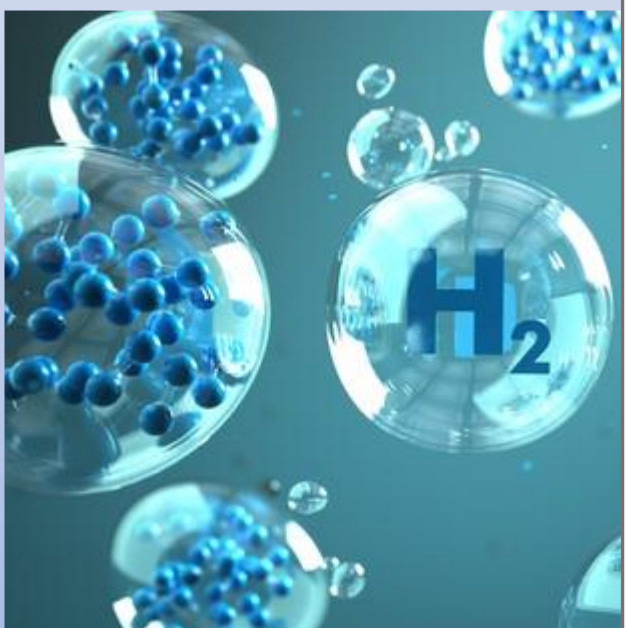

Understanding how the hydrogen technological innovation system in the Netherlands can be accelerated

M.Sc. Thesis Sustainable Business and Innovation

Bas Broekstra
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Abstract

To meet climate targets and avoid radical and irreversible climate change, society needs to drastically reduce Green House Gas emissions. This requires to transit away from the current fossil-fuel-based energy system to meet targets for greenhouse emissions set out in the European Green Deal (2019). In this respect, hydrogen technologies have the potential to fulfill a variety of different functions in the energy system. Hydrogen solutions have emerged as having favorable characteristics for certain applications. These characteristics include specific sectors in which electricity can not be applied or for long-term energy storage. For the latter application, electricity is currently restricted by limitations in battery technology. Therefore, the development of a hydrogen value chain is regarded as a valuable addition to electricity in the energy transition. In the Netherlands, this potential of hydrogen has been acknowledged for decades, as the country has extensive natural gas infrastructure and experience with power in the form of gas. However, the hydrogen innovation system in the country remains in a state of lock-in for a long time and only recently accelerated as a result of external shocks such as climate change. The Technological Innovation System (TIS) framework has been applied as the theoretical basis to analyze the hydrogen transition. This study aimed to investigate the dynamics in the hydrogen innovation system hampering its development and to recommend how this can be overcome. In doing so, this study exposed different barriers that may prevent the hydrogen system from developing. These barriers have been linked to the theory of systemic problems, to fully understand how the innovation processes and structural components of the system are connected. Accordingly, this study has conducted a qualitative event-history analysis from 2017-2022, in combination with interviews with hydrogen innovation system actors. The results indicated several barriers which are present and which are withholding the system from accelerated development. First, this study has demonstrated that hard-institutional failures are the main barrier. The supporting institutional frameworks needed for the system to develop lack clarity, are absent, or do not support system development. Secondly, these problems induce barriers to resource mobilization and market formation, which prevent the system from developing into the next phase. Like previous studies, this paper has demonstrated that these systemic problems are not independent and induce a hampering innovation system. This is induced through the interactions between system functions or missing structural components.

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1. Introduction

Today's society faces various social, environmental, and economic challenges (Mazzucato, 2018). Climate Change is one of these problems and is caused by the extensive emissions of Green House Gases (GHG). Carbon dioxide is one of these GHG, and is one of the main contributors to global warming (IPCC, 2019). Scientists and international politicians have been debating how to solve the climate change issue for many years. A recent breakthrough on an international level was the 2015 Paris Agreement in which 194 countries signed a declaration striving to avoid radical and dangerous climate change (UNFCCC, 2015). These countries vowed to achieve this by limiting global warming to well below 2 degrees Celsius and striving for 1.5 degrees Celsius (UNFCCC, 2015). In reaction to this declaration, the Netherlands initiated the 2019 'Climate Agreement', while the European Union initiated the Green Deal in that same year. Both these agreements aim to decarbonize the economy by committing to the agreements made in Paris (2015) to reduce carbon emissions with respectively 49% in 2030, and 95% in 2050, compared to 1990 levels (UNFCCC, 2015). More recently, these objectives were increased to a 55% reduction in 2030, and 100% in 2050, under the fit for 55 packages (European Commission, 2021a).

A major source of the extensive emission of GHG is the reliance of global society on power generated from fossil fuels (Abe et al., 2019; IRENA, 2018). These power sources are embedded all around us and are used for heat, electricity, industry, and transport. Fossil fuels come in different forms including natural gas, petroleum, and coal providing more than 80% of all energy consumed (Iordache et al., 2013; Rusman & Dahari, 2016). However, decarbonizing the energy system, to contribute to the current EU Green Deal targets, is an immense task and consists of changing dimensions such as power production, power storage, and application changes (e.g., electrification of industry or mobility) (Dickinson et al., 2017). These dimensions are largely based on fossil-fuel infrastructure or technology which reflects the embeddedness of the current fossil-fuel-based energy system. Challenging this lock-in requires solutions that over time will be able to replace the fossil-fuel system not only in technology but also in scale and cost prices.

The route envisaged in the European Green Deal (2019) to change the energy system, mainly aims to achieve this by switching to renewable energy sources, such as solar and wind power (European Commission, 2021a). However, most renewable sources are subject to fluctuations and have electricity as the main energy carrier which is not the solution for all applications (Dickinson et al., 2017). A mix of solutions pathways is needed to ensure a safe, affordable, clean, and reliable energy supply in the future. Hydrogen can play an important part in changing the current system as a carbon-free energy carrier**.** If produced with renewable energy, hydrogen does not emit carbon dioxide (green hydrogen) and has the potential for applications in industry, transportation, the built environment, and power storage (Nationaal Waterstof Programma, 2021).

In the Netherlands, hydrogen has been a topic of interest for decades (International Energy Agency, 2004). However, it gained traction as an energy carrier as a direct consequence of the international and European climate change debates. Part of the current mission is to radically change the current energy mix to carbon-free sources. The Dutch government sees hydrogen as a key technology in such a system, since carbon-free gasses are indispensable in a safe, clean, reliable, and spatial adaptable energy system (EZK, 2020). To ensure that the future energy system full-fills these ambitions the 2019 “climate agreement” contains a section on hydrogen that focuses on five key areas:

- Carbon-free feedstock for heavy industry (process industry);
- Carbon-free energy carriers for high-temperature heat for the process industry;
- Controllable carbon-free energy capacity, energy storage for prolonged periods, and energy transportation over long distances;
- The usage for mobility, such as passenger or (heavy) freight transport;
- Applications in the Built environment, for example, heating (Dutch Government, 2019).

The application of hydrogen technologies throughout various sectors evolves around the technologies for hydrogen production, storage, transportation, and fuel-cell technologies. The system is interdependent and the co-development and co-upscale of these technologies throughout various sectors (from production to consumption) are needed to create a working hydrogen system and sub-systems. This means that hydrogen requires a whole value-chain in overlapping sectors to emerge.

To accelerate the hydrogen ambitions derived from the Dutch Climate Agreement, the country initiated a substantial “national hydrogen program”. In this “National Hydrogen Program” (NWP) a commission is appointed to plan and prepare short-term and long-term targets. The main aim of the NWP is to connect stakeholders and facilitate, accelerate, and monitor the progress of the hydrogen mission. Within the NWP, stakeholders from various sectors are involved to develop hydrogen technologies and applications. These stakeholders include actors from various markets, knowledge institutions, infrastructure companies, and public organizations (Nationaal Waterstof Programma, 2022). The “Climate Agreement” depicts that a primary goal of this program is technological development to increase efficiency and ‘’reduce cost (Dutch Government, 2019). These are preconditions to ensure hydrogen is feasible and has the potential to challenge the existing energy system.

The development of a hydrogen system has been a promising sustainable alternative to different functions in the energy system (International Energy Agency, 2004). Yet, the future of hydrogen in the energy system is a complex and comprehensive challenge that according to various studies requires radical changes involving complex interlocking social, economic, and technological processes (Rosenbloom, 2017; Turnheim et al., 2015). In 2009, a study on the system around hydrogen for fuel cell application sketches these dilemmas as in the past, recurring technological, economical, and societal barriers have held back large-scale development and diffusion of hydrogen technologies (Suurs et al., 2009).

To understand and recommend how to overcome such problems in the hydrogen transition taking a system perspective is needed. This can be done by employing a Technological Innovation System (TIS) analysis. A TIS allows one to understand and identify drivers and barriers in an innovation system surrounding a certain technology (Hekkert et al., 2007), in this case, a value chain. The framework uses a set of functions to analyze the behavior of the system around the chosen technology. The fulfillment of these functions indicates if the system functions properly (Kieft et al., 2017; Negro & Hekkert, 2008). Over the last decade, this structural-functional approach of the TIS has been used by various scholars to identify systemic problems that inhibit the functioning of innovation systems for various emerging technologies or embedded sectors (Satalkina & Steiner, 2020; Wesseling & van der Vooren, 2017a). Wieczorek and Hekkert (2012), broadened the concept of systemic problems by connecting them to the systemic structures of the TIS.

The presented analysis combines the two approaches to understand the systemic barriers in the Dutch hydrogen innovation system with the intent to provide a policy recommendation to overcome them. This study presents an analysis of the Dutch hydrogen technological innovation system and its development over the past 20 years with specific attention to the 2017-2022 period. This is done with the aim of better understanding how the industry, system actors, and society can be stimulated to accelerate technological developments and upscale hydrogen applications. Therefore, to develop the TIS framework and to better understand how innovation systems evolve the following research question is formulated:

What is hampering the development of the hydrogen technological innovation system in the Netherlands and how can the transformation of the energy system to integrate hydrogen be accelerated?

This study can provide an understanding about how innovations systems evolve and what barriers prevent acceleration. Thereby, the academic relevance is that the presented study can contribute more thorough understanding of systemic barriers hampering innovation system from developing. In addition, this study is of societal relevance as it provides more insights into how the transition to a carbon free energy system can be accelerated.

Following the introduction, chapter 2 will describe the theory of innovation systems and systemic problems in which this research is embedded. Subsequently, chapter 3 will provide insight into the applied research methodology. Chapter 4 describes the context of the analysis by explaining the hydrogen value chain. Thereafter, chapter 5 describes the system structures of the hydrogen innovation system in the Netherlands. Chapter 6 describes the results of this study by presenting the functioning of the Dutch innovation system. Chapter 7 discusses the results and links them back to the literature. Lastly, chapter 8 provides an answer to the research question.

2. Theory

2.1 Innovation policy

Governments around the world are increasingly considering innovation policies as a means to tackle socioeconomic-technological challenges (Mazzucato, 2016; van der Loos et al., 2020). These challenges are also referred to as "societal challenges", which relate to problems embedded in society including climate change, cancer, or demographic aging. These complex challenges have the potential to be dealt with through a wide-ranging change in technology, production, and consumption, thus through innovation (Fagerberg & Hutschenreiter, 2020). Innovation plays an important role in tackling societal challenges, such as climate change (Hekkert et al., 2020). However, the difficulty is that addressing societal challenges through innovation requires radical behavioral, technological, and system changes. This means multi-level involvement from various system actors (e.g., public, private, and non-profit) for these challenges to be successfully addressed. Governments attempt to achieve this through innovation policies, which aim to steer the direction of innovation in such a way as to successfully address these societal challenges, influencing various system levels (Kattel & Mazzucato, 2018; Mazzucato, 2016).

Several frames of innovation policy exist. The first innovation policy frame focused on stimulating economic growth by fixing market failures by addressing under-investment in research and development (Hekkert et al., 2020). The second innovation policy frame, in addition to fixing market failures, aims to strengthen national innovation networks (Schot & Steinmueller, 2018). More recently, a third 'Mission-Innovation Policy' (MIP) or 'Transformative Innovation Policy (TIP) frame emerged, which has a stronger focus on addressing societal challenges, such as climate change (Mazzucato, 2018). MIP aims to transform innovation into the desired direction that improves the system and warrants guidance of directionality by the government so that societal problems may be better addressed (Schot & Steinmueller, 2018).

However, over recent decades, policymakers have struggled to operationalize and implement innovation policy measures (Hekkert et al., 2020). System thinking approaches have been used to better understand the innovation processes in socio-technical systems, but, so far many studies showed that these transformative processes in incumbent or emerging markets have been slow (Negro et al., 2012). Nevertheless, these system thinking approaches such as 'Innovation System' (IS) have been dubbed valuable concepts to understand innovation dynamics (Kuhlmann et al., 2010). These systems can contribute to understanding how policy targets set by governments can be achieved, for example, the mission to decarbonize by transitioning the energy system. The next section explains these innovation systems and provides a deeper explanation of how the behavior of these systems can be studied.

2.2 Innovation systems

In the literature, it is commonly accepted that innovations or technological changes do not occur in isolation, but rather through a complex process involving different levels of analysis and different kinds of relationships among different agents and institutions (Leoncini, 1998). Over time this notion prevailed in the creation of the concept of 'Innovation Systems', which refers to a system thinking approach to understanding how existing (socio) technologic systems transit to a new state (Carlsson et al., 2002).

In general, system engineers define a system as*" being made up of components, relationships, and attributes"* (Carlsson et al., 2002). *Components* are the organs of the system and take a variety of different forms: actors or organizations, such as individuals, private organizations (e.g., businesses), banks, universities, research institutions, and public organizations. Components can be physical or technological artifacts (e.g., infrastructure) such as power lines in electrical systems, or gas-stations in automotive systems, or diagnostic techniques. They can also be institutions in the form of legislative artifacts including regulatory laws, traditions, and social norms (Carlsson et al., 2002). *Relationships* are the links or interactions between two or more different components in a system and can take various forms. Which depend upon the properties and behavior of at least one or more other components (Carlsson et al., 2002). Last*, Attributes* are the properties of these system components and the relationships between them, which eventually characterize the system.

However, given the fact that systems serve different purposes, it is not surprising that a variety of system-thinking approaches exist. These perspectives of innovation policy concepts have been described in several dimensions based on physical, technological, sectoral, or geographical boundaries (Carlsson et al., 2002). The regional innovation system (RIS) focuses on a specific region (Cooke et al., 1997). The National Innovation System (NIS) focuses on the boundaries of a specific country (Edquist & Lundvall, 1993). The sectoral innovation system (SIS) focuses on a specific industry or sector (Hekkert et al., 2007). The technological innovation system (TIS) instead of being bound to a geographical boundary or sector, focuses on the system around a specific technology (Hekkert et al., 2007). Figure 1 shows these different innovation systems and how they overlap.

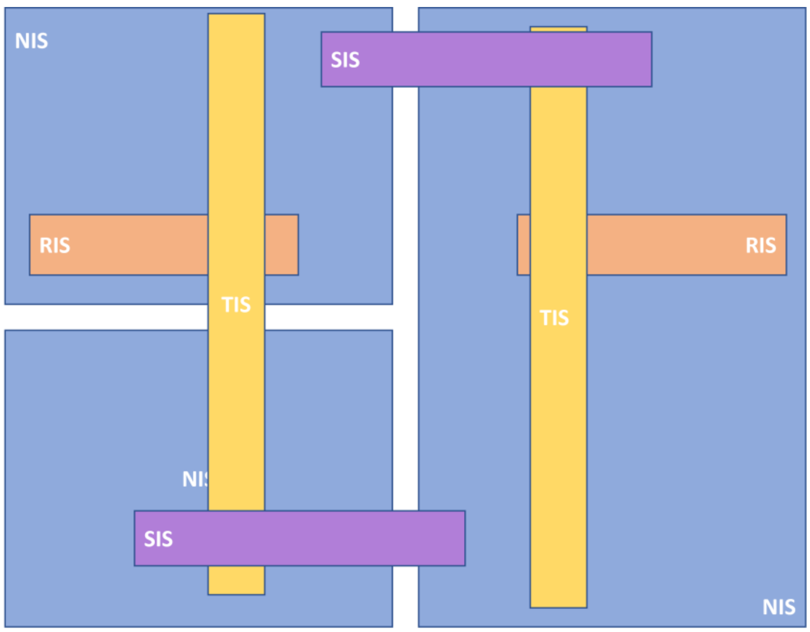


Figure 1: Overlap of innovation system perspectives adapted from Hekkert et al. (2007).

2.2.1 Technological Innovation System

Out of these different dimensions, the technological innovation (TIS) system approach is most suitable for studying the hydrogen case in the Netherlands. The TIS is focused on how an innovation system is developing and functioning around a specific technology (Bergek et al., 2015). Moreover, the TIS set itself apart from the other system as it can exceed geographical boundaries and different sectors allowing it to incorporate a whole value chain (Bergek et al., 2015). Because of these reasons the TIS allows to study of the development of the hydrogen innovation system in the Netherlands, which involves the diffusion and development of hydrogen technology across its value chain and different sectors (e.g., transportation, hydrogen production). Such a TIS, according to literature, can be defined as "*all institutions and economic* *structures that affect both rate and direction of technological change in society* (Edquist & Lundvall, 1993). The development of this system is based on the co-existence and evolution of the relationships among the different system actors surrounding the technological direction. This includes institutions of science and technology, industry, and the political system (Kuhlmann et al., 2010; Wieczorek & Hekkert, 2012). Within the literature, the TIS has proven itself to be valuable in exploring and understanding the dynamics of system changes and conditions for the success of emerging innovations (Hekkert et al., 2007). Analyzing a TIS provides a means for a systemic understanding and evaluation of a transition in terms of the processes and structures in a specific technological field that support or hamper the diffusion of these innovations (Hekkert et al., 2007).

2.2.2 System structures

The TIS both includes structural and functional elements of an innovation system. There are four structural elements (i) actors, (ii) institutions, (iii) infrastructure, and (iv) networks. These are to be regarded as the building blocks (structural elements), a schematic overview is presented in figure 2.

i) Actors – a variety of system actors can be distinguished and are categorized into knowledge institutions, education organizations, market and industry actors, public and governmental organizations, and supportive organizations

ii) Institutions – the second structural element involves both hard institutions (law, regulations, standards, and rules) and soft institutions (norms, behaviors, ethics)

iii) Infrastructure – refers to the physical, intellectual, and financial infrastructures present in the system

iv) Networks – the last structural element refers to the fact that system actors operate in networks (Hekkert et al., 2011; Kuhlmann et al., 2001; Wieczorek & Hekkert, 2012).

The structural analysis is a critical step in the TIS framework, as it provides an overview of the presence and absence of structural elements. Missing or weak structural elements can cause systemic problems as they could influence the working of the innovation system (Wieczorek & Hekkert, 2012). The next step is to analyze how the system functions, which is done via the seven functions described in the next section. (Alquist & Lundvall, 1993; Liu & White, 2001).

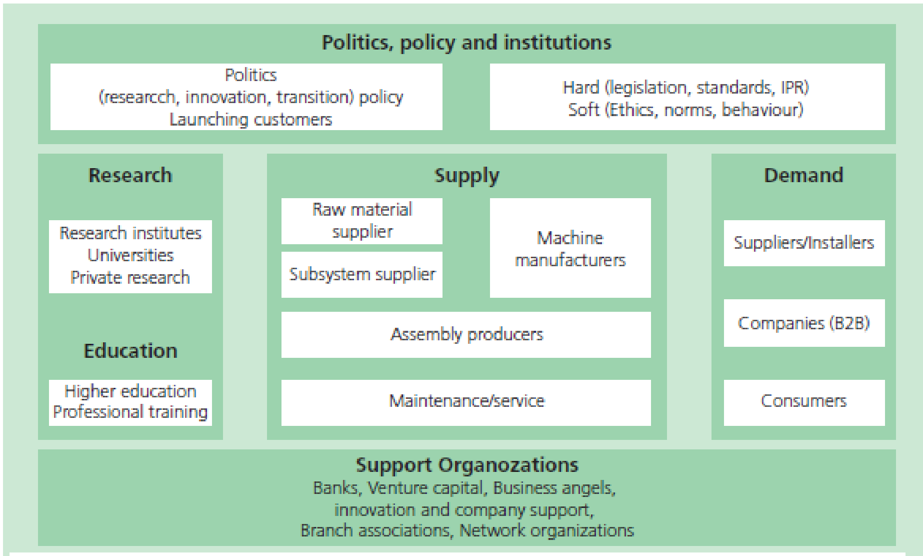


Figure 2: Schematic composition of technological innovation system adapted from Kuhlmann et al. (2001).

2.2.3 Functional analysis

To assess the process of development and diffusion of technological change, insight into these structural dimensions of a TIS is not enough to assess the performance of the system (Wieczorek & Hekkert, 2012). Therefore, functions are added to the framework. These functions have been developed by various scholars, and provide insight into the behavior and dynamism of innovation systems. Studies like Lundvall (1993), Liu and White (2001), and Hekkert et al. (2007), all proposed different sets of activities that map, describe, and analyze the system behavior that supports technological change. The latter Hekkert et al. (2007) is the first to combine insights from prior studies and proposed a set of functions integrating and summarizing these activities. This set of functions describes and explains changes in a technological innovation system (Hekkert et al., 2007). These functions are defined as *"the contribution of a component or set of components to the system's performance"* (Negro & Hekkert, 2008), the seven functions are presented in table 1.

Table 1: The system functions adapted from Hekkert et al. (2007), and Wieczorek et al. (2013).

The system function	Description
SF1: Entrepreneurial experimentation, upscaling, and business model transformation	Experiments with solutions (or clusters of solutions) to enable learning; creation of markets for new solutions; and creation of business model innovations to stimulate the diffusion of solutions, building production capacity.
SF2: Knowledge development	The creation and development of knowledge through “learning by searching” and “learning by doing”. These activities result in new technical and socio-institutional knowledge to develop the technology under investigation.
SF3: Knowledge diffusion	Refers to activities that result in the exchange and diffusion of knowledge through networks. Knowledge-sharing activities include media, reports, workshops, stakeholder meetings, etc. In this context, the phasing out focuses on knowledge exchange processes that are obstructing the mission.
SF4: Guidance of the search	This function refers to the process of selecting or rejecting a specific direction of technological development. System actors formulate goals, targets, visions, or expectations, set priorities, and provide direction in research and development. These processes aim to provide a clear direction in the system. Moreover, this function refers to coordination among the system actor to accelerate their goal and align the system structures to foster the development of the technological direction. This can be achieved by the creation of a coalition, roadmaps, and agendas for the transition.
SF5: Market formation	Refers to the creation of markets and support for upscaling social and technical solutions
SF6: Resources allocation	The mobilization and allocation of resources (physical, human, and financial) to support all the key activities/functions of the innovation system.
SF7: Creation of legitimacy	Create the legitimacy for change and counteract resistance to prioritization 1) of the problem and 2) development and diffusion of the solutions, to out phase harmful practices, habits, and technologies.

The build-up of these seven system functions jointly determines the chance of successful development of the technology under investigation (Suurs et al., 2009). These system functions can be fulfilled positively or negatively and interact with each other (Negro et al., 2012). For example, *resource mobilization* can be underrepresented, which hampers the development of the system in other areas (e.g., scale-up of activities in the system, function 1). This means that the functions interact impacting the system dynamics.

To put into context how system functions interact figure 3 represents an example of a Science and Technology push motor from the literature (Suurs, 2009). This example is dominated by *knowledge development (F2), knowledge diffusion (F3), the guidance of the search (F4),* and *resource mobilization (F6).* The dynamics of this feedback between system functions involve a sequence of positive expectations and research outcomes (F4). Subsequently, these lead to guidance activities which result in the government setting up a research and development program (F4). This program mobilizes financial resources to support system activities (F6). The allocation of these resources allows for a boost in scientific activities in the system (F2), and the diffusion of knowledge through conferences or meetings (F3). Eventually, in later phases of development, the allocation of these financial resources can subsidize pilot projects or demonstrations (F1). If the results of these scientific or pilot activities are positive, it could lead to more guidance activities (F4) and allocation (F6) of more funds for more R&D or investment in technology. This example indicates a positive feedback loop as a result of the interaction between system functions (Suurs, 2009).

These interactions can also lead to a negative feedback loop. For example, when the outcome of R&D (-F2), or demonstration projects (-F1) are negative these hamper further guidance activities (-F4) and allocation of resources (-F6). The interaction or composition (fulfillment) of the system functions describe the dynamics (behavior) of the system. Moreover, in the provided example, the composition and interactions of the function lead to lock-in or breakdown of the functioning of the system through negatively fulfilled functions or negative interactions (Suurs et al., 2009). According to the literature, over time for systems to establish themselves, it is therefore important that the system functions reinforce each other.

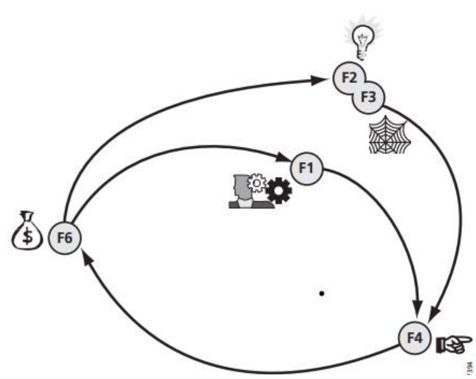


Figure 3: Feedback loop system funtions adapted from Suurs (2009).

2.2.4 Operationalization of the TIS framework

To operationalize the TIS framework, a few steps are required to be taken by scholars (figure 4). The first step is stating the system boundaries. Secondly, the structural components of the system are described. Then, the phase of development of the technological dimension under investigation is stated. Subsequently, the fulfillment of the system functions is analyzed. The previous steps allow for the identification of barriers that can be related to larger systemic or structural problems hindering system development (Negro & Hekkert, 2008). This is an important aspect because the Dutch Hydrogen System has been developing for over two decades. The TIS framework is used as the theoretical foundation to analyze the Dutch Hydrogen System. In addition, the concept of systemic barriers is adopted (Wiezcorek & Hekkert, 2012) to connect the barriers in the hydrogen system to its structural components. As such, the next section elaborates on those systemic barriers.

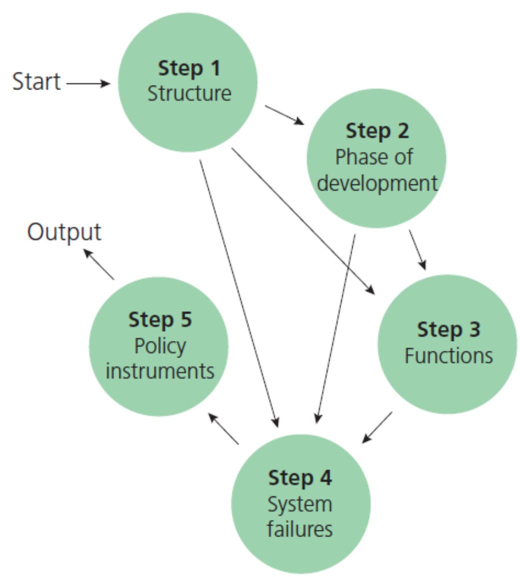


Figure 4: Analytical steps TIS framework adapted from Hekkert et al. (2011).

2.3 Systemic problems and lock-in in technological innovation systems

Over time, innovation systems mature and the structural components around a specific technology or sector become established, infrastructures will optimize, networks solidify, and the predominancy of technology becomes clear. This means that the structural components in 'mature' systems align and become interdepend (e.g., the current fossil energy value chain). To induce this process for a (novel) technological innovation system, it typically requires economic growth for the system to establish itself along with or to replace incumbents. For mature systems, changes are more often induced by external pressures (e.g., climate change, resulting in decarbonizing), requiring more directionality in the system transition (Negro et al., 2012; Wesseling & van der Vooren, 2017b).

However, innovation systems do not function perfectly and can inhibit structural barriers or problems (*systemic problems*) hampering or preventing an innovation system from developing (Negro et al., 2012; Wesseling & van der Vooren, 2017b). This has been the case in the development of the Dutch hydrogen value chain. For example, radical developing technologies (e.g., the development of a hydrogen value chain), or addressing large external pressures (e.g., climate change) require a system-wide change to contest the current regimes and overthrow stability. Therefore, transformations in a system often require structural changes in system components to establish a transition (Wesseling & van der Vooren, 2017a). While in a developing system it means the components have to function efficiently to foster change (Negro & Hekkert, 2008). The more radical a novel technological domain is, the more structural change it will induce in current structural components and value chains of embedded markets (Wesseling & van der Vooren, 2017b). The system functions described in section 2.2.3 help to understand the behavior of these systems in these processes.

Wieczorek & Hekkert (2012) defined these systemic problems as *"problems that hinder the development of innovations systems"* (Wieczorek & Hekkert, 2012, p. 78). Their study examined systemic problems to systemic innovation recommending systemic instruments to overcome these problems. To do so, their study recognized that explanations as to why certain system functions are weak or absent can be related to the overall structure of the innovation system (as described in section 2.2.2). The literature has shown that including a broader conceptualization of the system structures in the TIS framework strengthens its analytical capacity (Bergek et al., 2015). The TIS framework addressed in the previous section elaborates on the processes and structures of the TIS, but events and relations between them are not discussed and remain neglected in its scope (Weber & Rohrbacher, 2012).

In this context, Wieczorek and Hekkert (2012) introduced a framework that connects systemic problems in the system to its structural elements. This way their study conceptualizes the systemic problems in a TIS as being related to one of the four structural elements. These elements are actors, institutions, interactions, and infrastructure. Then structural problems are defined as being related to (i) the presence or capabilities of system actors, (ii) the presence or quality of institutions, (iii) the presence or quality of networks or interactions, or (iv) the presence or quality of the system's infrastructure. A further explanation is provided in table 2. Therefore, this study integrates the approach to barriers in the TIS framework by Wieczorek and Hekkert (2012). This replaces the system failures step (section 2.2.4). This means that the barriers in the Dutch hydrogen system are classified as structural-functional barriers. This perspective allows the inclusion of a wide perspective between the different structural components and the interactions in the system.

Table 2: Categorization of systemic problems in innovation systems adapted from Wieczorek et al. (2012).

System element	Type of systemic problem	Explanation of the systemic problem
Actors	Presence related	System actors needed in the system are not present
	Capacity related	The actors present in the system lack certain competencies or have difficulty in developing visions or strategies to support system development
Hard and Soft institutions	Presence related	Institutions are absent
	Capacity related	Institutions that are present lack the quality or capacity to support system development.
Networks and interaction	Presence related	Interactions are missing because of cognitive distance between actors, differing objectives, assumptions, capacities, or lack of trust
	Quality related	Strong network problems—when some actors are wrongly guided by stronger actors and fail to supply each other with the required knowledge Weak network problems are caused by weak connectivity between actors, which hinders interactive learning and innovation
infrastructure	Presence related	The needed infrastructure is not present in the system
	Quality related	The infrastructure which supports the system is not working or functioning properly

3. Methodology

This chapter describes the methodological approach used for studying the Dutch hydrogen innovation system. First, section 3.1 discusses the research design. Secondly, section 3.2 will discuss the data collection. Finally, section 3.3 addresses the data analysis phase.

3.1 Research Design

To understand the context of this paper this section addresses the research design which was chosen to conduct this study. The theory of technological innovation systems (TIS) was used to study the case of the Dutch hydrogen innovation system. The analytical steps of the framework (explained in section 2.2.4) were used as a basis as these involve five clear steps. In addition, the theory of systemic problems is intertwined with these analytical steps. The study has a qualitative approach and used primary data from publications which were used to create an event-history database and interviews.

To understand the context of the study the next chapter describes the hydrogen value chain. This context is needed to understand the analysis of the Dutch hydrogen innovation system. Thereafter, chapter 5 presents the analyzes of the system structures of the hydrogen innovation system in the Netherlands, which is the first step of the TIS theory. This is explained in the next chapter: “Hydrogen System Structures”. This stage sets the system boundaries and provides insight into the structural components (e.g., actors, networks, and institutions) surrounding the Dutch hydrogen innovation system. Subsequently, the main part of this study is presented in chapter 6. This chapter describes the functional analysis which is a combination of secondary qualitative data obtained through the event history analysis of grey publications and primary data from interviews with system actors in the Netherlands. The data in the event-history database and transcript of the interviews contain information about the fulfillment of the system functions (part of TIS theory). Thus, it indicates information about the performance/dynamics of the Dutch innovation system. The Netherlands was chosen as a case study because the country has launched an ambitious plan for hydrogen development in its 2019 climate agreement (see introduction).

3.2 data collection

This study used three methods for data collection. First, through desk research literature was consulted to better understand the hydrogen value chain. This resulted in both grey and white literature. This data consisted of reports and scientific articles, which were presenting information about the complete hydrogen value chain which needs to be developed to realize the hydrogen economy (see chapter 4, the hydrogen value chain). These literature sources were obtained via key search terms in Google Scholar.

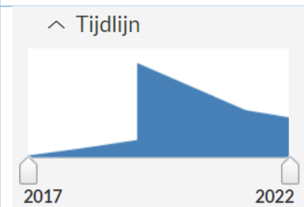
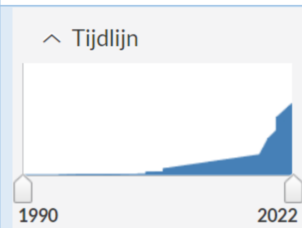
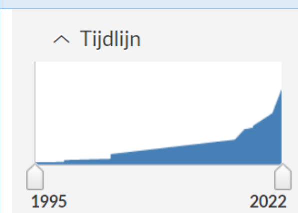
These search terms include but are not limited to ‘*hydrogen value chain’, ‘the hydrogen economy’, ‘development of hydrogen technologies’,* and *‘the hydrogen transition’.*

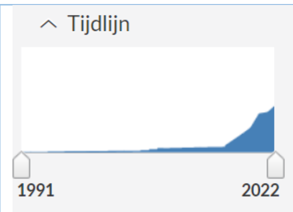
Secondly, to develop a qualitative event-history database according to the method developed by Poole et al. (2000), grey literature was consulted via LexisNexis (Poole et al., 2000). Building an event-history database this way allows us to understand the conceptual and practical foundations of the empirical case under investigation through a collection of qualitative historical data (Suurs et al., 2009). The following steps were taken in line with the operationalization of an event history analysis by Suurs et al. (2009), each step is further explained below:

- Collection of publication data via LexisNexis
- Timeframe selection (2017-2022)
- Database construction. This was an inductive process during which the system functions provided the conceptual framework to structure the database. Events were allocated to these system functions by allocation indicators (explained below).
- Mapping of the events per year
- identification of structures in the data (also contributed to the construction of the structures of the TIS).

The input information for this database was obtained via LexisNexis, which is a scientific search engine. Via this platform key search term allows a scholar to find publications on specific topics. The results consisted of different types of publications including magazines, reports, news articles, and scientific articles. The search engine was for each search-term limited to articles originating from the Netherlands. The following table 3 contains the search terms in English and their Dutch translation, the correlating number of hits, and the number of derived events. Saturation for the search terms was assumed if the set of articles did not reveal new insights into the Dutch hydrogen innovation system. Furthermore, to remove duplicates from the database, it includes information about the articles from which events are derived including title, publication year, and publication platform. This allowed double-checking the events present in the database to ensure no duplicates are added. The number of derived events refers to the number of events per search term that could be linked to the allocation indicators (Appendix A) for the system functions.

Table 3: results key search terms LexisNexis data collection.

Original search terms in Dutch	Translated terms in English	Number of publication hits (*With duplicates)*	Hits over time *'Tijdlijn" translates to 'timeline'*	Number of derived events (Both negative + positive)
Waterstof AND productie AND nederland	Hydrogen AND production AND the Netherlands	5231		196
Waterstofketen AND nederland	Hydrogen value chain AND Netherlands	119		9
Transport AND Waterstof AND Nederland	Transportation AND Netherlands	2902		98
Industry AND Waterstof AND Nederland	Industry AND hydrogen AND Netherlands	207		11
Gebouwde omgeveing AND waterstof AND Nederland	Built environment AND Hydrogen AND Netherlands	351		17

Waterstof AND opslag AND Nederland	Hydrogen AND storage AND the Netherlands	2998		165
Total number of events (both negative and positive)				*496*

The goal of this data collection step was to find as much information as possible about the hydrogen activities in the Netherlands. To structure this data collection step, the key-search-terms were based on the hydrogen categories mentioned in the Dutch Climate Agreement (2019). Therefore, the key-search-terms presented in table 3 are related to the following six categories.

- Carbon-free feedstock for heavy industry (process industry);
- Carbon-free energy carriers for high-temperature heat for the process industry;
- Controllable carbon-free energy capacity, energy storage for prolonged periods, and energy transportation over long distances;
- The usage for mobility, such as passenger or (heavy) freight transport;
- Applications in the built environment, for example, heating (Dutch Government, 2019).

The timeframe for the analysis is 2017 onwards. The decision for this timeframe is based upon one central argument. The reason for choosing 2017 as a starting point was the publication of the revised renewable energy directive (RED2) in Europe in 2018. Member states like the Netherlands are subjected to these binding European directives (European Parliament, 2018). The 2018 directive is a consequence of intensifying climate debate since the Paris Agreement (2015). These developments on an international level provide more attention to the energy transition and therefore more attention to topics like hydrogen. These are underlying factors for the spike in events from 2018 onwards.

Secondly, the LexisNexis search revealed that out of 11808 hits, more than 9600 are related from 2018 onwards. This is approximately 81% of all publications for the included key-search-terms. In table 3, a column is added, which presents a graph indicating the number of hits for that specific key-search-term. The Y-axis presents the number of hits, and the x-axis presents the years. These graphs visualize the acceleration point in 2018 for each search term. Therefore, the justification for choosing 2018, and to funnel the research, the year 2017 was chosen as a starting point in order not to miss important events before the acceleration in 2018 (see table 3). Therefore, the event-history analysis scope includes data from 01-01-2017 until 20-07-2022.

The total amount of identified events based on the found publications was 496. These events both include positive and negative influences on the hydrogen topic. The coding process for the events was set up as followed. Each publication is scanned to identify the topics discussed. Through allocation indicators, the events are allocated to the system functions discussed in section 2.2.2. These indicators are derived from studies by Negro et al. (2012) and Wesseling & Meijerhof (2021). The allocation indicators are described in Appendix A. When a publication contained an event that could be allocated/coded to a system function by an indicator it was filed in excel. Positive values (+1) indicate a positive influence on the system function. While a negative (-1) indicator means a negative influence on the system function (Negro et al., 2012). Important to mention is the fact that events in systems functions can induce (assumed) effects in other functions. This is explained by the interaction and dependencies between system functions (section 2.2.3). This effect is called the second-order effect and is to be prevented. The events in the data in this study are only coded on first-order effect meaning that they are coded on the actual primary event. Another factor to mention is that certain events can address more than one function. For these events, a distinction is to be made between form and content. To exemplify, a coalition of private organizations can collaborate on a new research project. This is to be coded as two separate events. The research project is to be coded as F2-knowledge development, and the collaboration of private organizations is to be coded as F3-knowledge diffusion.

The third and last round of data collection is interviews with hydrogen system actors. The insights from these system actors are to substantiate the findings from the event-history analysis. 13 actors participated in this round, out of 39 actors sought out. Two of the thirteen interviews were conducted in real life. while the other 11 were carried out via MS Teams. All interviews lasted between 35 and 75 minutes. To get a complete overview of the hydrogen system, the aim was to interview at least one actor per system component. However, out of the four engaged financial institutions, none replied. Also, snowballing effect with the interviewed actors did provide these results. This problem was attempted to be solved by asking the organized organizations how they would finance their hydrogen activities. The system actors interviewed were not chosen at random but based on the identification of their hydrogen activities. Therefore, a purposive sampling strategy was used (Bryman, 2012). During the interview process, interviewees were asked for consent (see consent form, appendix E), and data is anonymized (see table 4 below). The interview guide was continuously improved based on insights from previous interviews and event-history results. Also, the guide is adjusted per system actor to ensure only relevant questions and insights are asked. The interview questions are based on diagnostic questions as described by Negro et al. (2011). Moreover, the interviews were semi-structured allowing for adjustment of questions during the interviews. An example of the interview guide is added to this paper in appendix B.

Table 4: Anonymized interviewees

Interview	Organization	code
1	Industry organization	IO1
2	Industry organization	IO2
3	start-up	IO3
4	Energy supplier	IO4
5	Energy supplier	IO5
6	Industry mobility company	IO6
7	Public research organization	RO1
8	Public intermediary	RO2
9	Energy infrastructure	EI1
10	Energy Infrastructure	EI2
11	Energy Infrastructure	EI3
12	National government	NG1
13	National government	NG2

3.3 Data analysis

3.3.1 Identifying the structural components of TIS

The analytical step was to identify the system structures of the hydrogen innovation system in the Netherlands. This step was based on two methods of data collection, namely, desk research and event-history data. Chapter 5 shows the results of the structural analysis discussing the actors, networks, and institutions present in the Dutch hydrogen system. Additionally, the interviews with system actors were used to strengthen findings from the systemic analysis. As the theory explained (section 2.2), these structural components are the building blocks of the TIS. Missing components could lead to barriers or systemic problems (Negro & Hekkert, 2008). This analytical step allowed us to understand which structural components were missing and contributed at the step of the TIS together with the functional analysis of why barriers or systemic problems are present.

3.3.2 Functional analysis of the system

Chapter 6 discusses the results of the functional analysis of the Dutch hydrogen innovation system. This analysis was based upon the event-history data and strengthened with the system actor interviews. the goal of this step is to elaborate on the performance of the innovation system. This was done based on the system functions as discussed in section 2.2.2. Insights from the performance of the system revealed current behavior in the innovation system and allowed the identification of barriers present in the system. Triangulation through multiple data sources aimed to provide deeper insights into the results or to find a deeper explanation of contradicting claims. This triangulation was done using the data obtained from the interviews with system actors. The data obtained through these interviews were anonymized and quotes are validated with the system actors. Interviews were transcribed and analyzed using the tool Nvivo (Bryman, 2012). Because the interview guide is based on the TIS system functions the coding process is also structured according to these functions. The answers of the system actors were linked to these functions and led to deeper insights into the functioning (performance) of the hydrogen innovation system. Through axial coding, connections are made between system function categories and sub-codes (Bryman, 2012). This process resulted in 107 individual codes differentiated over negative and positive influences over the system functions (Code book in appendix C).

3.3.3 Identifying systemic barriers and problems + performance evaluation

In this stage, the results of the structural analysis and functional analysis were used to identify systemic problems caused by missing structural components or caused by the interaction of system functions. The latter is explained by the interrelated interactions between these functions. The dynamics indicate the problems occurring in the system and provided the input for the policy recommendation or intervention points. To structure this stage of the analysis the structural-functional approach by Wieczorek et al. (2012) was followed.

3.3.4 Data validity and reliability

Throughout the research, process data was iteratively collected meaning that new insights were continuously included to improve the research. Moreover, the triangulation of the different data collection methods ensured the internal validity of the results.

4. Background: The Hydrogen value-chain

As explained in the introduction, to address the pressing issue of climate change the world's energy infrastructure will see a drastic transformation away from being primarily based on fossil-fuel technologies. Electrification is not the solution for all sectors and energy applications because of technological drawbacks (Dickinson et al., 2017). For example, electricity cannot be stored for prolonged periods because of limitations to battery technology (al Shaqsi et al., 2020), which also hampers the application of electricity for (heavy) transportation (e.g., trucking or aviation). Another limitation is that for some industrial applications electricity cannot be used such as for high-temperature industrial processes. While electricity can also not be used for long-term energy storage which is currently done through natural gas (de Bruyn et al., 2020). To fulfill a variety of different functions in the energy system a diverse set of solutions is needed (Dickinson et al., 2017). Energy carriers fulfill a specific function in this current energy system. For these different purposes, hydrogen may provide a versatile solution owing to hydrogen's applicability as an energy storage solution (Salimi et al., 2022).

Hydrogen and hydrogen carriers have specific beneficial characteristics; for instance, hydrogen can be compressed or liquified for transportation, it has a high energy density, and can be used for high-temperature processes (Thema et al., 2019). Moreover, when produced with renewable energy sources; hydrogen can be used for various applications without emitting any pollutants (Yue et al., 2021). However, current infrastructure and energy networks are not built around hydrogen. Therefore, to realize a hydrogen system a whole value chain needs to be developed (Lacey et al., 2020).

As the introduction highlighted this requires the development and scale-up of interdependent hydrogen domains such as production, storage, and application developments. A successful hydrogen transition requires the emergence and development of a hydrogen value chain. Figure 5 represents the hydrogen value chain. This section explains the technological context of this paper by sketching the various stages of the hydrogen value chain starting with production, followed by explaining hydrogen distribution and storage. Lastly, the hydrogen end-users are explained.

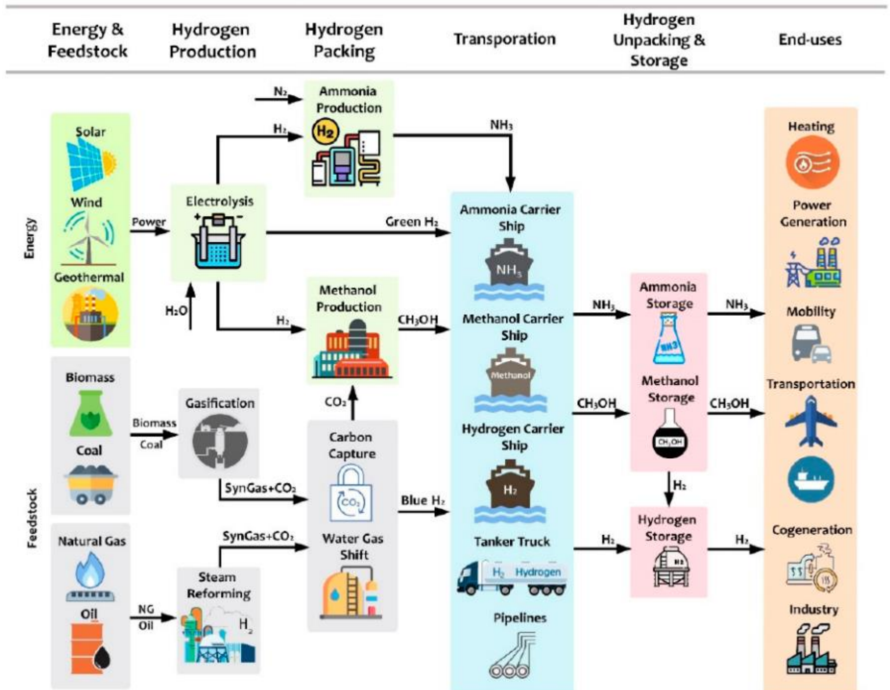


Figure 5: the hydrogen value chain, adapted from Salimi et al. (2022)

4.1 Hydrogen production

Most hydrogen that is used today is produced with fossil fuels (e.g., produced with coal, biomass, natural gas, or oil). In this context, two types of hydrogen are distinguished blue and grey hydrogen. Gray hydrogen is directly produced by fossil sources and in the process carbon dioxide is emitted into the atmosphere. Blue hydrogen adds an extra step of carbon capture and storage, ensuring that released carbon dioxide is stored in locations such as abandoned gas fields, preventing its release into the atmosphere (Salimi et al., 2022).

The third source of hydrogen is green hydrogen. This is obtained from renewable energy sources (e.g., solar or wind energy) and is produced via electrolysis. In this process, electricity is used to split water into hydrogen and oxygen by passing the electricity through an electrolyzer (Masoudi Soltani et al., 2021). This does not produce greenhouse gas emissions and is therefore renewable and sustainable. However, large investments are needed in the development and upscale of green hydrogen capacity to kick-start the hydrogen economy making hydrogen widely available.

A variety of actors in the Netherlands are therefore planning to invest in large quantities of electrolyzer capacity. For example, large energy suppliers such as Shell, BP, or Vattenfall are all developing projects for the production of green hydrogen (TKI Nieuw Gas, 2021). In some cases, this involves the production of hydrogen via natural gas in combination with carbon capture and storage (CCS) in abandoned natural gas fields. While other projects focus on the development of large electrolyzers' that produce green hydrogen with renewable electricity.

4.2 Hydrogen distribution and storage

In the current energy system, natural gas is widely used as a manner to store large quantities of electricity for prolonged periods (Gürsan & de Gooyert, 2021), or as feedstock in the industry for high-temperature processes (de Bruyn et al., 2020). While energy for road vehicles is often stored in the form of gasoline or diesel. These are examples of current fossil technologies and fuels, which are widely used in the energy system to store and transport large amounts of energy (Mitsushima & Hacker, 2018). Hydrogen has the potential to replace some of these energy applications. Additionally, from the point of production, hydrogen needs to be transported or stored for the time and place that it is needed. Storage and transportation are critical elements in the hydrogen value chain, and their implications depend on the development of different markets (Salimi et al., 2022). Hydrogen can be transmitted or stored in liquid or gaseous forms. For transportation depending on the place of production and end application different modes of hydrogen transmission include pipelines, maritime ships, or road distribution (Vázquez et al., 2018).

A significant advantage of hydrogen is that it can be stored (e.g., in salt caverns) naturally for prolonged periods without large losses. Moreover, existing natural gas infrastructure (pipelines) can be refurbished for the use of hydrogen (Ahmad et al., 2021). Underground, hydrogen can be stored in salt caverns which have the potential to create large storage capacity (de Bruyn et al., 2020). These technologies have been proven through tests, and have knowledge based on extensive experience with natural gas. Although hydrogen has a low volumetric density at atmospheric pressure compared to other energy carriers such as oil or natural gas. When available in large quantities stationary means of storage provide the opportunity to store large quantities of hydrogen (Salimi et al., 2022).

However, stationary transportation infrastructure (pipelines) and storage applications (salt caverns) are not available or accessible from all geographical locations. More mobile transportation and storage applications are also needed. In this regard, various technologies are in developed or in development including hydrogen-fuel tanks for trucks, and large fuel tanks for road transportation. For these solutions, the size and weight of storage tanks form a more limiting factor to how much energy can be stored and transported (Salimi et al., 2022). For example, for mobility applications availability of re-fueling infrastructure is needed for the diffusion of hydrogen in mobility. Not all refueling stations will be directly coupled to hydrogen pipelines. For such applications, road transportation of hydrogen via large trucks (e.g., tanker trucks) will be required. But also, for global hydrogen transportation maritime hydrogen tankers need to be developed, or tankers that can transport a hydrogen carrier such as methanol (de Bruyn et al., 2020). In the hydrogen supply chain, the need for these different functions allows actors to develop new businesses such as in refueling stations, hydrogen road transportation, or in maritime transportation.

4.3 Hydrogen end-uses

When available in sufficient quantities and at the places where it can be used. Hydrogen has applications in a variety of different sectors. Some emerging sectors or needed physical infrastructure have already been discussed in sections 4.1 and 4.2. For example, hydrogen storage, hydrogen transportation infrastructure, hydrogen road transportation, and hydrogen-refueling stations. More sectors can use hydrogen, for example, hydrogen is used as a raw material in a variety of process- and chemical industries (de Bruyn et al., 2020). It has the potential to be used in high-heat industrial processes to replace current fossil-based technologies. For example, hydrogen can replace natural gas or coal in the steel industry as energy feedstock (Dutch Government, 2019). These industries can switch from the use of grey hydrogen to green hydrogen to further decarbonize these processes.

Also, in the mobility sector hydrogen can be used as a power source for a variety of different applications. First, hydrogen can be used as a power source for fuel-cell-powered vehicles (e.g., buses, cars, trucks, trains, and farm vehicles). These vehicles do not emit carbon dioxide. Secondly, hydrogen can be used to produce synthetic fuels for example for aviation (de Bruyn et al., 2020), which in theory is part of the closed carbon cycle, meaning that no additional carbon dioxide is emitted (Baroutaji et al., 2019). Hydrogen also has the potential to be used in the built environment to be used for heating or to produce electricity via fuel-cells or generators. These technologies are in various stages of development, with some technologies being proven and requiring upscale and market development. While other technologies such as synthetic fuel for aviation are less developed and still expensive (de Bruyn et al., 2020).

5. Hydrogen system structures

To understand how the system around the hydrogen economy is diffusing and developing, this section defines the system structures surrounding hydrogen technologies. In specific, this section discusses the actors, institutions, and networks present within the hydrogen system. The focus is on the system surrounding the broader scope of hydrogen technologies in the Netherlands.

5.1 Actors

The event-history analysis identifies 122 individual actors (table 5) who are involved in the hydrogen system in the Netherlands (2017-2022). The data indicate a wide variety of public and private actors. First, there are different types of public actors which start with the European Commission, which is responsible to develop and operationalize European regulations and directives including those for the energy, industry, and mobility domains (Schutze, 2020). The Dutch national government translates European targets and regulations, and national agreements into a national policy framework, and regulations, and develops policy instruments to help reach their targets (NG1, NG2). The operationalization of these sustainability targets is also appointed to regional and local authorities such as Provincial governments and municipalities which have to develop their local strategies (Dutch Government, 2019).

Secondly, besides public authorities, there are a variety of other public actors including public research organizations, public intermediaries, and semi-public energy infrastructure organizations. Examples of research organizations are TNO, ECN ("Energieonderzoek Centrum Nederland", which is founded by TNO), and PBL ("Planbureau voor de Leefomgeving"). These organizations are involved with hydrogen research and testing, or with the assessment of policy plans (Savelkouls, 2019). Universities are also heavily involved in research and development or pilot projects in collaboration with public and private actors (Geijp, 2017; Provincie Groningen, 2020; van de Weijer, 2021). TKI ("TopConsortium voor de Kennis en Innovatie") is an example of a public intermediary, which aims to bring together different actors in the system to foster innovation (RO2). Another example of an intermediary is Institution for Sustainable Process Technology (ISTP), which brings together sector actors to develop and standardize technologies for industries (Westerveld, 2022). In the case of hydrogen, the ISTP is working with industry stakeholders to develop a standardized 1-gigawatt electrolyzer design (IO1, IO2). Large parts of the energy markets in the Netherlands are public markets for which public organizations such as Tennet (national electricity), Enexis, Stedin (regional gas and electricity), and GasUnie (national gas backbone) are designated to develop and maintain the national energy infrastructure (EI1, EI2). These organizations are also involved in hydrogen development.

Third, besides public organizations, a variety of private organizations spread over various sectors are involved in the development of hydrogen solutions. Many organizations cooperate with consultancy firms that support public and private organizations with knowledge development and pilot projects (e.g., PWC, or engineering firms) (IO5). Other organizations have the role of inspecting, testing, or certifying technologies in line with regulations (e.g., Kiwa) (Branse, 2019). In the mobility sector, Hyzon Motors manufactures hydrogen trucks (DvhN, 2021), while GreenPlanet operates a hydrogen refueling station (Green Planet, 2022). In the industrial sector, large organizations like OCI, Yara, or Shell are identifying green hydrogen as a means to reduce carbon emissions and replace grey hydrogen (Provincie Groningen, 2020). TATA Steel could use hydrogen as feedstock in the production process for metal (de Waard, 2021). In these various sectors, start-ups like H2Storage or HySiLabs develop businesses with innovative hydrogen technologies to fulfill a variety of functions in the future hydrogen value chain including innovative storage tanks, new fuel cell technology, and innovations in electrolyzers (IO3). Large energy organizations including Eneco, Vattenfall, and Equinor are developing renewable energy sources/locations and plan to operationalize electrolyzers to produce green hydrogen (Provincie Groningen, 2020). On some occasions, these private organizations work together to develop hydrogen solutions under consortiums (e.g., NorthH2), where various organizations along the hydrogen value chain partner up to develop hydrogen projects or to combine lobbying power. These are examples of private-private collaborations.

Finally, there are non-profit organizations like GreenPeace or Milieu Defensie that pressure public and private actors to reduce harmful practices, sometimes promoting solutions such as green hydrogen, or changing regulations to foster hydrogen development (van Hofslot, 2021). While Non-profit organizations like the New Energy Coalition aim to stimulate, promote, and accelerate the development of renewable energy technologies (Savelkouls, 2020).

Table 5: Hydrogen Innovation System Actors

Category	Sub-category	Actor
National and regional government	*International Authority*	*European Commission, European Parliament,*
	National government	*Ministry of Economic and Climate Affairs, Ministry of Infrastructure and Water Management, National Hydrogen Program (NWP), RLi Council for living environment*
	Regional government	*Province of Groningen, Province of North-Holland, Province of Friesland, Province of South-Holland,*

		Province of Utrecht, Province of Zeeland, Province of Drenthe, Province of Limburg
	Local government (Municipalities)	*Bergen, The Hague, Breda, Rotterdam, Groningen, Den Helder, Utrecht, Old Ambt, Emmen*
	(semi) Public organizations	*Port of Groningen, Port of Rotterdam, Port of Amsterdam, GasUnie, Alliander, Enexis, Stedin, TenneT, Energiebeheer Nederland (EBN), TKI, Port of Den Helder, PBL Netherlands Environment Assessment Agency, TNO, ECN Energy-research Institute, TKI. Consortium for TopSectoren, NAM*
Private and Corporate organizations	*Energy organizations*	*RWE, Eneco, Vattenvall, Uniper, Essent, Shell, Equinor, Solinor, GroenLeven, Morgezon, Engie, TotalEnergies, Lhyfe, Orsted, BP, Hygro, SolarDuck*
	Industry (chemical or process)	*OCI, Nobian, Nouryon, Yara, TATA Steel, HyCC, AkzoNobel, Hysilabs, NedMag, HyEt, Holthausen Clean Technologies, Air Liquide*
	Consultancy	*BlueTerra, Bloomberg, Delphy, PWC, DNV-Gl,*
	Energy infrastructure and technical support (storage, transportation)	*Energy Stock, Evos, Veco, Bam, Damen, Siemens, Demcon, H2Storage*
	Mobility Sector	*Fokker, Damen, Arriva, GreenPlaten, FietenOil, HySolar, New Holland, Hyzon Motors, GE Renewable Energies,*
	Financial institutions	*Green Investment Group*
	Built Environment	*Remeha*
	Consortiums	*NorthH2, Electriq Global, AgroFossilFree, Ship2Drive, Institute for Sustainable Process Technology (ISTP), Waterstof Coalition, Hydrogen Platform (waterstof platform)*
Civil Society		*New Energy Coalition (NGO), FNV metal (trade union), Milieu Defensie (NGO), Natuur en Milieu (NGO), KIVI (Royal Institute for Engineers), LochemEnergy, General consumer association*
Academia and Research professionals		*Technical University Delft, Technical University Eindhoven, Royal University Groningen, ROC Emmen, Professors in Energy science (anonymous), University of Maastricht, TNO, Stenden University of Applied Sciences, Wageningen University. Hanze University of Applied Sciences, KIWA NV, PBL, RLi*
Community		*Lochem energy, Local neighbor pilot initiative project*

International Organizations	*Green Peace, International Energy Agency (IAE), Corporate Europe Observatory (CEO)*

5.2 Institutions

The Dutch government is committed to meeting the sustainability targets set out in the European Green Deal (2019), which draws upon the agreements made in the Paris Agreement (2015). This agreement is leading on an international level and intends to reduce global warming to 1.5 degrees Celsius compared to pre-industrial levels (UNFCCC, 2015). The Netherlands first committed to the Paris agreement in 2015 being one of 194 countries that signed the agreement (Dutch Government, 2019). This resulted in the National Climate Agreement (2019) in which the country states its ambitions across various dimensions of sustainability including the energy transition, mobility, and industry. The European Green Deal followed that same year. The overarching goal is to reduce carbon emissions by 49% in 2030, compared to 1990 levels. Eventually reaching a 95% reduction in 2050 (Dutch Government, 2019). This requires an incremental change in all societal systems. One of the first measures to stimulate the reduction in carbon emissions in the industry was the CO2 tax. 1 ton of CO2 emissions is equal to 1 emission right. These rights are limited and can be traded on the energy trading system (ETS). This leaves actors with an incentive to invest in less polluting processes. Yearly, the amount of emissions rights is lowered proving the incentive for all industry actors to reduce their emissions over time (Dutch Emission Authority, 2022; European Commission, 2021).

Regulations like the ETS system are designed on a European level and stem from regulations published in European Directives. These directives state binding targets and regulations for EU member states. The European Commission can amend directives with delegated acts. These indicate rectifications, changes, or clarifications to directives on specific topics (Schutze, 2020). For example, in the energy domain, the Renewable Energy Directives (RED) indicate European energy policy and provide a guideline for member states to develop their national energy policy framework (RO2, IO1, IO5). Within these directives are regulations for various aspects of the energy system among which is hydrogen. To illustrate how regulations change over time a quote from the interviewee (IO5):

''In RED2, the classification of green hydrogen was relatively strict, to get your hydrogen certified. Now the European parliament has said we lower the strict H2 compliance. Instead of demonstrating on an hourly basis that your electrolysis was using electricity from renewable sources. In a recent delegated act, the European Commission amended this strict definition for RED2 green hydrogen compliance. They

broadened to for example demonstrating the energy sources for green hydrogen on a monthly basis. This provides more opportunities for the market" – IO5

The Dutch national government translates European targets and regulations, and national agreements into a national policy framework, and develops policy instruments to support their targets (NG1, NG2). The different ministries are designated to develop these policies for their respective domains of responsibility. For example, the Ministry for Economic Affairs and Climate Policy is responsible for the national energy policy (NG1). While the ministry for Infrastructure and Water Management is responsible for the national mobility targets (NG2). As indicated in the introduction, the Dutch National Climate Agreement (2019), is a public-private agreement stating the Dutch ambitions to comply with targets derived from the Paris Climate Agreement (2015). In this agreement the country identifies five categories of potential, or functions for hydrogen in the sustainability transition:

- Carbon-free feedstock for heavy industry (process industry);
- Carbon-free energy carriers for high-temperature heat for the process industry;
- Controllable carbon-free energy capacity, energy storage for prolonged periods, and energy transportation over long distances;
- The usage for mobility, such as passenger or (heavy) freight transport;
- Applications in the Built environment, for example, heating (Dutch Government, 2019).

An example of one of the ambitions of the climate agreement is to realize a 3–4-gigawatt electrolyzer capacity in 2030 (Dutch Government, 2019). Subsidies can be seen as an incentive for companies to invest in upscale of for example electrolyzes/ or research and development for hydrogen technologies. For example, The MOOI-subsidy scheme is appointed to research projects for the categories mentioned above. While the DKTI-transport scheme aims to stimulate demonstrations project for sustainable transportation. The DEI+ ("demonstration Energy and Climate innovation") provides a subsidy for energy-saving and innovation projects. Additionally, there are multiple fiscal schemes for sustainable investments such as "Energie inversteringsaftrek" (EIA), 'Willekeurige afschrijving milieu-investeringen' (Vamil), and the 'Milieu-inversteringsaftrek' (MIA) (TKI Nieuw Gas, 2022).

These national subsidies and some European innovation programs have mobilized financial means for system actors to invest in hydrogen technology (EI2, EI3, IO3, NG1). These mainly focus on research and development or small-scale pilot projects. However, for the upscale of hydrogen technologies, current government instruments are not suitable for accelerating the hydrogen system (IO1, IO2, IO5).

Additionally, as of now, there are no binding targets for hydrogen or specific guidelines for hydrogen market development. Although, these are currently in development and large funds have been allocated for the sustainability transition (IO1, IO2, NG1). The European Union and national governments are developing the exact regulations and targets and operationalization frameworks.

5.3 Networks

In the Netherlands, public and private actors are collaborating in a variety of ways to establish elaborate networks in the hydrogen system. The data indicate a wide variety of private-private and public-private collaborations. These networks are focused on different settings for research and development, business case development, lobbying, or public-private consultation. For example, the NorthH2 project is an industry consortium aiming to kick-start the hydrogen economy. It is an international consortium connecting various actors in the hydrogen value chain which aim to work together (NortH2, 2022). The "Waterstof Coalitie" (translated as the *hydrogen coalition*) is a pact between various types of actors from various industries to lobby the government for hydrogen regulations (IO1) (Waterstof Coalition, 2021). In 2021, the National government initiate the NWP (National Hydrogen Program), which is a platform on which the government works together with private actors on how they could reach hydrogen ambitions (NG1). Regional infrastructure operators like Stedin, Enexis, or Alliander also work together as a sector with research institutions and universities to develop common standards and safety regulations for the sector under the HyDelta-1 and HyDelta-2 programs (EI2, EI3). Other examples are the ISTP program, which brings together sector actors to develop and standardize technologies for hydrogen production (IO1). This is a government-initiated institute to develop industry technologies together with system actors (Institute for Sustainable Process Technology, 2022). Furthermore, over de last five years, public and private organizations have organized various hydrogen symposiums and webinars which aim to create legitimacy for hydrogen technologies and inform sector actors about current technological possibilities and provide actors a platform to showcase their capabilities (NG2). For example, in October 2022, the national hydrogen days are organized in S-Hertogenbosch, which is a symposium, where organizations can showcase their hydrogen technologies (IO3).

5.4 System structure summary

In summary, the system structures indicate that there is a strong basis in the Dutch hydrogen system. A variety of incumbent organizations are involved in the system. These include large energy suppliers, large engineering firms (e.g., Siemens or Damen), and Large industrial players (e.g., OCI, Yara, and Air Liquide Products). Also, public organizations are involved in the development of the system which is reflected in the involvement of research and development organizations (e.g., TNO, ECN) and education organizations (e.g., Eindhoven or Delft university), and the national and regional government. A variety of supporting organizations are also involved in the system such as branch organizations (e.g., branch organizations of regional network operators), network organizations (e.g., Waterstof platform, NGO-New Energy Coalition, or 'Nationale waterstof program"). However, the data does not include sufficient information on the presence of financial institutions supporting the system. Additionally, the data includes small-scale organizations (e.g., start-ups and scale-ups), but not in sufficient numbers. Large incumbents are most present in the system. The networks present in the system seem to be sufficient to support the system as there are a variety of private-private and public-private networks present. Although institutions are present to support carbon technologies the data indicates that these are not specific enough to support the development of the hydrogen system.

6. Results: the development of system functions over time

In this section, the dynamics or behavior of the hydrogen innovation system in the Netherlands is investigated based on the system functions described in section 2.2.3. Figure 6 plots the number of accumulated events included in the database over the time frame (2017-2022). This graph presents the outcome of the event-history database analysis and provides insight into the development of the hydrogen innovation system. This section is divided into three time periods based on the database analysis.

- *Background: European hydrogen context*
- *Period 1: development NL up to 2018*
- *Period 2: acceleration between 2019 and 2021*
- *Period 3: from 2022 onwards*

First, a contextual background is provided based on desk-research about hydrogen development in Europe. This is important to understand because the Netherlands as an EU member state is subjected to targets and regulations originating in the European Union. Therefore, events occurring on a European level have an impact on the national level. Secondly, the development of the Dutch Hydrogen Innovation system is described up to 2018 (period 1). As explained in the methodology (section 3.2), in 2019, on a European and National level climate agreements are signed which resulted in an acceleration of events from 2019 onwards (figure 6). To understand the development leading up to the acceleration period 1 is restricted to events up to 2018. Third, between 2019-2021 (period 2) the event data indicates a significant increase in system activities. To capture the dynamics of this period after the publication of the climate agreements. Lastly, 2022 onwards reflects (period 3) the recent developments in the system. More detailed graphs of the development per system function are available in appendix D. In addition, the data from the event-history analysis is further substantiated by the interviews.

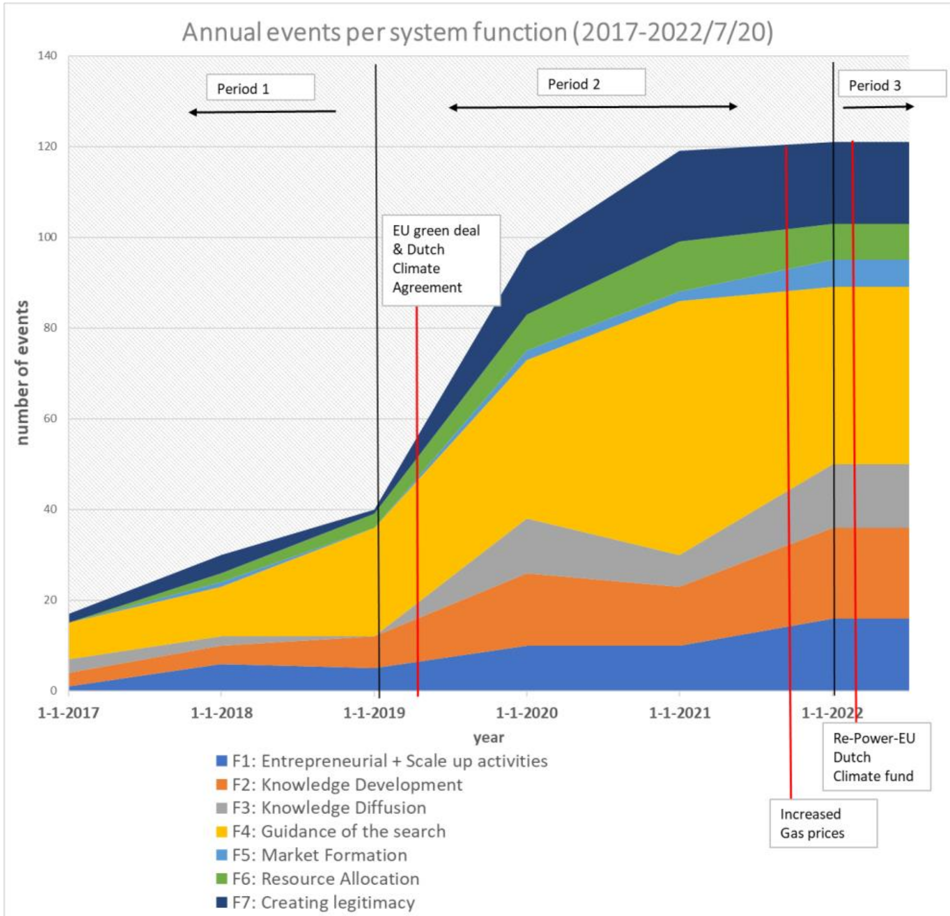


Figure 6: Cumulative representation of events per system function over time in Dutch Hydrogen Innovation System (2017-2022).

6.1 A Brief European background

For decades, hydrogen or synthetic fuels have been in the discussion to have a potential function in the energy system (Graves et al., 2011; Rönsch et al., 2016). However, interest in hydrogen technologies did not gain a lot of traction until climate concerns appeared over two decades ago (Decourt, 2019; Suurs et al., 2009). A reflection of these concerns is the Kyoto Protocol (1997), in which 55 countries agreed to attempt to reduce greenhouse gas emissions (F4) (UNFCCC, 1998). An indirect consequence of the Kyoto Protocol was the development of European emission norms in the 2000s (Suurs et al., 2009). These events stimulated the focus on a more sustainable energy system.

A starting point for hydrogen in Europe is 2000 when the European Commission released a first onlook on the outline of a future energy system strategy. This Green Paper focused on three pillars of a future energy system: climate change, economic competitiveness, and security of energy supply (European Commission, 2000). The focal point was on carbon-neutral energy sources such as renewable energy (e.g., PV or wind), and renewable fuels (e.g., biofuels or hydrogen). In theory, this is one of the first publications from the European Union, which promotes the use and development of hydrogen as a source of energy (Decourt, 2019)(F4).

Such publications of the EU influenced various knowledge development activities (F2) (e.g., pilot projects or R&D programs) under the European Research Framework Programs (F4), which also included schemes to mobilize financial resources for R&D (F6). An example is the CUTE program which funded the research and demonstration (F6) of hydrogen fuel-cell powered buses (F1-F2) under a collaboration between various European Cities and Private organizations (F3) (Including Amsterdam and Barcelona) (Binder et al., 2006).

In addition, In this same period, Europe initiated a platform including various high-level stakeholders from different (sector)groups in the hydrogen and fuel cell domains (F3). These stakeholders were from various research, business, and policy backgrounds, and expressed their future onlook in their release of the "*Hydrogen Energy and Fuel Cells. A vision of our Future"* publication (F2-F4) (European Commission, 2003). These developments eventually led to the creation of the Hydrogen and Fuel Cell Technology Platform in 2004. This was an initiative of the European Commission to guide and structure research and development on hydrogen topics (F4) (Decourt, 2019).

Over the years, these platforms and changing EU frameworks have stimulated various research and development programs (F4) across Europe. In turn, these stimulated scientific publications (F2), and small-scale pilot projects (F1) (Decourt, 2019). In 2008, this platform evolved into a public-private partnership the: Fuel Cells and Hydrogen Joint Undertaking (F3-F4). Such platforms are at the forefront of influencing resource mobilization (F6), creating legitimacy among private and public actors (F7), and stimulating research projects across Europe (F2) (Lymperopoulos et al., 2019).

Over the years that followed various research and development projects have been subsidized and initiated by the EU and some member states (F4-F6). Moreover, the climate debate intensified resulting in the first renewable energy directive (RED1). Which is formally called 2009/28/EC and was published in 2009 and states the minimal levels of renewable energy sources in the EU for the 2009-2021 period (European Commission, 2009). In 2015, 197 countries including the EU, signed the Paris Agreement, vowing to minimize global warming to a maximum of 1.5 degrees Celsius (UNFCCC, 2015). This agreement resulted in new benchmarks regarding greenhouse gas emissions reductions. Developments like these accelerated the urgency to drastically change our current energy systems to a system based on renewables. Moreover, it pushed investments in renewable energy sources contributing to the drastic reduction in costs for renewables (wind and solar) over the last decade as upscale increased. This was amongst others achieved by massive subsidized renewable energy projects across European member states (Capozza et al., 2021), and incentivized renewed attention to hydrogen.

With the development of lowering renewable electricity prices, the cost of renewable energy carriers such as hydrogen became more interesting. Additionally, it became apparent that electrification of the energy system also has its barriers (Dickinson et al., 2017). Subsequently, to overcome some of these barriers, energy carriers like hydrogen can play important in some sectors (e.g., industry or (heavy) transportation) (International Energy Agency, 2019). However, specific regulations on hydrogen in the energy transition were not included in EU policies until 2018. In that year, the EU amended RED1, with the Renewable Energy Directive (EU 2018/2001), or short RED2. This directive was the first that lays down a legally binding definition of renewable liquid and gaseous transport fuels of non-biological origin (F4-F5), such as hydrogen (European Parliament, 2018). This was the first legally binding definition that hydrogen for climate mitigation purposes had to full fill. Moreover, in the wake of the Paris Agreement, the European Union ratified the European Green Deal in 2019 (F4), which specifically states clean fuels including hydrogen have a profound function in the future energy system (F7) (European Commission, 2019). These developments led to the publication of the European Hydrogen Strategy (F4) in 2020 (European Commission, 2020). This agreement focused on innovation, stimulating the scale-up and development of infrastructure in the hydrogen domain (European Commission, 2020).

To summarize, for the last two decades, hydrogen has been under the attention of the European Union. Although hydrogen had peaks of interest and years of less attention (European Commission, 2020). Over this period the EU has been involved in the development of the hydrogen innovation system in various ways through research programs (F2), platforms (F3), or the mobilization of financial resources (F6) (e.g., funds for research). More recently, the EU is adopting binding climate agreements resulting in new incentives to transition to a renewable energy system. Today, these developments combined with the cost decline of renewable energy and technological developments result in revived attention to the function of hydrogen in the energy system. This is reflected in the new hydrogen coordination and resource mobilization (F4-F6) activities within the European Union and thus its member states. Throughout the results, recent developments in the EU are discussed.

6.2 Period 1: development NL up to 2018

6.2.1 High-level early development in the Netherlands 2000-2017

Hydrogen is not new to the Dutch energy system. For decades, the country has had a large hydrogen industry. Nowadays, the Netherlands is also the second largest producer of hydrogen in Europe (F5-F6) (TNO, 2020). Primarily, this hydrogen is produced using natural gas and accounts for approximately 10% of the annual gas consumption in the country (IO1). This hydrogen is used as a raw material in the country's chemical industry and its oil refineries (F5) (TNO, 2020). As such, only making the current hydrogen cycle sustainable would already save a lot of carbon dioxide emissions. Moreover, this experience also means that the country has a lot of expertise with hydrogen in use for industry (F1), how to produce it using conventional methods, how to transport it through pipes, and how to store and handle it safely (International Energy Agency, 2004). This history indicates that the country has an extensive hydrogen industry and knowledge base (F2).

The discussion to use hydrogen to decarbonize the energy system emerged when the climate change debate intensified in the early 2000s (Suurs et al., 2009). This was an indirect effect of the changing direction on a European level and its vision for a future energy system (European Commission, 2000), which foresees a large shift away from current fossil-based technologies. Moreover, the Netherlands sees hydrogen as a technology with a large potential as it can (re)use its existing natural gas experience and infrastructure when hydrogen develops (International Energy Agency, 2004). In this context, in 2004, a report published by the International Energy Agency (IEA) indicated that Dutch universities, institutions, and the private sector were involved in R&D and collaborations focused on: hydrogen production, handling, storage, infrastructure, and hydrogen applications (F2-F3). Non-technical programs focused on public awareness, safety, and standard development (F2-F5-F7) (International Energy Agency, 2004). Coordination of the hydrogen efforts has always been guided by public institutions including ECN (Energie Onderzoekcentrum Nederland) and TNO (Bakker et al., 2011), and the government. Private actors seeing the potential of hydrogen technologies were also involved in privately initiated programs (F2-F4) (Suurs et al., 2009), including Shell and GasUnie.

On a national and international level, the Dutch system actors were also involved in international and EU-subsidized programs (F2-F3-F6) including the aforementioned CUTE program (Amsterdam-Municipality, GVB, and shell), the European codes and standards program (F2) (Shell), NaturalHy which tests the mixing of natural gas and hydrogen (F1) (GasUnie), and HyNet; a European Commission founded network project (F3) for industrial actors (Shell-Hydrogen) (International Energy Agency, 2004). The mobilization of resources for these R&D projects was a combination of private and public sources (F6) and its creation was dependent on the lobbying power (F7) targeted at local and national government, and the EU (Bakker et al., 2011). Eventually, these financial means were mobilized through tax incentives and had an approximate budget of 10-30 million euros per year (F6) (International Energy Agency, 2004).

Regardless of the variety of organizations operating in the chemical and energy industries, and the fact that the country has an extensive knowledge base and infrastructure for natural gas. In the context of developing hydrogen as part of the energy transition, the system remains stuck in primarily the generation and development of new knowledge and technologies. Specific supporting activities (F4) for market development (F5), upscale (F1-F6), or resource mobilization (F6) to stimulate the use of hydrogen for further decarbonization remain under-represented (Suurs et al., 2009).

A new shift started in the 2010s when it became apparent that natural gas did not have a future in the Dutch energy system (IO1, RO2). Like the Kyoto protocol, similar (external) events, like the introduction of the ETS system in 2002, which resulted in companies including the price of carbon in their financial quotations (IO1), or the introduction of the Renewable Energy Directive (2009) intensified the climate change debate, increasing attention to hydrogen.

This shift is to be illustrated by the attention of a public intermediary (TKI) for natural gas replacements. This organization started to provide attention to topics related to power to x (e.g., gas), or x to power in 2012 (RO2). These topics focused on what could substitute natural gas in a future energy system including solutions such as hydrogen (RO2). Since TKI is a public intermediary, it collaborates with the Dutch government and private actors to promote innovation and guide the development of technologies (F3-F4). The involvement of this intermediary indicates that the government has been involved in the hydrogen topic. These developments also led to the founding of a TKI subsidiary (2015-2016), “TKI Nieuw-Gas”, which translates to “TKI New Gas”. This organization specifically aims to stimulate the development of innovation for natural gas alternatives including hydrogen (RO2). These events indicate that public system actors specifically focused their attention on hydrogen from 2018 onwards.

6.2.2 Development NL 2017-2018

To synthesize against that backdrop, these developments, over time, resulted in the development of a larger hydrogen innovation system and (sub) system in the EU member states. For the Netherlands, in 2017-2018, the event-data indicates a small number of activities in the Dutch hydrogen Innovation system. Although these are rising between both years (figure 6). The system activities focus primarily on function 4 (see appendix D). This means that the system is creating expectations and providing direction for hydrogen development. Function 4 is important because resources in an innovation system are limited, thereby, providing the right direction is required (Hekkert et al., 2007). In 2017 & 2018, this is reflected by a large number of feasibility studies performed by both private and public actors. These feasibility studies are triggering activities in the system to map the potential for hydrogen technologies. Therefore, these are not only considered as (F4) activities but also stimulate (F2) further knowledge creation.

The first example is a collective feasibility study between Nouryon, Tata Steel, and the Port of Amsterdam (F2-F3) to understand how waste streams can be used to produce hydrogen (van Leeuwen, 2018). This can contribute to the further reduction of carbon emissions in these organizations' processes. The second example is GasUnie, which initiated a feasibility study (F4) to understand to what extent hydrogen can act as a substitute for natural gas (van der Lugt, 2017). In 2018, GasUnie and AkzoNobel also announced a joint feasibility study to build a 20MW electrolyzer in Delftzijl (F4) (Geijp, 2018b). Later that year, the 100MW electrolyzer capacity threshold was surpassed by an announcement for a feasibility study by the Green Hydrogen Cluster NL (F4) (Decourt, 2019). Such activities are aimed at developing the knowledge base of organizations and indicate the commitment of these organizations to certain technological directions (IO2, EI2). Moreover, these activities, like the other examples often occur in collaboration with other system actors thereby contributing to knowledge diffusion (F3). This reflects that functions interact and influence each other. This interaction can develop both ways either strengthening other functions or weakening them.

Interviewees (IO2) indicate that pre-competitive feasibility studies are used to better understand the potential of a certain technology, the potential of the market, and the business case feasibility. This means that for private organizations such as industrial actors this function provides direction (F4). Without this knowledge or guidance, these private actors can not develop adequate business cases. Consequently, Without the right business case, they will not continue and provide an FID (financial investment decision) (F6) for a project (IO2 and IO5).

This guidance of direction (F4) in the system can also be provided by public actors such as the Dutch national government (Dutch Government, 2019). However, in these years there is not yet sufficient clarification as to which direction the hydrogen innovation system is developing. As the interviewee (RO1) indicates:

"for a long time, there was little guidance in the application and direction for hydrogen technologies from the government. Moreover, there were no specific regulations, goals or targets at all, or at least on paper, no specific expectations" - (RO1).

In this first period, the data indicates primarily private actors or public institutions (e.g., research institutions or intermediaries) which are providing this guidance through the mentioned feasibility studies. Another way for private actors to commit to the energy transition and hydrogen solutions is by committing to carbon reduction targets. For example, in 2018, AkzoNobel commits to its sustainability strategy and publicly states that hydrogen solutions are part of this strategy (F4) (Geijp, 2018b). While also GasUnie indicates to remove carbon dioxide emissions from their operations in due course (F4) (Geijp, 2018a). These actions provide direction in the system and indicate in which direction organizations are developing.

The absence of guidance by the government is reflected in the fact that in this period on various occasions coalitions of system actors lobby (F7) at the government for more specific hydrogen targets, regulations (-F4), and coordination activities (-F4). This would indicate an absence of these activities from the side of the government. In 2018, Greenpeace, an independent international environmental NGO, formed a hydrogen coalition (F3-F4) consisting of various system actors amongst others including Technical University Delft, Tennet, Alliander, Vattenfall, Eneco, Essent, Harbour of Amsterdam, Harbour of Rotterdam, OCI and Yara (van der Lugt, 2018). This platform aimed to use their combined lobby power (F7) to pressure the Dutch government to develop better coordination frameworks for hydrogen and consider more synthesis between the various dimensions in the energy transition (e.g., renewable electricity and hydrogen) (van der Lugt, 2018). The sequence of these events put the interactions between system functions into context. First, a platform/coalition is created by Greenpeace in which various system actors collaborate. Subsequently, this platform is used to create legitimacy for hydrogen solutions (F7) by lobbying the government for better guidance activities for hydrogen development (F4).

Also, regional governments (provinces of Drenthe, Friesland, and Groningen) lobby at a national level for hydrogen development and better guidance (F7) (van Dongen, 2018). The formation of lobby groups can be considered a coordinating activity by system actors (F4). In these cases, these activities are performed by other actors than the national government.

Additionally, scientists, such as Ad van Wijk (Delft University) and Dr. Jepma (Groningen University) are advocating the development of hydrogen in the Netherlands (F7) (Geijp, 2017; Lomme, 2018). These advocating activities by academic professionals or other actors also steer the direction of research and development (F2). Nevertheless, according to various system actors (IO1, IO2, EI1, EI2), the government must take the lead in providing direction and coordination activities. This is reflected by the following quote by the interviewee (IO1):

"It is important that the government intervenes in markets and coordinates the energy transition because the market actors itself will not be able to come to a consensus about how to accelerate the transition and meet the climate goals" - (IO1)

A direct consequence of the lack of guidance and coordination by the government is a hampering innovation system (Suurs et al., 2009). It does not mean that these coordination activities are absent at all. But as findings by Suurs et al. (2009) and the previous quote by (IO1) suggest lack of guidance by the government will lead to a hampering innovation system, potentially leading t lock-in.

However, there are developments for coordination. For example, in 2015, the Dutch government did commit to the Paris Agreement (2015), which aims to cut greenhouse gas emissions (F4). In 2017 and 2018, there is not yet any clarification on the European or national level on how the ambitions from Paris are going to be operationalized, and what this will mean for hydrogen development.

Like in the last two decades, system actors in various sectors are involved in hydrogen entrepreneurial activities (F1). For example, Remeha is developing and testing hydrogen heating products for households (F1), which can be used for the built environment (VNO-NCW, 2021). Future Proof Shipping (FSP) started developing a design for a fuel cell driven (powered by hydrogen) inland freight ship (F1) for the transportation sector (VNO-NCW, 2021). The public operator of the national gas infrastructure (GasUnie) operationalized a small-scale pilot project, namely, a 1MW green hydrogen electrolyzer (F1) at their Zuid-Wenden facility (Geijp, 2018b). A start-up named Hygro is developing an integrated windmill electrolyzer design (F1-F2) (de Ronde, 2017). These examples indicate that the system actors are developing and testing hydrogen solutions for a variety of sectors including transportation, energy production, and heating.

Also for knowledge development (F2), various actors are involved in a variety of different activities. For example, public research organizations like TNO are involved in the development of hydrogen technologies (Savelhouls, 2018). However, as indicated, this actor, like others (e.g., ECN) has been involved in directing and performing hydrogen knowledge development for over two decades

(International Energy Agency, 2004). Ongoing knowledge development projects include research into what role hydrogen electrolysis can play in the energy system by DNV-GL, TNO, and Enpuls (F2) (Savelhouls, 2018), or in another study by research engineering consultancy organization KIVI by providing an onlook (feasibility study) towards the energy system in the Netherlands in 2050 (F2-F4) (Westerveld, 2020).

Additionally, a public intermediary, TKI Nieuw Gas, published a report in 2017, stating the various organizations in the Netherlands which are involved in the hydrogen sector (F7) (TKI Gas, 2018). This report indicates various organizations being involved in entrepreneurial hydrogen activities (F1-F2). In addition, the report also indicates the first inputs for a hydrogen roadmap for different sectors (F4). The content for this report discusses how hydrogen can contribute to the climate agreement targets from Paris in the Netherlands (TKI Gas, 2018). Interviewee (RO2) indicates that such intermediaries aim to facilitate and connect innovative organizations of all types (e.g., start-ups, regional governments, universities, and industrial organizations) for the development of hydrogen technologies. They connect and inform actors to and about subsidies or other system actors as well as publicly contribute to creating legitimacy by promoting system actor activities (F7) (RO2).

There is no specific information about resource mobilization in this period within the database. It is mentioned that a variety of R&D projects and small-scale pilot receives European or national Funding (F6), but specific government policies for the implementation of hydrogen solutions are not present. *A lack of direction/guidance* or the ability to mobilize resources is an often-presented barrier in technological innovation systems (Nevzorova, 2021). Like in the decades before, this period is characterized by a variety of hydrogen system activities, but specific guidance, upscale, and allocation of resources are under-represented.

6.3 Period 2: acceleration between 2019 and 2021

Although the hydrogen innovation system in previous years was not dormant. From 2019 an acceleration occurred continuing into 2021, which is clearly shown in figure 6. In this period, the innovation system functions become very dynamic starting with a sharp increase in guidance of the search (F4) activities (appendix D). The most notable events are the publication of the Dutch Climate Agreement (2019) and the European Green Deal (2019) (F4) (Dutch Government, 2019; European Commission, 2019). These European and National agreements are the cornerstones for climate policies or targets in the Netherlands for years to come (F4). The characteristic acceleration in events from 2019 onwards is partly induced by these events. The publication of these agreements is a major guidance activity (F4) and can be regarded as large external shocks shaking the current energy system. Such external events have been mentioned in earlier sections (sections 6.1 and 6.2) and are external influences that impact the dynamics of the hydrogen innovation system and can include activities related to system-external actors, networks, or institutions (Ulmanen & Bergek, 2021).

The potential effect of these external shocks can be illustrated by points addressed by both interviewees (IO4, IO5). These industrial system actors indicate that climate change requires them in time to transit away from their current business models which rely heavily on fossil fuel-based technologies (IO4-IO5). The climate agreements fast-track these transitions and related regulations state the conditions for these organizations to induce change. This implies that because of these external shocks system-wide change is induced (Ulmanen & Bergek, 2021). Different shocks have occurred, and these events contributed to the decarbonization of society and the energy system to be at the forefront of public and private debate.

The above-mentioned external shocks, occurred multiple times throughout the last two decades. For example, as explained in section 6.1, the Kyoto Protocol (1997), induced carbon emission regulations for the industry in Europe and provided the stimulus for the EU to develop a vision of the future energy system in 2000 (European Commission, 2000). Thus, two decades ago, these events also led to an increase in hydrogen activities (International Energy Agency, 2004).

Interviewee (IO1) mentioned another important external shock making hydrogen a more feasible solution. Namely, from October 2021 onwards, fossil-based energy sources drastically increased in price (IO1). These events impacted the cost deficits for (green) hydrogen solutions and their fossil-fuel counterparts (IO1, IO2). A study by Schnuelle et al. (2022) highlighted the effects of these events on price developments on conventional and future energy carriers (Schnuelle et al., 2022). Figure 7, represents their price development forecasts. Initially, the price deficit between green hydrogen (blue area) and the expected increase in price for natural gas or crude oil was not forecasted to be equal until the late 2020s or in the 2030s (figure 7). However, with the actual prices of fossil fuel alternatives rising rapidly the price difference between conventional fossil fuels and the sustainable alternative of green hydrogen is close to being equal in 2022. For large industrial organizations, these external events including climate agreements and increased energy prices provide incentives to accelerate the transition to sustainable alternatives like hydrogen. Thereby, these developments lead to increased activity by system actors for hydrogen technologies (IO1).

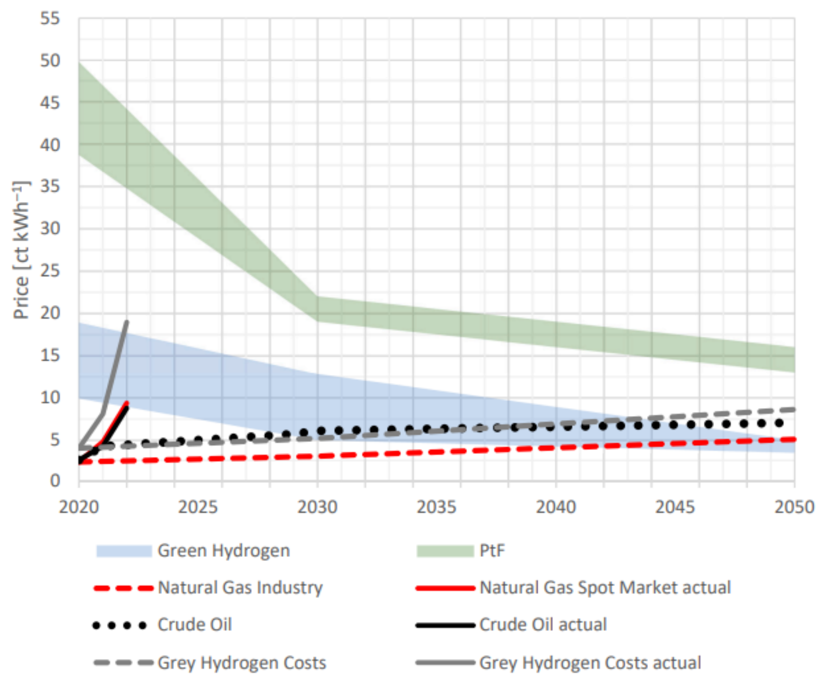


Figure 7:Expected production costs of green hydrogen and synthetic fuels up to 2050 compared to price projections for grey hydrogen, natural gas (prices for industry customers), and crude oil (dashed lines), without consideration of increasing CO2 emission costs. Prices for grey hydrogen, natural gas, and crude oil in solid lines represent the actual price developments. Adapted from Schnuelle et al. *(2022).*

Still, three out of thirteen system actors indicate that the upscale and market formation of the hydrogen system will not go fast enough without the right guidance from the government (IO1, IO2, EI2). These actors stress that more guidance is needed in terms of specific targets, regulations, standards, and policies (-F4, -F5). Interviewee (IO1) indicates that private actors without guidance will never have enough incentives to change fast enough and reach the current climate targets within their projected scope (IO1). Moreover, the interviewee states (IO1):

”Economic considerations always win for private actors. Certainly when they have shareholders to account to. Even when organizations are willing to change these economic considerations win, and only slow change will be realized” - (IO1)

This also relates to the event of rising prices for fossil fuels. When the price gaps between different technologies are decreasing organizations will be more openly considering the hydrogen transition (IO1). These reconsiderations occur when the system conditions (in this case reduced price for hydrogen) change, which could fast-track the transition.

Although these (external events) contributed to increased attention to the hydrogen system, actors stress that in the 2019-2021 period: From the perspective of the national government, it is unclear which direction the system is developing in, and for what applications and sectors the government is providing priority to (IO2, IO3, EI2). In 2021, an event from the database, a lobbying activity by large incumbents (Shell and BP), indicates these organizations lobby at the government for long-term consistency and guidance for green hydrogen strategy (van der Lugt, 2021). Another example is the lobby of the Hydrogen Valley Coalition in the northern part of the Netherlands (Provincie Groningen, 2020). This coalition consists of private (e.g., GasUnie, shell, Equinor, OCI) and public actors (e.g., province of Groningen, Royal University of Groningen), and developed elaborate plans for a regional hydrogen system in the provinces of Groningen, Friesland, and Drenthe. For these plans, long-term and consistent institutional frameworks are needed to stimulate and support its development in terms of regulations and financial finances (Provincie Groningen, 2020). Therefore, this coalition is actively lobbying for clear institutional frameworks (e.g., clear subsidy instruments) at the governmental level (F7) (Geijp, 2019).

The province of Limburg also lobbied at the governmental level for a clear investment plan of the government in terms of hydrogen infrastructure as this is essential for hydrogen development in the region (van der Schoot, 2021). In addition, together with actors from the region, the regional government (Noord-holland) (F3), is engaged in the development of a regional hydrogen system by initiating hydrogen feasibility studies, providing implications for road maps (F4), and lobbying at a national level for resources and policy instruments (F7) (Provincie Noord-Holland, 2022). Another event initiated by private organizations is an occasional coalition (F3) of large incumbents Vattenfall, port of Rotterdam, Engie, BP, GasUnie, Nouryon, and Shell who collectively urge the government for better coordination and clearer guidelines regarding the Dutch hydrogen mission (F7) (van Dijk, 2019).

These lobby events by public and private actors (F7) indicate that improvements are needed in the guidance of the search activities (-F4). However, the events also indicate that the involvement of (regional) public actors and the large incumbent is occurring. Interviewee (EI1, IO1) stresses that on a national level for the system to develop consistency is needed in terms of long-term and clear institutional frameworks (EI1, IO1). Interviewees (IO1, IO2, EI1) indicate that without stimulating institutional frameworks (-F4) for up-scale, the system remains stuck in technology and knowledge development, and it will not be able to invest in infrastructure mobilization (-F6), which will hamper market development (-F5). Thus, this can be seen as a barrier induced by a *lack of guidance*, illustrating negative feedback between functions (-F4 -> -

F6 and -F2). This is another example of potential feedback mechanisms in an innovations system as demonstrated by Suurs (2009).

Regardless, of these lobby events for better frameworks, there is an increase in guidance of the search activities by the government in this period (F4). For example, following the publication of the Dutch Climate Agreement (2019), multiple government officials openly discussed the point of the need for supporting policy frameworks to realize the hydrogen ambitions stated in the Climate Agreement (SavelKouls, 2019; van Santen, 2022; Westerveld, 2021b). These events acknowledge the importance of more specific policy instruments and can be regarded as the creation of legitimacy and as lobbying activities (F7). They indicate that within the government officials see the need for more supportive institutions.

These claims are supported by the elaborate lobby activities for financial support and better policy instruments by other system actors. A first example is a lobby by an industry coalition (e.g., organizations not mentioned) addressing that more support is needed and faster (Laan, 2019). In addition, hydrogen platforms are formed, and multiple organizations join these collaborations. An example is the Hydrogen Valley Coalition, which lobbies for more financial support (Geijp, 2019). Large incumbents like TataSteel (de Waard, 2021), or NGOs like Greenpeace also aim to create more legitimacy for hydrogen development and lobby the government for specific guidance activities (F4) (van Hofslot, 2021).

To put these lobby events into context. The government aims to stimulate green hydrogen production capacity by 2020. Eventually, this should be scaled up to 500MW in 2025, growing to a 3-4GW electrolyzer capacity in 2030 (Dutch Government, 2019). However, around 2019-2021, there are no sufficiently supporting policy frameworks for this and the other hydrogen ambitions. The government did commit 40 million euros a year to the development of the hydrogen system (Dutch Government, 2019). However, the lobby events indicate that system actors do not regard this as sufficient. Therefore, these system actors are actively lobbying for more financial support is needed (F7) to realize the ambitions.

These calls for more guidance also originate from regional governments in Drenthe and Groningen. These regional authorities lobby to accelerate the development of an action plan for hydrogen development in these provinces (F7) (Geijp, 2019). Regional governments are subjected to decisions and targets set by the national government; therefore, they stress the importance of clear institutional frameworks (NG1).

To put into context how certain system actors struggle to develop their hydrogen ambitions, a quote by the interviewee (EI3):

"as regional operator of gas infrastructure, our grid is coupled to the national Gas pipe of GasUnie. We know that there is a possibility that we will use hydrogen in this existing gas infrastructure in the future. We are preparing for that. But how much hydrogen we will get is uncertain. For us, it is one or the other, we do not have a double pipe. GasUnie does have this, so they can do both. Again we have no idea about what availability is in terms of hydrogen and when. There is no specific target for priority to specific sectors" - (EI3)

This quote illustrates the uncertainty and lack of guidance (-F4), in this case, it creates uncertainty in market formation (-F5), since specific targets/regulations/roadmaps (-F4) regarding the development of the hydrogen markets and hydrogen distribution are missing.

Regardless of the lobby activities for more guidance, the government is involved in a number of (positive) guidance activities. In 2020, the government publishes its hydrogen vision for the future stipulating the foreseen role of hydrogen in the energy system (Dutch Government, 2020). Moreover, this event aimed to create legitimacy for the development of hydrogen technologies by explaining the opportunities that this transition entails (F7) (Dutch Government, 2020). This vision expressed information about how the hydrogen transition should be tackled through extensive national and international collaboration (Dutch Government, 2020).

In this context, a notable event following these calls for more guidance by the government is the launch of the National Hydrogen Program (NWP) in 2021. This is a government-initiated program that aims to accelerate system development (Nationaal Waterstof Programma, 2022). Moreover, it coordinates knowledge development by initiating studies to understand current knowledge gaps and to better map what role hydrogen can play in the energy transition(Nationaal Waterstof Programma, 2021). This is done through private-public collaboration via this program. Interviewee (NG1) mentions:

''By the NWP we work together with sectoral working groups (representing specific sectors), and NWP-affiliated organizations to develop a hydrogen route map for the Netherlands for the coming years. We work together with the stakeholders to understand what is needed for development and what routes are most feasible to develop in" - (NG1).

The quote illustrates that the government is aiming to develop in collaboration with system actors more clarity into how the hydrogen ambitions can be realized (NG1). This collaboration between the public and private system actors occurs on more levels. Regional energy infrastructure actor (EI2) mentioned that:

"We are collaborating with the government on several levels. Nationally through our branch organization Netwerkbeheer Nederland. On a regional level, we are in contact with municipalities which we provide advice for what solutions, including hydrogen, are best suitable for specific areas in the energy transition"- (EI2)

This quote illustrates that regional energy operators are collaborating with other operators via their branch organization (F3), which in turn is collaborating with the national government. In addition, these actors also support regional governments in their energy transition strategies (EI1, EI2).

Also, large industrial actors are in contact with the government via various ways through lobby coalitions, or on an individual level. Both interviewees (IO1 and IO5) state that their organizations are involved in discussions with the Dutch ministries to lobby for their interests. These points illustrate that the regional and national governments are actively engaged with different system actors to develop hydrogen solutions or strategies, or policy instruments. This government involvement is illustrated by the event in which the national government initiated a program for system consultation with large industry actors about their requirements for a hydrogen upscale policy instrument (F3-F4) (Dutch Government, 2021a).

However, not all organizations or system actors have this link with the government but can find connections to other actors in other ways. As a quote by the interviewee (RO2), from an intermediary indicates:

"It funny that you ask. Yesterday, I was talking to a large energy supplier, and we were having a discussion about hydrogen, and this organization told me a lot of things. But at the end of the conversation I told this actor, these are interesting points, go tell or discuss them with the government. If you need me to make an appointment for you, I can do that. But policymakers must hear these things, or problems first hand. So they know what is going on and what aspects you are struggling with" - (RO2)

This quote illustrates two aspects. First of all, it indicates that this intermediary supports the innovation system and aims to connect different actors in the system (F4). Secondly, there is a low threshold for system actors to engage in a dialogue. This is strengthened by the fact that 11 out of the 13 interviewees indicated that their organizations are involved with other system actors in dialogue for hydrogen system development through lobby activities or collaborations in projects.

This attention to hydrogen is also reflected by the expanding number of private and public system actors which are involved in the hydrogen innovation system. Actors are increasingly contributing to guidance activities (F4), knowledge development activities (F2), and entrepreneurial activities (F1) (see the upwards trend in appendix D). Multiple large incumbents have entered the hydrogen system, while the data also indicates a growing number of small and medium-sized organizations being engaged in hydrogen activities. For example, H2Storage a startup is developing hydrogen storage containers for road transportation (F1) (RVO & TKI, 2021). In 2019, Remeha introduced a new design for a hydrogen boiler (F1) (VNO-NCW, 2021). Aliander and Groenleven participated in a pilot project integrating an electrolyzer and solar field (Atsma, 2021). In 2021, DemCon, a VDL spin-off, introduced a 1MW electrolyzer conceptual-design (F1) (Kuitert, 2021). Nedmag developed and tested a hydrogen burner for high-heat processes (Reijn, 2020). While Hyzon Motors, in 2021, opened a hydrogen truck production facility in Groningen (DvhN, 2021). Shell in collaboration with Delft University and KLM has been developing synthetic kerosine for aircraft using hydrogen as a raw material (F2-F3) (van de Weijer, 2021). Another development is different large industrial and energy incumbents who announce their plans to invest in large amounts of green hydrogen production capacities (TKI Gas, 2018). VoltH2 aims to invest 25MW in Zeeland (Duijnmayer, 2021b). Shell aims to invest in a 200MW electrolyzer in Rotterdam (TKI Nieuw Gas, 2021). While BP and HyCC announced their intention to operationalize a 200MW electrolyzer in Rotterdam (TKI Nieuw Gas, 2021). Thus, a great variety of organizations are active in the hydrogen system in different sectors.

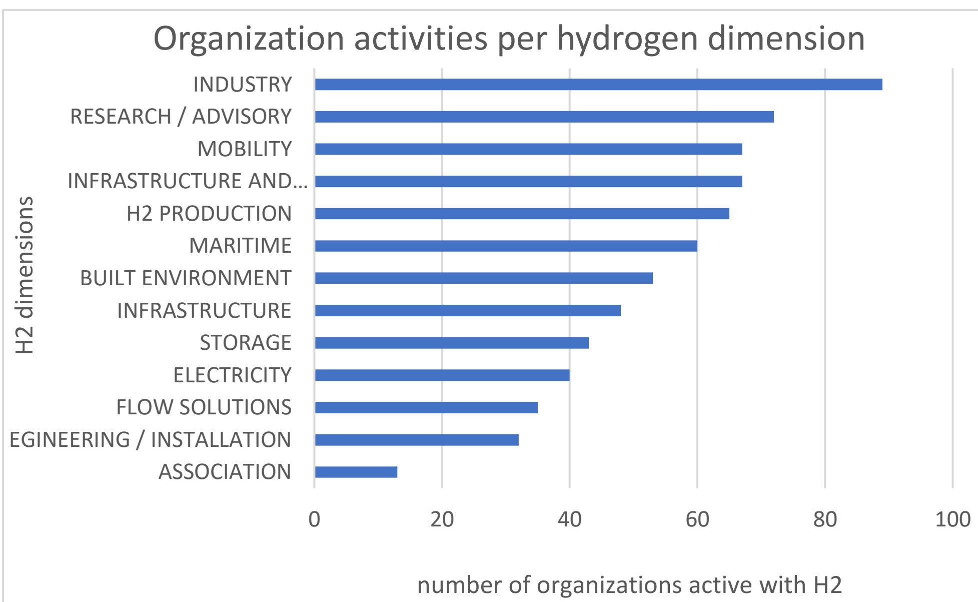


Figure 8: Number of organizations in NL active in various H2 dimensions adapted from (RVO & TKI, 2021)

The variety of different organizations and sectors is illustrated in a publication of the "The Dutch Enterprise Agency" (RvO) in collaboration with the TKI (research organization/intermediary). These organizations published a report on the hydrogen activities of Dutch public and private organizations (RVO

& TKI, 2021). This report indicated a total of 97 organizations that are engaged in hydrogen activities in various sectors. Figure 8 is a representation of these organizations and the different hydrogen dimensions in which they are active (RVO & TKI, 2021). The publication illustrates that a wider variety of different organizations, in a variety of sectors are experimenting, testing, and developing hydrogen solutions in the Netherlands.

To continue the actor activities. Eight out of these thirteen interviewees collaborated in experiments or pilots with other system actors (F3) (IO1, IO3, IO4, IO5, IO6, EI1, EI2, EI3). This again illustrates the large networks present in the system. For example, the interviewee (EI2) indicated that within the energy infrastructure sector the organizations collaborate via their branch organizations to synchronize the development of technology, safety standards, and tests (F2-F3). These actors even established a common test project in the green village in delft to operationalize a small-scale test environment (F1-F2), under the Hydelta1 Programme (HyDelta, 2022). This project is developed under a consortium that included partners such as the university (Delft) and public research institutions (e.g., TNO)(EI2, EI3). Additionally, start-ups and other organizations are also invited to test their respective innovations in this test facility (EI2). The energy operators (EI2, EI3), indicate that operating in a public (energy infrastructure) market enhances collaboration among the parties.

Different events exemplify that public research organizations and universities are involved in a variety of research, development, and pilot programs (F2-F3). These organizations contribute to knowledge development and steer scientific research (Hekkert et al., 2007). For example, Eindhoven University has a research lab (EIRES) to develop and test (new) hydrogen technologies (van Meer, 2020). While in Emmen, the local educational organization for technicians started a collaboration with surrounding industry actors under (EmmTranCie) program (F3) not only to develop technologies (F2), but also to provide test facilities (F2), and stimulate the training of the right people (F6) (Provincie Drenthe, 2019).

Private organizations also collaborate to develop hydrogen solutions in a variety of ways. For example, the interviewee (IO1), indicates that their organization is developing solutions with a local partner:

"one of the hydrogen routes that we develop is locally produced hydrogen out of waste gasification. We developed this project in collaboration with a local waste processor. The waste is processed into pellets, the pellets end up in a coal gasifier, this process results in steam, synthetic gas, and hydrogen. The latter we can directly cycle (in dutch: "fietsen") in our production process. This solution is great because we can

use the expertise of the partner to produce hydrogen and reduce carbon emissions while providing a business case for them" - (IO1)

The incentives for industrial organizations like these are to drastically reduce their GHG emissions since European and National laws in time (F4) will force them to operate carbon neutral (IO1, IO5). In this example, the industrial organization is actively searching for solutions to reduce carbon emissions in its current operations.

For other organizations, future operations require a change in the business model (F1), as a result of regulation changes or climate ambitions. Interviewee (IO5) explained that due to future targets in the Dutch Climate Agreement, and the European Green Deal, they are not able to operate in the future because their organization primarily operates fossil-based assets in the energy sector (IO5). Consequently, this organization is actively searching for new business opportunities like hydrogen production, and renewable energy (IO5). However, in technological transitions incumbents will encounter difficulty in changing their business models (Engwall et al., 2021).

In emerging systems like the upcoming hydrogen system, there are also private organizations purposefully founded to develop a business model for the upcoming markets (F1) (Engwall et al., 2021). For example, the interviewee (IO3), is part of a start-up developing innovative hydrogen fuel tanks. While, Interviewee (IO2) indicates that their organization is founded as a subsidiary of two large established chemical companies, and they specifically develop scalable hydrogen projects in collaboration with industrial organizations. An example of the latter is HyCC an industrial organization developing scalable renewable hydrogen projects (Bruijns, 2020).

Furthermore, a growing number of companies commit to the development of hydrogen technologies by participating in feasibility studies or including hydrogen in their decarbonization or sustainability strategies (F2-F4). These initiatives are identified through a variety of different events (appendix A). From 2019 onwards, a growing number of large incumbents in chemical and energy industries (E.g., Eneco, RWE, Equinor, GasUnie, Shell, HyCC, DeNora, Yara, OCI) are publicly stating their intention to invest in (green) hydrogen technologies or start collaborating through a variety of hydrogen coalitions and consortiums (F3) (e.g., NorthH2, Ship2Drive, Djewels, Sea2land, H2Hermes, HyNetherlands, H-vision) (TKI Nieuw Gas, 2021). Examples of actors committing to hydrogen are GasUnie (van Kooten, 2020), TataSteel (Stooker, 2021), and Yara (Duijnmayer, 2021b).

Interviewee (IO2) indicates that the development of these consortiums or collaborations is important:

"Hydrogen is new. Everything needs to be developed in this system. And organizations only invest when they have a closed business case. Therefore, you need a buyer when you are aiming to invest in green hydrogen production. At this stage, the government is also still a factor because we need them for the current price deficit. Otherwise, we do not invest. When the business case is losing money" (IO2)

Collaboration through these consortiums is important to develop a solid business case by ensuring that demand and supply are connected (IO2). Currently, there is no large market for hydrogen (-F5) and thus synchronized development is needed throughout various stages of the hydrogen value chain (IO2, EI2). Collaborations will contribute to the development of the system as a stimulating activity for market development (F5), but also as knowledge diffusion (F3), and it stimulates the mobilization of infrastructure (F6) (de Bruyn et al., 2020).

To explain this, take the example of NorthH2. This consortium aims to produce green hydrogen with renewable electricity from Wind Farms on the North Sea. The collaborating partners are Groningen Seaports (Port operator), Shell, RWE, Equinor (Energy Companies), and GasUnie (gas infrastructure and storage) (Provincie Groningen, 2020). These organizations have the support of the regional government (province of Groningen) to develop this project which aims to integrate different steps in the hydrogen value chain: production, transportation, and storage (Provincie Groningen, 2020). Additionally, other system actors like the chemical industry organization OCI partnered up with this consortium as a future customer (NortH2, 2022). This means that these consortia also foster market formation (F5). Synchronized development in the value chain is important to break-through the current status quo, which is explained by five out of 13 interviewees as the chicken-and-egg story. As the following quote illustrates the status quo has to be solved (IO2):

"*We moeten het kip en ei verhaal een keer doorbreken om het systeem te helpen" - (IO2).*

Interviewees explain this metaphor as follows, organizations are waiting for other parts of the hydrogen value chain to develop before investing largely in hydrogen themselves (IO1, IO2, IO3). For example, a central question remains without the upscale activities of hydrogen electrolysis (Hydrogen supply). Then, other parts of the hydrogen value chains in various sectors will not develop upscale activities, because no green hydrogen will be available (IO1, IO5). This metaphor implies that without the right incentives through guidance, resource mobilization, or market formation, the system will not develop and remain in a lock-in (Suurs et al., 2009).

This chicken-and-egg story is a commonly used metaphor in the hydrogen system and provides a clear explanation of one of the reasons why market formation activities are under-represented in the data (Appendix D). Activities aimed at stimulating market formation are primarily undertaken by small organizations. For example, a regional operator of a renewable gas station, Green Planet, aimed to start up a project, leasing hydrogen-powered vehicles, and trucks in 2021 (Polman, 2021). The core business of this actor is to supply green sources of power including hydrogen to the mobility sector (Green Planet, 2022). However, the current market size for hydrogen-powered vehicles is so small, that such organizations must set up projects involving various actors in the value chain to create a market (F1, F5) (IO6). Therefore, by investing in a lease project for hydrogen-powered vehicles this actor stimulates the development of the regional mobility market but also ensures demand for its services. Interviewees (IO3 and IO6) are both part of small organizations dealing with similar problems and indicate that they experience or foresee difficulty to upscale their activities as there is no/ or a small market (IO3, IO6). As (IO6) indicates:

"Being a small regional organization in mobility, it can be difficult in establishing a foothold in the market because it is difficult to connect to other organizations in the value chain. For example, when we find a potential partner which wants to use hydrogen-powered vehicles and use our infrastructure, then it sometimes is difficult to find a manufacturer willing to participate in such projects and convert vehicles to hydrogen drivelines. These organizations favor large-scale projects where they can spread development cost, over more than a couple of units" - (IO6)

This quote illustrates that small-scale organizations can have trouble in upscaling their activities, since other parts of the hydrogen value chain are not yet developed, or large system actors lack the incentive to invest in that development (IO6). These findings refer to a barrier related to *the formation of markets* (F5) or the *allocation of resources* (F6) since there is no financial incentive to invest in hydrogen projects. Especially small organizations can encounter difficulties in establishing themselves among incumbent markets in these innovation system dynamics (Hill & Rothaermel, 2003). There are favorable tax regimes (F5), and some European and national subsidy funds available for these projects (F6). However, these are available in limited quantities and do not cover the complete business case (IO3).

Not only the absence of a market is a problem for system actors. Other negative market formation activities are also forming a problem. Multiple events in the database indicate that system actors lobby for clear standards for hydrogen and market guidance activities (F7). For example, ACM lobbies with the government for better guidance in the formation of hydrogen markets before the government should invest in infrastructure (e.g., backbone), to ensure that when infrastructure is present it is also used (Duijnmayer, 2021a). These events also originate from government officials including the state secretary for Climate Change, who stated in (2021), that some sectors should be “forced” to use hydrogen (van Santen & van der Walle, 2021). This requires the involvement of the government in market formation through policy, which incentivizes (forces) other system actors to invest in hydrogen.

Currently, for some markets like mobility, or in some other sectors, there are no, or a lack of certain standards or regulations (F5). These lobby activities indicated that regulations are missing to support market development. Aforesaid problems can be illustrated by two quotes from interviewees (IO5, IO3). Firstly, the interview (IO5), addressed an EU regulation that did not foster the development of green hydrogen upscale and prevented market formation. The quote takes the example of the strict green hydrogen certification as it was too strict in regards to green hydrogen certification requirements in the European Renewable Energy Directive Two (RED2). As the interviewee (IO5) states

’’In RED2, the classification of green hydrogen was relatively strict, to get your hydrogen certified as green you had to demonstrate almost on an hourly basis that your electrolyzer was using electricity from renewable sources” (IO5)

In practice, these strict regulations meant that to get your green hydrogen certified, your project had to have almost a direct connection between the electrolysis location and the wind or solar site (IO5). In practice, this is almost impossible, the regulations focused on a small scope and strict traceability of the origin of the energy used to produce the green hydrogen (European Parliament, 2018). In the current market setting, this would in practice result in a large bottleneck for potential green hydrogen producers (-F4) (IO5).

Interviewee (IO3) indicated that for them a barrier was no regulation, as a result of using hydrogen in a new setting. For example, their organization is developing tanks for hydrogen storage under high pressure, around 700 bar (IO3). They encountered a problem regarding safety regulations. Recently, this actor was planning, to do a pilot project in collaboration with a potential client. In this pilot, they retrofitted an excavator to be powered on hydrogen using their tanks as storage tanks. When applying for the permits to do this test, the regional government concluded that no regulations were dictating how to deal with tanks under these pressures in normal neighborhoods. This delayed this test project since the regional government had to check what regulations could apply (IO1). This illustrates that such permitting processes or regulatory changes could be conservative, or slow processes.

Another example of slow and bureaucratic processes is illustrated by a permitting process experienced by an entrepreneur in the Dutch innovation system. In 2019, Hygro a start-up that developed a new design for an integrated windmill and electrolyzer (F1), published that they started the procedure and permit application to operate a pilot project for their design (de Ronde, 2017). However, going forward to 2021, this pilot is not yet operational partly due to slow permitting processes (-F5) (Vuijk, 2022).

Another example was provided by the interviewee (IO5):

"in terms of standards, there is another point of discussion. For example, the government has stated that they will stimulate the development of a national hydrogen backbone, well GasUnie does this. But still a public organization. And I do not know why this standard is this way. But electrolysis makes pure hydrogen, but now they have a standard for hydrogen in this national backbone of 98%. This is not that pure. This means that clean hydrogen from electrolysis ((99.9%) is put in the backbone. However, the purity of 98% can for example not be used in mobility. They need clean hydrogen. So you put clean hydrogen in a system, which makes it less pure. This system allows the transportation of this hydrogen to various locations, thus where it is needed. But when you want to use it at these locations for mobility then you have to add an additional step to again purify the hydrogen before it can be used" - (IO5)

According to the interviewee (IO5), this purity for the national hydrogen backbone was standardized in their perspective without market consultation (IO5). This actor implied that the lobby for blue hydrogen (hydrogen production from natural gas with carbon capture storage) was won by large incumbents (e.g., shell or BP) (IO5). That could imply that the coordination activities from the government are not completely transparent.

The insights from the interviews and the event-history data indicate that with increased activities system actors are experiencing barriers to market formation and see a lack of activities stimulating market development (F5). For some sectors standards still need to be developed or are not supporting system development. For other applications scale-up is problematic. Additionally, in some sectors, the creation of demand needs to be simulated by better guidance or market stimulation policies for hydrogen markets (EI1). These findings correspond to findings by Suurs et al. (2009), and Negro et al. (2012) and hamper system development.

Simultaneously, the data and analysis have indicated that system actors are actively lobbying (F7) for these guidance activities (F4), which in time should support resource mobilization and market formation activities.

Like market formation, resource mobilization is currently under-represented in the data (appendix D). Although these activities are rising in this period the lobby events indicate that more is needed for system development. Interviewee (RO1) indicates that the mobilization for pilot projects or research and development is often not a problem (RO1). However, support is needed because such activities often involve high investment costs (RO1, IO1).

The data indicates that these funds originate from various sources: European funds, subsidies from the government, or private channels such as companies or investment funds. For example, in 2019, the Hydrogen Valley Coalition was allocated 90 euros million from a European innovation fund to develop their regional hydrogen system (de Veer, 2020). Regional governments are often participating in funding regional projects. In 2020, the province of Drenthe, allocated 1.6 million euros for feasibility studies to understand the potential of developing the hydrogen system in the region (Duijnmayer, 2020). The national government has allocated various subsidy schemes for research and development programs. To exemplify, a consortium, Ship2drive, which is a collaboration between small, large, and public organizations received a subsidy from the Dutch government of 24,3 million euros to explore the feasibility of hydrogen for shipping (Nieuwsblad Transport, 2021). In 2021, the government allocated an initial amount of 73 million euros, potentially growing to 232 million euros for R&D and demonstration projects for the use of hydrogen in chemical and energy-intensive industries (Westerveld, 2021a). This subsidy is allocated by TKI (intermediary), which also acts as a program manager. In 2021, the government was developing a specific policy instrument to support electrolyzer scale-up from 2022 onwards. This instrument has a total budget of 252 million euros (van Santen & van der Walle, 2021).

In 2021, on a European level, an important development is the third round of the IPCEI program, which is an Important Project of Common European Interest (European Commission, 2021c). The IPCEI focuses on innovation projects aiming to tackle market failures and address societal challenges. Hydrogen projects will be part of the entitled technologies for the IPCEI states. Nominated projects, which are allocated the IPCEI status will be entitled to large amounts of national subsidy allocations, without being restricted by fair competition regulations (IO2) (European Commission, 2021c). The next steps will involve the government selecting projects for IPCEI and nominating them at the European level, which happened in 2021 when the Dutch government filed a list with different projects for de IPCEI status (Dutch Government, 2021b).

However, as explained before, the lobby data indicates, that system actors still do not regard this as enough activities for resource mobilization (-F7). However, developments in guidance activities including the launch of the national hydrogen program, and system consultation for policy design are indicators that progression can be expected in other functions going forward.

These problems with resource mobilization are also represented in the fact that there is a lack of mobilization of infrastructure in the Dutch hydrogen system (-F6). The data does not indicate large upscaling activities or investments in operational projects related to infrastructure in terms of hydrogen production, transportation, storage, or use. However, the importance of this is stressed by multiple interviewees (IO1, IO2, EI2, EI3, NG2, RO1), and can be illustrated by the following quote (IO2):

“Theoretically there is a lot of effort being invested in hydrogen. But yes without actually building the infrastructure and upscaling its capacity we do not learn more about these technologies. Just if you think practically. There is currently almost nothing operational. Thus we have to invest in building it to learn more about what does work and what is not working” - (IO2)

Interview (IO2) does not only stress the importance of upscaling infrastructure for hydrogen development. However, the quote indicates that upscaling infrastructure is required for further knowledge development (F2). The activities related to the upscale of infrastructure are limited to feasibility studies and investment decisions. Namely, in 2021, the government and its partners (e.g., Gas Unie, and consultancy firm PWC) published the results of the feasibility studying the potential of a national hydrogen backbone (van Kooten, 2020). Later, the government published its commitment to invest 750 million euros over the coming decade in the development of the hydrogen backbone to stimulate the development of the hydrogen infrastructure in the Netherlands (Postuma, 2021).

In terms of mobilizations for human resources, the data does not indicate any events. However, six out of thirteen interviewees indicate an increase in human resource capacity in the hydrogen system (RO1, EI1, EI2, NG1, IO2, RO2). For example, an Interviewee (RO1), which is a researcher in a public research institute, indicated, that within their organizations the amount of people involved in hydrogen has risen significantly starting with 6 people, and growing to over 50 nowadays (RO1). Interviewees (EI1, EI2, and NG1) indicate similar events within their respective organizations where over the years an increased number of human resources are being dedicated to the development of the hydrogen system. As the interviewee (RO2) indicates:

”only within the government a minimum of 25 people are dedicated to hydrogen. And these people are pretty experts in this field. You know, a couple of years ago, we had to explain government people things.

For example, in one of our first feasibility studies, the result of this study, we had to explain to the highest boss within the ministry. Now, everybody understands" - (RO2)

Regardless of this increase in human capacity and increase of human knowledge. Multiple interviewees indicate that human resources also form a capacity restriction like it is in all other sectors (RO1, RO2, EI1, and EI2). As EI3 suggests:

"like other sectors, there is a shortage in staff also for our company, it is difficult to get people in the current market" (EI3)

These quotes illustrate that upscaling activities for hydrogen can induce problems with human resource mobilization.

6.4 Period 3: from 2022 onwards

Going into period 3, the system functions remain very dynamic. The acceleration of system activities continues into 2022. Like the start of period 2, shocks by external events keep influencing the hydrogen innovation system. Interviewees (IO2, IO5) designate this to be a continued effect of the rising fossil fuel prices in October 2021. Moreover, in the first quarter of 2022, new external shocks lead to the Re-Power-EU agreement on a European level in March 2022. While on a national level the new government coalition reached an agreement on a large climate fund of 35 billion euros until 2030 (F6). These are both direct effects of the Russian invasion of Ukraine (Kuzemko et al., 2022). Appendix D indicates the activities per system function for 2022. Although the data for 2022 is only partial (7/12 months until July 2022), there is in most functions an increase in events.

As illustrated in period 2, a variety of system actors are engaged in entrepreneurial or knowledge development activities (F1, F2). An interviewee within the National Hydrogen Program in the Netherlands (NG1), confirms the positive stance on hydrogen activities stating that:

"*I think that it is going pretty well with the development of hydrogen. For example, GasUnie is busy developing the hydrogen backbone. But also, in other sectors, a lot of activity and progression can be seen in testing and research. But also supporting tasks such as safety standards and regulations activities are developing. And together with these stakeholders, we are now looking into how we can best achieve the hydrogen ambitions". – (NG1)*

Many organizations continue to introduce new designs, are engaged in pilot projects, or are developing innovative hydrogen projects. For example, Alliander in collaboration with other partners started to operationalize a pilot project for hydrogen boilers in consumer homes, with a total of 10 houses included in the test (F1-F2) (de Ronde, 2022). While TNO (research organization) published results of a new cheaper electrolyzer design in collaboration with foreign partners (F1) (Besteman, 2022). A Variety of other small pilot projects also become operational. An increase is noted in the data concerning operational and intentional projects. The events indicate positive discourses about the development of hydrogen projects and technologies. This is reflected by findings from the interviews in 2022. Eight out of the thirteen interviewees indicated that they believe that the current level of knowledge about hydrogen technologies will allow them to apply it in their operation (IO1, IO2, IO4, IO5, IO6, EI1, EI2, EI3, RO1). interviewee (RO1) adds:

'Of course, we still have to learn about hydrogen technologies, but without starting to build things you will not learn what you will encounter in operational environments' (RO1)

A notable trend is an increase in publications portraying large incumbents which aim to invest in green hydrogen production (TKI Nieuw Gas, 2021). An active lobby is presently aiming to create legitimacy to mobilize the resources (F6) to support these green hydrogen plans. A clear example is a "Call to action" by a coalition of multiple large incumbents indicating the need to fast-track the hydrogen plans, and IPCEI allocation (van der Lugt, 2022a).

Moreover, the government is also publicly involved in this debate by stating to double their 2025 and 2030 ambitions for green hydrogen production (F4-F7) (van der Walle, 2022). Additionally, a publication indicates that a specific policy instrument is being developed for hydrogen upscale (F4-F6) (Akkermans, 2022). The government is involved in many more guidance activities in 2022. A first example is the agreement of the Dutch climate fund (Metronieuws, 2022), which is partially an effect of the Russian invasion, and the European Re-Power-EU agreement (F4) (Kuzemko et al., 2022). The Dutch government experienced the negative effects of being energy dependent and is now more committed to fast track the energy transition (NG1). Additionally, the government has committed to its involvement in the synchronized development of hydrogen production, storage, and infrastructure capacity as it recognized that this is needed for the system to develop (Dutch Government, 2022). Different feasibility studies or gap analyses have been conducted. For example, HyWay27 a feasibility study for the development of a national hydrogen backbone has been conducted, and the results have been published (F2-F4) (PWC, 2021). In other dimensions, such feasibility studies (gap analysis) have also been conducted leading to the recognition of the government mentioned (Nationaal Waterstof Programma, 2021). Following lobby activities from public and private actors (F7), the next aim is to develop a roadmap in collaboration with stakeholders from the National Hydrogen Program to create more long-term guidance for the hydrogen system (F4) (NG1). This development in guidance activities indicates an increase in support from the national government for hydrogen (F4). Eventually, these should be leading to concrete policy instruments which stimulate resource mobilization (F6), and guide market formation activities (F5).

Currently, these latter two functions are still under-presented and different events indicate the negative discourse around them (see appendix D). Multiple lobby (F7) events regard the current allocation of financial resources as not sufficient to develop the hydrogen system. For example, Bloomberg, a research firm, indicated that to realize the current ambitions more than 200 times more investments are needed to reach the 2030 climate targets (Besteman, 2022). Another example is the lobby by nine large coalitions that currently developing hydrogen projects who stating that these are in danger of stopping due to slow guidance of the government and the absence of supporting policy instruments (van der Lugt, 2022b).

Current policy instruments do not support hydrogen projects causing system actors to hold, or back out on (large) projects. For example, in 2022, Eneco backed out as the supplier of hydrogen for a test project for the built environment in GoereeOverflakkee. This actor could not agree on a price with the regional government on the price for hydrogen. However, the regional government could not provide more subsidies for it (Bezemer, 2022).

To illustrate the ambition of system actors in the hydrogen system a cumulative representation (table 6) of all the hydrogen production projects in the Netherlands. A total of approximately 5000 MegaWatt (MW) is intended to be built (TKI Nieuw Gas, 2021). Moreover, system actors aim to invest in upscale up to a total capacity of approximately 12800 MW. However, only 3MW is currently operational. Only Shell has made the investment decision (IO5) to operationalize their project in Rotterdam (200MW) (Schipper, 2022).

Table 6: Cumulative overview of all announced hydrogen production projects in NL, adapted from TKI Nieuw Gas (2021)

Project	Phase of development	Start project	Capacity (MW)	Upscale to (MW)	Upscale up to max (MW)
Djewels-2	FID	2020	40		
SCW + GasUnie	Demonstration	2020	18.6	100	
Vattenfall, Eemshaven-West	Feed	2020	10	100	
ELYgator	FEED	2020	200		
Shell, rotterdam	FEED	2020	200	1000	2000
BP + HYCC, Rottrdam	FEED	2020	225	1000	2000
Multiply	Operational	2020	2.6		
BrighH2	FEED	2020	50		
Haddock, Yara	Concept	2020	100		
SeaH2Land	feasibility study	2020	1000		
CurtHyl	FEED	2020	200		
Hy4Am	FEED	2020	10		
H-Vision	Concept	2020	1500		
GreenH2UB	FEED	2020	5		
GZI NEXY	FEED	2020	10		
NorthH2	feasibility study	2020	1000		
HyNetherlands	FEED	2020	100	1000	
Terneuzen, VoltH2	FEED	2021	25	80	
H2_erp	Pre-Feed	2021	150		
Uniper, Maasvlakte	FEED	2021	100	500	
RWE, EemsHydrogen	FEED	2021	50		
Hydrogen Wind Turbine, Energcon	Execution	2021	2.5		
H2Hermes	FEED	2021	100		
Total			**5098.7 MW**	**8878.7 MW**	**12878.7 MW**

These actors need financial support to invest in these projects. Without support, the business case is not feasible as renewable electricity is not yet available in sufficient quantities to make it cost-effective, and electrolysis is without scale-up still expensive (IO1, IO5, EI1). Additionally, these projects are closely connected to the upscale in renewable energy sources, indicating the importance of synchronized development between the hydrogen and other dimensions in the hydrogen system (IO1, IO5).

In terms of market formation activities (F5), the system is in a similar state as in period two. There are no sufficient supporting policy frameworks for the hydrogen markets yet. System actors are still actively lobbying for supporting policy frameworks and developments are to be expected regarding the positive developments in guidance of the search activities (see F7 events). As a result, the findings from Suurs et al. (2009) continue to apply to period 3, as the system fails to break through the lock-in by providing better guidance and resource mobilization (Suurs et al., 2009).

There are developments on the European level with the allocation of the IPCEI status to several Dutch projects allowing billions in investments to be committed to these projects for the European common interest (European Commission, 2021c). In September 2022, an amendment to RED2 (2018) was published by the European Commission (European Parliament, 2018). According to the interviewee (IO5), this updated version of RED3 will provide improved clarity and less restrictive regulations. These new regulations will make projects more feasible (IO5). Before this, three out of thirteen interviewees mentioned that European regulations have restricted the national development of the hydrogen system (IO2, IO5, EI2). This illustrates that the guidance activities in the system are improving.

Going forward six out of the thirteen interviewees stress the importance of more strict coordination by the government and clear institutional frameworks (IO1, IO2, IO3, IO6, EI2, EI3). This is deemed important because there are a lot of different sectors and system actors in the hydrogen innovation system, which also makes guiding its development difficult (NG2). An important aspect of this is to develop a long-term vision of regulations and policy instruments. This is illustrated by the following quote (EI2):

'Why are we not looking longer on the horizon? In European, for example, the renewable energy directive has a perspective until 2030. Also on a national level, we do not look much further, if look at 2030 at all. But many projects won't begin until later this decade. This means that you are building something beyond the regulations that you know of. Maybe there will be new or other regulations by that time. Will that help the system?" - (EI2)

However, such consistency is difficult to establish as the Dutch government has a newly elected government every four years (EI1). System actors stress the importance of these consistent policy instruments and targets to be developed to stimulate further develop the system (EI1, EI2).

6.5 Barriers and systemic problems in the hydrogen innovation system

After two decades of effort to develop the hydrogen innovation system, it seems to be in a state of acceleration over recent years. However, as explained in the functional analysis different factors are still hampering the development of the system. The most prominent barriers are related to system function *F4 – Guidance of the search*, *F5- market formation*, and *F6-resource mobilization*. These barriers have been experienced by the majority of system actors and may have been contributing to the hampering development of the hydrogen innovation system. This section further explains these barriers and couples them with systemic problems (blocking mechanisms) that have hampered the development of the system based on systemic problems developed by Wieczorek and Hekkert (2012).

First of all, a large barrier in the Dutch hydrogen innovation system is the absence or lack of quality in the *guidance of the search* activities by public actors. The system misses clear targets and policy interventions providing the right direction for the system to develop. Moreover, in its current form, this function does not sufficiently support the other system functions. There are three clear barriers in this domain:

- *Absence of actual supporting policy frameworks and long-term hydrogen policy goals/targets*
- *No clear/Clashing European frameworks or regulations*
- *Unclear which direction the system is developing in (which sectors or hydrogen applications have priority)*

All three of these barriers have been linked to an institutional-presence failure (systemic problem), see table 7. As the functional analysis has elaborated this implies that the current system structures miss adequate hard institutions (e.g., policies or targets) to stimulate the development of the system. The absence of these building blocks leads to systemic problems and other functions not working properly. Without these framework conditions in the innovation system, it will not (lock-in) or only slowly develop (Negro & Hekkert, 2008; Suurs et al., 2009). The lack of vision, long-term perspective, or clarity of *guidance (F4)* activities has been identified to be a major impact on the system. For example, without the right targets or vision (strategy) for the development of the system, actors are not sufficiently guided or incentivized to develop hydrogen solutions. While unsupportive subsidy programs or a lack of such policy instruments negatively impact the mobilization of financial resources needed to accelerate the system into the next step of upscaling hydrogen activities and infrastructure. Subsequently, through a negative feedback loop (function interaction) these barriers in guidance will impact other functions including the *market formation (F5)* activities or the *allocation of resources* (F6). These feedback mechanisms in the Dutch hydrogen system demonstrate how functions negatively or positively interact (Suurs, 2009).

In addition, the failure to stimulate the market formation and resource mobilization indicates a misalignment between the needs of the system to develop (e.g., financial support, standards, specific targets for use of hydrogen in sectors) and what is provided through guidance. These misalignments in supportive institutional frameworks and the need for system actors refer to an *actor-capacity failure,* and *network quality failure* (Wieczorek & Hekkert, 2012). Regardless of the extensive network presence in the system, this weakness in the network quality of the system refers to the inability of system actors to formulate and pack together a uniform message about the needed support in the system. As addressed in the analysis, small actors are experiencing difficulties in establishing themselves in the emerging hydrogen market. However, larger organizations are using the existing networks to lobby for more supportive framework conditions before investing in market formation (e.g., they have more incentives for a valid business case). Both situations indicate that these different types of actors lack the capacity (actor-capacity failure), or have difficulty in developing the hydrogen system. Moreover, the networks are unable to support this development which also indicates a network-quality failure (Wieczorek & Hekkert, 2012).

Secondly, *market formation (F5)* knows two recurring barriers. Namely, *Hydrogen is a supply-driven market,* and *no clear standards, targets, and regulations for markets.* The latter is *clear hard-institutions capacity and presence failure* (Wieczorek & Hekkert, 2012). As the analysis has demonstrated for some sectors of hydrogen applications there is a lack of standards or regulations which stimulate its market development or hampers projects from starting. Moreover, for actors, there is no long-term perspective about which markets are going to be stimulated. This creates uncertainty and makes system actors reluctant to invest in hydrogen technologies as they have no incentives. Moreover, current guidance activities and market formation activities focus on supply (hydrogen production) and neglect other parts of the value chain. This is also a clear institutional presence failure (Wieczorek & Hekkert, 2012).

The last domain, *resource mobilization (F6)* allowed identifying three more barriers related to *infrastructural and institutional presence failures.* These are present because of other barriers and system interactions. Namely, current institutional frameworks are unsupportive to mobilize the needed financial resources for hydrogen activity and infrastructure upscale. As a result, these are still not present in sufficient numbers in the system, which also hampers market development.

Table 7: Systemic barriers in the Dutch hydrogen innovation system

System Function	Barrier	Structural Element	Type of systemic problem	Description of the links between systemic problem
F1- Entrepreneurial activities and scale-up	Lack or no scale-up activities for hydrogen	Actors & institutions	Actor-capacity & institutional presence failure	System actors involved in hydrogen activities are having trouble upscaling their activities due to the absence of supporting institutional frameworks. (hard institutions)
F4- Guidance of the Search	Absence of actual supporting policy frameworks and long-term hydrogen policy goals/targets	Institutions	Institution-presence failure	Unclear where the hydrogen system is developing too. A vague direction is provided. For example, which sectors have priority when hydrogen becomes available. No specific vision or binding targets are on the horizon.
	No clear/Clashing European frameworks or long-term vision	Institutions, networks, actors	Weak network and institution-presence-capacity failure, actor capacity failure.	Current European institutions are not of sufficient quality to stimulate system development. Or are clashing with national or industry objectives.
	Unclear which direction the system is developing in (which sectors or hydrogen applications have priority)	Actors, Networks, Institutions	Network-quality failure	Actors indicate that they feel that there is sometimes a discrepancy in what the system needs and what guidance is provided which refers

				to network-quality failure. In some cases, actors fail to use their connectivity to guide the system in the right direction.
F5-Market formation	Supply driven market	Institutions, actors	Actors-capacity and institutional-presence failure	Actors in the system primarily focus on the production of hydrogen. The development of demand for these markets is underrepresented. Additionally, guidelines on which sectors should be using hydrogen are missing.
	No clear standards, targets, and regulations for markets	Institutions	Hard institutions (capacity and presence) failure	Institutions are missing or lack quality for supporting the development of hydrogen markets (safety standards for use of hydrogen, no regulations for the application of hydrogen, slow permitting processes).
F6-resource mobilization	Lack of financial support from the government	Infrastructure, Institutions	Presence & Hard institutional failure	The supporting financial institutional frameworks for infrastructure upscale are not present in terms of all aspects of the hydrogen value chain
	Lack of existing infrastructure	Infrastructure	Presence failure	Almost no infrastructure is available
	No hydrogen production capacity	Infrastructure, institutional	Presence failures	No institutional mechanism is present to support the upscale of supply capacity

7. Discussion

This section will reflect on the results (Chapters 4, 5, and 6) of this study concerning the theoretical framework (chapter 3) and method used (chapter 4). This is divided into two parts. First, the theoretical implication of this study is discussed as to how it contributes to the development of innovation system theory, and how it leads to a better understanding of systemic problems and barriers. second, suggestions will be made for future research. Third, the limitations to this study are discussed.

7.1 Implications for theory and future research

The main aim of this paper was to identify how the hydrogen innovation system has developed over the years, mapping the networks, actors, and dynamics of the system. This was achieved by operationalizing the analytical steps of the TIS framework to the case of hydrogen development in the Netherlands. Similar to previous literature, this study has demonstrated that systemic problems are not independent. Malfunctioning parts of the system invoke systemic problems or barriers in other parts of the system (Negro et al., 2012; Wieczorek & Hekkert, 2012).

First, weak-network quality (interaction between actor groups) results in the misalignment between institutional framework conditions and the requirements of different actors to develop the hydrogen system. This study has shown that, regardless of the extensive networks present, system actors, or groups of actors have been unable to stimulate better guidance activities in the presented timeframe. This implies that these hydrogen networks/platforms/lobby groups have been unable to create legitimacy for hydrogen activities (F7). Therefore, these activities did not result in better guidance activities (F4), and allocation of resources (F6). The implication of the theory is that weak-network quality hampers the buildup of the hydrogen innovation system. More insight is needed into how the collaboration activities between system actors in terms of consultation or lobbying can stimulate the development of innovation systems. This should result in more understanding on how to improve alignment between policy levels, different sectors and existing and new institutions (Negro & Hekkert, 2008; Ulmanen et al., 2009).

Secondly, the present institutional networks have been unable to support system development. This is reflected in the hard-institutional failure present in the system. The absence, lack of clarity, or lack of long-term perspective in guidance activities resulted in non-supportive institutional frameworks including policy targets, goals, or policy instruments. In their current form, these institutions are not supporting the development of the hydrogen system. This barrier is inducing other systemic problems in the formation of hydrogen markets across different sectors, and mobilization of resources (e.g., subsidies, upscale of infrastructure) needed for system development. These feedback mechanisms have been demonstrated by various scholars (Suurs et al., 2009; Negro et al., 2012). In this regard, the contribution to theory the empirical justification of the approach of using the theory of systemic problems in technological innovation systems, demonstrating that negative feedback results in systemic problems and lock-in.

In addition, these barriers and feedbacks demonstrate the fact that policymakers should focus more on coordinating activities and consultation with system actors to reduce misalignment between guidance activities and increase their ability to develop supportive institutional frameworks. Thereby the final implication for theory is that the technological innovation system approach should be broadened and focus more on coordination within the system. In this respect, this study demonstrates the need for these coordinating activities and justifies recent developments in innovation system theory. Namely, these findings show the need for directionality for system transitions which aim to solve societal problems in this case climate change (Elzinga et al., 2021; Wesseling & Meijerhof, 2021). A lack of coordinating activities (lack of directionality) in the present case resulted in suboptimal decision-making, and a hampering innovation system (Hekkert et al., 2020).

Therefore, a final suggestion for further research includes that policymakers need to exploit the development of the Mission-oriented Innovation System (MIS) approach, which has a stronger focus on providing directionality in system transitions (Elzinga et al., 2021). A MIS enables better coordination and monitoring of the goals of a system transition. Moreover, through enhanced collaboration in a central mission arena it guides the mobilization and creation of innovation system resources. Thereby this will better target the goal of the transition (Wesseling & Meijerhof, 2021). Therefore, applying this framework to similar cases such as the Dutch hydrogen innovation system, allows for a better understanding of coordination and collaboration activities. Consequently, the system resources and institutions will be better targeted to the goals of the system transition.

7.2 Limitations

Even though the results did provide an adequate understanding of what is happening in the Dutch hydrogen innovation system, the completeness of the results is limited in several regards. First, this research consisted of a technological innovation system analysis covering the development of the Dutch hydrogen innovation system, which involves the creation of a value chain in different sectors. Because of the broad scope of the hydrogen value chain in terms of the development and implementation of hydrogen applications in different sectors, bundling the analysis could have skewed specific information or resulted in misinterpretation of barriers. However, it has also resulted in valuable insights into how the interdependent parts of the hydrogen value chain need to be better coordinated in the transition.

In addition, this study represents a single case study, covering different dimensions in the hydrogen value chain. This resulted in a limitation in sample size due to time constraints. For example, because this study aimed at studying system level perspective and performance of the hydrogen value chain more types of organizations in different sectors could have provided different insights into which barriers and systemic problems are experienced by hydrogen system actors. Furthermore, the interviews were only conducted with actors who agreed to be interviewed. Some types of system actors did not reply and are missing from the sample. Interviews with a larger group and different types of system actors could have provided additional insights which might have been missed. Unfortunately, overcoming this limitation is difficult and out of the scope of this study.

8. Conclusion

This paper aimed to analyze the barriers hampering the development of the Dutch hydrogen innovation system. This was done by operationalizing the Technological Innovation System framework and the theoretical concept of systemic problems. This provided insight into the dynamics (functional elements) and build-up (structural elements) of the Dutch hydrogen innovation system and enabled the identification of the systemic problems present in the system, hampering its development. Accordingly, this study aimed to answer de following research question:

What is hampering the development of the hydrogen technological innovation system in the Netherlands and how can the transformation of the energy system to integrate hydrogen be accelerated?

Regardless of positive developments such as increased hydrogen activities by private and public actors contribute to system development, external shocks which contributed to the hydrogen and sustainability debate, and increasing policy involvement of the Dutch government influencing the dynamics in the system. This study concluded that several barriers are still present in the hydrogen innovation system. Out of all the different barriers, the lack of quality, long-term perspective, and clarity in guidance activities remain the most prominent hampering factor. These relate to hard institutional, actor-capacity, and network-quality failures, and are contributing through a negative feedback loop to barriers in resource mobilization and market formation. Subsequently, this prevents actors from further investing in hydrogen knowledge development and entrepreneurial activities.

To put into context the importance of improved institutional frameworks, the hydrogen markets are still in their infancy, and primarily 'first-movers' operate in the small hydrogen markets present. Under the current institutional framework conditions, the system will remain in a lock-in as large incumbents are reluctant to invest in upscale activities if system conditions are not providing incentives to accelerate the transition in terms of financial subsidies, or specific targets for the use of hydrogen in markets. Thus, these missing institutional conditions as a result of weak guidance activities impact the ability of the system to support the upscale of hydrogen activities, invest in hydrogen infrastructure, and develop hydrogen markets.

In conclusion, to accelerate the development of the hydrogen system, the data indicated that the government is playing a pivotal role in the transitions. This system actor can accelerate the transition by improving guidance. This should be achieved by disrupting the current institutional patterns, which should include new specific policy interventions to foster resource mobilization and market formation. These developments will induce investment in market activities and upscale infrastructure to break through the current lock-in. For example, a starting point could be a policy intervention that sets clear and binding targets for the production of green hydrogen supported by a clear policy instrument. This policy instrument should focus on reducing the cost deficit of hydrogen and its alternatives, thereby supporting the business case of projects. This intervention should be combined with specific regulations and binding targets for the use of hydrogen in some specific sectors to stimulate market formation. However, this should be achieved in consultation with other system actors and should be targeted at sectors in which renewable hydrogen can save most carbon dioxide emissions. These improved coordination activities are essential if we want to achieve the hydrogen transition and create a hydrogen value chain.

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X

B. Broekstra
Msc student Sustainable business and innovation

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Appendix A: Event-history allocation indicators

Adapted from Wesseling & Meijerhof (2021) and Negro et al. (2012)

Function	Positive indicators (+1)	Negative indicators (-1)
SF1: Entrepreneurial experimentation, upscaling, and business model change	Project started, organization entering the market, New companies, new pilots, introduction of new designs	Project stopped, organization leaving the market
SF2: Knowledge development	Research projects, technical projects, development projects, studies on technology, research groups, patents, new products, scientific publications	
SF3: Knowledge diffusion	Workshops, conferences, reports, platforms, knowledge collaborations	Deficit in sharing or knowledge withholding or protecting
SF4: Guidance of the search	Regulations by the government, deficit in government regulations, feasibility studies, new goals or targets, expectations of solutions, agreements about technological direction, process monitoring, coordinating activities, coalitions for guidance	Deficit in government regulations
SF5: Market formation	Regulation programs, Stimulation programs, Environmental standards, Specific favorable tax regimes, technical standards, adoption activities, activities to create demand.	Lack of regulation programs, Lack of stimulation programs, Lack of environmental standards, Lack of favorable tax regimes
SF6: Resources allocation	Subsidies for upscale or research, mobilization for human resources, creation of infrastructure, creation of financial resources	Lack of subsidies for research or upscale, lack in human resources, no infrastructure, lack in financial resources
SF7: Creation of legitimacy	Promotion of technology by system actors, lobby activity in favor of technology, Positive discourse (opinion, publication) against technology	Lack of promotion by system actors, lobby activity against the technology, Negative discourse (opinion, publication) against technology

Appendix B: Interview Guide English

Adapted from Wesseling & Meijerhof (2021) and Hekkert et al. (2012).

MIS system function	Description	Diagnostic questions
SF1: Entrepreneurial experimentation, upscaling, and business model change	Experiments with solutions (or clusters of solutions) to enable learning; creation of markets for new solutions; and creation of business model innovations to stimulate the diffusion of solutions, building production capacity.	• Are these the most relevant actors? • Are there sufficient industrial actors in the innovation system? • Do the industrial actors innovate sufficiently? • Do the industrial actors focus sufficiently on large scale production? • Does the experimentation and production by entrepreneurs form a barrier for the Innovation System to move to the next phase?
SF2: Knowledge development	The creation and development of knowledge through "learning by searching" and "learning by doing". These activities result in new technical and socio-institutional knowledge to develop the technology under investigation.	• Is the amount of knowledge development sufficient for the development • of the innovation system? • Is the quality of knowledge development sufficient for the development • of the innovation system? • Does the type of knowledge developed fit with the knowledge needs within the innovation system? • Does the quality and/or quantity of knowledge development form a barrier for the TIS to move to the next?
SF3: Knowledge diffusion	Refers to activities that result in the exchange and diffusion of knowledge through networks. Knowledge-sharing activities include media, reports, workshops, stakeholder meetings, etc. In this context, the phasing out focuses on knowledge exchange processes that are obstructing the mission.	• Is there enough knowledge exchange between science and industry? • Is there enough knowledge exchange between users and industry? • Is there sufficient knowledge exchange across geographical borders? • Are there problematic parts of the innovation system in terms of knowledge exchange? • Is knowledge exchange forming a barrier for the IS to move to the next phase?
SF4: Guidance of the search	This function refers to the process of selecting or rejecting a specific direction of	• Is there a clear vision on how the industry and market should develop? • In terms of growth

	technological development. System actors formulate goals, targets, visions, or expectations, set priorities, and provide direction in research and development. These processes aim to provide a clear direction in the system. Moreover, this function refers to coordination among the system actor to accelerate their goal and align the system structures to foster the development of the technological direction. This can be achieved by the creation of a coalition, roadmaps, and agendas for the transition.	• In terms of technological design • What are the expectations regarding the technological field? • Are there clear policy goals regarding this technological field? • Are these goals regarded as reliable? • Are the visions and expectations of actors involved sufficiently aligned to • reduce uncertainties? • Does this (lack of) shared vision block the development of the TIS?
SF5: Market formation	Refers to the creation of markets and support for upscaling social and technical solutions	• Is the current and expected future market size sufficient? • Does market size form a barrier for the development of the innovation system?
SF6: Resources allocation	The mobilization and allocation of resources (physical, human, and financial) to support all the key activities/functions of the innovation system.	• Are there sufficient human resources? If not, does that form a barrier? • Are there sufficient financial resources? If not, does that form a barrier? • Are there expected physical resource constraints that may hamper technology diffusion? • Is the physical infrastructure developed well enough to support the diffusion of technology?
SF7: Creation of legitimacy	Create the legitimacy for change and counteract resistance to prioritization 1) of the problem and 2) development and diffusion of the solutions, to out phase harmful practices, habits, and technologies.	• What is the average length of a project? Is there a lot of resistance towards the new technology, the set up of projects/permit procedure? • If yes, does it form a barrier?

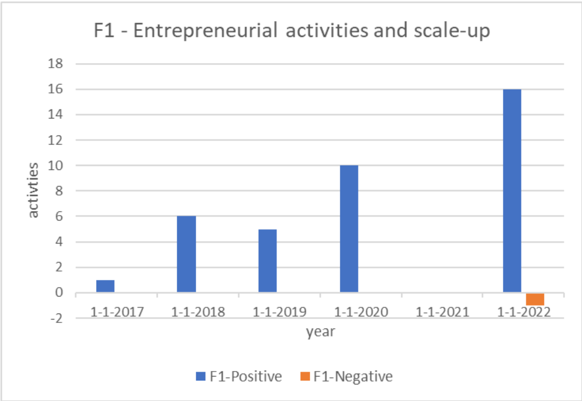
Appendix C: Nvivo Codes

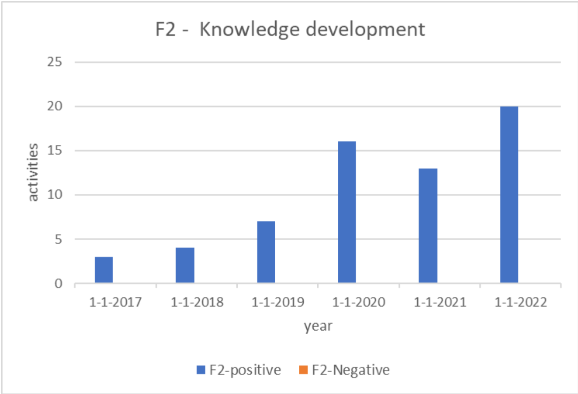
- Name
- Type of organization
- System functions
- consent
    - SF1 - Entrepreneurial experimentation, upscaling, and business model phase-out
        - Negative
            - no upscale activities
        - Positive
            - Business model transformation
            - H2 test project
            - Pilot collaboration
            - Hydrogen supply creation
            - upscale electrolyser
            - introduction new designs
            - Consortium for infrastructure upscale
    - SF2 - Knowledge development
        - Negative
            - technology needs development
                - electrolyser
            - more test facilities needed
            - no clear standards and safety
        - Positive
            - knowledge available for hydrogen upscale
            - basic knowledge development no competitive
            - open to collaborate on knowledge development
            - coalition studies
            - branches are developing knowledge
            - test centres for knowledge testing
            - research for to regulations
    - SF3 - (Withholding) Knowledge diffusion
        - Negative
            - no sharing with competition
        - Positive
            - h2 patforms
            - symposiums
            - branch collaborations
            - consortium collaborations
            - project collaborations cross sectors
    - SF4 - Guidance of the search
        - Negative
            - no clear targets
            - no clear goals

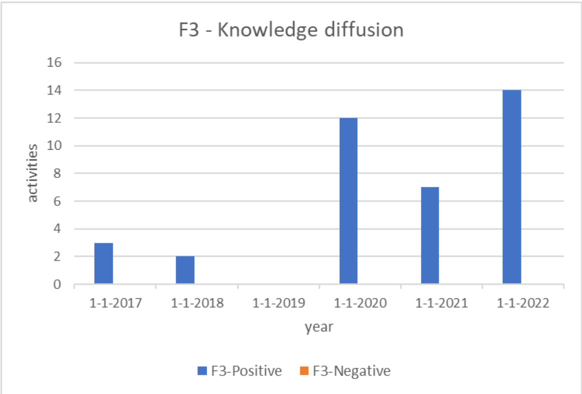
        - need stricter targets
        - goals for different sectors/dimensions needed
        - slow coordination
        - Regulations do not support goals
        - H2 not solutions for all sectors
        - No business case support
        - System wide change need better guidance
        - H2 value chain needs development
        - coordination of system difficult
            - many system actors
            - EU regulations restrict development
            - clashing nat + eu regulations
            - no alignment in regulations
            - regulations to strict
            - no long-term perspective taken
            - need clearer regulations
            - need more collaboration frammeworks
            - no clear routemaps
            - slow processes
    - Positive
        - Ambitious targets
        - Industry commitment to sustainability
        - EU targets for hydrogen
        - business case
            - feasibility increases
            - cost gap decreases
            - increase in renewables
            - system conditions are chaging
        - knowledge available for upscale
        - Good collaboration between sectors/government
        - intermediaries help actors
        - new eu regulations indevelopment
        - more coordination activities over recent period
        - facilitating +connecting of organizations through intermediaries
        - government more dedication to hydrogen development
            - allocation of climate change funds
            - National collaboration platform
            - System consultation present
- SF5 - Market formation and destabilization
    - Negative
        - business case development before marketization
        - No marker ordening/structures
        - need more commercial activity

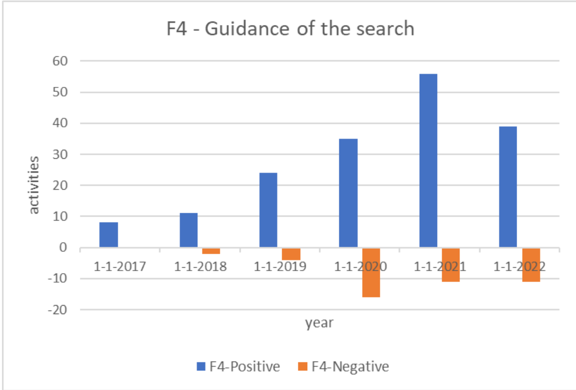
        - no standards/regulations for market development
        - no safety standards
        - no coordination for market formation
        - supply driven orientation
        - unsupportive regulation
        - primarily coorination needed for emerging markets
    - Positive
        - market potential research positive
        - standards are being developed
        - industry h2 application well developed
- SF6 - Resources (re)allocation
    - Negative
        - no risk cover
        - regulations for support unclear
        - no valid subsidies
        - human resource shortage
        - infrastructure + material shortages
        - no standards for infrastructure development
        - need to start upscaling/allocating resources
    - Positive
        - instruments for upscale being developed
        - allocation of subsidies ongoing
        - SDE+ positive subsidy design
        - Actors have increased h2 human resources
        - mobilization of test facilities/capacity
- SF7 - Creation and withdrawal of legitimacy
    - Negative
        - Large industry lobby for unfavorable blue hydrogen
        - lock-in in for negotiation gov-industry
        - industry lobby for more coordination
    - Positive
        - h2 platform lobby at government
        - industry coalitions lobby at government
        - organizations aim to create legitimization of h2 solutions to value chains
        - intermediaries create awareness of H2 potential among actors
        - creation of frameworks for investment decisions
        - Branches are lobbying
        - intermediaries help actors

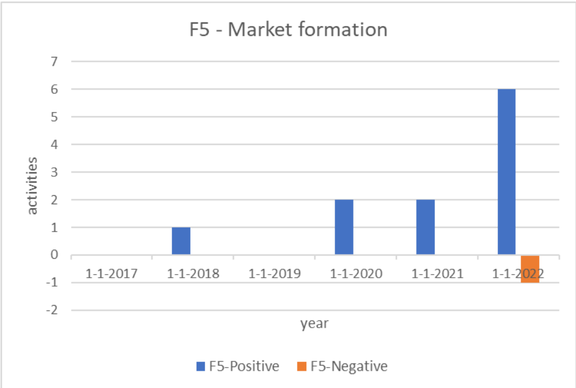
Appendix D: Display of individual system functions

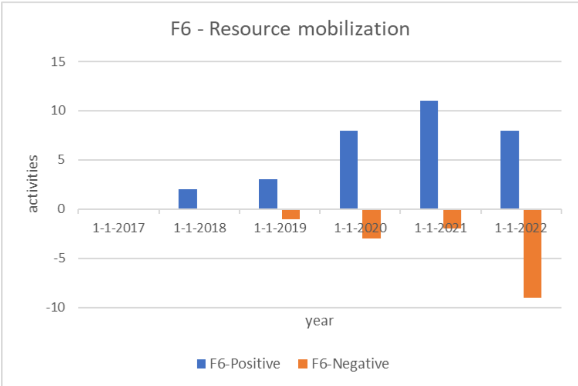


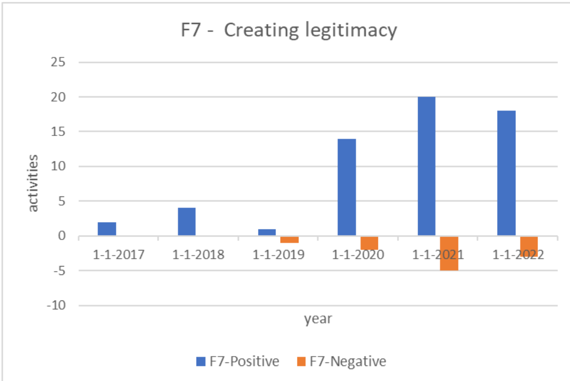












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Appendix E: Consent form interviews-english

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INFORMED CONSENT FORM for participation in

MSc thesis on understanding / analyzing the hydrogen mission innovation system in the Netherlands.

To be completed by the participant:

I confirm that :

- I am satisfied with the received information about the research;
- I have been given the opportunity to ask questions about the research and any question has been answered satisfactorily;
- I had the opportunity to think carefully about participating in the study;
- I will give an honest answer to the questions asked.

I agree that:

- The data to be collected will be obtained and stored for scientific purposes;
- The collected, completely anonymous, research data can be shared and reused by scientists to answer other research questions;
- Video/ and or audio recordings may also be used for scientific purposes.

I understand that:

- I have the right to withdraw my consent to use the data;
- I have the right to see the research report afterward.

Name of participant: ______________________________

Signature:____________________________ Date/Place: __/__/__, ____________________

To be completed by the investigator

I declare that I have explained the above mentioned to the participant what participation means and the reason for data collection. I guarantee the privacy of the data.

Name of Investigator: ______________________________

Signature:____________________________ Date/Place: __/__/__, ____________________