioned to serve as both a hub and a production center for SAF, mainly due to the presence of the Port of Rotterdam (R4; R8; R12; R13; R14; R16; R17), as discussed in the context of Guidance of the Search and Resource Mobilization. Nevertheless, the attractiveness of the Port of Rotterdam as a hub is declining because importing the necessary raw materials is becoming increasingly difficult (R8; R10).

Additionally, Schiphol Airport, one of Europe's largest airports, is critical in driving demand for SAF. Despite the Dutch aspiration to become a leading SAF hub (R9; R10), the uncertainty in policy and strategy from the Dutch government does not align with this ambition (R1; R2; R3; R4; R5; R6; R8; R9; R11; R14; R17). In particular, synthetic SAF is not a viable solution, as it lacks the scalability needed to meet market demands in the coming years (R5; R11).

"It is necessary to define a strategy on what scale to produce, what costs are attached, and for what year it should apply" (R11)

Government investments in SAF development are currently limited to the experimental phase (R1; R2; R5; R6; R8; R17), creating a disconnect between these early-stage developments and broader industry engagement (R1; R5). Bridging this gap would necessitate more significant support and commitment from the private sector (R1; R2; R8; R9; R10). While fuel suppliers are willing to offer SAF, they are contingent on airlines committing to purchase it. In turn, airlines are prepared to do so only if consumers are willing to absorb the additional costs (R1; R2; R4; R7; R8; R14; Arcadis, 2024).

However, the current lack of demand (R1; R2; R4; R7; R8; R17) severely limits the ability to scale up production and establish new facilities (R1; R4; R9; R14; R17). Airlines, driven by commercial interests, are likely to delay action until mandatory purchase requirements are enforced, mirroring the approach of fuel suppliers (R2; R8; R9). Commercial companies generally lack intrinsic motivation to invest in scaling up SAF production, and such efforts will only materialize if they prove to be financially profitable (R8; R10; R12).

5.5.2.1. Comparison of Bio-SAF & Synthetic SAF

Companies within the cluster generally exhibit indifference regarding whether they purchase bio-SAF or synthetic SAF (R1; R3; R12), as both types are blended into the fuel supply, with the primary focus being on the value of the certification (R1; R12). However, significant differences exist on the production side (R1; R2; R3; R12; R13). Synthetic SAF is inherently more expensive than bio-SAF (R1; R2; R3; R4; R5; R6; R12; R13; R16). The HEFA pathway is currently the only genuinely cost-effective option (R1; R2; R3; R4; R5; R6; R7; R8; R12; R13). However, as demand increases and HEFA feedstocks become scarce, it is anticipated that HEFA will become more expensive, potentially allowing other fuels to enter the market (R4; R8; R11). Advanced biofuels and synthetic SAF face competition from cheaper technologies (R8; R12; R17). Given the anticipated limitations in the scalability of bio-SAF in the future, it is prudent to encourage the development of synthetic pathways (R4; R11; R12).

The development of bio-SAF has helped remove some barriers to the development of synthetic SAF (R2; R6), including scaling up production (R2; R6), sales to fuel suppliers, and purchases by airlines (R6). This progress also applies to a better understanding of the market (R6; R16). Bio-SAF and synthetic SAF rely on the same institutions and stakeholders (R2; R6; R7; R8; R10), further linking their development pathways.

5.6. Resource Mobilization (SF6)

The role of the EU and Dutch institutional contexts in allocating financial, human, and physical resources to develop technologies to fulfill other system functions is examined to map this system function and the activities related to these physical resources within the cluster.

5.6.1. The EU & Dutch Context

The ReFuelEU mandate is not linked to the availability of feedstocks (R1; R9). There are regulation uncertainties regarding the supply of feedstocks to production facilities (R4), and no connection has been made between renewable energy and SAF production (R7). This lack of alignment is a significant barrier that needs to be addressed. Also, hydrogen production is not aligned with the mandate for bio-SAF and synthetic SAF (R1; R9). The allocation of other bio-SAF feedstocks across sectors is also lacking (R1; R9; R12; R16; Arcadis, 2024). All transport sectors require green electricity, leading to resource competition (R4; R17). In the energy transition policy, urgent and strategic decisions must be made regarding the availability of all technologies and feedstocks (R3; R9; R10; R16; R17), requiring a comprehensive overview (R11).

The scalability of bio-SAF is limited (R1; R2; R3; R4; R5; R6; R7; R9; R10; R12; Chatrier & Van Dijk, 2024) given the current production restrictions. With the expected future scaling, the HEFA technology, which relies on used cooking oils and animal fats, will not be able to meet demand (R1; R2; R4; R5; R6; R7; R9; R10; R12; R13; R14; R16; SkyNRG, 2024; Arcadis, 2024). Beyond scalability, future challenges include the efficient collection of feedstocks for bio-SAF (R4; R9), and not every production site is suitable for all types of feedstock (R7; R10). Investments in synthetic SAF are still lagging (R2; R3; R4; R6; R9; R11; R12). In 2026, the European Commission will assess expanding carbon pricing to allocate more bio-SAF and synthetic SAF feedstocks to hard-to-decarbonize sectors like aviation (Hernieuwbare Brandstoffen, 2024). However, a significant gap exists between current feedstock production, the ambitions set, and what is realistically achievable (R1; R7; Mutrelle, 2024).

The Dutch government refrains from actively developing the availability of feedstocks (R1; R2; R4; R5; R6; R8; R9; R10; R12; R13; R15; R16) but aspires to be an SAF hub (R9; R10). Additionally, the Randstad cluster is constrained by regulations concerning the construction of production facilities (R8), such as nitrogen emission standards (R8; R13; R17). However, the Dutch government could contribute to creating a more favorable environment for feedstocks and SAF (R12; R13) through improvements in permitting processes, infrastructure (R3; R12), and the development of green hydrogen (R13). The government should study the availability of feedstock supply and demand (R9).

5.6.1.1. Comparison of Bio-SAF & Synthetic SAF

For both bio-SAF and synthetic SAF, the necessary feedstocks are not aligned with the production levels needed to meet the mandate (R1; R7; R9; Mutrelle, 2024), and there is a lack of distribution planning for feedstocks across sectors (R1; R9; R12; R16; R17; Mutrelle, 2024; Arcadis, 2024). Additionally, there are uncertainties regarding the supply of feedstocks (R4; R17; Mutrelle, 2024). Thereby, the EU (R1; R9) and Dutch (R1; R2; R4; R5; R6; R8; R9; R10; R12; R13; R15; R16) policies are not well aligned with the availability of feedstocks.

5.6.2. The Cluster

The cluster includes a major airport, a vast port, and a strong foundation for fuel infrastructure (R10; R12; R17). However, the Port of Rotterdam is not necessarily an ideal location for hydrogen production (R4; R8; R13), but it plays a crucial role as a hub for importing feedstocks (R4; R12; R13; R14; R16; R17) and synthetic SAF (R4; R12; R16). Feedstocks such as hydrogen (R8; R16), green energy, and low-energy-density biomass are less suitable for long-distance importation (R8; R17). The Randstad should be cautious about dependence on non-European countries for these resources (R9; R11). However, Rotterdam is an excellent transit hub with its existing infrastructure and capabilities. For bio-SAF, Rotterdam is an excellent location because the process closely aligns with conventional refining processes (R13; R16). In the cluster, Neste is performing very well in bio-SAF feedstock (R5), and Shell is constructing a sustainable hydrogen plant in Rotterdam, which will supply its refinery (R6).

Shortly, a shortage will occur for the feedstocks such as green energy (R1; R4; R5; R7; R10; R13; R14), hydrogen (R1; R2; R3; R4; R5; R6; R7; R10; R12; R14; R15; R16; R17), and the further future also for biomass (R5; R6; R9; R10; R14; R17). Unfortunately, feedstocks such as hydrogen (R8; R16), green energy, and low-energy-density biomass are not easily imported over long distances (R8; R17). The cluster has no robust environment for green energy production (R10; R14), and generating green energy is not cost-effective (R10). There is uncertainty about where green energy will come from and the cost (R13; R16); the same applies to green hydrogen (R13; R14; R16). This presents a future challenge (R8).

Additionally, CO2 capture technology is lagging (R10; R17), the energy grid is at capacity (R3; R5; R10; R12; R13; R14; R17; Arcadis, 2024), and infrastructure needs expansion shortly (R3; R5; R10; R14; Chatrier & Van Dijk, 2024). When expanding in the cluster, available space is challenging (R8; R10; R13; R14; R17), particularly for storage or feedstock production (R8; R10; R14; R17).

5.6.2.1. Comparison of Bio-SAF & Synthetic SAF

Regarding distribution, bio-SAF and synthetic SAF can learn from each other (R16). Both types of SAF can utilize the existing infrastructures (pipelines, tankers, etc.), as they are blend-in fuels (R1; R2; R3; R4; R5; R6; R12; R16; Arcadis, 2024). However, significant amounts of hydrogen are required for bio-SAF and synthetic SAF production (R8; R11; R17; Arcadis, 2024). A resource shortage is expected within the cluster for bio-SAF and synthetic SAF (R1; R2; R3; R4; R5; R6; R7; R10). The uncertainty surrounding feedstock availability in the cluster makes it difficult for companies to make investment decisions (R13).

5.7. Creation of Legitimacy (SF7)

The role of the EU and Dutch institutional contexts in creating legitimacy for bio-SAF, synthetic SAF, and its feedstocks is examined to map this system's function. Additionally, the legitimacy of the sector and public perception are highlighted.

5.7.1. The EU and Dutch Context

Transparency and credibility from the government are crucial for gaining public legitimacy for SAF (R8; R10; R12; R13; R15; Mutrelle, 2024). The EU fails to communicate its feedstock policy and strategy to the sector, allowing the industry to focus on specific areas and make progress (R14). The EU could improve its communication regarding the environmental impact of flights (R6; R9; R12). Lobbying efforts influence specific policies (R1; R2; R3; R5). Respondents are generally satisfied with the lobbying around SAF regulations (R4; R5), such as the ReFuelEU mandate (R1; R3; R5). However, it is sometimes observed that certain lobbies or companies with close ties can influence policy decisions (R3; R4). Greenwashing can significantly damage the public's willingness to pay for SAF (R8; R12; R14; R15). The EU has introduced the Green Claims Directive to combat greenwashing (R15).

The national government is not transparent in its SAF strategy (R9; R13; R15) and could use existing platforms to target consumers and business travelers (R5; R9; R12). There is a lack of effective communication between the Dutch government and airlines in some areas (R14). It would be wise to cultivate a willingness to pay among business travelers, as they represent a significant share of the market (R12; Mutrelle, 2024). There is a lack of clarity regarding regulations for SAF certificates (R6; R15), which hinders companies from investing in SAF (R15).

The Dutch government often defers responsibility to Europe, which results in a lack of action at the national level (R5; R11). The Dutch institutional context holds too much confidence in SAF, as reflected in the ambitious 14% target (R9; R17). However, this mandate must now be reconsidered (R9; R17). The Advertising Code Committee is an excellent initiative (R8) to counteract greenwashing.

5.7.1.1. Comparison of Bio-SAF & Synthetic SAF

Developing SAFs is focused on short-term solutions (R5; R9; R12). However, developments in bio-SAF have already addressed some initial questions about synthetic SAFs, particularly in areas such as lobbying for regulations (R6; R8; R10). It is essential to embrace all possible forms of SAFs to meet targets (R1; R2; R6; R8; R11; R16; R17). The government frequently focuses on the success of innovation while the previous one has yet to be fully established (R8; R17); there is often an overly idealistic view of fuel solutions (R1; R2; R3; R8; R11; R13; R16; R17). Hopes are often pinned on a single type of fuel (R1; R2; R3; R8; R11; R16; R17), even though a particular fuel might serve as a partial (R1; R8) or temporary (R6; R8) solution. For instance, bio-SAF is sometimes dismissed because it is expected to be replaced by other innovations, even though we are far from reaching that point (R8; R11; R16). This might happen to synthetic SAF when the fuels are better established (R17).

5.7.2. The Cluster

Airports support SAFs and contribute to their development (R1; R2; R3; R4; R5; R8; R13). Transparency and credibility within the sector are crucial for gaining public legitimacy for SAFs (R7; R10; R12; R13; R15). NGOs and environmental organizations are generally critical of the environmental aspects of sustainable fuels (R1; R2; R9; R13). The negative perception of bio-based feedstocks leads to a lower, sometimes unjustified, public legitimacy (R1; R7; R8; R17). The role of airlines and fuel suppliers is discussed further below.

The role of NGOs and social media is vital in the controversial debate regarding resources and their nuances (R1; R7; R8; R17). The controversy surrounding the use of palm oil or its by-products due to concerns about deforestation contributes to this negative image, preventing the product from entering the supply chain even though it can be a good solution in specific contexts (R1; R8; R17). Similar negative perceptions exist regarding the cultivation of crops for biomass, which is often equated in public opinion with crops that could otherwise be used for food (R7; R17).

"In this sense, the use of certain feedstocks is sometimes based on perception rather than actual sustainability, and it is important to prevent this from happening with other feedstocks (R8)."

On the other hand, maintaining any form of demand helps sustain the value chain and the interests behind it (R9). However, we must be vigilant against the misuse of feedstocks (R1; R2; R4; R5; R6; R7; R8; R9; R10; R12; R16), such as with used cooking oil (R7; R9; R10; R12;

R16) and palm oil (R1; R2; R8; R9; R10). While the criticism is understandable (R1; R6; R12; R17), it does not contribute to overall support for sustainable fuels (R1; R6; R17). A solution lies in better monitoring, agreements, and verification of feedstock origins. Although efforts are being made in this direction, they are not yet sufficiently transparent (R1; R12; R17).

Consumers lack visibility and knowledge about SAF (R1; R2; R5; R7; R13; R14; R15). The complexity of SAF makes communicating effectively to the public (R7; R15) challenging. Consumers' understanding of SAF is mainly limited to the information airlines provide (R5; R12). As market-driven financial organizations, airlines are not typically focused on long-term projects like SAF (R5; R12), yet they bear significant responsibility for educating consumers about SAF (R7; R12; R14). In the past, airlines have damaged consumer trust, particularly with practices like offsetting flight emissions (R12). The government also has an educational role to play in this area (R7). Large fuel suppliers like Shell, AirBP, and Total in the cluster rely on Neste's production to meet the EU's SAF blending percentages (R5). Fuel suppliers are not transparent about certain information (R1; R3; R4; R5; R6; R7; R8; R10; R12; R13), such as the origin of feedstocks (R1; R4; R5; R6; R8), and they resist scaling up SAF production (R2; R5; R9; R10).

Additionally, consumers want to continue flying at the lowest possible cost (R10; R15). Difficult decisions, such as the future of SAF, are politically sensitive due to the associated costs, leading to a cautious political stance (R11). There is hope that the market will take the lead, but currently, that market is lacking (R11).

5.7.2.1. Comparisons of Bio-SAF & Synthetic SAF

Fuel suppliers and airlines provide minimal support for developing bio-SAF and synthetic SAF (R1; R2; R3; R4; R5; R8), reflected in their lobbying efforts (R3). They often communicate more about SAF than they implement, as seen in greenwashing claims (R8; R9; R14; R15). This behavior is also observed among fuel suppliers (R5; R15). However, (obliged) ESG reporting from companies will help address greenwashing issues and create transparency regarding SAF blending (R14).

Public legitimacy for SAFs is weak due to insufficient visibility and consumer knowledge about SAFs (R1; R2; R5; R7; R13; R14; R15; R17), overly idealistic views on fuels (R1; R2; R3; R8; R11; R13; R16; R17), negative perceptions of feedstocks (R1; R7; R8; R17), and the barriers as mentioned above from airlines and fuel suppliers. However, support for bio-SAF seems stronger than synthetic SAF (R2), primarily because bio-SAF is more cost-effective (R1; R2; R3; R4; R5; R6; R7; R8; R12; R13). The developments in bio-SAF have already addressed some initial questions for synthetic SAF, particularly in areas such as lobbying for regulations (R6; R8; R10).

5.8. Interaction Patterns within and across TISs

5.8.1. Institutional Contexts Related to Cluster

Table 6 presents the relationships between the comprehensive drivers and barriers within institutional contexts and those from the cluster. These interactions result in a TIS-TIS interaction, which is displayed as the *"mode of interaction."* The comprehensive drivers and barriers were derived from Appendices E, F, and G. In Table 6, the institutional context is abbreviated as IC. The relationships and the resulting *"modes of interaction"* are further elaborated below the table, categorized by system functions.

Understanding the relationship between the institutional contexts' drivers and barriers and the consequential TIS-TIS "mode of interaction" is critical for developing holistic strategies and policies. Enhancing drivers and mitigating barriers are essential to achieving the desired interactions within TISs, further discussed in the "policy implications."

Table 6. The drivers and barriers in the cluster related to the ICs, including the "mode of interaction," per SF.

SF	Drivers [+] and Barriers [-]: Institutional Contexts Related to Cluster	Mode of Interaction
1.Knowledge Development	[+ context]: The ICs hold funding programs to support R&D efforts [+ cluster]: Activities by actors in the cluster support the R&D efforts	Commensalism
	[- context]: The ICs feature ambiguities in policies and weak policy execution [- cluster]: An increase in R&D is needed to enable scalability	Competition
	[- context]: The Dutch IC provides equal support to the development of SAFs [-cluster]: Synthetic SAF technologies are relatively behind on bio-SAF and need significantly more support on R&D	Parasitism
2. Entrepreneurial Activities	[+ context]: The ICs hold funding programs, such as Horizon and National Growth Fund, to support demonstrations, pilots, and cooperation [+ cluster]: Actors establish activities and collaborate with these IC initiatives	Commensalism
	[- context]: The ICs provide minimal support to the development of SAFs and must do more to initiate demonstration projects and scale-up [- cluster]: Setting up production facilities is too risky, so support is needed	Competition
	[- context]: The Dutch IC provides equal support to the development of SAFs [- cluster]: The development of synthetic SAF is relatively behind on bio-SAF and needs significant support in activities	Parasitism
3. Knowledge Diffusion	[+ context]: The ICs facilitate programs and meetings in which knowledge is distributed, mainly about SAF in general or bio-SAF [+ cluster]: Actors in the cluster are participating in the activities facilitated by the institutional contexts	Commensalism
	[- context]: The Dutch IC sometimes characterizes inadequate communication with the sector [- cluster]: Communication between stakeholders is fragmented, leading to reinforcement of self-interest	Competition
4. Guidance of the Search	[+ context]: The EU IC holds policies that contribute to the confidence of the development of both SAFs [+ cluster]: The market aligns with the EU IC, as confidence in SAFs enhanced	Commensalism
	[- context]: The ICs contain uncertainties and ambiguity and could have focused more directly on scalability [- cluster]: Uncertainty and lack of guidance lack confidence in the cluster	Competition
	[- context]: The focus within ICs is not equivalent to both SAFs, as the blending rates are not gradual, leaving development behind [- cluster]: Cluster confidence in synthetic SAF is lacking, as it is not scalable	Parasitism
5.	[+ context]: The ICs hold policies that narrow demand and supply	Commensalism

	[+ cluster]: Airports and airlines comply with blending in percentages, stimulating bio-SAF	
	[- context]: The Dutch IC contains uncertainties, lacks support for scalability, and is not in line with the EU IC context [- cluster]: The cluster lacks support regarding demand, supply, and scalability in	Competition
	[- context]: The Dutch IC must support the development of the synthetic market [- cluster]: There is a lack of synthetic SAF to supply the market, and actors are indifferent to purchasing bio-SAF or synthetic SAF.	Parasitism
6. Resource Mobilization	[- context]: The EU IC contains uncertainties and misalignments regarding resource production, distribution, necessities, and potential achievability [- context]: The Dutch IC is not actively supporting/refraining from the development of feedstock availability [- cluster]: The cluster's attractiveness is decreasing with the development of SAF, as the feedstocks are less beneficial for transport [- cluster]: The Randstad cluster has limited capacity for expansion, the grid is full, and green electricity generation is lagging behind	Competition
7. Creation of Legitimacy	[+ context]: The EU IC contributes to the legitimacy of SAFs, with initiatives counteracting greenwashing and holding supporting SAF policies [+ cluster]: Actors (have to) hold initiatives that contribute to the creation of legitimacy, such as ESG reporting and facilitating initiatives at airports	Commensalism
	[- context]: The ICs lack transparency, communication, and strategy. Expressing in companies with close ties to ICs, a lack of informing consumers on emissions, and poor legitimacy for controversial biomass [- cluster]: Airlines and fuel suppliers lack activities, and NGOs are too critical regarding SAF, leading to a low extent of public legitimacy of SAF and resources	Competition
	[+ context]: The EU IC focuses on short-term SAF solutions, thus focusing on bio-SAF rather than synthetic SAF [- cluster]: Airlines and fuel suppliers focus on short-term SAF solutions	Parasitism

SF1 - Knowledge Development: Funding programs within the institutional contexts support the cluster's activities. Given that bio-SAF technologies are relatively more advanced than synthetic SAF, the *"mode of interaction"* is characterized as "*commensalism*," where synthetic SAF benefits from the progress of bio-SAF while bio-SAF remains unaffected. Additionally, the institutional contexts contain inhibiting factors, such as ambiguities in policies and weak policy execution, posing barriers to R&D efforts, which, in turn, hinder the R&D necessary for scalability within the cluster. This dynamic creates a "*competition*" *"mode of interaction,"* as both SAFs share overlapping structural elements. Moreover, the Dutch institutional context fosters a "*parasitism*" *"mode of interaction"* by holding a technology-neutral stance in which resources are allocated to the TISs "evenly." For equal development, technologies must receive relatively balanced, rather than absolute, support. Consequently, this current dynamic strengthens bio-SAF relative to synthetic SAF, as the TIS is already better developed. Thereby, respondents particularly emphasized the lack of support for synthetic SAF.

SF2 - Entrepreneurial Activities: Funding programs originating from the institutional contexts form a foundation for activities within the cluster, eventually creating a "*commensalism*" *"mode of interaction"* between bio-SAF [0] and synthetic SAF [+]. However, respondents indicated that the institutional contexts provide minimal support. They must do more to initiate demonstration projects and scale-up of both SAFs, as setting up production facilities by the sector alone is too risky, leading to *"competition"* as a TIS-TIS *"mode of interaction."* The Dutch institutional context holds a technology-neutral stance, in which technologies are entitled to the same support. Respondents argue that the development of synthetic SAF is falling behind and that significant support in activities is needed. The institutional context should be differentiated to maintain equal development. The current dynamic is causing a *"parasitism"* mode of interaction between the two TISs, as support is distributed to bio-SAF but should go to synthetic SAF for equal development.

SF3 - Knowledge Diffusion: The ICs are instrumental in supporting knowledge diffusion within the sector, and the sector actively contributes to distributing knowledge. Knowledge diffusion is about implementing SAF in general, focusing on bio-SAF since synthetic SAF is not in production, fostering a *"commensalism" "mode of interaction."* Dutch institutional context sometimes characterizes inadequate communication across the sector, leading to fragmentation between stakeholders. Respondents argue that this fragmentation enhances actors' self-interest and creates a "competition" TIS-TIS interaction. The sector advocates for a more integrated and holistic approach to knowledge diffusion to achieve the greater sustainability goal.

SF4 - Guidance of the Search: The EU institutional context implements policies that bolster confidence in the technologies, with the market aligning itself with these policies, thereby creating a *"commensalism"* mode of interaction. As a forerunner, bio-SAF paved the way for synthetic SAF in the EU institutional framework, such as the functioning of blending certificates. However, respondents have noted that the EU and Dutch institutional contexts feature multiple unclear and uncertain policies, additionally, a lack of scalability leads to a lack of confidence in the cluster, fostering a *"competition"* mode of TIS-TIS interaction. Furthermore, respondents expressed insufficient confidence in the development, as it is not scalable yet, and the institutional contexts lack equally distributed support in policies. The blending rates for synthetic SAF are not gradual, requiring a massive increase after 2030. This leads to a current *"parasitic"* dynamic, in which bio-SAF is acquiring the support that has to go to synthetic SAF.

SF5 - Market Formation: The institutional contexts implement policies to narrow the gap between demand and supply, which are adopted within the cluster, resulting in an increase for bio-SAF as the only scalable option, leading to a "commensalism" TIS-TIS "mode of interaction." However, the Dutch institutional context is characterized by uncertainties, insufficient support for scalability, and misalignment with the EU institutional context. Aviation taxes are not reinvested in making aviation more sustainable, as mandated by the EU. This lack of support is also reflected within the support in the cluster in the lack of demand and supply, leading to *"competition"* between the TISs. There is no market for synthetic SAF, and the price for synthetic SAF is higher than for bio-SAF. Respondents argue that the institutional contexts are responsible for creating this market as actors are indifferent to purchasing bio-SAF or synthetic SAF. The current dynamics create *"parasitism"* between the TIS-TIS.

SF6 - Resource Mobilization: The EU institutional context is marked by uncertainties and misalignments, regarding resource production, distribution, necessities, and potential achievability, and the Dutch institutional context lacks active support for developing feedstock availability within the cluster. Despite these challenges, the cluster currently holds a strong hub position in the SAFs sector due to the presence of the Port of Rotterdam, Port of Amsterdam, Schiphol, and RTHA, including its facilities, infrastructures, networks, and their ability to attract activities. The cluster's attractiveness is diminishing, as SAF feedstocks are less beneficial to transport, the cluster has limited capacity for expansion, the grid is full, and green electricity generation is lagging, leading to a *"competition" "mode of interaction."*

SF7 - Creation of Legitimacy: The EU institutional context initiates efforts that enhance the legitimacy of SAF, with initiatives counteracting greenwashing and policies supporting SAF development, such as ReFuelEU and EU ETS. These efforts result in increased activity among actors within the cluster and enhance public legitimacy. Countering greenwashing and activities fosters the legitimacy of bio-SAF, thereby fostering a TIS-TIS *"commensalism"* interaction. However, respondents argue that the institutional contexts suffer from a lack of transparency, communication, and coherent strategy. They indicated that companies maintain close ties to these institutional contexts, enabling them to influence policy. Additionally, education on emissions and some controversial biomass remains insufficient. The absence of a cohesive strategy leads actors to prioritize their interests, as reflected in the limited support provided by airlines and fuel suppliers within the cluster, which fosters *"competition"* between the TISs. It is crucial to emphasize the need for a long-term strategy for SAFs. Moreover, the EU institutional focus on short-term SAF solutions significantly shapes the SAF strategies of airlines and fuel suppliers, leading to a greater emphasis on bio-SAF over synthetic SAF, which creates a form of *"parasitism"* between the TISs.

5.8.2. The TIS-TIS System

Based on the preceding analysis, this section identifies and emphasizes the cause-effect relationships between the systemic drivers and problems arising from the TIS-TIS. Figure 5 provides an overview of the systemic drivers and challenges (rectangles) associated with the *"mode of interaction"* and illustrates their connections to the system functions (ovals). Additionally, the figure demonstrates the interdependent nature of the system functions. As system functions are intrinsically linked, their interactions extend beyond individual system functions, as examined in the analysis above.

Overall, Figure 5 illustrates how all systemic functions originate from the systemic drivers and problems, which stem from the Guidance of the Search (SF4). From this system function, one overarching systemic driver *("commensalism")* and three overarching systemic problems (two categorized as *"competition"* and one as *"parasitism")* are identified. The systemic driver and problems emerging from the Guidance of the Search (SF4) influence both Resource Mobilization (SF6) and Creation of Legitimacy (SF7). Resource Mobilization (SF6) transfers the systemic driver and problems within the identified *"mode of interaction"* to other system functions. The cause-effect relationships for each systemic driver and problem are discussed below the figure.

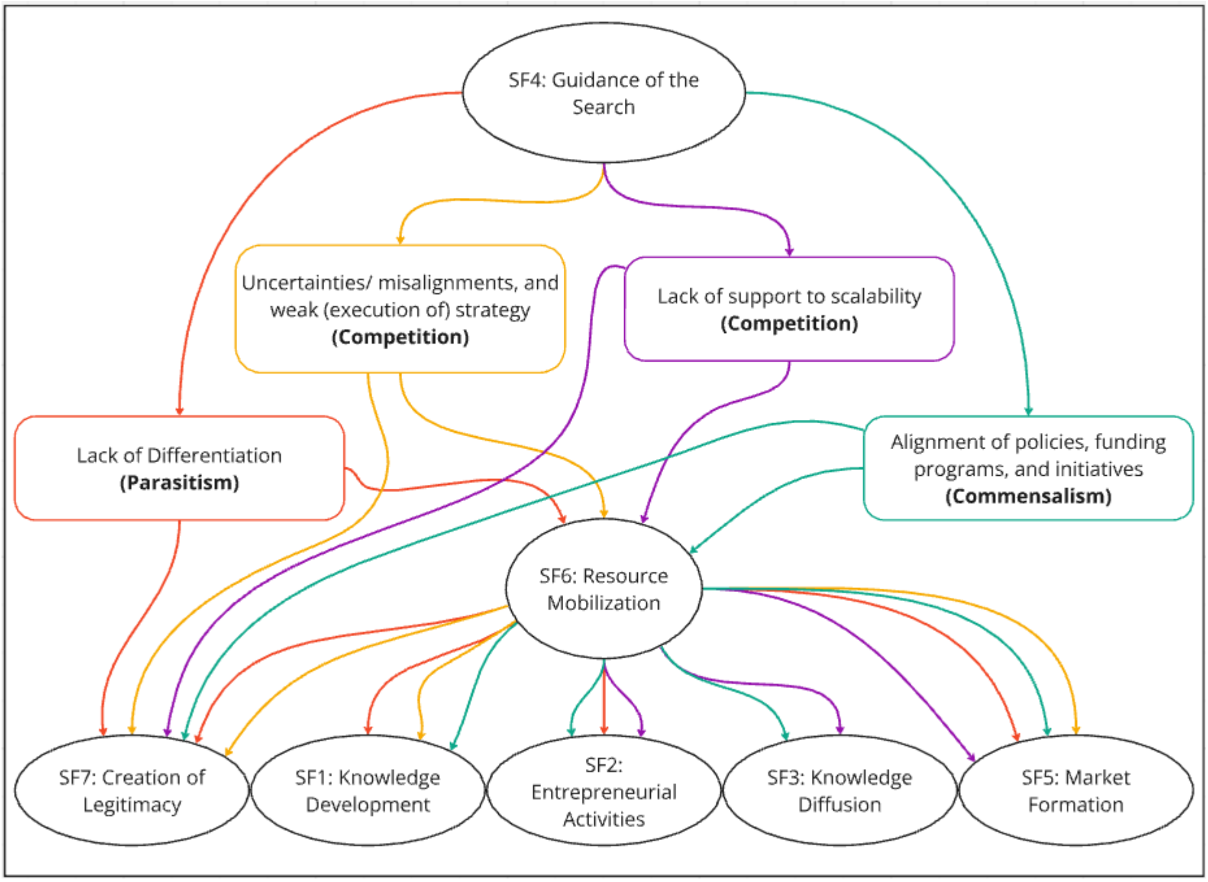

Figure 5. The identified systemic driver and problems of the TIS-TIS system are related to the interdependent system functions.

The four cause-effect relationships illustrate how the systemic driver (green rectangle) and systemic problems (red, yellow, and purple rectangles) stem from the TIS-TIS interactions of the Guidance of the Search (SF4). Each systemic driver and problem is directly linked to the Creation of Legitimacy (SF7). Furthermore, the systemic drivers and problems within the *"mode of interaction"* all impact Resource Mobilization (SF6), affecting other system functions.

Resource Mobilization (SF6) plays a pivotal role in the TIS-TIS system. Resource Mobilization (SF6) influences SF1, SF2, SF3, and SF5 in the green cause-effect relationship, with "commensalism" (bio-SAF [0] & synthetic SAF [+]) and impacts SF2, SF3, and SF5 in the purple cause-effect relationship, with "competition" (bio-SAF [-] & synthetic SAF [-]). It also affects SF1, SF5, and SF7 in the yellow cause-effect relationship, with "competition" (bio-SAF [-] & synthetic SAF [-]), and impacts SF1, SF2, SF5, and SF7 in the red cause-effect relationship, with "parasitism" (bio-SAF [+] & synthetic SAF [-]).

7. Discussion

7.1. Reflection on TIS-TIS Interactions

To gain a more nuanced understanding of "modes of interaction" between the TISs steered by their contextual nature, this section offers a detailed discussion of these interactions. Table 7 presents an overview of the patterns by displaying the frequency and percentage with which each "mode of interaction" occurs, categorized by institutional context and cluster. The data for this analysis are drawn from Appendices E, F, and G. The percentages in Table 7 are rounded.

Table 7. Quantity and percentages of "mode of interactions" per institutional context and cluster.

Mode of Interaction	EU Institutional Context	Dutch Institutional Context	Cluster	Total (%)
Competition [--]	26 - (28%) (63%)	31 - (33%) (79%)	36 - (39%) (52%)	93 (100%)
Neutralism [00]	1 - (100%) (2%)	-	-	1 (100%)
Parasitism [-+]	5 - (23%) (12%)	5 - (23%) (13%)	12 - (55%) (17%)	22 (100%)
Commensalism [0+]	9 - (27%) (22%)	3 - (9%) (8%)	21 - (67%) (30%)	33 (100%)
Total (%)	41 (100%)	39 (100%)	69 (100%)	

Table 7 indicates that *"commensalism"* is more common in the EU (27%) than in the Dutch (9%) institutional context. The differences between the EU and Dutch contexts are reflected in the occurrence that regulations for SAFs are set at the European level, with initiatives related to SAFs also being more strongly represented at this level. The cluster (67%) exhibits a significantly higher frequency of *"commensalism"* interactions than the institutional contexts. This indicates the cluster's positive characteristics, such as the activities executed by the Port of Rotterdam, Port of Amsterdam, Schiphol, RTHA, fuel suppliers, and the knowledge institutes.

In the EU institutional context, *"competition"* (63%) occurs nearly three times more frequently than *"commensalism"* (22%). In the Dutch institutional context, there are over ten times as many cases of *"competition"* (79%) than *"commensalism"* (8%). The institutional contexts exhibit characteristics that tend to foster negative TIS-TIS interactions rather than neutral-positive ones. Contributing factors include uncertainty, lack of clarity, and misalignments in strategy and policy to, for example, scalability and feedstocks. In the cluster, "competition" (52%) and "commensalism" (30%) are closer together, which is due to the characteristics of the cluster, discussed in the previous paragraph.

In the case of *"parasitism"* within the institutional contexts, all cases are negative for synthetic SAF and positive for bio-SAF, with one exception. In the cluster, all cases are negative for synthetic SAF and positive for bio-SAF. The underlying reason for this trend is the technology-neutral stance adopted by the Dutch institutional context and the predominant short-term focus within the EU institutional context. These factors contribute to the prevalence of "parasitic" TIS-TIS interactions.

Only one interaction is categorized under *"neutralism,"* in which the technologies do not affect each other. This interaction is found in the lack of allocation of bio-SAF feedstocks across sectors. Consequently, the *"mode of interactions,"* including *"symbiosis"* and *"amensalism"* that were not observed in this study, will be reflected in the following section.

7.2. Reflection on Theory

The theoretical framework highlights the significance of clusters where two technologies evolve simultaneously (Pérez-Alemán, 2005; Paraušić et al., 2017; Porter, 2007; Porter, 1998). This section reflects on the existing theory about the findings of this research.

First, the work of Trencher and Wesseling (2022) and Unruh (2000) suggests that barriers to less advanced niche technologies often stem from the presence of more advanced niche technologies. This study demonstrates that bio-SAF advancements hinder the development of synthetic SAF, and this dynamic can be attributed to systemic problems of *"competition"* and *"parasitism."* Unruh (2000) further posits that these barriers are deeply embedded in governmental institutions. This research corroborates this finding, which shows that both the EU and Dutch contexts contain uncertainties and misalignments, weak execution of strategy and lack of scalability leads to "competition" and lack of differentiation between bio-SAF and synthetic SAF and primarily focusing on short-term solutions, leading to *"parasitism."*

Secondly, Trencher and Wesseling (2022) argue that barriers in a technology's development can lead to additional barriers, a concept reflected in the findings for both TISs. Uncertainty in the distribution of feedstocks across sectors leads to *"competition"* in feedstocks, reinforcing *"competition"* in legitimacy, knowledge development, and market formation. This problem for "competition" is also recognized in the purple cause-effect relationships, both shown in Figure 5. Bio-SAF is more advanced than synthetic SAF and is already commercially scalable and affordable. Consequently, actors are directing more efforts towards developing bio-SAF, intensifying *"parasitism,"* described in the red cause-effect in Figure 5. These dynamics are consistent with those of Wesseling and Van der Vooren (2017), who suggest systemic problems can trigger and exacerbate other systemic issues.

Thirdly, Unruh (2000) posits that the institutional context is closely linked to the development of emerging technologies, and various scholars even emphasize the importance of institutional contexts in developing technologies (Trencher & Wesseling, 2022; Azar & Sandén, 2011; Jacobsson & Sandén, 2021; Gawel et al., 2017). This research aligns with the theory and demonstrates, for each system function in Table 6, how drivers and barriers from the institutional contexts are linked to the drivers and barriers within the cluster.

Fourthly, in doing so, a critical factor is determining which TIS-TIS *"mode of interaction"* this relationship leads to. The relevance of these "*modes of interaction"* is underscored by Sandén and Hillman (2011). This research strengthens this theory by highlighting how drivers and barriers in institutional contexts influence the TIS-TIS *"modes of interaction"* within a cluster. Table 7 shows a relation between the frequency with which specific *"modes of interaction*" appear within institutional contexts and how this frequency correlates with their occurrence in the cluster. The results analysis in Table 6 illustrates which TIS-TIS drivers and barriers are driven by the institutional context's drivers and barriers. In this section, "competition" and "parasitism" are already discussed, but the study also identified the interactions of *"commensalism"* and *"neutralism."*

In the research, respondent descriptions emphasize the maturity of bio-SAF, in which bio-SAF addresses the questions that lie ahead for synthetic SAF. The resulting TIS-TIS interaction "*commensalism"* between bio-SAF [0] and synthetic SAF [+] is underscored by Sandén and Hillman (2011) as a technology that benefits from the availability of experience. *"Neutralism*" occurs when two technologies deliver distinct services and rely on separate resources (Sandén & Hillman, 2011), as described in the previous section.

However, despite identifying four of the six “modes of interactions” posed by Sandén and Hillman (2011), the interactions *"symbiosis"* and *"amensalism"* did not occur in the study. With *“symbiosis,”* interaction is favorable to both, and “amensalism,*”* one technology is inhibited, and the other unaffected.

Sanden and Hillman (2011) argue that *“amensalism”* arises when a technology is excluded from the system of existing technologies without the existing technology benefiting from this exclusion. In cases where synthetic SAF was negatively influenced, *“parasitism”* occurred, as the TISs examined in the research overlap in their structural elements. Regarding technological constraints, interaction between the TISs leads to *“competition”* rather than *"amensalism."* In cases where there is support for the technologies, "commensalism" occurs because bio-SAF [0] technologies are more advanced than those of synthetic SAF [+]. *“Amensalism”* can also occur when an emerging technology [0] leads to a weakening of the other [-] (Zhang et al., 2017; Coccia, 2019). Despite synthetic SAF being an emerging technology, it will not weaken bio-SAF, as the development of both SAFs is necessary to achieve future goals.

Sandén and Hillman (2011) stress that “symbiosis” mainly occurs between emerging technologies. As a more mature technology, bio-SAF does not benefit from this interaction but can overcome future barriers for synthetic SAF, leading to *"commensalism."*

7.3. Theoretical Extension and Further Research

The research has successfully mapped the interactions between the TISs of bio-SAF and synthetic SAF within the Randstad cluster, thereby enhancing the understanding of the dynamics between two TISs and their contribution to developing both technologies within the cluster. Additionally, this study has provided valuable insights into how institutional contexts influence related TISs within a cluster that shares a common goal of sustainability. These findings have contributed to a broader understanding of approaching the development and diffusion of both technologies and have supported the formulation of effective policy implications that promote the integrated development of the two TISs.

The results and interactions identified in this research apply to the specific institutional contexts, clusters, and technologies studied to some extent. However, further research is required to establish generalizations and provide additional support for the findings presented. Additionally, the perception of the study's implications may vary.

Firstly, "symbiosis" and "amensalism" were not identified as TIS-TIS interactions in this study, suggesting that the relationship between drivers and barriers arising from institutional contexts and those from the cluster may differ. "Neutralism" was found only once. The discussion explores the conditions under which the "modes of interaction" were either present or absent and why they may or may not apply to this study. Based on the research and discussion, it appears that "modes of interaction" are influenced by the overlap of structural elements, the developmental stages of the TISs concerning each other, and the overarching purposes of both TISs. Further research could deepen the understanding of these factors and their relationship with "modes of interaction." This could enable studies to be compared at a higher level of aggregation and allow for long-term monitoring of case studies.

Secondly, this study did not examine the interactions between the EU and Dutch institutional contexts despite their potential impact on the final *"mode of interaction"* between the two technologies.

Thirdly, the approach from an institutional context could shift towards reducing energy consumption in aviation rather than solely focusing on the scalability of SAFs.

Fourthly, situating the global development of SAFs in Europe would be relevant. If the mandate for SAFs is disproportionately high compared to other regions outside Europe, there is a risk that airlines may opt to refuel in other continents. This consideration is crucial, given that 80% of fuel is allocated to long-haul flights (R1; R9; ICF, 2024).

Fifthly, Future research could explore whether and how a cluster of this significance influences institutional contexts with its developments.

7.4. Policy Implications

Theoretical perspectives highlight the importance of systemic interventions to facilitate technological progress in the sustainability transition (Negro et al., 2012; Bergek et al., 2008), with a critical role of governments (Chaminade & Edquist, 2010), in fostering the development of technologies, (McCann and Ortega-Argilés, 2015), and in mitigating risks and uncertainties (Jacobsson & Bergek, 2004). The research developed a framework that enables the mapping of systemic drivers and problems through TIS-TIS modes of interaction, derived from the relationships between drivers and barriers in both the institutional context and the Randstad cluster. This unique framework provides a foundation for policy implications to alter the nature of TIS-TIS interactions, thereby fostering the integrated development of bio-SAF and synthetic SAF.

7.4.1. Competition and Parasitism

The study posits that Europe will experience a future shortage of available feedstocks for bio-SAF, emphasizing the necessity of advancing synthetic SAF as a complementary solution. The European Union has established blending targets for both forms of SAF (Figure 3), as their combined implementation is critical to achieving sustainability objectives. However, within the existing institutional frameworks, the Randstad cluster exhibits *"competition*" and *"parasitism"* TIS-TIS interactions, which hinder the integral development of bio-based and synthetic SAF. The following policy implications offer potential solutions to disruptive interactions.

Competition

Uncertainties and misalignments in the overall policy framework for SAFs within the institutional contexts result in weak (execution of) strategies in the institutional contexts and cluster. Collectively, these issues reinforce the criticism of the lack of support for scalability. Addressing these challenges within institutional contexts would encourage bio-SAF and synthetic SAF development.

First, institutional contexts can increase support for demonstration projects and establish SAF production facilities. Respondents highlighted that current investments remain confined mainly to the R&D and pilots, with investments in upscaling production perceived as too risky, as evidenced by the suspension of construction at Shell's SAF plant.

Second, financial support for smaller entities is critical for fostering development. The transition to commercial-scale production is currently dominated by larger companies, leaving smaller players underrepresented in the industry. More efficient assistance would help diversify participation in SAF development.

Third, government commitment to production targets is essential to overcoming the uncertainty that is present in industry progress. A clear governmental commitment could incentivize actors to invest and innovate. While initiatives such as ReFuelEU focus primarily on fuel suppliers, this could be improved. Policies can add incentives such as guaranteed income for suppliers and policies that engage airlines and consumers directly.

Fourth, while the national mandate set by Dutch institutions is a step forward, it has introduced uncertainty and misalignments. Respondents argue that these efforts at the European level would be more effective, fostering certainty.

Fifth, greater clarity on resource distribution is necessary to promote the development of SAFs and their feedstocks. Institutional contexts play a crucial role in shaping the perception and viability of SAFs, and ensuring transparent, equitable resource allocation would enhance industry confidence and accelerate growth.

Parasitism

The study identifies a lack of differentiation between bio-SAF and synthetic SAF for both institutional contexts and cluster, leading to a disproportionate development the bio-SAF and synthetic SAF relative to each other. The following policy implications may contribute to better balance.

First, the national government can address the infrastructure required to produce synthetic SAF at scale. Respondents noted that the energy grid within industrial clusters is already at capacity, making it difficult to access green energy for new SAF projects. This limitation hinders the development of large-scale synthetic SAF production facilities.

Second, additional support is necessary to scale up R&D and pilot projects. Too few ongoing initiatives are creating a robust market for synthetic SAF. Without this scaling, the transition to commercial production remains stagnant.

Third, effective incentives can be developed to ensure the production of synthetic SAF by 2030. The lack of clear financial and policy-driven incentives has led to minimal activity in this area, slowing the industry's progress.

Fourth, the significant price disparity between synthetic SAF and bio-SAF must be addressed. Policy measures should narrow this price gap, making synthetic SAF more economically competitive and attractive to producers and consumers.

Fifth, institutional frameworks lack a long-term vision. This lack of foresight results in industrial clusters primarily focusing on bio-SAF rather than exploring synthetic SAF. A more forward-thinking approach is required to promote the balanced development of SAFs.

7.5. Limitations

The study has several limitations. There are two primary practical constraints. First, in a qualitative study, it is not feasible to interview all relevant parties within the cluster. Consequently, a representative sample of the cluster was selected for interviews, as outlined in Table 3. Second, the limited duration of the interviews presents a constraint. The study encompasses seven system functions, two types of fuels, two institutional contexts, and one cluster, resulting in diverse information. While not every result was discussed with every respondent, this does not detract from the primary findings of the research. However, more extended interviews would have allowed for more comprehensive respondent input on certain statements. A third limitation is found in the delineated scope of the study. While contributing to its significance, the contemporary relevance of the research topic has also resulted in dynamic changes during the study.

Besides a warrant of clarification, the ratings provided by respondents for the system functions are based on the full range of parameters discussed within each system function. Therefore, these ratings should be considered indicative rather than definitive.

For the sake of simplicity, the study did not differentiate between types of bio-SAF, although there are essential distinctions in practice. For instance, HEFA technology is more advanced than other forms of bio-SAF.

8. Conclusion

To answer the following research question: *"What are the drivers and barriers to developing and diffusing bio-SAF and synthetic-SAF in the Randstad cluster, in the EU and Dutch institutional contexts?,"* a qualitative case study mapped the drivers and barriers of bio-SAF and synthetic SAF technologies from the perspective of institutional contexts and the Randstad cluster, using the TIS framework. The study compared these drivers and barriers, identifying joint TIS-TIS "modes of interaction." These "modes of interaction" represent overarching systemic drivers and barriers that influence the TIS-TIS development of bio-SAF and synthetic SAF within the cluster, as shaped by institutional contexts. This approach provides insight into how the institutional environment impacts the development and interaction of these technologies.

The study found that the institutional contexts' drivers and barriers massively affect the interactions between the TIS of bio-SAF and synthetic SAF in the Randstad cluster. These "modes of interaction" shape the development of both technologies and are linked to a set of systemic drivers and barriers. The research indicates that, from the institutional contexts, "commensalism," "competition," and "parasitism" arise between the TISs in the Randstad cluster, as shown in Table 7. These modes of interaction demonstrate how institutional dynamics either promote or hinder the development of bio-SAF and synthetic SAF, influencing their respective progress within the cluster.

This research finds that one driver and three barriers contribute to the development and diffusion of bio-SAF and synthetic SAF in the Randstad cluster, in the EU and Dutch institutional contexts:
Driver: Alignment of policies, funding programs, and initiatives (*"commensalism"*).
Barrier: Uncertainties/ misalignments and weak (execution of) strategy *("competition").*
Barrier: Lack of support to scalability (*"competition").*
Barrier: Lack of differentiation (*"parasitism")*

These findings are essential to the EU's sustainability goals. The EU has set blending targets for bio-SAF and synthetic SAF (Figure 3), as their combined implementation is critical to achieving broader sustainability objectives. However, within the current institutional frameworks, the Randstad cluster identifies *"competition"* and *"parasitism"* TIS-TIS interactions. These modes of interaction hinder the integrated development of bio-based and synthetic SAF, creating obstacles that are misaligned with the overarching goal of sustainability. Addressing these inhibiting interactions is vital for meeting the EU's objectives.

Overall, this research underscores the pivotal role of TIS-TIS interactions in the holistic development of emerging technologies. It emphasizes the importance of considering institutional contexts to create a synergistic environment that nurtures interdependent drivers and addresses shared challenges. The findings advocate for a more integrated policy approach, highlighting that scalability and sustainability in SAF development not only depend on technological advancements but also on the strategic alignment of institutional support mechanisms. This integrated approach is essential for overcoming systemic barriers and achieving the broader sustainability goals.

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Reference List

Abrantes, I., Ferreira, A. F., Silva, A., & Costa, M. (2021). Sustainable aviation fuels and imminent technologies-CO2 emissions evolution towards 2050. *Journal of Cleaner Production*, *313*, 127937.

Alkemade, F., Hekkert, M. P., & Negro, S. O. (2011). Transition policy and innovation policy: friends or foes?. *Environmental innovation and societal transitions*, *1*(1), 125-129.

Arcadis (2024, February 13). *Onderzoek infrastructuur duurzame energiedragers luchtvaart.* Open Overheid. https://open.overheid.nl/documenten/dpc-2c7853815e6ff11e6d7249f8da6eb17704f49461/pdf

Asheim, B. T., Boschma, R., & Cooke, P. (2011). Constructing regional advantage: Platform policies based on related variety and differentiated knowledge bases. *Regional studies*, *45*(7), 893-904.

Azar, C., & Sandén, B. A. (2011). The elusive quest for technology-neutral policies. *Environmental Innovation and Societal Transitions*, *1*(1), 135-139.

Bauen, A., Bitossi, N., German, L., Harris, A., & Leow, K. (2020). Sustainable aviation fuels status, challenges and prospects of drop-in liquid fuels, hydrogen, and electrification in aviation. Johnson Matthey Technology Review, 64(3), 263–278. https://doi.org/10.1595/205651320x15816756012040

Bergek, A., Hekkert, M., Jacobsson, S., Markard, J., Sandén, B., & Truffer, B. (2015). Technological innovation systems in contexts: Conceptualizing contextual structures and interaction dynamics. *Environmental innovation and societal transitions*, *16*, 51-64.

Bergek, A., Jacobsson, S., Carlsson, B., Lindmark, S., & Rickne, A. (2008). Analyzing the functional dynamics of technological innovation systems: A scheme of analysis. *Research policy*, *37*(3), 407-429.

Bergek, A., Jacobsson, S., & Sandén, B. A. (2013). 'Legitimation'and 'development of positive externalities': two critical processes in the formation phase of technological innovation systems. In *The Dynamics of Sustainable Innovation Journeys*(pp. 55-72). Routledge.

Borrás, S., & Edquist, C. (2013). The choice of innovation policy instruments. *Technological forecasting and social change*, *80*(8), 1513-1522.

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative research in psychology*, *3*(2), 77-101.

Bryman, A. (2016). Social Research Methods. Oxford university press.

Brynolf, S., Taljegard, M., Grahn, M., & Hansson, J. (2018). Electrofuels for the transport sector: A review of production costs. *Renewable and Sustainable Energy Reviews*, *81*, 1887-1905.

Cabrera, E., & Melo de Sousa, J. M. (2022). Use of Sustainable Fuels in Aviation—A Review. In Energies (Vol. 15, Issue 7). MDPI. https://doi.org/10.3390/en15072440

Campbell, S., Greenwood, M., Prior, S., Shearer, T., Walkem, K., Young, S., ... & Walker, K. (2020). Purposive sampling: complex or simple? Research case examples. *Journal of research in Nursing*, *25*(8), 652-661.

Carlsson, B., Jacobsson, S., Holmén, M., & Rickne, A. (2002). Innovation systems: analytical and methodological issues. In Research Policy (Vol. 31).

Carlsson, B., & Stankiewicz, R. (1991). On the nature, function and composition of technological systems. *Journal of evolutionary economics*, *1*, 93-118.

Chaminade, C., & Esquist, C. (2010). Rationales for public policy intervention in the innovation process: Systems of innovation approach. In *The theory and practice of innovation policy*. Edward Elgar Publishing.

Chatrier, M. & Van Dijk, D. (2024). *SAF AND HYDROGEN FOR AVIATION.* Rotterdam The Hague Airport. https://www.rotterdamthehagueairport.nl/wp-content/uploads/1294597-white-paper-DEf.pdf

Chung, S. (2002). Building a national innovation system through regional innovation Systems. *Technovation*, *22*(8), 485-491.

Chiaramonti, D., Talluri, G., Scarlat, N., & Prussi, M. (2021). The challenge of forecasting the role of biofuel in EU transport decarbonization in 2050: A meta-analysis review of published scenarios. Renewable and Sustainable Energy Reviews, 139, 110715.

Coccia, M. (2019). A theory of classification and evolution of technologies within a Generalised Darwinism. *Technology Analysis & Strategic Management*, *31*(5), 517-531.

Delbecq, S., Fontane, J., Gourdain, N., Planès, T., & Simatos, F. (2023). Sustainable aviation in the context of the Paris Agreement: A review of prospective scenarios and their technological mitigation levers. In Progress in Aerospace Sciences (Vol. 141). Elsevier Ltd. https://doi.org/10.1016/j.paerosci.2023.100920

Detsios, N., Theodoraki, S., Maragoudaki, L., Atsonios, K., Grammelis, P., & Orfanoudakis, N. G. (2023). Recent Advances on Alternative Aviation Fuels/Pathways: A Critical Review. In Energies (Vol. 16, Issue 4). MDPI. https://doi.org/10.3390/en16041904

Edquist, C. (2001). The Systems of Innovation Approach and Innovation Policy: An account of the state of the art. In *DRUID conference, Aalborg* (Vol. 12, p. 15).

EASA. (2024a). *Fit for 55 and ReFuelEU*. (2024, February 23). EASA. https://www.easa.europa.eu/en/light/topics/fit-55-and-refueleu-aviation

EASA. (2024b). *ReFuelEU Aviation.* EASA Europe. https://www.easa.europa.eu/en/light/topics/refueleu-aviation

EASA (2024c). *What are Sustainable Aviation Fuels?.* EASA Europe. https://www.easa.europa.eu/eco/eaer/topics/sustainable-aviation-fuels/what-are-sustainable-aviation-fuels

European Commission. (2022). *Research & innovation for aviation*, Publications Office of the European Union. https://data.europa.eu/doi/10.2777/086649

European Commission. (2024a). *Net-Zero Industry Act.* European Commission. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/green-deal-industrial-plan/net-zero-industry-act_en

European Commission. (2024b). *Renewable and Low-Carbon Fuels Value Chain Industrial Alliance.* Transport Europe. https://transport.ec.europa.eu/transport-themes/clean-transport/alternative-fuels-sustainable-mobility-europe/renewable-and-low-carbon-fuels-value-chain-industrial-alliance_en#our-value-chain

Gawel, E., Lehmann, P., Purkus, A., Söderholm, P., & Witte, K. (2017). Rationales for Technology-Specifc RES Support and their Relevance for German Policy. Energy Policy, 102, 16–26.

Geels, F.W., 2004. From sectoral innovation systems to socio-technical systems: insights about dynamics and change from sociology and institutional theory. Research Policy 33, 897.

Hekkert, M. P., & Negro, S. O. (2009). Functions of innovation systems as a framework to understand sustainable technological change: Empirical evidence for earlier claims. *Technological forecasting and social change*, *76*(4), 584-594.

Hekkert M, Negro S, Heimeriks G, and Harmsen R (2011) Technological Innovation System Analysis: A manual for analysts. Universiteit Utrecht Faculty of Geosciences, Copernicus Institute for Sustainable Development and Innovation.

Hekkert, M. P., Suurs, R. A., Negro, S. O., Kuhlmann, S., & Smits, R. E. (2007). Functions of innovation systems: A new approach for analysing technological change. *Technological forecasting and social change*, *74*(4), 413-432.
Hernieuwbare Brandstoffen (2024, January). *Progress in Commercialization of Biojet/Sustainable Aviation Fuels (SAF).* Hernieuwbare Brandstoffen. https://www.hernieuwbarebrandstoffen.nl/post/iea-bioenergy-task-39-progress-in-commercialisation-of-biojet-sustainable-aviation-fuels-saf---technologies-and-policies-2024
Hileman, J. I., Ortiz, D. S., Bartis, J. T., Wong, H. M., Donohoo, P. E., Weiss, M. A., & Waitz, I. A. (2009). *Near-term feasibility of alternative jet fuels* (No. PARTNER-COE-2009-001). Rand Corporation.
Hoffman, A. J. (1999). Institutional evolution and change: Environmentalism and the US chemical industry. *Academy of management journal*, *42*(4), 351-371.
Huurman, B. (2023, 17 november). *Rotterdam The Hague Airport accelerates sustainable fuel blending - Rotterdam The Hague Airport*. Rotterdam The Hague Airport. https://www.rotterdamthehagueairport.nl/en/rotterdam-the-hague-airport-accelerates-sustainable-fuel-blending/
ICF (2024, June). *Role of Airports in Scaling up SAF.* ACI Europe.
Jacobsson, S., & Bergek, A. (2004). Transforming the energy sector: the evolution of technological systems in renewable energy technology. *Industrial and corporate change*, *13*(5), 815-849.
Jacobsson, S., & Johnson, A. (2000). The diffusion of renewable energy technology: an analytical framework and key issues for research. *Energy policy*, *28*(9), 625-640.
Jacobsson, S., & Lauber, V. (2006). The politics and policy of energy system transformation—explaining the German diffusion of renewable energy technology. *Energy policy*, *34*(3), 256-276.
Jacobsson, S., & Sandén, B. (2021). Technological discontinuities and the climate transition in Europe: the role of policy in two traditions of economic thinking. *The European Union and the Technology Shift*, 57-83.
Johnson, A., & Jacobsson, S. (2001). Inducement and blocking mechanisms in the development of a new industry: the case of renewable energy technology in Sweden. *Technology and the market: demand, users and innovation*, 89-111.
Ketels, C., Lindqvist, G., & Sölvell, Ö. (2006). *Cluster initiatives in developing and transition economies*. Stockholm: Center for Strategy and Competitiveness.
Klein-Marcuschamer, D., Turner, C., Allen, M., Gray, P., Dietzgen, R. G., Gresshoff, P. M., ... & Nielsen, L. K. (2013). Technoeconomic analysis of renewable aviation fuel from microalgae, Pongamia pinnata, and sugarcane. *Biofuels, Bioproducts and Biorefining*, *7*(4), 416-428.
Markard, J., Hekkert, M., & Jacobsson, S. (2015). The technological innovation systems framework: Response to six criticisms. *Environmental innovation and societal transitions*, *16*, 76-86.
Malecki, E. J. (2021). The geography of innovation. *Handbook of regional science*, 819-834.
McCann, P., & Ortega-Argilés, R. (2018). Smart specialization, regional growth and applications to European Union cohesion policy. In *Place-based Economic Development and the New EU Cohesion Policy* (pp. 51-62). Routledge.
Mutrelle C., (2024, January 24). *The Challenges of scaling up e-kerosene production in Europe.* Transport & Environment. https://te-cdn.ams3.cdn.digitaloceanspaces.com/files/2024_01_E-kerosene_Tracker_TE.pdf

Negro, S. O., & Hekkert, M. P. (2008). Explaining the success of emerging technologies by innovation system functioning: the case of biomass digestion in Germany. *Technology Analysis & Strategic Management*, *20*(4), 465-482.

Negro, S. O., Vasseur, V., van Sark, W. G. J. H. M., & Hekkert, M. P. (2012). Solar Eclipse: The rise and "dusk" of the Dutch PV Innovation System. *International Journal of Technology, Policy and Management*, *12*(2012), 135-157. https://doi.org/10.1504/IJTPM.2012.046923

Neste. (2024), *Rotterdam Refinery.* Neste. https://www.neste.com/about-neste/how-we-operate/production/rotterdam-refinery

Okolie, J. A., Awotoye, D., Tabat, M. E., Okoye, P. U., Epelle, E. I., Ogbaga, C. C., Gülec, F., & Oboirien, B. (2023). Multi-criteria decision analysis for the evaluation and screening of sustainable fuel production pathways. iScience, 26(6).

Paraušić, V., Domazet, I., & Simeunović, I. (2017). Analysis of the relationship between the stage of economic development and the state of cluster development.

Pérez-Alemán, P. (2005). Cluster formation, institutions and learning: the emergence of clusters and development in Chile. *Industrial and corporate change*, *14*(4), 651-677.

Porter, M. E. (1998). *Clusters and the new economics of competition* (Vol. 76, No. 6, pp. 77-90). Boston: Harvard Business Review.

Porter, M. E. (2007). *Clusters and economic policy: Aligning public policy with the new economics of competition*. Institute for Strategy and Competitiveness at Harvard Business School.

Rijksoverheid. (2024). *CO_2-uitstoot luchtvaart verminderen.* Rijksoverheid. https://www.rijksoverheid.nl/onderwerpen/luchtvaart/co2-uitstoot-luchtvaart

Sandén, B. A., & Hillman, K. M. (2011). A framework for analysis of multi-mode interaction among technologies with examples from the history of alternative transport fuels in Sweden. *Research policy*, *40*(3), 403-414.

Scheelhaase, J., Maertens, S., & Grimme, W. (2019). Synthetic fuels in aviation - Current barriers and potential political measures. Transportation Research Procedia, 43, 21–30. https://doi.org/10.1016/j.trpro.2019.12.015

Schneider, C., Lechtenböhmer, S., & Samadi, S. (2020). Risks and opportunities associated with decarbonising Rotterdam's industrial cluster. *Environmental innovation and societal transitions*, *35*, 414-428.

Shahriar, M. F., & Khanal, A. (2022). The current techno-economic, environmental, policy status and perspectives of sustainable aviation fuel (SAF). Fuel, p. 325. https://doi.org/10.1016/j.fuel.2022.124905

Shehab, M., Moshammer, K., Franke, M., & Zondervan, E. (2023). Analysis of the Potential of Meeting the EU's Sustainable Aviation Fuel Targets in 2030 and 2050. Sustainability (Switzerland), 15(12). https://doi.org/10.3390/su15129266

Shell. (2024, July 2). *Shell to temporarily pause on-site construction of European biofuels facility.* Shell. https://www.shell.com/news-and-insights/newsroom/news-and-media-releases/2024/shell-to-temporarily-pause-on-site-construction-of-european-biofuels-facility.html

SkyNRG (2024, June). *Sustainable Aviation Fuel Market Outlook.* SkyNRG. https://skynrg.com/skynrg-releases-sustainable-aviation-fuel-market-outlook-2024/

Soone, J. (2021). RefuelEU Aviation. In *European Parliamentary Research Service*. https://www.europarl.europa.eu/RegData/etudes/ATAG/2023/751437/EPRS_ATA(2023)751437_EN.pdf

Suurs, R.A.A., Hekkert, M.P., 2009. Cumulative causation in the formation of a technological innovation system: the case of biofuels in the Netherlands. Technol. Forecasting Social Change 76, 1003–1020.
Su-ungkavatin, P., Tiruta-Barna, L., & Hamelin, L. (2023). Biofuels, electrofuels, electric or hydrogen?: A review of current and emerging sustainable aviation systems. In Progress in Energy and Combustion Science (Vol. 96). Elsevier Ltd. https://doi.org/10.1016/j.pecs.2023.101073
Stichting RHIA. (2021, October). *Regiovisie SAF.* Stichting RHIA. https://stichtingrhia.nl/wp-content/uploads/2021/12/RHIA-Regiovisie-SAF.pdf
Stichting RHIA. (2022, 17 October). Over RHIA - Rotterdam the Hague Innovation Airport. Rotterdam The Hague Innovation Airport. https://stichtingrhia.nl/over-rhia/
Trencher, G., & Wesseling, J. (2022). Roadblocks to fuel-cell electric vehicle diffusion: Evidence from Germany, Japan and California. *Transportation Research Part D: Transport and Environment*, *112*, 103458.
Tulips. (2024). *Overview of TULIPS projects and demonstrations.* Tulips Greenairports. https://tulips-greenairports.eu/tulips-projects-and-demonstrations/
Unruh, G. C. (2000). Understanding carbon lock-in. *Energy policy*, *28*(12), 817-830.
Verhoeven, N. (2020). Thematische Analyse. Boom Uitgevers.
Wesseling, J. H., & Van der Vooren, A. (2017). Lock-in of mature innovation systems: the transformation toward clean concrete in the Netherlands. *Journal of cleaner production*, *155*, 114-124.
Wesseling, J., Kieft, A., Fuenfschilling, L., & Hekkert, M. (2022). How socio-technical regimes affect low-carbon innovation: Global pressures inhibiting industrial heat pumps in the Netherlands. *Energy Research & Social Science*, *89*, 102674. https://doi.org/10.1016/j.erss.2022.102674
Wieczorek, A. J., & Hekkert, M. P. (2012). Systemic instruments for systemic innovation problems: A framework for policy makers and innovation scholars. *Science and public policy*, *39*(1), 74-87.
Zhang, G., McAdams, D. A., Shankar, V., & Darani, M. M. (2017). Modeling the evolution of system technology performance when component and system technology performances interact: Commensalism and amensalism. *Technological Forecasting and Social Change*, *125*, 116-124.

Appendices

Appendix A - Semi-structured Interview Guide

Semi-structured interview:
- Questions between brackets are asked if the interviewee can answer the first question
- Depending on the interviewee (and company), I can ask my questions regarding bio-SAF **and** synthetic SAF

1. **Pre-interview**
   Send the informed consent form.

2. **Interview Questions Guide**

Introduction
- Thanks for participating in the interview.
- The interviewee is asked if he or she agrees to have the audio recorded. The interviewee is made aware that he or she is mentioned anonymously in the report, and the company's name is unrelated to any statements.
- Introduction research

Questions

1. Knowledge Development: Learning by searching and by doing. Scientific, technical, and practical knowledge that forms the foundation for innovation and technological advancements, enabling the growth and maturity of a TIS. E.g., R&D
- On a scale from 1 to 5 (very weak-very strong). How would you rate the performance of this system function regarding the TIS of bio-SAF and synthetic SAF?
- Why did you not rate it higher/lower? What problems prevent this function from being higher than you stated? //// What makes you choose this low score?
- Do you know which actors ((Governmental) organizations, institutions, companies, etc) are involved in these projects, and what are their roles?
- (Are there any interactions between (the TIS of) bio-SAF and synthetic SAF regarding knowledge development?)
- (Are you aware of any barriers to developing this knowledge?)
- (Can these barriers somehow be related to the EU or Dutch institutional context? (policies, regulations, projects, etc.))

2. Entrepreneurial Activities: Entrepreneurial experimentation and commercialization of innovations (e.g., pilots). This also includes the number and quality of activities, the extent of new entrants, and business cases.
- On a scale from 1 to 5 (very weak-very strong). How would you rate the performance of this system function regarding bio-SAF and/or synthetic SAF?

- Why did you not rate it higher/lower? What problems prevent this function from being higher than you stated? //// What makes you choose for this low score?
- Do you know which actors ((Governmental) organizations, institutions, companies, etc) are involved in these projects, and what are their roles?
- (Are there any interactions between (the TIS of) bio-SAF and/or synthetic SAF regarding these pilots, projects, actors?)
- (Are you aware of any barriers in developing these projects and business cases?)
- (Can these barriers somehow be related to the EU and Dutch institutional context? (policies, regulations, projects, etc.))

3.Knowledge Diffusion: Exchange of tacit and codified knowledge in networks, including learning by interacting and by using.

- Are there any platforms or networks that facilitate knowledge exchange of bio-SAF and/or synthetic SAF?
- On a 1-5 likert scale (very weak-very strong), how would you rate the performance of this system function?
- Why did you not rate it higher? What problems prevent this function from being higher than you stated? //// What made you choose for this low score?
- (Are there any interactions between (the TIS of) bio-SAF and/or synthetic SAF regarding these platforms and networks?)
- (Are you aware of any barriers to exchanging knowledge via these platforms and networks?)
- (Can these barriers somehow be related to the EU and Dutch institutional context? (policies, regulations, projects, etc.))

4.Guidance of the Search: The extent of providing directionality toward the focal technology by identifying actions of different stakeholders and the priorities of (for example government). So, this system function is looking at the targets set for the coming decades regarding for both bio and synthetic SAF, in relation to their current technological developments. Ambitions require a form of legitimacy and support towards the developments of SAF (bio and synthetic) and the allocation of resources has to be stimulated in the process. For example, look at activities around the innovations, whether they are in line with the set goals.

- On a 1-5 likert scale (very weak-very strong), how would you rate the performance of this system function?
- Why did you not rate it higher? What problems prevent this function from being higher than you stated? //// What made you choose for this low score?
- How are research and development efforts directed in the technological field of bio-SAF and synthetic SAF?
- (Are there any interactions between (the TIS of) bio-SAF and/or synthetic SAF regarding these directions?
- (Are you aware of any barriers that affect the direction of developments in the fields of bio-SAF and synthetic SAF?
- (Can these barriers somehow be related to the EU and Dutch institutional context? (policies, regulations, projects, etc.))

5. Market Formation: Creating demand for the technology, notably through protected spaces, e.g., induced by regulations, policy, and standards on EU and national level.

- On a 1-5 likert scale (very weak-very strong), how would you rate the performance of this system function?
- Why did you not rate it higher? What problems prevent this function from being higher than you stated? //// What made you choose for this low score?
- How is the market for bio-SAF and/or synthetic being developed?
- (Are there any interactions between (the TIS of) bio-SAF and/or synthetic SAF regarding the market developments?)
- (Are you aware of any barriers regarding market developments and bio-SAF and/or synthetic SAF)
- (Can these barriers somehow be related to the EU and Dutch institutional context? (policies, regulations, projects, etc.))

6. Resource Mobilization: Allocating financial, human, and physical resources to fulfill other system functions, with an focus on the system functions of knowledge development (2) and entrepreunerial activities (1).

- On a 1-5 likert scale (very weak-very strong), how would you rate the performance of this system function?
- Why did you not rate it higher? What problems prevent this function from being higher than you stated? //// What made you choose for this low score?
- What resources (financial, human, and physical) are critical for the development of bio-SAF and/or synthetic SAF
- (Are there any interactions between (the TIS of) bio-SAF and/or synthetic SAF regarding the need for resources?)
- (Are you aware of any barriers, regarding the resources critical to developing bio-SAF and/or synthetic SAF?)
- (Can these barriers somehow be related to the Eu and Dutch institutional context? (policies, regulations, projects, etc.))

7. Creation of Legitimacy: Create stakeholder support for the technology, e. g., through lobby. This system function is about the level of support regarding developments. This function can be analyzed by mapping the rise and growth of interest groups and their lobby actions. So basically the power of lobbying

- On a 1-5 likert scale (very weak-very strong), how would you rate the performance of this system function?
- Why did you not rate it higher? What problems prevent this function from being higher than you stated? //// What made you choose for this low score?
- What strategies are employed to build support among the public and critical stakeholders for bio-SAF and/or synthetic SAF?
- (Are there any interactions between (the TIS of) bio-SAF and/or synthetic SAF regarding strategies supporting these innovations?)
- (Are you aware of any barriers regarding the strategies that are being developed to support bio-SAF and synthetic SAF among stakeholders and the public?)
- (Can these barriers somehow be related to the EU and Dutch institutional context? (policies, regulations, projects, etc.))

Extra

- (Is the current EU institutional policy focused on bio-SAF and synthetic SAF interactions?)

Closing & Validation

- Okay, that was the interview.
- What you said earlier about …. Can I interpret it as ….. Or did I misinterpret it …..
  → Reach a consensus about the ambiguities
- Do you have any questions for me?
- At the end of my research, I will share how I used the data
- Thanks for the interview

Appendix B – Structural Element per Respondent

The summary below shows the named structural elements by respondents. The author is aware that relationships between actors also function as networks. Also, institutions and infrastructures can serve as networks and networks can also fall under infrastructures. For simplicity, structural elements are not double listed.

Structural Element	Type	Name	Respondents
Actor	Fuel Suppliers	Shell	R1; R2; R4; R5; R6; R7; R8; R9; R10; R11; R12; R13; R14; R16;
		NESTE	R1; R2; R4; R5; R6; R7; R8; R9; R10; R12; R13; R14; R15; R16;
		Total	R1; R5; R11
		SkyNRG	R1; R2; R3; R4; R5; R7; R8; R9; R10; R12; R14; R16; R17
		Air BP	R2; R5
	(Air)ports	RTHA	R1; R2; R3; R4; R5; R11; R12; R13; R14; R16; R17
		Schiphol	R1; R2; R3; R4; R8; R9; R10; R12; R13; R14; R15; R16;
		Port of Rotterdam	R1; R2; R3; R6; R8; R9; R10; R11; R12; R13; R14; R16; R17
		Port of Amsterdam	R3; R4; R9; R12; R16;
	Airlines	KLM	R1; R2; R3; R4; R6; R8; R9; R10; R11; R12; R14;
		Transavia	R1; R13; R14;
	Knowledge Institutes	NLR	R2; R7; R8; R10;
		TU Delft	R1; R2; R3; R5; R8; R9; R10; R11; R16; R17
		Universiteit Utrecht	R1; R11; R17
	European Governments	European Commission	R2; R7; R12;
		EASA	R2;
		European Innovation Fund	R5; R10;
	National Governments	Ministry of Infrastructure & Water Management	R1; R2; R7;R8; R9; R10; R11; R14; R17
		Ministry of Economic Affairs & Climate	R2; R7; R8; R10; R11; R14; R16;

		RVO	R10; R16; R17;
	Consultancies	Power2X	R6;
	NGOs	Natuur en Milieu	R9; R10;
		WNF	R1;
Networks	Consortia	Duurzame luchtvaarttafel	R1; R2; R3; R4; R5; R6; R8; R9; R10; R12; R16; R17
		Tulips	R1; R2; R3; R4; R5; R6; R7; R16
		RHIA	R1; R2; R4; R13; R14; R16; R17
		ACARE	R1;
		TNO	R3; R11; R12; R17
	Regional collaborations	RTHA & Port of Rotterdam	R1; R2; R13;
		Synkero (plant)	R3; R4; R5; R17
		Zenid	R1; R2; R3; R4; R5; R16; R17
Institutions	Hard Institutions	ReFuelEU	R1; R2; R3; R4; R5; R6; R7; R8; R9; R10; R11; R12; R13; R14; R16; R17
		REDII/III	R1; R2; R5; R7; R8; R9; R10; R12; R16; R17
		EU ETS	R1; R2; R3; R4; R5; R6; R7; R8; R9; R12; R17
Infrastructures	Financial/knowledge	Horizon	R2; R4; R5; R6; R8; R12;
		National Growth Fund	R2; R5; R6; R7; R9; R10; R16; R17
		European Innovation Fund	R5; R10;
		DEI+	R16

Appendix C – Ratings of System Functions per Respondent

The survey shows several specifics. The (bio) and (syn) mean that a respondent gave a different grade for each TIS. The * means that the respondent gave two marks, for example, a 1 and 2 (=1.5). Due to the size of the system function, not every respondent gave a rating everywhere.

System Function	Score + Respondents				
Knowledge Development	**1**	**2**	**3**	**4**	**5**
	R11*;	R8*; R9*; R11*; R12(syn);	R1; R3; R4; R7(syn); R8*; R9*; R14(syn); R16; R17	R10; R12(bio); R13; R16*;	R2; R7(bio); R14(bio)
Entrepreneurial Activities	**1**	**2**	**3**	**4**	**5**
		R17	R2*; R3; R4(syn); R5; R6(syn); R7; R14; R16;	R1; R2*; R8*; R10; R13;	R4(bio); R6(bio), R8*;
Knowledge Diffusion	**1**	**2**	**3**	**4**	**5**
			R1; R2; R4; R5*;	R3; R5*; R8; R10; R12; R13;	
Guidance of the Search	**1**	**2**	**3**	**4**	**5**
		R6(syn);	R1; R2; R3; R10; R13*; R16; R17;	R4; R5; R6(bio); R7; R8; R13*;	
Market Formation	**1**	**2**	**3**	**4**	**5**
		R5*; R9; R14; R17	R1; R2; R3; R5*; R10; R12;	R4; R6; R8;	R7;
Resource Mobilization	**1**	**2**	**3**	**4**	**5**
		R2(syn)	R1; R2(bio); R3; R8; R10; R13;		
Creation of Legitimacy	**1**	**2**	**3**	**4**	**5**
	R7*;	R1; R7*;	R5;	R3;	

Appendix D – Code Scheme

1. Choose between:
   - “bio-SAF”
   - “synthetic SAF”
   - “both”

2. Select the relevant structural elements:
   - “actors”
   - “networks”
   - “institutions”
   - “infrastructures”

3. Select the relevant system functions:
   - “knowledge development”
   - “entrepreneurial activities”
   - “knowledge diffusion”
   - “guidance of the search”
   - “market formation”
   - “resource mobilization”
   - “creation of legitimacy”

4. Choose between:
   - “EU institutional context”
   - “Dutch institutional context”
   - “cluster”

5. Choose between:
   - “*drivers*”
   - “*barriers*”

Appendix E – Drivers in the Institutional Contexts

SF	Drivers in the Institutional Contexts	SAFs & Mode of Interaction	EU/Dutch Context
Knowledge Developme nt	Europe supports R&D efforts (R1; R2; R3; R5; R8), with subsidies allocated for them through the Horizon Innovation Fund (R1; R2; R6; R8; R12), such as the Tulips project (R1; R2; R3; R4; R5; R6; R7).	Both, Commensalism	EU
	The Dutch government holds initiatives that support the R&D bio-SAF and synthetic SAF, like the National Growth Fund (R2; R5; R6; R7; R16; R17). Additionally, knowledge development is fostered within the Sustainable Aviation Table (R2; R10; R16).	Both, Commensalism	Dutch
Entrepreneurial Activities	Horizon finances the Tulips project (R1; R2; R3; R4; R5; R6; R7), which conducts pilots on the scalability of SAF (R4)	Both, Commensalism	EU
	Startups can approach the European Innovation Fund for financing needed for production and scaling up (R5).	Both, Commensalism	EU
	The Net-Zero Industry Act also focuses on scaling sustainable energy production (R16)	Both, Commensalism	EU
	The Dutch government contributes to pilots through subsidies (R3; R7; R10; R11; R16; R17), such as the National Growth Fund (R2; R5; R6; R7; R10; R16; R17) and the DEI+ program	Both, Commensalism	Dutch
Knowledge Diffusion	European funding facilitates collaborations that involve knowledge sharing (R1; R2; R3; R4; R5), such as the Horizon program with the Tulips project (R1; R2; R3; R4; R5; R6; R7), led by Schiphol (R1; R2; R3; R4). As part of this initiative, the EU Clearing House is being established (Tulips, 2024) to support startups in bringing SAF technologies to market (R4). The EU recently introduced the Renewable and Low-Carbon Fuels Value Chain Industrial Alliance, which focuses on SAFs for aviation (and fuels for water transport) (R16).	Both, Commensalism	EU
	The government actively encourages knowledge diffusion (R2; R4; R7; R8; R10; R12; R13; R16). The Ministry of Infrastructure and Water Management (I&W) is open to engagement with stakeholders from the aviation sector (R2; R4; R7; R10; R12; R13; R16).	Both, Commensalism	Dutch
Guida nce of the Searc	Policy-wise, the scaling up of bio-SAF and synthetic SAF is being addressed comprehensively through ReFuelEU (R1; R2; R4; R5; R10; R12), with blending percentages in ReFuelEU targeting both bio-SAF and synthetic SAF (R1; R2; R3; R4; R5; R7; R8; R10; R12).	Both, Commensalism	EU

	The phasing out of EU ETS allowances is helping to narrow the price gap between kerosene and SAFs (R1; R2; R7; Mutrelle, 2024).	Both, Commensalism	EU
Market Formation	ReFuelEU is an effective political measure (R1; R2; R3; R4; R6; R7; R8; R9; R12; R13) for reducing the gap between market demand and production costs (R1; R2; R3; R4; R7; R8; R12; R13) and providing certainty of demand (R8; R12; R13; R16), which positively influences investments in production facilities (R8).	Both, Commensalism	EU
	EU ETS regulations contribute to the market formation of SAF (R1; R2; R5; R7; Mutrelle, 2024)	Both, Commensalism	EU
	Regulation plays a decisive role in determining which technologies and approaches succeed, meaning policy is crucial in shaping market developments (R1; R2; R3; R4; R6; R7; R8; R9; R13)	Both, Commensalism	EU
Resource Mobilization	In 2026, the European Commission will assess expanding carbon pricing to allocate more bio-SAF and synthetic SAF feedstocks to hard-to-decarbonize sectors like aviation (Hernieuwbare Brandstoffen, 2024).	Both, Commensalism	EU
Creation of Legitimacy	An excellent initiative to counteract greenwashing is the role of the Advertising Code Committee (R8)	Both, Commensalism	EU
	Respondents are generally satisfied with the lobbying around SAF regulations (R4; R5), such as the ReFuelEU mandate (R1; R3; R5).	Both, Commensalism	EU
	Developments in bio-SAF have already addressed some initial questions about synthetic SAFs, particularly in areas such as lobbying for regulations (R6; R8; R10)	Both, Commensalism	EU
	The EU has introduced the Green Claims Directive to combat greenwashing (R15).	Both, Commensalism	EU

Appendix F – Barriers in the Institutional Contexts

SF	Barriers in the Institutional Contexts	SAFs & Mode of Interaction	EU/Dutch Context
Knowledge Development	The Dutch government maintains a technology-neutral stance regarding investments and support (R16).	Synthetic SAF, Parasitism	Dutch
	However, the REDIII regulation poses challenges for scaling up R&D efforts, particularly for synthetic SAF (R9; R17).	Both, Competition	EU
	The Dutch government frequently commissions external companies to conduct studies, even when the knowledge already exists within the sector (R1; R2).	Both, Competition	Dutch
	The Dutch government has faced a shortage of scientific personnel for many years, which has resulted in insufficient attention to barriers within R&D (R11).	Both, Competition	Dutch
	Government policy to focus on the R&D of synthetic SAF is lacking (R9; R11; R14).	Both, Parasitism	Dutch
	The high costs of investing in R&D make it hard to support a technology successfully (R16).	Both, Competition	Both
	R&D is a barrier to scalability (R1; R2; R3; R4; R5; R6; R7; R8; R9; R10; R11; R14; R16).	Both, Competition	Both
Entrepreneurial Activities	The Dutch government maintains a technology-neutral stance regarding investments and support (R16).	Synthetic SAF, Parasitism	Dutch
	Significant funding and support are still required for the development and scaling up of synthetic SAF (R2; R3; R4; R6; R9; R10; R11; R14; R16; Mutrelle, 2024), and to a certain extent for advanced bio-fuels as well (R8; R14; R16). Investment timelines for both types of SAF are behind (R7; R9; R10; R14), particularly for synthetic SAF (R1; R4; R9; R10; R11; R14; Mutrelle, 2024).	Both, Competition	Both
	From the Dutch institutional context, it is challenging to secure specific necessities for a project's initiation (R1; R3; R4; R6; R8; R12).	Both, Competition	Dutch
	The National Growth Fund provides minimal support for SAF (R9; R17).	Both, Competition	Dutch
	The EU and Dutch institutional contexts must do more to initiate demonstration projects and scale-up efforts (R11; R14).	Both, Competition	Both
Kn ow -	Communication between the Dutch Ministries of I&W and Economic Affairs and Climate Policy (R10) and contact between airlines and the Dutch Ministry of I&W (R14) can be improved.	Both, Competition	Dutch

	Communication between the Dutch government and various sector stakeholders, such as resource providers, technological and scientific entities, and industry players, is fragmented (R11; R17). This fragmentation hinders the cohesive integration of all necessary elements for development (R11; R17).	Both, Competition	Dutch
Guidance of the Search	The blending targets within ReFuelEU are solid, but they could have been set higher, especially in the early years (R1; R2; R4; R5; R9; R13), as there is a gap between these targets and the broader climate ambitions (R1; R2; R4; R5; R6; R9).	Both, Competition	EU
	Uncertainties in regulations and strategy cause parties to hesitate, making it challenging to develop a clear strategy and business case (R1; R4; R6; R9; R10; R12; SkyNRG, 2024). This hesitation leads to a reluctance to enter into long-term contracts, creating a vicious cycle (R12; Arcadis, 2024).	Both, Competition	EU
	The ReFuelEU mandate and policies primarily target fuel suppliers (R1; R5; R6; R7). There is a lack of legislation for airlines and consumers (R5; Mutrelle 2024); currently, airlines are only linked to policies focused on production (R6). To better support fuel suppliers, incentives could be developed for them (R6; R17), such as guaranteed income (R6; R17) or price certainty (R8).	Both, Competition	EU
	There is a lack of incentives to supply synthetic SAF before 2030 (Mutrelle, 2024).	Synthetic SAF, Parasitism	EU
	The REDIII regulation exempts the aviation sector from specific sustainability measures, making it difficult for SAF producers to scale up R&D and establish a viable business case (R9).	Both, Competition	EU
	Since SAF is more expensive than emissions credits, the EU ETS is unlikely to contribute significantly to the development of SAF (R9).	Both, Competition	EU
	There is uncertainty surrounding the flexibility mechanism (R4; R6; R12; R16) due to regulations fluctuating between European and national policies (R6). Additionally, the Directorate-General for Climate Action (DG CLIMA) and the Directorate-General for Mobility and Transport often do not coordinate effectively (R6; R12; R16). As a result, one department applies the flexibility mechanism, while the other requires SAF to be supplied to a specific airport (R6; R12).	Both, Competition	EU
	There is also uncertainty regarding the linkage between REDIII and ReFuelEU, as their objectives differ (R12). Companies find it challenging to understand how these policy packages are interconnected (R12).	Both, Competition	EU
	Europe primarily focuses on stimulating fundamental research (R8; R17) and demand through ReFuelEU (R8), but investment subsidies for actual scaling up are insufficient (R6; R8; R9; R17).	Both, Competition	EU

	There is a lack of clarity in the regulations regarding SAF, which hinders companies from investing in SAF (R1; R4; R6; R9; R10; R12; R15; R17; SkyNRG, 2024)	Both, Competition	EU
	The ability to offset emissions through EU ETS from other sectors poses the risk that actual SAF blending might progress slowly (R9; R16).	Both, Competition	EU
	The scaling up of synthetic SAF is not gradual, requiring a massive increase after 2030 (R1; R6; R5; R12; R16), which is almost unachievable (R5; R6; R12; R16).	Synthetic SAF, Parasitism	EU
	The Netherlands lacks policy clarity (R1; R2; R3; R4; R5; R6; R8; R9; R11; R13; R14; R17; Arcadis, 2024). This absence of clear policy is reflected in the insufficient support from the Dutch government for scaling up SAF production (R1; R2; R3; R4; R5; R6; R8; R9; R11; R14; R17), particularly for synthetic SAF (R10; R11; R12), with a specific focus on resources (R17)	Both, Competition	Dutch
	Government support is lacking to turn SAF into a winning strategy, as it is not backed by solid policy (R1; R2; R3; R4; R5; R6; R8; R9; R14; R17).	Both, Competition	Dutch
	The Dutch government should prioritize the production of a certain amount of synthetic SAF (R3; R10; R11), regardless of the costs, to stimulate market development (R11).	Synthetic SAF, Parasitism	Dutch
	Subsidies from the Dutch government are highly uncertain (R1; R2; R5; R6; R7; R9; R14; R17), and the application processes and regulations are lengthy (R1; R3).	Both, Competition	Dutch
	Investments from the National Growth Fund are directed towards established large companies like Shell rather than startups, even though startups can potentially make a significant impact (R14; R17).	Both, Competition	Dutch
	The revenue from the aviation tax is supposed to be reinvested in the development of (R1; R9; R14), as mandated by the EU, but this is not being fully implemented (R1; R9).	Both, Competition	Dutch
	Different departments within the Ministry of Economic Affairs and Climate Policy (EKZ) have distinct interests (R16).	Both, Competition	Dutch
	Regulatory uncertainties concerning compliance also exist, particularly regarding where and how to report (R12; R14). A comprehensive documentation package to guide companies is lacking (R12).	Both, Competition	Dutch
	The Renewable Fuel Unit subsidies arek not aligned with the RED and other regulations (Arcadis, 2024).	Both, Competition	Dutch
	The interaction between EU and Dutch regulations and strategies often does not align well, leading to confusion (R16; R17).	Both, Competition	Both
	Airlines are concerned about the costs associated with EU ETS and the availability of SAF (R12).	Both, Competition	EU
M	The Netherlands is exploring ways to do more, but efforts remain mainly at the legal level (R9).	Both, Competition	Dutch

	The national mandate target is not legally binding, as the European regulation mandates only a 6% blending requirement by 2030 (R1; R2; R3; R4; R7; R12; R16; R17)	Both, Commensalism	Dutch
	The current aviation tax generates 200 million euros, but this revenue is not reinvested in making aviation more sustainable; instead, it goes into the general state budget (R1; R9; R14) despite EU requirements that it be for sustainability efforts (R1; R9)	Both, Competition	Dutch
	There is no existing market for synthetic SAF, so leaving this to the sector is ineffective. The government must establish this market (R11; R17; Arcadis, 2024).	Synthetic SAF, Parasitism	Dutch
	The Dutch government's uncertainty in policy and strategy (R1; R2; R3; R4; R5; R6; R8; R9; R11; R14) is not aligned to become a hub for SAF (R9; R10).	Both, Competition	Dutch
	Government investments in SAF development extend only to the experimental phase (R1; R2; R5; R6; R8; R17)	Both, Competition	Dutch
Resource Mobilization	The ReFuelEU mandate is not linked to the availability of feedstocks (R1; R9).	Both, Competition	EU
	There are regulation uncertainties regarding the supply of feedstocks to production facilities (R4)	Both, Competition	EU
	No connection has been made between renewable energy and SAF production (R7).	Both, Competition	EU
	Hydrogen production is not aligned with the mandate for bio-SAF and synthetic SAF (R1; R9)	Both, Competition	EU
	The allocation of other bio-SAF feedstocks across sectors is also lacking (R1; R9; R12; R16; Arcadis, 2024).	Bio-SAF, Neutralism	EU
	In the energy transition policy, urgent and strategic decisions must be made regarding the availability of all technologies and feedstocks (R3; R9; R10; R16), requiring a comprehensive overview (R11).	Both, Competition	EU
	The Dutch government is not actively supporting the development of feedstock availability due to a lack of policy (R1; R2; R4; R5; R6; R8; R9; R10; R12; R13; R15; R16) but aspires to be a SAF hub (R9; R10).	Both, Competition	Dutch
	the Netherlands is constrained by regulations concerning the construction of production facilities (R8), such as nitrogen emission standards (R8; R13; R17).	Both, Competition	Dutch
	There is a significant gap between current feedstock production, the ambitions set, and what is realistically achievable (R1; R7; Mutrelle, 2024).	Both, Competition	EU
	The scalability of bio-SAF is limited (R1; R2; R3; R4; R5; R6; R7; R9; R10; R12; Chatrier & Van Dijk, 2024) because of feedstock shortages (R1; R2; R4; R5; R6; R7; R9; R10; R12; R13; R14; R16; SkyNRG, 2024; Arcadis, 2024) and lack of efficient feedstock collection (R4; R9)	Bio-SAF, Parasitism	EU
	Investments in synthetic SAF are still lagging (R2; R3; R4; R6; R9; R11; R12).	Synthetic SAF, Parasitism	EU

	For both bio-SAF and synthetic SAF, the necessary feedstocks are not aligned with the production levels needed to meet the mandate (R1; R7; R9; Mutrelle, 2024), and there is a lack of distribution planning for feedstocks across sectors (R1; R9; R12; R16; R17; Mutrelle, 2024; Arcadis, 2024). Additionally, there are uncertainties regarding the supply of feedstocks (R4; R17; Mutrelle, 2024).	Both, Competition	EU
	The Dutch government is refraining from actively developing the availability of feedstocks (R1; R2; R4; R5; R6; R8; R9; R10; R12; R13; R15; R16). However, the Netherlands could contribute to creating a more favorable environment for feedstocks and SAF (R12; R13) through improvements in permitting processes, infrastructure (R3; R12), and the development of green hydrogen (R13).	Both, Competition	Dutch
Creation of Legitimacy	However, it is sometimes observed that certain lobbies or companies with close ties can influence policy decisions (R3; R4).	Both, Competition	EU
	The Dutch government often defers responsibility to Europe, which results in a lack of action at the national level (R5; R11).	Both, Competition	Dutch
	The Netherlands places too much confidence in SAF, as reflected in the ambitious 14% target (R9; R17). However, there is now a need to reconsider this mandate (R9; R17).	Both, Competition	Dutch
	The focus to development of SAFs is on short-term solutions (R5; R9; R12)	Synthetic SAF, Parasitism	EU
	The EU should improve its communication regarding the environmental impact of flights (R6; R9; R12).	Both, Competition	EU
	The EU fails to clearly communicate its feedstock policy and strategy to the sector, allowing the industry to focus on specific areas and make progress (R14).	Both, Competition	EU
	The national government is not transparent in its SAF strategy (R9; R13; R15) and could use existing platforms to target consumers and business travelers (R5; R9; R12). It would be wise to cultivate a willingness to pay among business travelers, as they represent a significant share of the market (R12; Mutrelle, 2024).	Both, Competition	Dutch
	There is a lack of effective communication between the Dutch government and airlines in some areas (R14).	Both, Competition	Dutch
	There is a lack of clarity regarding regulations for SAF certificates (R6; R15), which hinders companies from investing in SAF (R15).	Both, Competition	Dutch
	It is essential to embrace all possible forms of SAFs to meet targets (R1; R2; R6; R8; R11; R16; R17). The government frequently focuses on the success of innovation while the previous one has yet to be fully	Both, Competition	Dutch

	established (R8; R17); there is often an overly idealistic view of fuel solutions (R1; R2; R3; R8; R11; R13; R16; R17). Hopes are often pinned on a single type of fuel (R1; R2; R3; R8; R11; R16; R17), even though a particular fuel might serve as a partial (R1; R8) or temporary (R6; R8) solution. For instance, bio-SAF is sometimes dismissed because it is expected to be replaced by other innovations, even though we are far from reaching that point (R8; R11; R16).		

Appendix G – TIS-TIS Interactions in the Cluster

SF	TIS-TIS Interaction	Mode of Interaction
Knowledge Development	The Tulips project supports the R&D of bio-SAF and the R&D on synthetic SAF in (R4).	Commensalism
	Within bio-SAF, the HEFA technology is significantly more advanced than the alcohol-to-jet technology (R3; R10; R14; R16). Bio-SAF technologies are relatively ahead of synthetic SAF (R1; R2; R3; R4; R5; R6; R7; R9; R10; R11; R12; R13; R14)	Parasitism
	The development depends on the same institutions and stakeholders, such as certification and blending (R2; R8).	Commensalism
	Within the cluster, contributions to the R&D of bio-SAF and synthetic SAF come from airports such as Schiphol and RTHA (R1; R2; R4; R14), commercial companies (R1; R2; R3; R4; R5; R6), and knowledge institutes (R1; R2; R8; R9; R10; R16).	Commensalism
	R&D is needed to enable scale-up of bio-SAF and synthetic SAF (R1; R2; R3; R4; R5; R6; R8).	Competition
Entrepreneurial Activities	The cluster holds a strong position as a hub for producing, storage, and transporting fuels with the Port of Rotterdam (R6; R8; R11; R12; R13; R14; R16; R17) and the Port of Amsterdam (R3; R17; Arcadis, 2024), which includes infrastructure for pilots and demonstrations regarding SAF (R11; R12; R13). The Port of Rotterdam aims to play the same supply role with SAF as with kerosene, accelerating the production of bio-SAF and synthetic SAF production in the region (Chatrier & Van Dijk, 2024).	Commensalism
	Multiple actors like Schiphol and RTHA (R1; R2; R3; R4; R5; R8; R13; R16; R17), but also Neste and SkyNRG (R1; R2; R3; R4; R5; R8;) are contributing to SAF activities in the cluster.	Commensalism
	The focus is primarily on bio-SAF (R1; R2; R4; R6; R7; R9; R12). Investments in synthetic SAF are still lagging (R2; R3; R4; R6; R9; R11; R12).	Parasitism
	The challenge for synthetic SAF lies in creating a network of partners, collectively taking the steps towards commercial scaling (R6; R10; R11), and securing the necessary financing (R6; R10; R11; R15).	Parasitism
	Securing a grid connection and providing wind energy for the Synkero project is challenging due to the Dutch government's lack of help (R3; R5).	Parasitism
	Investments in production facilities, such as a SAF plant, are risky (R1; R2; R6; R12; R17; Arcadis, 2024), which causes delays. Realizing these facilities takes a long time (R1; R2; R4), and there must be certainty that a plant will continue operating (R1; R4; R12; R13; R17).	Competition
	Transitioning from the R&D/pilot phase to commercial production is challenging for small entities (R1; R2; R3; R4; R14; R17; Mutrelle, 2024), and the task is often left to large companies (R14; R17; Mutrelle, 2024). The region provides various examples of business cases encountering multiple barriers (R1; R2; R5; R9; R10; R12).	Competition

	Limited activity exists in synthetic SAF (R6; R7; R9; R10), and too few pilots, particularly on synthetic SAF, are available to achieve effective scaling (R11; R14).	Parasitism
Knowledge Diffusion	Multiple meetings (R1, R2, R3, R4, R5, R6, R7) discuss bio-SAF and synthetic SAF.	Commensalism
	During the meetings organized by the Ministry of Infrastructure and Water Management (I&W), the potential for integrating synthetic SAF into the cluster's industry was also discussed.	Commensalism
	The cluster commercialization and growth have decreased centralized knowledge sharing (R1; R3; R4; R5; R6; R7; R8).	Competition
	Communication between the government and various sector stakeholders, such as resource providers, technological and scientific entities, and industry players, is fragmented (R11; R17). This fragmentation hinders the cohesive integration of all necessary elements for development (R11; R17).	Competition
Guidance of the Search	Both types of SAF depend on the same governmental and institutional support (R6; R8; R10).	Commensalism/ Competition
	The cluster has significant technical potential and ambition (R1; R2; R3; R5	Commensalism/ Competition
	The market aligns with the ReFuelEU mandate, which boosts confidence (R2; R4; R8; R17)	Commensalism
	Confidence is higher in bio-SAF development than synthetic SAF (R1; R2; R3; R4; R6; R9; R10). This is primarily because bio-SAF is more advanced in its development (R1; R2; R3; R4; R6; R9; R10; R12; R13; R16), particularly with the HEFA technology (R1; R2; R3; R10; R12; R16), which is already commercially scalable (R1; R2; R3; R6; R7; R10; R12; R13; R16). Efforts must not solely focus on developing bio-SAF (R12); both bio-SAF and synthetic SAF should be developed in parallel (R12; R16).	Parasitism
	The advancements in bio-SAF have already addressed some of the initial questions for synthetic SAF, as both rely on the same governmental and institutional frameworks (R2; R6; R7; R8; R10), such as for subsidies (R7), blending mandates (R2), and certification processes (R2).	Commensalism
	Sector support for scaling up is lacking due to insufficient government guidance regarding production targets, timelines, and pricing (R11; Arcadis, 2024).	Competition
	Confidence in the availability of feedstocks within the Randstad cluster for bio-SAF and synthetic SAF is not strong (R1; R2; R3; R4; R5; R6; R7).	Competition
	Confidence in synthetic SAF is shallow because significant technological improvements are still needed before scaling up can become a reality (R14).	Parasitism

Market Formation	At RTHA, airlines have agreed to meet the national target of 14% (R1; R2; R4 R12; R13). Similarly, Schiphol has agreed with KLM to pursue a 10% blending target by 2030 (R1; R2; R4; R12) and has implemented an airline incentive program (R4).	Commensalism
	The Netherlands is well-positioned to serve as both a hub and a production center for SAF, primarily due to the presence of the Port of Rotterdam (R4; R8; R12; R13; R14; R16; R17). Additionally, Schiphol, one of Europe's largest airports, is crucial in driving demand for SAF. The Netherlands aspires to become a SAF hub (R9; R10). Additionally, Schiphol, one of Europe's largest airports, is crucial in driving demand for SAF. The Netherlands aspires to become a SAF hub (R9; R10),	Competition
	Companies in the cluster are generally indifferent about whether they purchase bio-SAF or synthetic SAF (R1; R3; R12), as both are blended, and the focus is on the value of the certification (R1; R12).	Parasitism
	Synthetic SAF is inherently more expensive than bio-SAF (R1; R2; R3; R4; R5; R6; R12; R13; R16). Currently, the HEFA pathway is the only genuinely cost-effective option (R1; R2; R3; R4; R5; R6; R7; R8; R12; R13)	Parasitism
	Given the limited scalability of bio-SAF in the future, it is prudent to encourage the development of synthetic pathways (R4; R11; R12).	Commensalism
	Bio-SAF development has helped remove some barriers to developing synthetic SAF (R2; R6). This includes scaling up production (R2; R6), selling to fuel suppliers, and purchasing by airlines (R6). The same applies to understanding the market (R6; R16). Bio-SAF and synthetic SAF rely on the same institutions and stakeholders (R2; R6; R7; R8; R10).	Commensalism
	The cluster in the Netherlands had already prepared for the 14% national target, which easily positions the sector to meet the 2030 goals (R12)	Parasitism
	The agreements on increased blending percentages and RTHA and Schiphol SAF incentives are stimulating (R1; R2; R4; R12; R13).	Commensalism
	Government investments in SAF development extend only to the experimental phase (R1; R2; R5; R6; R8; R17), leaving a gap between these developments and industry engagement (R1; R5). Bridging this gap would require support from the sector (R1; R2; R8; R9; R10). Fuel suppliers are willing to offer SAF, but only if airlines are committed to purchasing it. Airlines, in turn, are willing if consumers are ready to pay the additional cost (R1; R2; R4; R7; R8; R14; Arcadis, 2024). However, the lack of demand (R1; R2; R4; R7; R8; R17) hinders the ability to scale up and build production facilities (R1; R4; R9; R14; R17). Airlines, driven by commercial interests, will likely wait until mandatory purchase requirements compel them to act, similar to fuel suppliers (R2; R8; R9). Commercial companies lack intrinsic motivation (R1; R2; R9; R12), and scaling up and increasing demand will only occur if an investment is profitable (R8; R10; R12).	Competition
	The attractiveness of the Port of Rotterdam as a hub is decreasing because the necessary raw materials are becoming more challenging to import (R8; R10).	Competition
	Synthetic SAF is not a viable solution, as it cannot provide the market with the necessary scalability (R5; R11).	Parasitism

	The national mandate has also introduced further uncertainties within the sector (R16; R17).	Competition
Resource Mobilization	Neste is performing very well in bio-SAF feedstock (R5)	Competition
	Shell is constructing a sustainable hydrogen plant in Rotterdam, which will supply its refinery (R6).	Competition
	The Port of Rotterdam is not necessarily an ideal location for hydrogen production (R4; R8; R13), but it plays a crucial role as a hub for importing feedstocks (R4; R12; R13; R14; R16; R17) and synthetic SAF (R4; R12; R16). Feedstocks such as hydrogen (R8; R16), green energy, and low-energy-density biomass are less suitable for long-distance importation (R8; R17).	Competition
	However, Rotterdam is an excellent transit hub with its existing infrastructure and capabilities. For bio-SAF, Rotterdam is an excellent location because the process closely aligns with conventional refining processes (R13; R16).	Competition
	Both types of SAF can utilize the existing infrastructures (pipelines, tankers, etc.), as they are blend-in fuels (R1; R2; R3; R4; R5; R6; R12; R16; Arcadis, 2024).	Competition
	Significant amounts of hydrogen are required for bio-SAF and synthetic SAF production (R8; R11; R17; Arcadis, 2024). A resource shortage is expected within the cluster for bio-SAF and synthetic SAF (R1; R2; R3; R4; R5; R6; R7; R10).	Competition
	The cluster includes a major airport, a vast port, and a strong foundation for fuel infrastructure (R10; R12; R17).	Commensalism
	In the near future, a shortage will occur for the feedstocks such as green energy (R1; R4; R5; R7; R10; R13; R14), hydrogen (R1; R2; R3; R4; R5; R6; R7; R10; R12; R14; R15; R16; R17), and the further future also for biomass (R5; R6; R9; R10; R14; R17). Additionally, CO2 capture technology is lagging (R10; R17), the energy grid is at capacity (R3; R5; R10; R12; R13; R14; R17; Arcadis, 2024), and infrastructure needs expansion shortly (R3; R5; R10; R14; Chatrier & Van Dijk, 2024).	Competition
	The uncertainty surrounding feedstock availability in the cluster makes it difficult for companies to make investment decisions (R13).	Competition
	When expanding in the cluster, available space is challenging (R8; R10; R13; R14), particularly for storage or feedstock production (R8; R10; R14; R17).	Competition
	The cluster has no robust environment for green energy production (R10; R14), and generating green energy is not cost-effective (R10).	Competition
	There is uncertainty about where green energy will come from and the cost (R13; R16); the same applies to green hydrogen (R13; R14; R16).	Competition
	Feedstocks such as hydrogen (R8; R16), green energy, and low-energy-density biomass are not easily imported over long distances (R8; R17). This presents a future challenge (R8).	Competition

Creation of Legitimacy	Airports support SAFs and contribute to their development (R1; R2; R3; R4; R5; R8; R13).	Commensalism
	NGOs and environmental organizations are generally critical of the environmental aspects of sustainable fuels (R1; R2; R9; R13). The negative perception of bio-based feedstocks leads to a lower, sometimes unjustified, public legitimacy (R1; R7; R8; R17).	Competition
	Consumers lack visibility and knowledge about SAF (R1; R2; R5; R7; R13; R14; R15). The complexity of SAF makes communicating effectively to the public (R7; R15) challenging. Consumers' understanding of SAF is mainly limited to the information airlines provide (R5; R12).	Competition
	Airlines bear significant responsibility for educating consumers about SAF (R7; R12; R14). In the past, airlines have damaged consumer trust, particularly with practices like offsetting flight emissions (R12).	Competition
	Airlines are not typically focused on long-term projects like SAF (R5; R12)	Parasitism
	The government also has an educational role to play to the public (R7).	Competition
	Consumers want to continue flying at the lowest possible cost (R10; R15).	Competition
	Difficult decisions, such as the future of SAF, are politically sensitive due to the associated costs, leading to a cautious political stance (R11). There is hope that the market will take the lead, but currently, that market is lacking (R11).	Competition
	Fuel suppliers and airlines provide minimal support for developing bio-SAF and synthetic SAF (R1; R2; R3; R4; R5; R8).	Competition
	Support for bio-SAF is stronger than for synthetic SAF (R2), primarily because bio-SAF is more cost-effective (R1; R2; R3; R4; R5; R6; R7; R8; R12; R13).	Commensalism
	The developments in bio-SAF have already addressed some initial questions for synthetic SAF, particularly in areas such as lobbying for regulations (R6; R8; R10).	Commensalism
	Airlines might view SAF as an advantage if it can be used for EU ETS compliance and customer communication (R12).	Commensalism
	ESG reporting from companies will help address greenwashing issues and create transparency regarding SAF blending (R14).	Commensalism
	Fuel suppliers allocate minimal budgets to the energy transition, reflected in their lobbying efforts (R3). Airlines oppose SAF mandates and kerosene taxes (R2; R9) and often communicate more about SAF than they implement, as seen in greenwashing claims (R8; R9; R14; R15). This behavior is also observed among fuel suppliers (R5; R15).	Competition
	Large fuel suppliers like Shell, AirBP, and Total in the cluster rely on Neste's production to meet the EU's SAF blending percentages (R5). Fuel suppliers are not transparent about certain information (R1; R3; R4; R5; R6; R7; R8; R10; R12; R13), such as the origin of feedstocks (R1; R4; R5; R6; R8), and they resist scaling up SAF production (R2; R5; R9; R10)	Competition

	Public legitimacy for SAF is weak due to insufficient visibility and consumer knowledge about SAF (R1; R2; R5; R7; R13; R14; R15; R17), overly idealistic views on fuels (R1; R2; R3; R8; R11; R13; R16; R17), negative perceptions of feedstocks (R1; R7; R8; R17).	Competition
	The unclear regulations and negative public opinion hinder the development of the certificate market for smaller entities (R15). These smaller contributions could collectively support the development of SAF (R15).	Competition