Electrochemical synthesis of hydrogen in the Dutch energy system

A structural-functional TIS analysis

Master thesis submitted to Delft University of Technology

in partial fulfilment of the requirements for the degree of

MASTER OF SCIENCE

in **Complex Systems Engineering and Management**

Faculty of Technology, Policy, and Management

by

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To be defended in public on 22nd of August 2022

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Foreword

Dear reader,

This thesis project marks the end of my fruitful and enjoyable time as a student. It serves as graduation project for my master Complex Systems Engineering and Management at the Delft University of Technology. It has been an interesting journey, which started at the University Utrecht and ended up in Delft. I am glad I have done my masters at Delft, and even though the restricting COVID-19 measures made it more difficult, I have met some fun people.

During the project, I have gained useful insights and help from multiple people, and I want to take a moment to thank them for it.

First of all, my first supervisor, Gijsbert Korevaar. I would like to thank you for the interesting discussions concerning the topic of my thesis, the required steering and scoping you gave, and the feedback throughout the project period. Your feedback was always properly constructed, useful and well received.

To my second supervisor, Geerten van de Kaa. I would like to thank you for your particularly straight to the point feedback during the official meetings, and the effort it took to complement my graduation committee as chairperson.

Third, a thank you to Nico Baars, my external supervisor from Strukton Power. During our weekly meetings, we held interesting discussions on the topic, which partly resulted in the thesis presented here. Also, from the start, you were very open to welcome me into the company, something I can only appreciate.

Fourth, a thank you to Usman Hassan, my buddy at Strukton Power. Not regularly discussing the content of my thesis, but often everything else, which was also most welcome. During our weekly lunch hikes, we have had some relaxing conversations which took my mind of my thesis and overall, led to some fun afternoons. Thank you again for your effort in providing me with useful feedback on my final version of my thesis and open attitude towards me.

Fifth, I would like to thank everybody else at Strukton Power, with a special shoutout to the R&D team. During multiple meetings, presentations, and informal conversations, you have helped me shape and formulate my thesis.

Sixth, thank you to all the interviewees who took the effort and time to answer my questions to the best of their knowledge and point me in the right direction. Without your input, the analysis of this thesis would lack the punch.

And last but not least, not just concerning my thesis project but my study period overall, I would like to thank my parents for giving me the opportunity to study in the first place. Without your support it would have been a very difficult scenario to graduate from either my bachelor's or master's program. Additionally, special thanks go out to my girlfriend, Lisa, who supported me when things got stressful, and I was at risk of becoming overwhelmed. You have kept my head sain.

Extended summary

Due to the growing share of renewable energy sources (RESs) to counter global warming and fossil fuel depletion, the energy sector is electrifying at an increasing pace. However, not all sectors can electrify fully or at an even speed. The industry sector for instance, is heavily reliant on fossil fuelled feedstocks. Power-to-X is named in literature to resolve that dependency. A practical example of the Power-to-X principle is the electrochemical synthesis of hydrogen. In consideration, the Dutch industry sector uses 100PJ of hydrogen annually, mostly synthesized via the steam reforming reaction (SMR). Due to the direct exertion of CO_2 accompanied by SMR, the increasing desire to limit dependency of fossil fuel exporting nations, and the need for electrification, the Dutch government has issued targets for the installed capacity of electrolysis technology. With the use of electricity, water is split into oxygen and hydrogen, creating no polluting emissions, and absolving the need for fossil fuels. The Dutch government aims to have 500MW of electrolyzers capacity installed by 2025, and 8GW by 2030. However, currently there is 1MW of capacity installed. This thesis aimed to find the rationale behind the discrepancy between the reality and the set targets. From a review on scientific literature led that techno-economic articles aiming to analyse which factors limit the increase in capacity, solely focus on the shortcomings of the technology and its effect on the adoption. In this thesis, the Technical Innovation System (TIS) is analysed in an effort to delineate what the impact of the innovation system is on the development of the technology. The Netherlands is taken as a geographical scope to be able to include national policies and campaigns.

The structure of the TIS consists of four components, the actors, technology, network, and institutions, respectively. These components form the boundaries of the system. The components of the TIS perform key processes for the development of the technology, consisting of seven system functions (SFs). These SFs entail the entrepreneurial activity (SF1), knowledge development (SF2), knowledge diffusion (SF3), guidance of the search (SF4), market formation (SF5), resource mobilization (SF6), and creation of legitimacy (SF7). The appreciation of the SFs leads to the barriers and drivers of the system. With the discovery of the barriers, the analysis allows to elaborate on the discrepancy between the reality and the targets. The outcome of the impact the system has on the technology is also used to develop a recommendation to Dutch policy makers to resolve certain barriers. Additionally, it is used to aid Strukton Power in their decision to enter the system, and in what manner. With the use of a structural-functional analysis as proposed by Hekkert et al. (2011), an inductive research approach is taken, and the following research question is answered:

How do the systemic functions impact the implementation and development of electrochemical synthesizes of hydrogen in the Netherlands and how can this performance be improved?

The data is gathered via 13 expert interviews, consulted via the network of the researcher, that of Strukton Power or as recommendation via previously interviewed experts. By transcribing each interview, the ability is created to label the statements to conduct the analysis. Analyses of the structural components have been iteratively verified during the interviews, and the different experts were explicitly asked for their view on the structural components. Gaps in the available knowledge of the experts or specific data are consulted via desk research. The public database on Dutch subsidized hydrogen electrolysis projects from 2014 onwards served as dataset for the network analysis. With the use of operational indicators partly derived from relevant TIS literature and partly additionally constructed during the data gathering in this thesis, the interviews have been used to appreciate the performance of the SFs on a Likert scale. This method resulted in a label score. The weight of argumentation is added by

implementing an analysis score. The label score served as backmarker, the analysis score as eventual score. Low performing SFs (1-2 on a Likert scale) lead to a systemic problem in itself. High performing SFs (4-5 on a Likert scale) form a driver of the system. However, well performing SFs are still able to house a systemic problem, and re-occurring barriers are mentioned as a systemic problem as well. The systemic problems are listed, and the insights of the different analyses are used to qualitatively argument a recommendation for Dutch policy makers and for Strukton Power.

At least 108 stakeholders, active in 18 different stakeholder groups, have been identified in the actor component. A stakeholder group represents a responsibility or role in the functioning of the TIS. However, roles and institutional responsibilities are limiting the exact delineation of the stakeholders since these differ heavily per project. Three different electrolysis approaches were considered. The preference of a specific approach highly depends on the use-case, yet the Polymer Electrolyte Membrane (PEM) electrolysis technology is currently implemented most in European projects. The formal network analysis showed that the system is highly interconnected. The industry and knowledge institutes and universities are most active in Dutch electrolysis projects, whilst the government and DSOs attribute the least. The institutional arrangements for the TIS consists of different legislative packages, including the Dutch gas law. Specific standards on efficiency measures, transport permits, and certifications for multi-MW electrolysis installations are not present. The Dutch and European government both attribute with public fundings via subsidiary trajectories.

The seven key processes are assessed. By doing so, the impact of the systemic functions is given. The resource mobilization scored a 2, the entrepreneurial activity, knowledge diffusion, guidance of the search, and market formation a score of 3, and knowledge development and creation of legitimacy a score of 4. In total, 36 systemic problems arose from the analysis. The systemic problems concentrate around the market uncertainty, lack or absence of institutional guidance and incentives, reluctant attitude of stakeholders, and insufficient resource availability. Systemic problems occurred in all system functions.

Dutch policymakers are advised to focus on the additional supply of RES and tightness of technical personnel and impose hydrogen synthesis in tender projects for RES realisation from now on. Strukton Power is recommended to further explore opportunities of the technology, with a focus on large scale electrolyzer projects with a capacity over 100MW. Two strategies are suggested. One in which knowledge on the electrolysis process is internalized to act as system integrator, and one where the current experience on electrical engineering is externalized to electrolyzer manufacturers as supplier of power systems.

The relevance of the seven system functions is questioned in the context of sustainable technologies since this analysis showed the extremes housing within SF4. Additionally, the use of a label score and an analysis score delivered a method for decreasing the subjective influence of the researcher with the ability to indicate weights to an argument. Both add to existing innovation literature and could be considered by future TIS analysists. Furthermore, this analysis showed the impact the innovation system has on the development of the technology. This is in contrast with existing techno-economic research on the challenges for hydrogen electrolysis, whom reason from the perspective of the technology. Further research could include adoption theory, in which the preferences of consumers are added, whilst the TIS analysis would result in the current capabilities of the system to uphold to these preferences.

List of abbreviations

ΔG	Delta of Gibbs free energy
A m^{-2}	Amperes per square meter
AC	Alternating current
ACM	Authority consumer and market
AEL	Alkaline electrolysis
BoP	Balance of Plant
CAPEX	Capital expenditure
CCS	Carbon capture and storage
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CoSEM	Complex systems engineering and management
CP	Chemical producer
DC	Direct current
DMP	Data management plan
DSO	Distribution system operator
e^-	Electron
EAC	(Ministry) of Economic Affairs and Climate
EB	Engineering bureau
EC	Energy consultancy
ECom	European Commission
EMS	Energy management system
EPO	European Patenting Office
Eq.	Equation
ESCO	Energy service company
ETS	Emissions trading scheme
EU	European Union
FCH JU	Fuel cell hydrogen joint undertaking
GHG	Greenhouse gas
GW	Giga Watt
GWh	Giga Watt hour
H^+	Proton
H_2	Hydrogen
H_2O	Water
H_3O	Hydroxonium
HS	Hydrogen supplier
IEA	International Energy Agency
IEM	Industrial equipment manufacturer
IND	Industry
j	Current density
KI	Knowledge institute
kT	kiloton
kV	kilovolt
kWh	kilo Watt hour
LNG	Liquefied natural gas
Mtoe	Million tonnes oil equivalent
MW	Mega Watt
NEA	Netherlands Enterprise Agency
NGO	Non-governmental organization
O_2	Oxygen
O^{-2}	Oxygen ion
OEM	Original equipment manufacturer
OH^-	Hydroxide ion
OPEX	Operational expenditure
PEM	Polymer electrolyte membrane
PI	Policy implementor
PM	Policy maker
PPA	Power purchase agreement
PS	Power systems
PtG	Power-to-Gas
PtX	Power-to-X
R&D	Research and development
RED	Renewable energy directive
Redox	Reduction-oxidation
RES	Renewable energy source
SC	Sector coupling
SF	System function
SMR	Steam reforming reaction
SOEC	Solid oxide electrolysis cell
SQ	Sub question
SSM	Supervisory Service of Mines
TIS	Technological Innovation System
TRL	Technology Readiness Level
TSO	Transmission system operator
TWh	Terra Watt hour
V	Volt

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1. Introduction

The emissions of greenhouse gasses (GHG) form a large driver behind the global climate change (IPCC, 2014). The climate change results in surging global temperatures, biodiversity loss, rising sea levels, and more extreme weather events like floods and droughts (Masson-Delmotte et al., 2021). In addition, the depletion of fossil fuels leads to the urge to generate energy via renewable sources, like wind- and solar power (Verma et al., 2016). However, the increasing shares of renewable energy sources (RES) in the energy mix own an intermittent and volatile character (Verma et al., 2016). Additionally, the increase in RES provide strain on the electrical distribution infrastructure, which needs to deal with spikes in supply. Also, the dominant form of energy generated by RES is electricity, increasing the need to electrify sectors such as industry, transportation, and residential heating (He et al., 2021). However, the electrification of a sector as complex, inert, and vast as the industry, can be very costly or impractical (Fridgen et al., 2020; He et al., 2021). Sector coupling (SC) poses a promising process to combine the electrification of the energy sector and the fossil-based industries (Fridgen et al., 2020). SC is referred to as 'the coupling of electricity, heat, and mobility, as well as the coupling of industrial processes and their respective infrastructures while increasing the flexibility of energy demand in the industrial, household and transport sectors' (Robinius et al., 2017 in Fridgen et al., 2020, p. 2). SC provides a means to transpose electricity to other forms of energy, which are more suitable in other sectors (Fridgen et al., 2020).

Different technologies exist for such purposes, e.g., conversion to chemical bounds like methanol or hydrogen, in a process often referred to as Power-to-Gas (PtG) or Power-to-X (PtX) (Rahman et al., 2020). Transposing the electricity in chemical bounds also provides the possibility to bridge the gap between supply and demand of RES, an aspect mentioned as a disadvantage of renewable generation (Verma et al., 2016). Since chemicals are directly stackable and storable, the utilization of the energy can be more flexible than electricity (Rahman et al., 2020). Additionally, the beforementioned chemicals are already widely used in the global industry sector, as feedstock for crucial processes like the synthesis of fertilizers via the Haber-Bosch process (Soloveichik, 2019).

Globally, 275 Mtoe of fossil fuels are used annually to synthesize hydrogen for the industry sector, accounting for 2% of the total global primary energy demand (Griffiths et al., 2021). The Dutch process industry alone, uses 100PJ of hydrogen annually (*Klimaatakkoord*, 2019). Since the energy and industry sector account for more than 65% of the global CO_2 emissions (IEA, 2021a), large efforts can be made to decarbonize the industry sector whilst overcoming cumbersome aspects of RES. SC with the use of hydrogen synthesis could form an important pathway towards a more sustainable industry sector (Noussan et al., 2021).

However, for a successful transition, an emphasis on technology alone is not sufficient in a socio-technical layered system such as the energy or industry sector. Moreover, due to the ongoing decentralisation of the energy system, additional actors, roles, and assets get involved, increasing complexity. As mentioned in Bidmon and Knab (2018), the contextual elements of a complex, multidisciplinary, and multi-actor system in transition also contribute to the arena for structural change. Thus, in addition to the technical characteristics, the economic, institutional, and social aspects need to be taken in to account for a full assessment (Bidmon & Knab, 2018). The intricate set of factors create a holistic context of the system wherein the technology is imbedded, indicated as the innovation system (Wieczorek & Hekkert, 2012).

Due to the current transitional nature of the energy system, engineering companies face difficult decisions when investing in and operating their assets in the Dutch energy system. But from a societal perspective it is important that these companies do invest, as it can accelerate the energy transition. Hence for such companies it is important to understand the complex arena that is the energy system. In this thesis, an assessment of the innovation system surrounding hydrogen synthesis in the Netherlands is conducted. With the use of an innovation system analysis, the relevant areas are analysed that structure the system. By subsequently assessing the performance of the system, the drivers and barriers for its development are exposed. These insights of the system and the particular effect on the development of the technology help further shape the discussion on the potential of the hydrogen economy, and hydrogen electrolysis specifically. For instance, with the outlining of the drivers and barriers, actors may discover a fitting role or attribution to absolve certain challenges or exploit opportunities. In such manner, this thesis also attributes to the further development of the system.

By analysing a system as complex, heavily governed, and inert as is the energy sector, whilst undergoing a transition, the assessment in the thesis has had to manage different perspectives and trade-offs proposed by the different actors involved. Due to the nature of hydrogen synthesis, technical insights and its understanding are required. Yet to offer a holistic perspective, institutional, economic, and social aspects are considered as well. These characteristics align with a typical CoSEM thesis.

Insights gathered on the barriers of the system are used to concoct a recommendation to Dutch policy makers to resolve these barriers. Additionally, the assessment of the innovation system is used to consult Strukton Power, a Dutch electrical engineering company, in their decision-making process to enter the system of energy conversion in the Netherlands.

1.1 Core concept

In literature, three main methods for hydrogen synthesis are delineated, applicated with the colours grey, blue, and green hydrogen production (Robledo et al., 2018; Dawood et al., 2020). Steam reforming of natural gas or coal is the conventional and common utilized method for hydrogen production (Griffiths et al., 2021). As can be seen in equation (Eq.) 1, methane *(CH_4)* originating from natural gas or coal is heated with steam *(H_2O)* in a steam reforming reaction (SMR), and forms carbon monoxide *(CO)* and hydrogen *(H_2)* (LeValley et al., 2014). In a water-gas shift reaction the resulting CO is used to create additional H_2. However, CO_2 is a by-product of the latter reaction, as can be seen in reaction Eq. 2 (LeValley et al., 2014). The reaction illustrated in Eq. 3 provides the overall reaction (LeValley et al., 2014). The suffix *(g)* signifies that the chemicals are in a gaseous state.

$$CH_4(g) + H_2O(g) \rightarrow CO(g) + 3H_2(g) \qquad \textit{Eq. 1}$$

$$CO\ (g) + H_2O\ (g) \rightarrow\ CO_2(g) +\ H_2\ (g) \qquad \textit{Eq. 2}$$

$$CH_4(g) +\ 2H_2O\ (g) \rightarrow CO_2\ (g) + 4H_2\ (g) \qquad \textit{Eq. 3}$$

Due to the resulting emission of CO_2 and use of fossil fuels, this method is referred to as grey hydrogen (Dawood et al., 2020). Blue hydrogen production is referred to as a similar production method, however, the product gas CO_2 is captured and stored (CCS) instead of released into the atmosphere (Dawood et al., 2021). This process has a low impact on the GHG emissions, but still uses fossil fuels (Dawood et al., 2021). In 2020, the production method of grey and blue hydrogen accounted for almost all global hydrogen synthesis, respectively 94% and 5% (IEA, 2021a).

The third method to produce hydrogen is via an electrochemical process, often referred to as green hydrogen production (Dawood et al., 2021). The use of electricity to electrochemically produce hydrogen is also referred to as hydrogen electrolysis in literature and is used interchangeably. In the process, hydrogen is synthesized by leading electricity through water, splitting it into oxygen and hydrogen (Dawood et al., 2021). Since green hydrogen electrolysis can use renewable electricity and water as inputs, it aligns with the decarbonization and electrification of the industry sector and provides a means to counter timing misarrangements between RES and demand of electricity. With a total production of 30 kilotons (kT) of hydrogen worldwide in 2020, green hydrogen production via electrolysis only accounted for 0.03% of total generation (IEA, 2021a).

An important sidenote, however, is that electrochemical synthesis of hydrogen cannot be issued as 'green hydrogen' in all situations. Green hydrogen production via an electrochemical process theoretically only utilizes electricity from a RES, whilst hydrogen production via an electrochemical process could also utilize electricity from a fossil fuelled powerplant. However, since the production technology and value chain of hydrogen need not change depending on the origin of the electricity (Dawood et al., 2021), literature regularly makes no distinction. Since the scope of the thesis is on the innovation system of the electrolysis technology, the focus will be on the technology in general. However, it is argued that the electrification of hydrogen production is more compatible within the sustainable energy system than grey or blue hydrogen. With this notion, the lack of purely focusing on green hydrogen whilst still adding relevance towards a sustainable future is justified.

Concerning the capabilities, hydrogen is mainly used in industry for the synthesis of ammonia and methanol in fertilizers and as a process chemical for cracking crude oil (Dawood et al., 2021). Other potential implications of hydrogen are the use in residential heating, mobility propulsion via fuel cells or internal combustion engines, and grid services in terms of Power-to-X for stabilisation and peak shaving (Griffiths et al., 2019). Figure 1 provides an illustration on the different routes of hydrogen, including production.

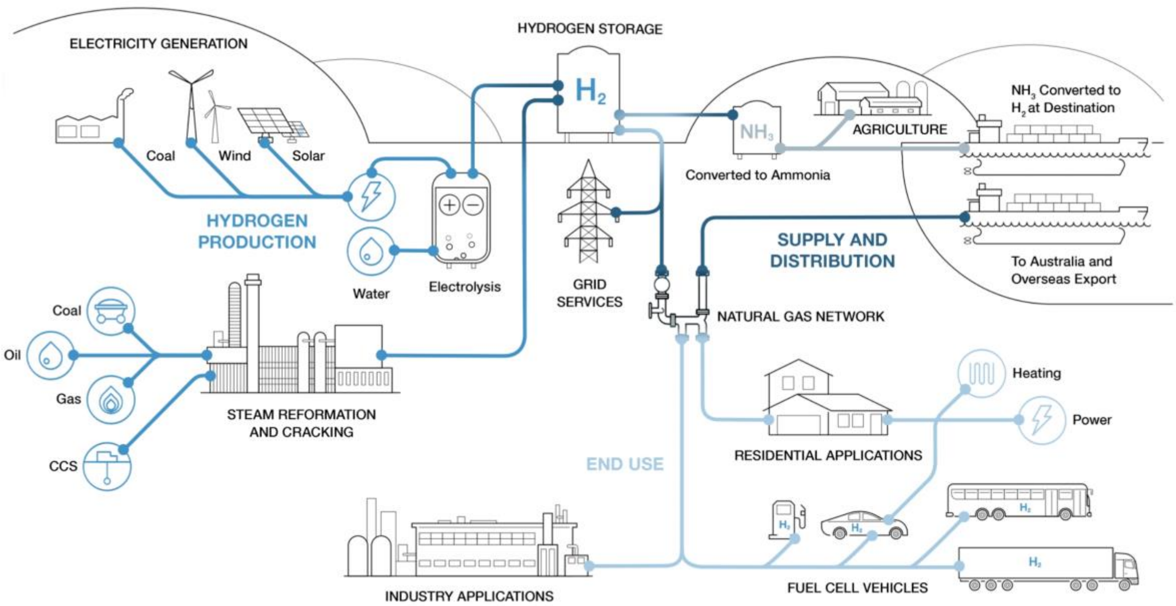


Figure 1: Systemic illustration of production and demand of hydrogen (Cummins, n.d.)

As an energy carrier and to overcome seasonal effects of energy supply, hydrogen electrolysis and storage was proposed as a solution as early as the mid 1970's (Dell, 1975). Since then, expectations of the technology have been endorsed (McLarnon & Cairns, 1989; Zhang et al., 2016; Modisha et al., 2019). Furthermore, in the Climate Agreement presented by the Dutch government in 2021, the aim is to have 500MW of electrolysis capacity installed and operational by the end of 2025, and 3-4GW by 2030 in the Netherlands (Yesilgöz-Zegerius, 2021). Due to the recent geopolitical crisis with Russia and the subsequent European desire for energy independency, the Dutch Minister of Climate and Energy has doubled that goal to 8GW in 2030 (Stellinga & van der Walle, 2022).

To put those targets in perspective, a total of 300MW of electrolysis capacity for hydrogen production was operational worldwide in 2020, of which 1MW in the Netherlands (IEA, 2021b). The large gap between the target of the Dutch government and the actual installed capacity worldwide in 2020, in addition to the consideration that only 0.03% of the global hydrogen consumed is generated via electrolysis, consolidates in a discrepancy between the prospects and reality. In regard of that large gap, this thesis project serves a main target. It aims to analyse the innovation system to discover what might cause this discrepancy. Yet by doing so, it aims to provide interesting angles to the complex problem and provide structured leads on where to kick-start the further development of the system. In such manner, the discussion on the prospects and utilization of hydrogen electrolysis will likely gain new or different insights.

The theoretical framework is assessed in Chapter 2, as well as a literature review that led to the research question. Additionally, the main research question is divided into four sub questions (SQs). In Chapter 3, the research method for data gathering and analysis are delineated. In Chapter 4, the analysis is conducted on the gathered data. Chapter 5 provides the interpretations of the found results, the limitations, contributions, and mentions further research topics. In Chapter 6 the conclusion to the research question is given.

2. Theory

The following chapter delineates the theoretic framework used, a literature review resulting in a knowledge gap and a subsequent research question.

2.1 Technological Innovation System

Analysis of the Technical Innovation System (TIS) served as theoretical framework, since it is often used in literature to analyse potential barriers in an innovation system and provides a structured method to fathom which components and functions cause these barriers (Bergek et al., 2008; Wieczorek & Hekkert, 2012). Formally, a TIS is defined as 'a dynamic network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion, and utilisation of technology' (Carlsson & Stankiewicz, 1991, p. 93, in Wieczorek et al., 2015). In other terms, a TIS embodies the dynamics of a multi-actor socio-technical system, which is shaped or being shaped under certain institutional arrangements, with the aim of developing and utilizing a technology. The notion of the TIS also correlates with the widely worn idea within innovation theory that innovation is not a standalone act but a collective act, performed within the socio-technical environment of a system (Bergek et al., 2008; Hekkert et al., 2011).

A TIS analysis allows for a focus on emerging and mature systems (Bergek et al., 2015). The analysis of a structure of a TIS has been prevalent in innovation theory (Hekkert et al., 2011), however, with the addition of a functional analysis proposed by Hekkert et al., (2007), the opportunity arises to assess the performance of the TIS. The functional analysis assesses seven system functions (SFs). The seven SFs have been delineated in innovation literature and cover the key processes of the TIS. The appreciation of the SFs leads to the barriers and drivers of the system. The structured method also creates the possibility to link the cause of the specific barrier or driver to a component of the TIS (Bergek et al., 2008; Wieczorek et al., 2013). By doing so, the possibility arises to propose policy recommendations, which can be aimed at specific functions and components. With the clear delineation of seven key processes believed keen for development of a system, and the possibility to link a found barrier to a specific component, the analysis will create clarity in the behaviour of the Dutch hydrogen electrolysis system. Via this approach, the framework befits the main target of the thesis project mentioned in the introduction. The structural-functional TIS analysis, as proposed in the paper by Hekkert et al. (2011), is conducted.

Although a TIS analysis can cross national borders (Bergek et al., 2015), the Netherlands is taken as geographical boundary of the analysis. Since national characteristics like policy measures contribute to the shaping of the innovation system, a geographical scope is useful (Sharif, 2006).

2.1.1 Structure of the TIS

The structure of a TIS consists of four main components (Hekkert et al., 2011). These components form the boundaries of the system. The components are described in Table 1:

Table 1: Name and description of structural components TIS.

Component	Definition
Actors	An actor is defined as ‘a social entity, person, or organization, able to act on or exert influence on a decision’ (Enserink et al., 2010, p. 80). Actors of a TIS are considered influential and have a direct impact on the functioning and development of the system because ‘through choices and actions, actors actually generate, diffuse, and utilize technologies’ (Hekkert et al., 2011, p. 5). The actor component also has a direct impact on the other three components, since they generate and develop the technology, form the formal and informal networks, and create or alter the institutions. Due to the apparent complexity and size of the TIS, the boundaries of involvement of an actor in the system is not limited beforehand towards actors directly utilizing or creating the technology. By doing so, an effort is made to analyse the wider context of the TIS. In line with the delineation regarded in Bergek et al. (2008), actors active in the value chain are considered as well, thus including knowledge institutes, policy makers, and feedstock providers. The boundaries of the actor analysis haven been depicted in section 4.1.1. An actor implies on a company, organisation, institute, association etc. An actor involved in the TIS is regarded a stakeholder, due to the ability to directly influence the system. Therefore, mostly the term stakeholder is used if an actor active in the TIS is considered.
Technology	Often regarded in terms of ‘knowledge’ or ‘technology’ (Bergek et al., 2008; Hekkert et al., 2011), this component revolves around the technical innovation of the TIS. The different technology trajectories of hydrogen electrolysis have been analysed in section 4.1.2, to provide an overview of the mechanisms and to be able to include arguments based on the characteristics of the technology in the other analyses.
Networks	This component revolves around the formal and informal networks. The network of a TIS involves the direct and indirect relations between the different stakeholders active in the system (Bergek et al., 2008). These networks can be utilized by the stakeholders for, e.g., innovative purposes, market formation or lobby activities (Bergek et al., 2008). Mutual knowledge development, joint ventures, multi-actor projects are all examples of arrangements wherein a network is created between stakeholders of the TIS.
Institutions	The institutions form the ‘rules of the game in a society, or, more formally as the humanly devised constraints that shape human interaction’ (Hekkert et al., 2011, p. 5). Institutions constrain and enact the system (Decourt, 2019). With the use of hard institutional instruments such as laws, regulations, and standards, policy makers aim to mould a system or market. Soft institutions like norms, ethics, and culture also play a role in a national TIS (Bergek et al., 2008). Since subsidies can be used to stimulate research and implementation of the technology, they have been considered as institutions as well.

2.1.2 Functions of the TIS

The system functions of the TIS are the key processes that influence the performance and direction of the system (Suurs & Hekkert, 2009). TIS literature has conformed seven SFs, which have been depicted in Table 2. The description is interpreted from Hekkert et al., (2007) and Suurs and Hekkert (2009).

Table 2: Name and description of system functions TIS

System function	Description
SF1. Entrepreneurial activities	Consists of the activity of stakeholders previously or presently engaged in the system or planning to become engaged in the system. The entrepreneurial activity is interwoven with the actor component but is mainly focused on the private stakeholders (Bergek et al., 2008). By experimenting and implementing the technology, the relevant stakeholders, directly influence the system. Eventually, these stakeholders form not only the executive branch of the technology, but also develop the market, contribute to the infrastructure, and create the tacit knowledge on the operation and design of the technology.
SF2. Knowledge development	Process of the knowledge creation via R&D investment, pilot projects, knowledge institutes etc. Via learning-by-searching and learning-by-doing, knowledge is generated. Increased learning results in more efficient implementation of the technology, but also increased insights in its applications.
SF3. Knowledge diffusion	Process of the network activities amongst bodies of knowledge, creating a diffusion of previous experiences, projects, analyses, and outcomes. The function entails the availability and diffusion of knowledge amongst the stakeholders involved.
SF4. Guidance of the search	Process of the guidance of the TIS via regulations or positive- or negative expectations of experts and target setting by governments and industry. These activities have an impact on the stakeholders involved in the system or planning to participate. By guiding the search, the design space becomes focused, increasing efficiency of the development, e.g., by indirectly delineating the potential R&D trajectories.
SF5. Market formation	Process of the design and structuring as well as the sheer size of the market, aiming to provide opportunity for market parties to interact with each other. The projected size and design of a market impact the potential for the innovation.
SF6. Resource mobilisation	Process of the human, financial, and physical resources required for the functioning of the TIS. The availability, allocation, and quality of financial means, human labour and material feedstocks are necessary for the development of the system and the performance of other SFs.
SF7. Creation of legitimacy	Consists of the gut feeling of the technology, including the resistance to change or the creation of awareness, influencing the legitimacy of the TIS. The process of creating legitimacy for the technology entails the acceptance by the general public and the stakeholders involved.

2.2 Research question

To understand the developments concerning hydrogen electrolysis and address a relevant knowledge gap, a scientific literature review has been conducted.

The literature review has led to the insight that the systemic approaches to explain the impact of the technology often include institutional and economic aspects. Yet they tend to lean towards the technological aspects to explain the barriers of the development of hydrogen electrolysis. For instance, Hu et al. (2020) have analysed the advantages, barriers, and solutions of implementation of Power to Hydrogen in Germany from a process engineering perspective. Due to this perspective, most barriers consisted of a chemical engineering origin (Hu et al., 2020). Butler and Spliethoff (2018) took a techno-economic perspective to analyse the status of the hydrogen economy and aimed to understand the lack of development. However, they focus on the specific electrolysers used in the process, narrowing the origin of a potential barrier. Abe et al. (2019) performed a techno-economic analysis on hydrogen electrolysis and storage but mainly focus on the storage technology and materials. Due to their scope, the challenges found for the future hydrogen economy purely resolve around the storage mechanism. Due to the large offer of engineering-based analyses presented in literature, the barriers found often revolved around the technical aspects of electrochemical hydrogen synthesis. That suggested that the technical aspects of the concept are the main barrier, or that non-technical aspects are more easily overlooked. With the use of a structural-functional TIS analysis, this thesis has balanced the different aspects influencing an innovation system.

Mazloomi and Gomes (2012), Parra et al. (2019) and Poluzzi et al. (2021) did analyse from a more balanced system perspective. The analyses include institutional and social aspects on potential barriers of hydrogen synthesis. Mazloomi and Gomes (2012) also included the mechanism and market design of the power grid to analyse the applied feasibility. However, these studies do not include a geographical scope. Therefore, direct causations between national policies or social campaigns and the institutional or social barriers are challenging to make. In this thesis, the Netherlands serves as the geographical boundary for the TIS analysis. This allows for the inclusion of national policies and institutions and their influence on the performance of the TIS.

Additionally, the perspective of the accumulated research is all on what characteristics of the technology are raising barriers for the development and market entry. Whilst in this thesis, the focus is on if the structure and performance of the innovation system raise barriers for the development of the technology. This difference is illustrated in Figure 2, and serves as the main contribution of this thesis towards the current literature concerning the subject.

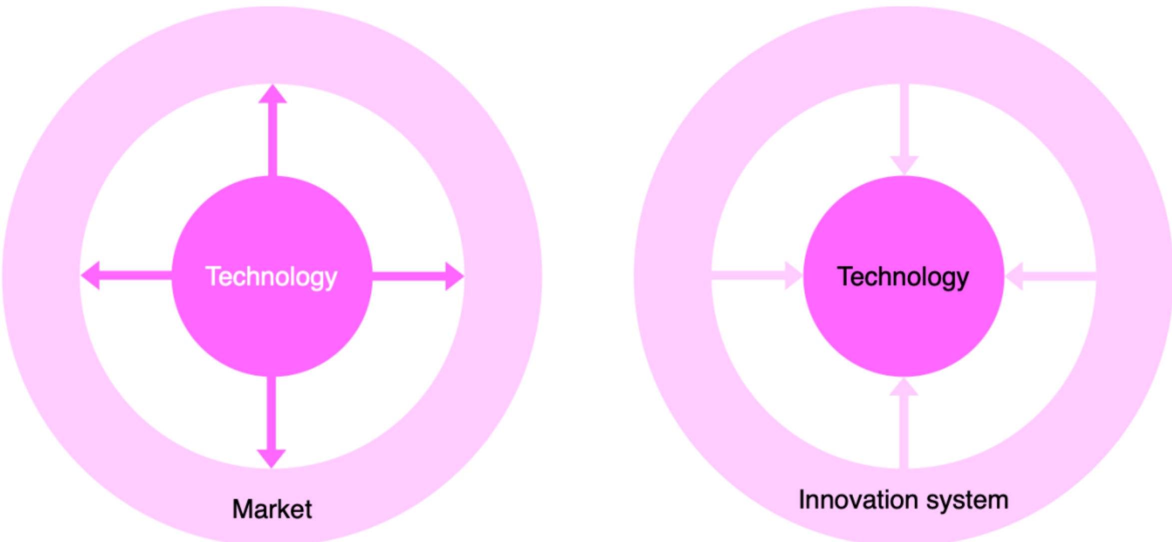


Figure 2: Perspective from accumulated literature (left), perspective of thesis project (right)

The insights from the literature review have led to three different knowledge gaps. First, current literature is often technology-biased towards the barriers, creating a lack of understanding of the influence other systemic aspects have on the development. Second, the lack of geographical boundaries in the system analyses do not provide direct insights in the influence of specific policies. Third, barriers found during the literature review are mainly from the perspective of the technology, not from perspective of the innovation system. From the research objective and the knowledge gaps found in literature, the main research question is derived, namely:

How do the systemic functions impact the implementation and development of electrochemical synthesizes of hydrogen in the Netherlands and how can this performance be improved?

2.3 Sub research questions

The innovation system concerning hydrogen synthesis is analysed in its structure and performance of the key processes, assessing the impact the system has on the technology. This impacting can be either accelerating or inhibiting. To provide structure to the analysis, this section divides the main research question in four SQs.

At first, an in-depth overview of the structure of the TIS is required to understand the four components. This resulted in the following question:

SQ 1. What do the four structural components of the TIS for hydrogen electrolysis in the Netherlands entail?

First, the outcome of the actor analysis resulted in a delineation of the different stakeholders involved, and to provide structure, these stakeholders are categorised in different stakeholder groups. These stakeholder groups have been assigned specific responsibilities of the system. Second, the technology has been assessed by analysing the chemical principle and the different electrolysis approaches found during the data analysis. Important indicators have been formulated and each electrolysis approach is assessed according to those indicators. A technology map including the up- and downstream processes is constructed. This technology map also acts as the boundary setting for the other analyses. Third, a network analysis is conducted to map the relations between the different stakeholders, and their corresponding stakeholder group. By doing so, the formal relations of the TIS are assessed. And fourth, institutional arrangements such as regulations, laws, and subsidies are mapped. By doing so, the most important policy instruments of the Dutch government and European Union can be assessed on their impact on the development of the TIS.

With the completion of the structural analysis, the TIS can be assessed on the functioning of the seven key processes labelled as SFs. The performance of these SFs shows the impact the processes have on the system. The following SQ is derived:

SQ 2. What is the performance of the seven system functions of the Dutch TIS for hydrogen electrolysis?

With the assessment of the SFs and the delineation of the impact, an additional effort is made to create insight in the systemic origin of the found barriers. These systemic problems manifest themselves within the TIS and limit the development of the system. Such an emphasis also allows for a structured method to propose policy instruments. To find the systemic problems, the following SQ is derived:

SQ 3. What systemic problems arise from the performance of the system functions, inhibiting the development of hydrogen electrolysis in the Netherlands?

With the identification of the systemic problems, an effort could be done to decrease these problems and increase the performance of the TIS. This is done by proposing certain policies. Additionally, the outcome of the structure and function of the system serve as a background to the recommendation of Strukton Power, to which function and level a system entry would be rational. This relates to the final SQ:

SQ 4. What recommendations can be made to increase the performance of the innovation system and what role can Strukton Power take?

3. Methodology

3.1 Data collection

By assessing the impact the system has on the development of the technology with a structural-functional TIS analysis, an inductive research approach is used. For the TIS analysis, qualitative data on the dynamics of the system is required. As is mentioned in section 1.1, the implementation of the technology is low, limiting the available data. With the use of expert interviews, tacit knowledge can be accumulated that is not retrievable in literature. Desk research is used for the initial overview of the system, to draft the experts of the system, arrange the interview questions, and to fill potential data gaps found during the expert interviews.
The following sections discuss how the data is gathered and analysed. Due to the fact that the development of the system is a continuous process and future data might contradict earlier data, and the time limitations considered in this thesis project, the data is gathered no later than the 31st of May 2022.

3.1.1 Desk research

The desk research includes the use of scientific articles gathered with databases like Scopus and Web of Science. This assures a peer review process is conducted, increasing the quality of the statements. Articles are considered useful if they are published no later than 2012, to reduce the risk of consulting outdated statements. Backwards and forwards snowballing and the manual selection by scanning the title and abstract, served as the strategy for the data collection. Reports, policy instructions, press releases, roadmaps, and other non-scientific literature, have been gathered with search engines like Google or specific websites of an organization that appear from the actor analysis. To guarantee the reports, statements, or other data originate from the subjected organizations, these written sources are consulted on their own website, e.g., Rijksoverheid.nl for statements by the Dutch government. Qualitative data taken from written sources are triangulated for validating purposes.

3.1.2 Expert interviews

Semi-structured interviews are conducted with different experts on the topic, creating an open conversation fitting the flexible characteristic of qualitative data (Creswell & Clark, 2017), whilst assuring all aspects are brought up. Interview questions are derived based on the technology map and actor analysis and involve an iterative process after each interview or discovery. Potential interviewees need to be able to attribute to the data of the research, otherwise, the quality of the research will decrease. Thus, a form of selection is necessary. To ensure the quality of the statements made by the interviewees, their knowledge on the topic is asked for prior to the request for the interview, or the experts are explicitly endorsed by interviewed experts. Potential interviewees are employees of the stakeholders involved in hydrogen projects, and a start is made by scanning through specific websites of associations and hydrogen electrolysis projects. An effort is made to interview employees from multiple stakeholder groups, to allow for a wide perspective of the TIS and increase validity. An overview of the experts interviewed, and their corresponding stakeholder group is depicted in Table 3. The names of the interviewees add no academic value and are left out. The interviews are recorded via Microsoft Teams or with the internal microphone of a MacBook and later transcribed for internal validity.

Table 3: Overview of interviewed experts

#	Actor	Stakeholder group	Code in text
1	Dutch DSO (anonymized)	DSO and energy consultancy (EC)	DSO/EC1
2	Strukton Power	Power systems (PS)	PS1
3	TU Delft	Knowledge institutes and universities (KI)	KI1
4	Strukton Power	Power systems	PS2
5	TU Delft	Knowledge institutes and universities	KI2
6	DNV GL	Energy consultancy	EC2
7	Strukton Power	Power systems	PS3
8	NEA & Ministry of EAC	Policy implementor (PI) and policy maker (PM)	PI/PM1
9	Royal HaskoningDHV	Engineering bureau (EB)	EB1
10	Chemical producer (CP) and plant constructor (anonymized)	Industrial equipment manufacturer (IEM) and industry (IND)	IEM/IND1
11	Electrolyzer manufacturer (EM) (anonymized)	Electrolyzer manufacturer	EM1
12	Petrochemical multinational (anonymized)	Industry	IND2
13	Gasunie	Gas TSO	GAS1
14	Province of Zuid-Holland*	Policy maker	PM2

*Attempts were made to interview policy makers from provinces with industrial clusters, such as the province of Zuid-Holland. But due to time restrictions from the interviewee, the contact was limited to personal contact via email. This resulted in answers partly via mail exchange and via existing reports and attachments. The corresponding contact are depicted under 'personal contact 1'.

3.1.3. Data management

At the start of the interview, explicit consent was asked and received from the interviewee. It was made clear that this thesis might become publicly available in due time and no sensitive data should be shared. The transcription was eventually typed out, anonymized, and communicated to each interviewee, to provide the opportunity to scan through the conversation and adjust if necessary. Once consensus was reached on the transcription, the text was implemented in Appendix B and used for data analysis. Furthermore, a data management plan (DMP) has been made on http://dmponline.tudelft.nl to assure compliance with codes and regulations of TU Delft considering the handling of the data.

3.2 Data analysis

The coming sections depict the different methods used to analyse the gathered data.

3.2.1 Structural analysis

The four components from Table 1 form the structure of the TIS. Each component has been analysed according to a specific method. Per analysis, the method is explained.

Actor analysis

A delineation of the different stakeholders active in the TIS provides a sense of context and forms the basis for the network analysis. However, to collectively sum all stakeholders as is frequently done in empirical structural TIS analyses (Decourt, 2019; Wieczorek et al., 2015), the stakeholder landscape remains superficial. With the creation of stakeholder groups, an effort is made to provide depth to the stakeholder landscape. The different groups are constructed in the actor analysis in section 4.1.1, with the use of the stakeholder analysis performed by Schlund et al. (2022, Table 1 & 2), the interviews conducted in this thesis and considerate assumptions. During the data gathering, the division of the stakeholder groups are presented to the different interviewees. By doing so, an interactive process is created, leading to the iteration and validation of the assumptions made in the delineation of the tasks and responsibilities of the stakeholders. The product of the actor analysis is a table with the different stakeholder groups, including their specific role or responsibility in the TIS.

Technology analysis

The technology analysis is used to provide background on the different trajectories of an electrolyzer. By doing so, the other analyses are able to include technical aspects. With the delineation of the chemical principle behind the electrolyzer technology, an overview could be substantiated of the three different electrolysis methods. The analysis leads to a technology map. The technology map contributes to the understanding of the technology and the system. With the use of desk research, an initial technology map including up- and downstream processes is made. During the interviews with experts especially involved in the technological development, the results of the technology are shown, discussed, and altered if necessary. By doing so, the outcome of the technological analysis is verified. Those specific technical experts were consulted in interview (KI1; KI2; EC2).

Network analysis

Due to time limitations, the large size of the system, and the high variety and number of stakeholders, the informal network has not been analysed. The focus of the network analysis has been on the formal connections. To gain insight in the formal network, two databases for projects concerning hydrogen electrolysis in the Netherlands are consulted. The first database is from the International Energy Agency (IEA) (IEA, 2021c), and the second of Topsectoren Energie (Topsectoren Energie, n.d.). By filtering on hydrogen electrochemical production in the Netherlands, a list of projects is accumulated. Additional projects provided in interviews are enlisted as well. The list is shown in Figure 14 in Appendix D. Per project, the consortia are given, providing insights in the different stakeholders that have been involved with a subsidized project over the last eight years. Future planned projects that have no concrete investment decision are left out of the list. Since by far, most implementations of hydrogen electrolyzer technology is still on a project level, this method for data gathering suffices. Since the use of public money in the form of a subsidy forces a public announcement, the databases can be considered reliable. Likely, different stakeholders experiment with the implementation of the technology behind closed doors, but since that is difficult to discover or verify, the public databases serve as basis with additional data from the conducted interviews. The database shows the connection between different stakeholders, not what type of contribution a stakeholder provides. Therefore, it is not possible to differentiate between governing, or financial contributions for instance, and solely a connection is illustrated. Another remark has to be made on the involvement of the government. Since all projects in the database and resulting from the interviews are subsidized with public money, one could argue that the government is involved in all of the projects. However, only the direct involvement of the government, province or municipality within a project consortium is considered. The direct involvement allows for an active contribution and adjustments made to the project. Whilst issuing a subsidiary at the initial phase of a project, results in a more passive role. With the use of software program Gephi and Excel, the network layouts are visualized. The multiple network layouts illustrate who is in collaboration with whom, and what the frequency of participation is.

Institutional analysis
As is stated by Hekkert et al. (2011, p. 5), 'even though informal institutions have a strong influence on the speed and direction of innovation, they are impossible to map systemically'. Therefore, in this thesis, the focus has been on the formal institutions. Institutions can cover a wide array of subjects, so to ensure the feasibility of the analysis in terms of time constraints, subjects deemed most important have been considered. These subjects include the acquaintance of electricity and water since those feedstocks form the main inputs of the electrolysis process. For simplicity, the operation of the electrolyzer has been assumed as uniform, making no distinction in approach of electrolysis. In line with the technological analysis, the transport of hydrogen is considered as well. The analysis leads to a textual overview of the main institutions applicable to the system.

3.2.2 Functional analysis

By appreciating the SFs, an effort is done to assess the performance of the TIS. With the use of a five-point Likert scale, each SF is rated from one (lowest performance) to five (highest performance). The use of a Likert scale provides enough levels to differentiate amongst the SFs, whilst not overshooting in sensitivity. Especially the latter is fitting with the use of qualitative data, since a backdraft of the qualitative arguments made in the analysis is the difficulty to exactly define which level a SFs is. With the use of a Likert scale, the levels differentiate well enough to delineate amongst those scores with the use of qualitative data. Besides, the use of a Likert scale is prevalent in functional TIS analyses (Hekkert et al., 2011; Wieczorek et al., 2015). Low performing SFs (1-2 on a Likert scale) lead to a systemic problem in itself. High performing SFs (4-5 on a Likert scale) form a driver of the system. A score of 3 is considered neutral. For all functions go that re-occurring barriers within SFs mentioned in the interviews will be considered as systemic problems as well. In that manner, high performing SFs can still house a systemic problem.

To determine the score, two mechanisms are used. The first, the label score, is used as a benchmark. The second, the analysis score, serves as the leading score and concludes as the performance of the SFs. The use of a benchmark is used to decrease the subjectivity of the qualitative analysis and integrate the gathered data in a structured manner. The analysis score, however, is used to add weight to certain arguments, providing depth and hierarchy amongst statements made by the experts.

First, the formation of the label score is explained. To operationalize the gathered data from the experts to the assessment of the SFs, Table 4 is concocted and is used in the analysis. Operational indicators from previous TIS analyses served as a guideline, as presented in Negro et al. (2007, Table 1), Suurs & Hekkert (2009, Table 3) and Vasseur et al. (2013, Table 1). By doing so, the validity of the operational indicators is preserved. If an operational indicator is recognized during the analysis of the transcription, a label is attributed after the statement. A positive or negative impact is also assessed, leading to a data analysis that is well falsifiable. For example, in case an expert mentioned the execution of a demonstration project, an 'SF1+' label is attributed to that statement, in accordance with Table 4. Per specific scenario or statement, a label is only assessed once within the same SF. It is possible to label statements with multiple SFs. Future projects and partnerships that have no final decision are not included in the assessment of the SFs, since these might not go through and would poison the outcome. During the data gathering, certain factors came up that were assessed to influence the performance of the TIS, whilst they were not presented in previously mentioned TIS analyses. Therefore, these factors are interwoven as operational indicators during the analysis.

Table 4: Operationalization assessment system functions

System function	Operational indicators	Impact
SF1. Entrepreneurial activities	Demonstration project / explorative activities started by stakeholder Actor enters market Balanced stakeholder presence Joint undertaking of stakeholders to clear barriers	+
	Demonstration project / explorative activities stopped by stakeholder Stakeholder leaving market Imbalanced stakeholder presence	-
SF2. Knowledge development	R&D expenditure / investment Public funding for learning Demonstration pilots and projects focussed on learning Increase in published articles / patenting	+
	No particular knowledge development Reduction of R&D expenditure / investment Reduction in academic studies Decrease in published articles / patenting	-
SF3. Knowledge diffusion	Workshops / conferences Joint pilots and projects focussed on learning Learning in tune amongst actors, preventing repetition Collaborations between knowledge institutes and companies Collaborations between different stakeholders to clear barriers	+
	Lack of collaboration between stakeholders Lack of transparency of results learning activities No / low willingness to cooperate in learning activities	-
SF4. Guidance of the search	Positive outcomes of pilots / studies towards system Target setting showing confidence in the system Expert confidence in structural components / hydrogen Clear standards / technical guidance Forced restrictions on feedstock origin, operations, or emissions	+
	Negative outcomes of pilots / studies towards system Doubt / uncertainty in structural components / hydrogen Lacking standards / technical guidance creating uncertainty Restricting, lacking, or contradictive institutions	-
SF5. Market formation	Growing market size Clear market design Low threshold for system entry Protected niche markets Clear delineation stakeholder responsibilities	+
	Unclear or lacking market design High threshold for system entry Complex stakeholder responsibilities	-
SF6. Resource mobilisation	Capital investment in financial, physical, or human resources Sufficient availability of financial, physical, or human resources Financial subsidies Short decision period, fast resource mobilisation	+

	Rejection of financial investment Insufficient financial, physical, or human resources Long decision period, slow resource mobilisation	-
SF7. Creation of legitimacy	Lobby activities Support by public campaigns Encouragement technology / hydrogen by public	+
	Lack of support by stakeholders Public fear towards technology / hydrogen Discouragement technology / hydrogen by public	-

At the end of each interview, the positive and negative labels are summed per SF. A Table of the raw score is depicted per interview in Appendix F. The label score is equal to the portion of positive labels related to the total numbers of levels, times the range of the Likert scale. IN short, equation 4 is used to calculate the label score.

$$Label\ score = \frac{\sum Positive\ labels\ of\ SF}{\sum Total\ labels\ of\ SF} * 5 \qquad \textit{Eq. 4}$$

However, since the label score does not allow for weighing certain arguments more than others, an analysis score is performed as well and is formed as follows. Each SF is individually analysed with the use of qualitative arguments. Arguments related to the SF are elaborated on in the analysis, and if deemed necessary, the benchmarking label score is adjusted. At the end of the analysis of each SF, a separate paragraph is dedicated to the argumentation of the analysis score. Although this increases the risk of making the analysis too subjective, the possibility to weigh the barriers and drivers to rate the performance of the SFs justifies the risk. In an effort to decrease said risk, the arguments are solely made with the backing of the data. The outcome of the functional analysis is a spider chart containing both the label and analysis score.

3.2.3 Systemic problems

Re-occurring barriers are considered as systemic problem. The systemic problems are accumulated per SF, and the component or multiple components directly contributing to, or influenced by are given. The outcome of the analysis is presented in a table containing the systemic problems.

3.2.4 Recommendations

The results from the previous SQs together with specific statements made during the interviews, the ability arises to provide Strukton Power with a recommendation on the involvement in the system. Additionally, by having identified the lower performing SFs, in combination with the structural components of the system, well considered policy recommendations can be made as well. The outcome of the analysis is presented as a textual recommendation.

4. Analysis

4.1 SQ 1 Structural analysis

The structural analysis has been used to analyse and map the four components the TIS, providing an overview and understanding of the system.

4.1.1 Actor analysis

The stakeholder groups delineated in Table 5 represent the different types of stakeholders active in the TIS. The different groups have a direct or indirect impact on the TIS, either by giving direction via institutions, by increasing knowledge creation, initiating entrepreneurial activities or by market creation (Hekkert et al., 2011).

Table 5: Overview of stakeholder groups active in the TIS, partly adapted and adjusted on the stakeholder analysis of the hydrogen supply chain in Germany by Schlund et al., (2022, Table 1 & 2)

Stakeholder group	Stakeholder definition
Associations	Organizations that represent the interest of different members of the value chain, involved with, e.g., lobbying, knowledge accumulation and social awareness creation.
DSO	Regional distribution system operator (DSO) of electricity and natural gas, responsible for mid-low voltage grid (from 50kV downward).
Electricity TSO	National transmission system operator of electricity (TSO), responsible for high to mid voltage grid (380-50kV). The Dutch TSO for electricity is TenneT.
Electrolyzer manufacturer (EM)	Manufacturers and distributors of electrolyzers, independent on the type of electrolyzer.
Energy generation	Companies involved with the generation of electricity, or mining of fossil fuels such as natural gas.
Energy consultancy (EC)	Firms involved with consultancy projects on e.g., infrastructure, material flows, certificates, policy design and implementation concerning an energy topic.
Engineering bureau (EB)	Responsible for the integration of the different technological and institutional aspects of electrochemical synthesis of hydrogen. Closely related to energy consultancy firms but are more deeply concerned with the quantitively engineering implementation of projects (EC2).
Energy service companies (ESCOs)	ESCOs are considered as wholesalers of electricity and gas to third parties. ESCOs form the market party and close the contracts between energy generators and consumers.
Gas TSO	Dutch TSO for natural gas, responsible for the high-capacity grid, ensuring the necessary amount of natural gas in the system and involved in connection market parties. The Dutch gas TSO is Gasunie.
Governmental agencies	Organisations under direct supervision or control of the Dutch government, applicated to transpose policy and implement it, stimulating change via institutional instruments, e.g., tax reductions, subsidiaries, feed-in tariffs (PI/PM1).
Industry sector	Industrial parties can be both on the supply and demand side, including grey and blue hydrogen producers, chemical processors (hydrocarbon cracking in refineries), material producers (metals, fertilizers).

Industrial equipment manufacturer (IEM)	Companies involved with the manufacturing and installation of industrial equipment required for hydrogen production, such as compressors, pipelines, deoxidizers and other up- and downstream considerations (IEM/IND1). Actors capable of constructing entire industrial plants are also part of this stakeholder group (IEM/IND1).
Knowledge institutes and universities	Organizations involved with public research and development (R&D) and testing of hydrogen technology, expanding theoretical understanding, and increasing production capacity and efficiency.
National government, Ministries, and municipalities	National and transnational governmental bodies and Ministries, responsible for hard and soft institutions (regulations, laws, standards, permits), policies, energy security and availability, tax reductions.
Non-governmental organizations (NGOs)	NGOs represent causes as, e.g., ecological, environmental, social, consumer protection.
Power systems	Responsible for power electronic hard- and software, such as transformers, rectifiers, DC busbars, auxiliary power supply, energy management system (EMS), electricity security.
Society	Dutch citizens, concerned with energy security, affordability and availability, environmental pollution and storage and production risks.
Water provision	Companies responsible for water cooling of electrolyzers and supplier of demineralized and purified water (KI2).

A non-exhaustive list of organizations and companies active in the Dutch TIS and its surrounding supply chain is drafted in Table 9 in Appendix A.

To gain context of the system and develop an interview strategy, an effort is made to emphasize these in a structural actor representation diagram provided by Hekkert et al. (2011). The diagram is set in five different types of stakeholders. The five different stakeholders as given by Hekkert et al. (2011) are expressed in bold at the top of each light pink rectangle in Figure 3. Since the analysis is conducted prior to the expert interviews, the delineation of the stakeholders is based on desk research. With the framework provided in Figure 3, specific stakeholders are sought that fitted the type, pre-set by the diagram. For instance, for the demand type of stakeholders, the industry sector is filled in since the Dutch industry is a large consumer of hydrogen, as was made clear in the introduction. Figure 3 provides the overview of the found stakeholders prior to the interviews.

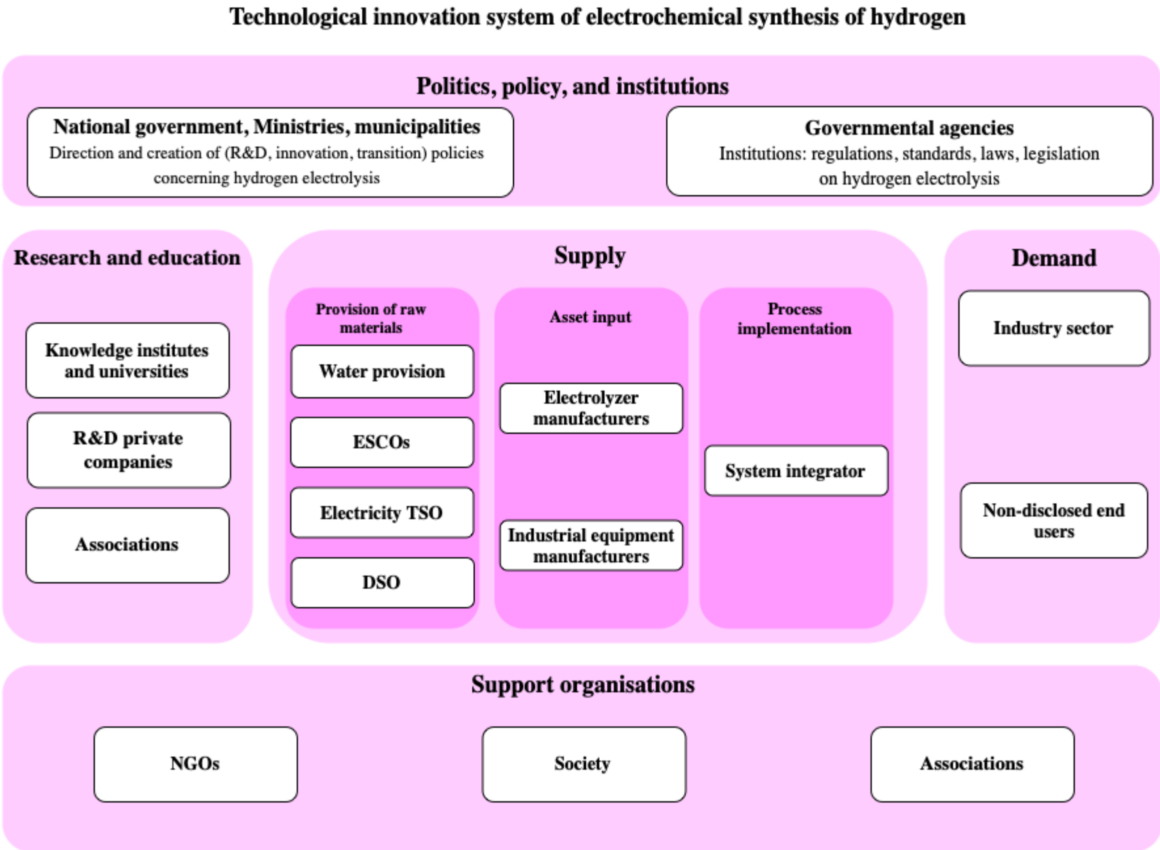


Figure 3: Preliminary analysis on roles of stakeholder groups, based on Kuhlmann & Arnold (2001) in Hekkert et al. 2011, Figure 2.

However, as became clear during the conducted expert interviews, the exact roles of the stakeholders strongly depend on the project in terms of size, type of consortium and purpose of research (DSO/EC1; KI1; EB1; EC2; IEM/IND1; IND2). Therefore, the preliminary roles presented in Figure 3 are no longer deemed accurate. From the expert interviews became clear that there is no standard pattern of the different roles, and the closest representation of roles is made with the delineation of stakeholder groups in Table 5.

4.1.2 Technological analysis

In the coming section, the technology regarding electrochemical synthesis of hydrogen has been analysed. The analysis of the technology is necessary to deeper explain the chemical and physical aspects of the system. The outcome of the analysis serves as a general overview of the technology and its status. The chemical principle of electrolysis and a summarized comparison of three types of electrolyzers are discussed. In a technology map, the utilities needed for the operation of a production facility are delineated.

Chemical principle

As mentioned, the electrolysis of water into hydrogen is an electrochemical process, in which a non-spontaneous reduction-oxidation (redox) reaction takes place (McMurry et al., 2016). The meaning of nonspontaneous reflects on the Gibbs free energy, a concept from thermodynamics, meaning the availability of energy for a transformation in a chemical reaction. In the case of a positive delta of Gibbs free energy (ΔG), the end products of a reaction have a higher combined available energy than the reactants and vice versa. In the case of a non-spontaneous reaction, ΔG is positive and thus, in appliance with the first law of thermodynamics, energy must be added for the reaction to take place. In an electrolysis process, this energy is provided in the form of electrical energy. The amount of electrical energy required depends on different aspects, e.g., the reactants, the kinetic equilibrium of the reaction and the type of electrolyzer and is expressed as the electric potential (U), measured in volt (V). The redox reaction of water into oxygen and hydrogen has a standard potential requirement of 1.23V under standard conditions (25 degrees Celsius, atmospheric pressure) (McMurry et al., 2016). In practice however, additional U of up to 1V is required due to Ohmic losses caused by, e.g., the lower conductivity of the substance near the surface, bubble formation and mass transfer limitations of the electrolyte (Götz et al., 2016). The term overpotential is used for the additional voltage that is required from the standard potential to the actual occurrence of the reaction (KI1). With a higher overpotential, the efficiency decreases because more electrical energy is required than theocratically necessary (KI1; KI2). The use of a catalyst decreases the energy required for the activation of the reaction, reducing U. The type of electrolyzer, pressures and temperatures are different parameters adjustable to decrease the Ohmic losses and increase efficiency, reducing operational costs (Götz et al., 2016; McMurry et al., 2016). Ongoing research in the field of electrolysis is dedicated to decrease the overpotential (KI2). In case of high temperatures and pressures inside an electrolyzer, the electrical potential can be below 1.23V, since the additional energy required for the reaction is delivered in the form of heat (KI2).

An external source with a potential U creates an electrical current that is provided to the water via two separate electrodes. With the electrical ‘push’, the accumulation of electrons causes one electrode to become negatively charged and is called the cathode. The opposite is the case in the other electrode, the anode. Due to the design of the system, the electricity must be provided as a direct current (DC) (McMurry et al., 2016). In the case of water electrolysis, or any aqueous solution for that matter, the presence of an electrolyte is necessary (McMurry et al., 2016). The electrolyte allows for the transportation of ions through the solution, carrying a charge and closing the electrical loop, allowing electrical current to flow through the cell (McMurry et al., 2016). This charge carrier differs between the types of electrolyzers (KI2).

At the surface between the electrode and electrolyte, the actual reaction takes place. In the case of water electrolysis in an alkaline electrolyzer, water molecules at the cathode surface reduce to hydrogen gas and hydroxide ions (Eq. 5). At the anode, water molecules oxidize to oxygen gas and protons. As illustrated in Eq. 5 and Eq. 6, the uptake of an electron (*e^-*) reduces the water molecule, whilst the release of an electron oxidizes the water molecule. Eq. 5 and Eq. 6 represent the half-reactions, Eq. 7 is the overall cell reaction of water electrolysis in an alkaline electrolyzer. Additionally, dissolved (*aq*) protons and hydroxide ions form water in a spontaneous reaction (Eq. 8). However, in certain alkaline electrolyzer designs, a membrane separates the compartments of the two electrodes and a salt bridge is added to allow the charge carrier to roam to the oppositely charged electrode (McMurry et al., 2016). In this manner, the compartments are chemically separated but electrically connected.

$$4H_2O\ (l) + 4e^- \rightarrow 2H_2(g) + 4OH^-\ (aq) \qquad \textit{Eq. 5}$$

$$2H_2O\ (l) \rightarrow\ O_2(g) + 4H^+(aq) +\ 4e^- \qquad \textit{Eq. 6}$$

$$6H_2O\ (l) \rightarrow 2H_2(g) +\ O_2(g) + 4H^+(aq) + 4OH^-(aq) \qquad \textit{Eq. 7}$$

$$4H^+(aq) + 4OH^-(aq) \rightarrow\ 4H_2O\ (l) \qquad \textit{Eq. 8}$$

Considering efficient operations, the overpotential is an important notion in the comparison between different electrolyzers and configurations (KI1). The different configurations of the system relate to the combinations of e.g., pressure, temperature, and catalyst materials (KI1).

In short, the overpotential is directly related to the efficiency of the system, since applying higher voltages than theoretically necessary whilst the output is similar, creates additional electricity costs (KI1). Overpotential also has a heavy toll on the internal materials of the electrolyzer (KI1). The overpotential creates additional heat, which stresses the materials of the stacks, current collectors, catalysts, membrane, tubes, and valves of the system (KI1). Concluding, overpotential creates additional feedstock and equipment costs, and decreases the expected lifetime of the module.

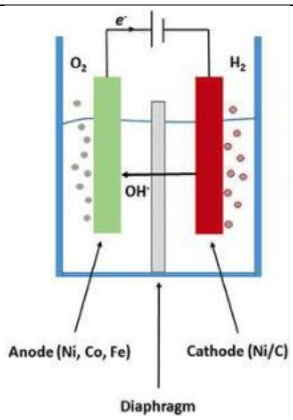
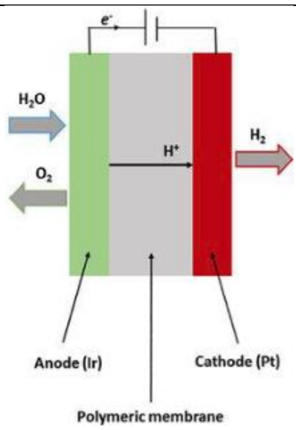
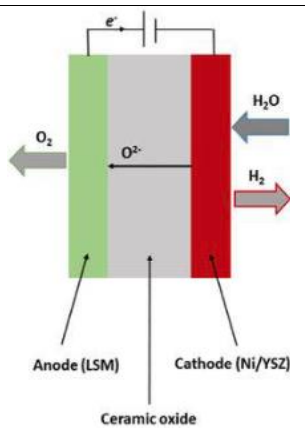
Another important notion is the current density, expressed as *j* and measured in amperes per square meter ($A\ m^{-2}$). The current density corresponds with the amount of current able to flow between the electrode and electrolyte (KI2). In the proximity of the cathode, a high current density offers more electrons that can be 'pushed' to the solution. Since ampere is a unit depended on time, a higher current density allows more water molecules to be reduced per area of electrode, per second (KI2). In essence, it relates to the number of electrons able to contribute to the redox reaction per area of the reactor. Therefore, the current density determines the output of hydrogen an electrolyzer can produce, regardless of the size of the module. Additionally, capital costs of the equipment can be minimized with a high current density since smaller units allow for similar production outputs.

The overpotential and current density are the two main factors in comparing electrolyzer systems and different configurations from a chemical engineering perspective (KI1; KI2). Most of the research objectives are related to improving these numbers whilst remaining within the limits of the materials, to not shorten the lifetime (KI1). An additional unit can be used to compare an electrolyzer with an internal combustion engine of hydrogen, or hydrogen synthesis via biomass conversion, and entails the kilowatt-hour (kWh) used per kilogram of hydrogen produced (KI1). However, since those methods are outside the scope of this thesis, the unit will not be elaborated on.

Electrolyzers

As mentioned, there are three main approaches for the electrolysis of water into hydrogen, namely: alkaline electrolysis (AEL) which includes the advanced membrane and high-pressure polymer alterations, Polymer Electrolyte Membrane (PEM) electrolysis and Solid Oxide Electrolysis Cell (SOEC) (KI1; KI2). With the use of insights from the interviews (KI1), (KI2), (EB1), (EC2) and (EM1), and additional data from Götz et al. (2016), McMurry et al. (2016) and IRENA (2020), Table 6 is formulated for the three different approaches. An important sidenote, however, is made in the interviews (KI1) and (KI2) and relates to the exact configuration of the electrolyzer and its manufacturer. The quantitative data in Table 6 do provide a general notion in comparison between the electrolyzers. However, since the technology is in rapid development and manufacturers differentiate due to a lack of a dominant design, the data range is large and highly depends on the specific system design of the producer. The current density is that much depending on choice of catalyst and other design factors that it is insufficient generalizable per electrolysis method and is thus not expressed as quantitative data range. The advantages and disadvantages of each approach are depicted in Table 11 in Appendix C.

Table 6: Indicators and data for different electrolysis approaches

	AEL	PEM	SOEC
Schematics			
Applied potential (V)	1.8-2.4	1.6-2.2	0.9-1.3
Charge carrier	OH^-	H^+/H_3O	O^{2-}
Pressure (bar)	1-30	30-70	1-10
Start-up time	Minutes	Minutes	Minutes-hours
Response time	Seconds-minute	Milliseconds	Minutes
Cell temperature (ºC)	40-90	20-100	500-1000
Electrolyte	Liquid (alkaline)	Polymer (solid)	Ceramic (solid)

Despite the differences between the three approaches, experts interviewed in (KI1; KI2; EB1) stated that there is no clear favourite. However, in interview (EM1) the PEM technology is mentioned as a clear favourite, with the remark that the particular expert worked at an electrolyzer manufacturer specifically dedicated to PEM. European projects are more focused on PEM electrolyzers, due to the higher pressures and flexibility of operation (EB1).
Overall, the wide range of pros and cons generate a trade-off scheme that favours different electrolyzers in different scenarios and use cases. As mentioned in interview (KI1), the highly efficient SOEC is not applicable for intermittent use due to the high start-up costs and time, but for an industry that operates around the clock, the efficient and constant synthesis of hydrogen is favourable. In the case of a limited budget and operation time, AEL suits the use case better (KI1). Due to the immediate response time and compact design, the PEM electrolyzer would be favourable in combination with a remote solar parc (KI2). Concluding, the preferred approach will depend on the context of the use case and will likely be tailor made per scenario.

In the scope of operation, the electrolyzer requires up- and downstream components referred to as the Balance of Plant (BoP). The relevance of the delineation of the BoP is like that of the concept of electrolysis; with the inclusion of up- and downstream components, their impact on the system functions can be considered. The exact boundaries of a BoP scheme are disputed (KI2), but in this thesis it is limited to the feedstock preparation, the secondary processes, the product treatment and include the input in three different transport infrastructures. These transportation means are explained at a later stage. Further applications of hydrogen are provided as a sense of context, but not deepened. The BoP resolves around the electrolyzer and is divided into an input and output schematic, together forming the technology map. The technology map is shown in Figure 4 and 5. The technology map is developed after consulting literature on the subject and is specifically verified and validated during the interviews (KI1) and (KI2).

The delineation of the different roles in the technology map are based on the components required for the electrolysis process, but from the interviews indirectly became clear that the specific scope for the operation is not set in stone. There seems to be a lack of a standardization in the role pattern, leaving a gap in allocating the different responsibilities and operations among the stakeholders. This issue is also amplified in the actor analysis in section 4.1.1. To enhance the workability of the technology map, the different components are accommodated in the most logical fashion and after discussing the issue with multiple experts (KI1; KI2; EC2). For instance, in certain module designs, all components and processes encircled under power systems in Figure 4, are integrated within the electrolyzer itself. That would mean there are still power system components, but there is no separate power system operator since that would be under the responsibility of the party operating the electrolyzer. As was mentioned in (EB1), the presence of a power systems operator and constructor is likely depended on the scale of the electrolysis plant. A larger system, hundreds of megawatts, or even multiple gigawatts, requires more power and the electrical input becomes more advanced and will more likely require a specialized power system operator and manufacturer (EB1). For the technology map, such a delineation of a power systems operator is made since that entails the area of expertise of Strukton Power.

Input

The input of an electrolyzer is illustrated in different blocks in Figure 4 and represents the main feedstocks for operation: water and electricity. The assumption is made that an ESCO arranges the delivery of electricity in terms of contracts but use cases can deviate from that principle (DSO/EC1). The high voltage grid is under control of the electricity TSO TenneT, and ranges from 380kV till 50kV (DSO/EC1). From there, the electrical potential is transformed to 10kV, and the electricity is transported via the distribution network of the DSO to the location (DSO/EC1). Depending on the scale of the electrolyzer design and operations, the connection is made with the 10kV or the 50kV network, represented by Path 1 and 2 in Figure 4.

The power systems operator provides the connection between the grid and the electrolyzer. The electricity is connected to transformers (trafo) to decrease the voltage level to the system requirements, which differ per size, design, and configuration. The electricity is rectified to DC and distributed via busbars. The electricity management system (EMS) includes the power operations and indicates when to conduct electricity, governed by the power software which includes the user interface, allowing for controls (PS1). Overarching to these processes, the electric security entails all grounding and kill-switches (PS1). The DC electricity is fed into the electrolyzer.

The second feedstock is water. However, to avoid rapid poisoning of the electrolyzer module, increase efficiency and reach high purity hydrogen, the water needs demineralisation (KI2). In case of a PEM electrolyzer, the water needs even further purification (KI2). Due to these additional requirements of the water provision, plant designs make use of an external module that arranges these process steps (KI2). The specific process adjustments, water output per time unit, demineralisation and purity levels need to be considered in agreement with the manufacturer of the electrolyzer (KI2). In the technology map, the responsibility of these processes is accommodated under water provision.

Finally, the system operator would oversee the actual process of electrolysis and arrange the operational parameters along with the desired output. The Original Equipment Manufacturer

(OEM) is regarded as the hydrogen technology provider and entail companies producing electrolyzer modules, which would sell the module to the constructor or system integrator. Again, the lack of standardisation of these processes leaves a margin for the interpretation of responsibilities, but this delineation is closest to the projected reality (EC2; EB1).

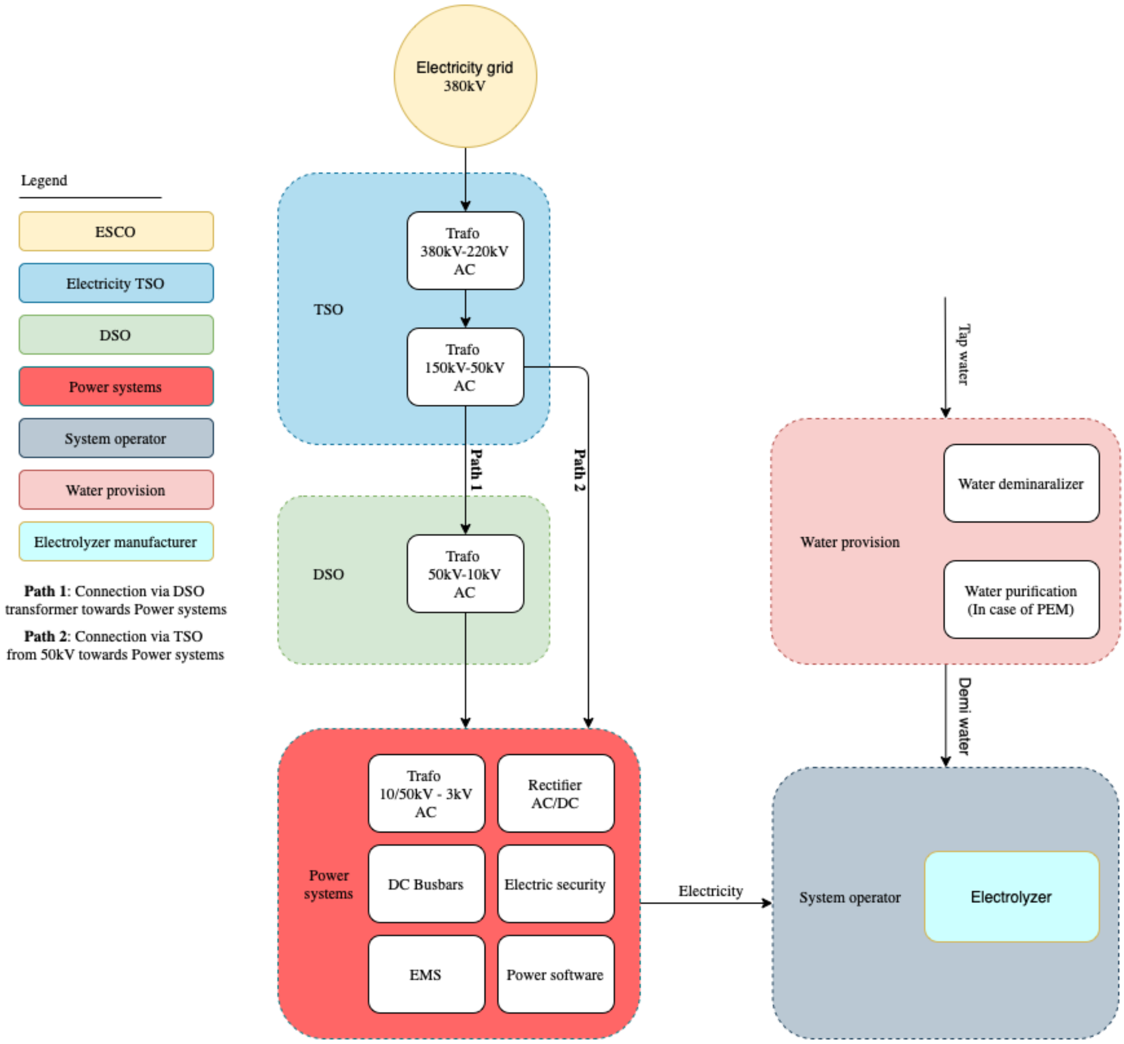


Figure 4: Overview of input electrolyzer accommodated in stakeholder groups

Output

The output of the electrolysis process is illustrated in Figure 5. The assumption is made that the system operator is presumed to operate and maintain all the processes illustrated within the grey square. The electrolyzer module is provided by an electrolyzer manufacturer. During the electrolysis process, thermal energy builds up due to the influx of electrical energy and the resistance it encounters in the material. The increase of thermal energy aids chemical kinetics and lowers resistance, but too much heat has a negative impact on the materials and lifetime of the module. Depending on the type of electrolyzer and configuration the ideal temperature alters, but to create an efficient and stable flow, it is key to maintain a constant temperature regardless of the approach (KI1). Therefore, a water-cooling module is connected to the electrolyzer. The generated heat is exerted outwards and can be utilized in a closed waste heat network to sell-off energy of what otherwise would go to waste. The water-cooling module is often provided by the same company as the water demineralisation and purification.

During the process of electrolysis, the liquid electrolyte will get contaminated with impurities and will result in loss of efficiency (KI2). Therefore, an electrolyte purification is required that rinses the liquid of any contaminants. When and in what quantity this will be done, is measured by a certain control mechanism linked to the electrolyzer. In most cases, these measurements, activation, and purification processes are automated and ultimately controlled by the internal computer of the electrolyzer (KI2). The industrial hardware is allocated to an industrial equipment manufacturer, which also produces the bulk of other BoP components, as seen in Figure 5. This again, is an assumption based on the different projects discussed during the interviews.

At the anode, oxygen is synthesized in a liquid as well as a gaseous state. A liquid/gas separator is used to exert the oxygen gas into the atmosphere, and the liquid oxygen will be reinserted in the process to turn into gas. With the increase of scale of operations, the exertion of oxygen gas is increased as well. However, there is a limit as to what quantity of oxygen gas per time unit may be pumped into the environment due to the explosion risk at high concentrations (EC2). A solution could be to capture the oxygen and sell it off, since the electrolysis process creates almost pure oxygen, which is in high demand by the chemical sector (KI2).

At the cathode, a similar process happens with hydrogen. The gaseous hydrogen is the output of interest. The gas is compressed further to decrease material use and increase efficiency. In the deoxidizer, any remaining oxygen is exerted from the mixture. The subsequent dryer exerts the remaining water vapour still present in the gaseous mixture. Eventually, the hydrogen gas is stored at a pressure of 30 to 700 bars, depending on the application and industrial equipment.

From the storage facility, the hydrogen can be transported via tube trailers, the most common method used to date (DSO/EC1). However, the Dutch government has ordered the preparation of the natural gas infrastructure to transport the hydrogen gas (EC2). The DSO is responsible for the local distribution of this network (DSO/EC1), whilst the national gas TSO Gasunie is responsible for the Dutch Hydrogen Backbone (EC2; EB1). It forms a network of large capacity gas-pipelines throughout the Netherlands and will be refurbished for the transport of hydrogen (EB1; GAS1). In the Netherlands, it connects the five industry clusters, namely, Rotterdam-Moerdijk, Chemelot, Northern Netherlands, North Sea Canal Area, and Zeeland (ISPT, 2020). The backbone should eventually link up to similar infrastructure in Europe (EC2). According to Gasunie, the backbone should be ready by 2030 (GAS1; Netbeheer Nederland, 2019). However, due to the lack of certificates, the transportation through public network is not yet possible, which is further elaborated on in the institutional analysis in section 4.1.4, part III.

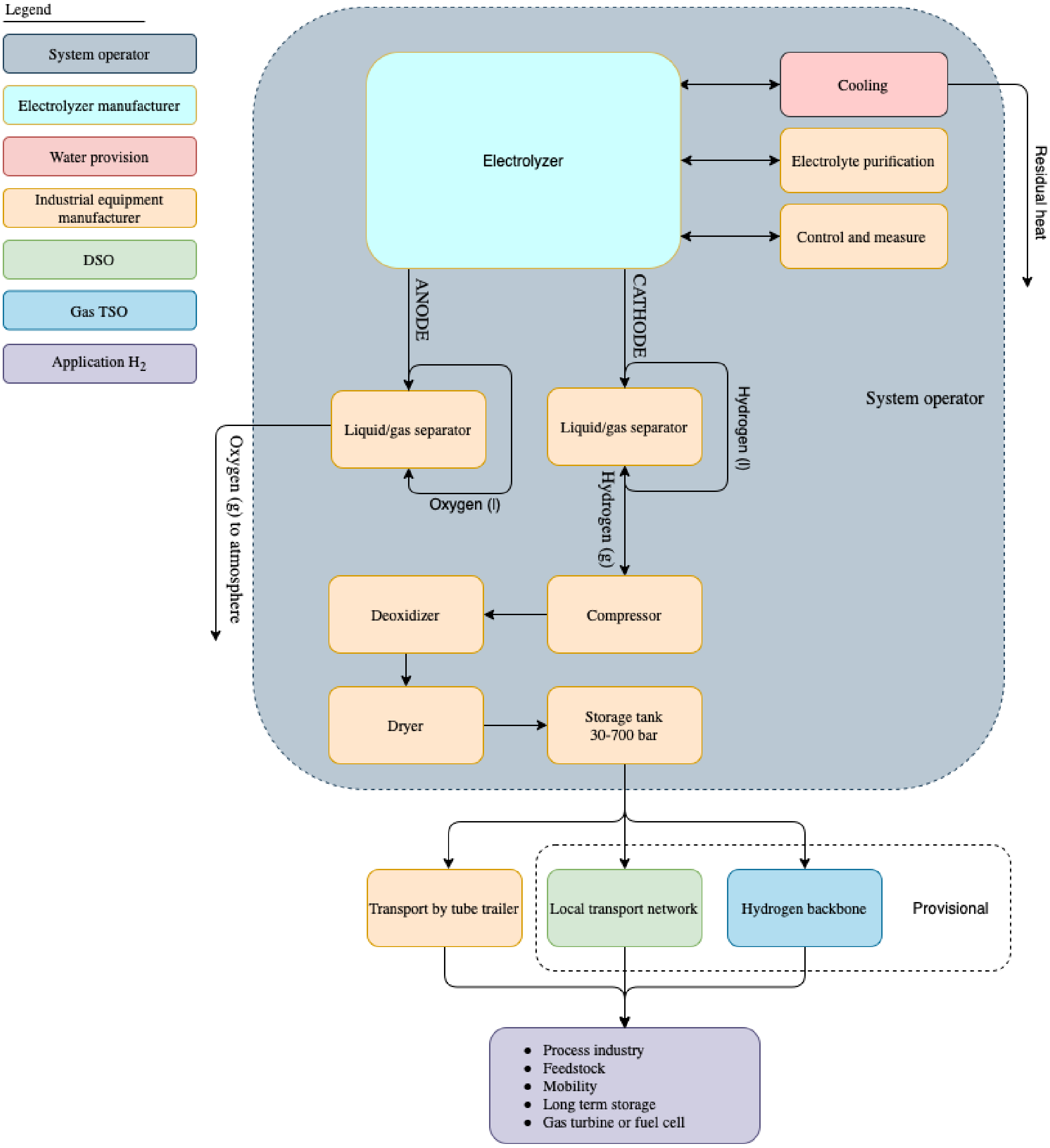


Figure 5: Overview of output electrolyzer accommodated in stakeholder groups

4.1.3 Network analysis

To gain an overview of all stakeholders involved in the system, the network layout of the Dutch TIS is presented in Figure 6. The purple lines between the stakeholders represent the edges. Edges are the links between stakeholders. Thicker lines represent multiple edges between the stakeholders, meaning they are connected in multiple projects. This visual representation goes for all network layouts presented in this thesis. Stakeholders that were not directly linkable to a stakeholder group from the actor analysis have been delineated in the stakeholder group 'other' but are not represented in the network analysis. Those stakeholders seem to have been incorporated for operational functions, with examples of actors such as a bakery and a dry cleaner. For full disclosure, these actors do have been listed in Figure 15 in Appendix D. Since these actors arguably have no impact on the TIS of hydrogen electrolysis in the Netherlands and unnecessarily complicate the visual network, this stakeholder group has been left out.

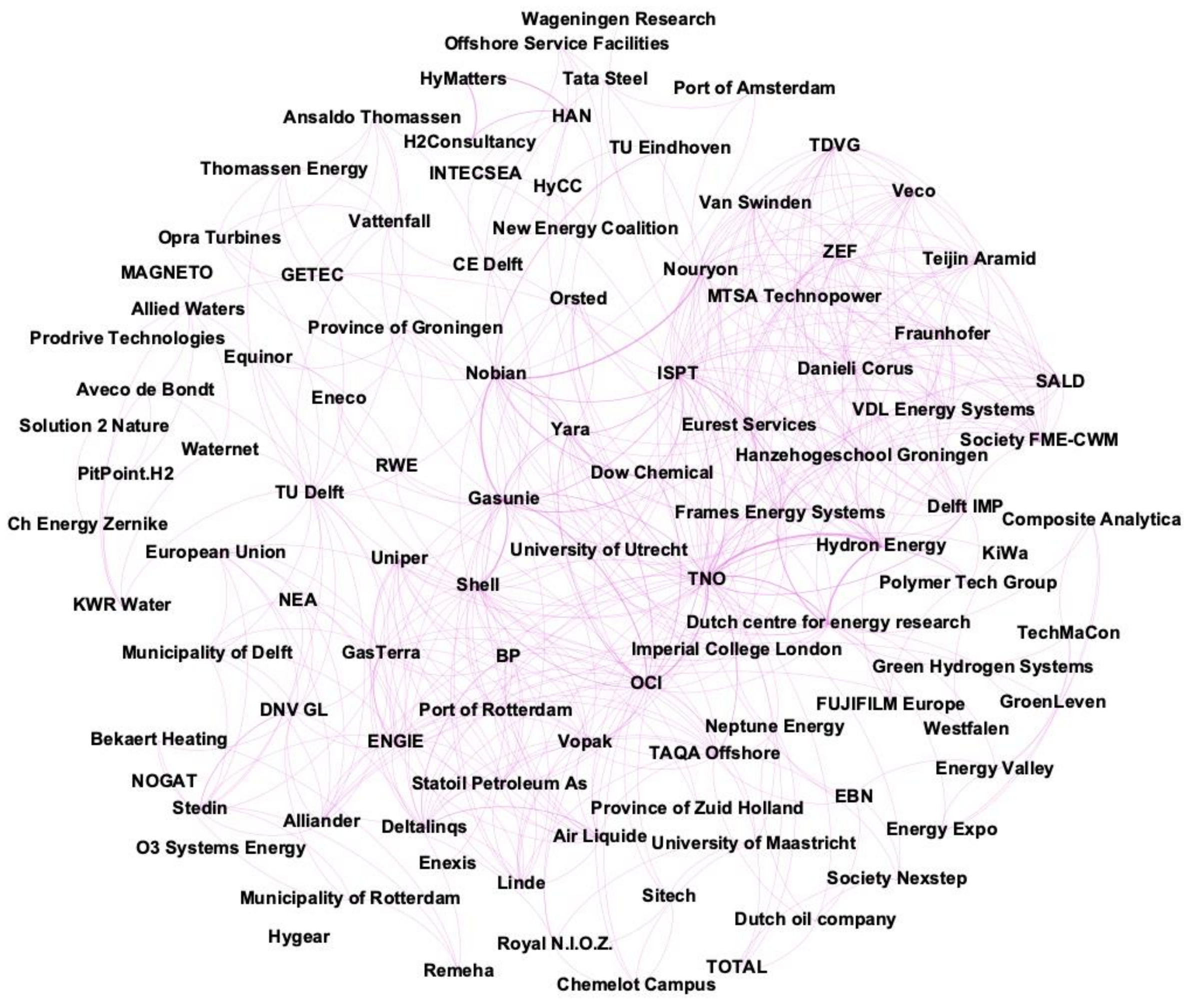


Figure 6: Network layout of stakeholders of the Dutch TIS active in hydrogen electrolysis projects from 2014 onwards

In the Netherlands, 41 projects concerning hydrogen electrolysis have either been completed or are in operation at the time of writing, since 2014. The Dutch TIS of hydrogen electrolysis based on the consortia data consists of 108 stakeholders. As seen in Figure 6, the stakeholders are interconnected. A higher density of edges could be the result of the randomized layout of the network, the fact that certain projects involve more stakeholders than others or the fact that a certain stakeholder is involved in multiple projects and thus exerts multiple edges. At first glance, more intense activity is seen between stakeholders in the middle and north-east corner of the layout. However, more network layouts will be required to untangle the integrated system of edges.

To gain understanding in what type of stakeholders are involved in the projects, the stakeholders have been categorized in the stakeholder groups delineated in the actor analysis in section 4.1.1. Similar to the network layout in Figure 6, the different stakeholders are linked if they are in the same consortium of a project. The size of the node is made relative to the number of degrees a stakeholder group has: more degrees is equal to a larger node. A degree is an integer and represents the number of connections a node has with another node. Certain nodes have a self-loop: an edge that bends back towards the same node, meaning there is a link between different stakeholders within the same stakeholder group. Nodes that were not connected to other nodes were removed via a filter in Gephi since it involved data malfunctions. An important sidenote on the network layout based on the degrees is that a large project consortium increases the number of degrees, whilst it remains a single project. Insights in the degrees are still useful because it provides an overview in direct links between different stakeholder groups, visualizing the level of interconnection in the system. The network layout solely based on degrees is displayed in Figure 16 in Appendix E. However, the degree has a skew impact on the visualization of activity from the different stakeholders and stakeholder groups. Therefore, the network layout in Figure 7 has been simulated by counting the number of different projects a stakeholder group is involved in. This integer is perceived as the precedence in a project and is shown next to the string of the stakeholder group.

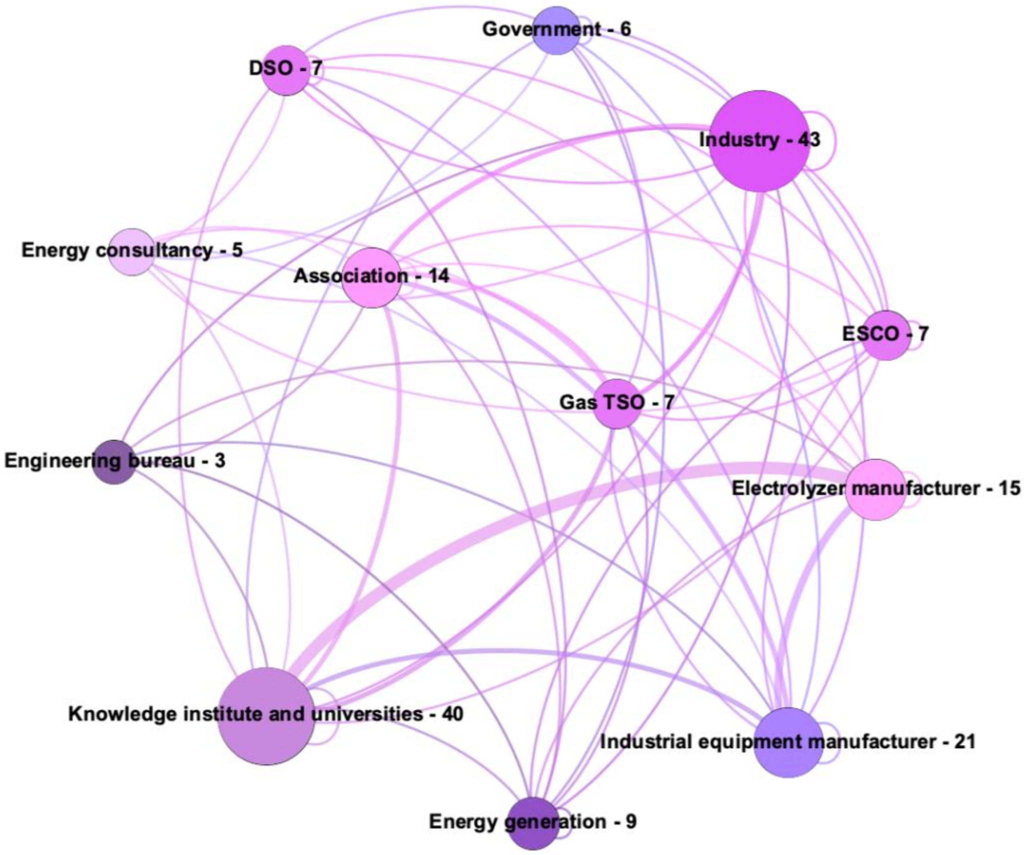


Figure 7: Network layout of involvement in number of projects per stakeholder group

From the network layout in Figure 7 can be derived that the industry and the knowledge institutes and universities are by far the best represented in the Dutch TIS. The industry seemingly contributes to 43 projects, whilst there are only 41 projects considered in the dataset. This is caused by the fact that a stakeholder group is counted multiple times if multiple stakeholders from the same group are involved within one project. An interesting remark can be made that more than half of the hydrogen electrolysis projects are conducted without the involvement of an electrolyzer manufacturer. In this network layout, the latter is most involved with the knowledge institutes and universities. The central and decentral government and semi-governmental DSOs contribute to six and seven projects, respectively. Important sidenote is that the Dutch government may not get directly involved with a project that is subsidized by public money, which is provided by that same Dutch government due to European tender rules (PS1). This could result in less direct involvement in the system, whilst the government would still stimulate the system via monetary institutions. In Figure 17 in Appendix E, a similar network layout has been made to Figure 7, yet the most active individual stakeholders are illustrated. The network layout is meant to visualize the most active stakeholders, thus individual stakeholders which are involved in two or less projects are not shown. By doing so, the network layout in Figure 17 remained organized and clear. With this final network layout, an interesting remark made in multiple interviews can be validated. In interview (DSO/EC1), (EC2), (IEM/IND1) and (EM1) a lack of standardization and the lack of involvement of stakeholders concerned with policy making contributing to the system is mentioned. In Figure 17, the 14 most active stakeholders are depicted, none of which are concerned with or capable of policy making. Another remark can be made that all 14 stakeholders are incumbent organizations and companies, potentially a result of the high system entry costs.

4.1.4 Institutional analysis

Due to the size and complexity of the TIS of hydrogen electrolysis, the institutional analysis is divided in four parts. The first part consists of institutions concerned with the input of the process. Second, institutions concerned with the manufacturing, installation, and operation of the electrolyzer, and BoP are analysed. Third, the institutions concerned with the output of the process, e.g., emissions and the transport of hydrogen. In the fourth part, institutions are analysed that concern the process as a whole and form a more general overlap.

Part I – input
The electricity TSO TenneT is responsible for the Dutch electricity grid from 380kV to 50kV, and the DSOs from 50kV downwards (DSO/EC1). As is also formulated in the Dutch Electricity act of 1998, an electricity TSO and DSO may not produce or actively trade in electricity (art. 10b. act 3. BWBR0009755, 1998). Generally speaking, a DSO is not allowed to trade or store energy, thus including hydrogen (DSO/EC1). Therefore, the assumption that an ESCO or a similar market party arranges the electricity contracts still holds and is in line with the technological analysis and conform reality in most cases (DSO/EC1).

One of responsibilities of the Dutch TSOs and DSOs is to transport natural gas and electricity and connect parties to those grids (DSO/EC1; GAS1). Due to the electrolysis mechanism, the focus is on electricity, and natural gas is left aside. A user of a connection pays a fixed tariff to the DSO, expressed in euro/MWh (EC2). The Authority Consumer and Market (ACM) supervises the DSOs and is responsible for the tariff setting (DSO/EC1; EC2). This fixed tariff is composed of the infrastructural investments needed for the connection and the projected transportation volumes of electricity (EC2). An interesting remark is concerned with the latter. The transportation volume is agreed upon a year in advance and entails a projection of the volume of electricity a party will consume that coming year (D-Vision & Ecorys, 2019). However, the transportation tariff is partly set in hindsight with the use of a kWmax, which entails the 15 minutes a month in which the highest capacity was reached in the contracted year (D-Vision & Ecorys, 2019). This kWmax is used as backwards tariff setting, whilst that exact power usage occurs only 15 minutes per month. If a kWmax is higher than the projected transported volume, the yearly tariff is increased based on that kWmax (D-Vision & Ecorys, 2019). In other words, if network congestion is apparent, and an operator of an electrolyzer wants to operate at full capacity, the operator could risk overshooting the transportation volume considered at the contract proposition. This mechanism does not lead to an incentive to relieve the congestion issues occurring on the grid, e.g., in times of high RES. On the other end, the business case for hydrogen electrolysis suffers. At times of high RES, the electricity price drops, hence, hydrogen could be produced at reduced costs. This mechanism is made aware by the ACM, and apparently undergoes a policy change (EC2) but at the time of writing no conclusion is published.

The origin of the label green hydrogen is still disputed. In case of the generation of renewable electricity, a certificate of origin is required to obtain the label 'green electricity' (EC2). However, for green hydrogen this is not yet the case (EC2; IND2; GAS1). This issue has been addressed in the Renewable Energy Directive (RED) II by the European Commission (ECom) in article 59 (ECom directive 2018/2001). This article states that 'guarantees of origin which are currently in place for renewable electricity should be extended to cover renewable gas … such as hydrogen' (ECom directive 2018/2001, article 59). The European directive entails an obligation for member states of the European Union (EU) to implement it into national law. To date, no such implementation has taken place in the Netherlands (EC2), which also resonates in the words of the province of Zuid-Holland. The province has 'a preference for the production of green hydrogen from completely fossil-free energy sources' (PM2, question 1). In short, there is a profound preference, but no enforceable definition of green hydrogen. This keeps creating uncertainty when hydrogen electrolysis can be labelled as green, which could pose as a problem in the future when European regulators want to achieve the use of 50% green hydrogen in industry by 2030 (PI/PM1; EC directive 2021/803). Besides the exact definition, there is also no organisation made responsible for the issue of such a label (KI1). An important remark was made in interview (PI/PM1) concerning a proposed leaked European delegated act. The supposed leaked document could not be retrieved, although associations like Hydrogen Europe published a comment on the leaked act as well (Collins, 2022). Therefore, the existence of the document cannot be verified but since the aftermath of the document was visible on news sites and the act was mentioned during the interview (EC2; EB1; PI/PM1; IND2), it is assumed to be real. In this act, the rules for green hydrogen are delineated (PI/PM1). First, the RES feeding the electrolyzer needs to come from an additionally build renewable electricity plant such as a wind farm, it is not allowed to use existing ones (PI/PM1). Second, the electricity must be generated within the same bidding zone, meaning it is not allowed to import electricity and utilize it (PI/PM1). The Netherlands consists of one bidding zone (PI/PM1). Third, the electricity needs to be consumed within 15 minutes of generation (PI/PM1). Two methods exist for complying to the third rule: a direct connection to a RES, or with the use of a Power Purchase Agreement (PPA) (PI/PM1). In a PPA construction, the electrolyzer could be connected to the main grid because one would be bound by operational hours per year (PI/PM1). These yearly operational hours correlate with the share of RES in the energy mix, and currently entail 2000-3000 hours (PI/PM1). In conclusion, if a party would uphold to these three rules and use an electrolysis process to synthesize the hydrogen, it would be labelled as green hydrogen according to that delegated act that should have been published in June of 2022 (PI/PM1). However, the delegated act is still up for revision, so no further conclusions can be made.

The preference of origin from the decentral government also resonates in the use of water. The statement of the province of Zuid-Holland to use 'preferably no scarce fresh water' (PM2, question 1), could increase purification costs and material use of the water feedstock. The purification set-up depends on the method of electrolysis and tolerance of the specific device (KI2; EM1), so the eventual impact is difficult to predict accurately. However, since it entails a preference, the sincerity of and the method for enforcement are unclear.

Concerning the input of water and electricity, unclear delineations of origin and difficult to legally enforce preferences increase the uncertainty for the implementation of the electrolysis technology. Additionally, the business case is undermined with the outdated tariff setting, which in turn does not serve as an incentive to decrease the congestion on the electricity grid.

Part II – hydrogen production

In light of the production of hydrogen via electrolysis, the manufacturing, installation, and operation of an electrolyzer and the BoP are considered. To further scope the analysis, the focus has been on the acquiring of certificates and permits, since this was a prevalent subject during the data collection. As additional data, a standard also delineates the design space of a device. If a range or limit is set on the pressure of a system, the manufacturer can design a device that is most efficient at that specific pressure (EC2). Since these standards will be market wide, all competitors will be required to uphold them to be able to operate their devices on the Dutch market. This also creates the possibility for producers of BoP components to calibrate their product to those properties. In those manners, standards contribute to a safe and efficient system.

Concerning hydrogen electrolyzers, a certificate is found in the form of NEN-ISO 22734:2019. However, this document is only obtainable at a fee of 175€, which was already mentioned during interview (EC2). From the preview copy becomes clear that the document involves operating conditions and safety standards (NEN-ISO 22734, 2022). However, no form of efficiency measurements or guidelines for connecting the electrolyzer with variable load from RES are mentioned, which is also made clear as a barrier in interview (EC2).

Additionally, a lack of standards on efficiency and utilization also contributes to unrealistically high expectation of the technology (KI1; EM1). Reports of requests for unrealistically high efficiency (KI1) or a desired hydrogen output that is multiple times the current maximum (EM1) are prevalent. These requests are made by actors who want to install an electrolyzer, mainly the industry sector (KI1; EM1).

The argument made is that the lack of standards hampers the efficient modification and production of electrolyzers as well as BoP components, increase transaction costs and giving room for unrealistic expectations. A potential reason could be the fact that the technology is not widespread amongst different actors or certifications like the NEN-ISO 22734:2019 leave too much room for interpretation.

Part III - output

In consideration of the electrolysis process, the output entails the transport from the storage medium to the application of the hydrogen gas. As mentioned in the technological analysis in section 4.1.2, the common method for local transportation is via pressurized tube trailers (DSO/EC1; IEM/IND1). On industrial sites, pipelines are used to transport grey hydrogen from the SMR reactor to the location of application, but no public network exists (IEM/IND1). The use of an integrate network of pipes capable of transporting large quantities of hydrogen could connect locations with nearby RES and high hydrogen demand, decreasing transport costs per volumetric unit (IEM/IND1). The Dutch Hydrogen Backbone by Dutch gas TSO Gasunie mentioned in the technological analysis could accomplish just that (EC2). Similar to the national natural gas grid, the backbone would remain the high-capacity ring with local branches constructed by the DSOs (DSO/EC1; GAS1). Gasunie would remain responsible for the high-capacity backbone and uphold a certain level of pressure, whilst the DSOs would be responsible for the local branches and connections to lower-level users (DSO/EC1). Gasunie is not allowed to determine what ‘colour’ of hydrogen is provided by the hydrogen suppliers to the backbone (GAS1).

However, even though Gasunie and the DSOs are made responsible by law for grid transport of hydrogen (art. 10d, act 2E, BWBR0011440, 2000), the DSOs ‘are not officially permitted to transport hydrogen. Just natural gas and electricity.’ (DSO/EC1, 14:23). Neither is Gasunie (IEM/IND1). The Dutch Supervisory Service of Mines (SSM), the supervisor of the public gas networks, has not issued a permit for the transport of hydrogen (DSO/EC1). According to interview (DSO/EC1), they are ‘literally being educated in hydrogen simultaneous to us. But they don’t know anything about hydrogen yet’ (DSO/EC1, 16:26). In other words, Gasunie and the DSOs are made responsible by law for the transport of hydrogen through public pipelines but are not permitted to actually transport it. In current projects the DSOs are allowed to transport hydrogen through a pipeline since it remains small-scale, but it remains no more than a condoning approval (DSO/EC1).

The foresights of an integrate hydrogen pipeline infrastructure have deemed the Netherlands as a fruitful country for the deployment of a hydrogen economy (EB1), but the physical infrastructure is not ready by 2030 whilst institutional arrangements still need to be set.

Part IV – General
An important legislation package in the context of the TIS is the European Fit-for-55. The Fit-for-55 package aims at a reduction of at least 55% of GHG emissions by 2030 in the EU, relative to 1990 and has been used to adapt the RED II mentioned in part I of the institutional analysis (ECom directive 2021/803). In this proposed directive, the target is set at a use of 50% of renewable hydrogen for energy and industry feedstock purposes by 2030 (PI/PM1; ECom directive 2021/803). However, the directive is still in the process of revision by the European Commission (PI/PM1; ECom directive 2021/803). The lack of clarity from the European Commission on the revision of the RED II directive also limits the Netherlands Enterprise Agency (NEA) in creating adequate instruments for financial incentives and regulations (PI/PM1).

In light of the recent war in Ukraine and the crisis with Russia, the EU issued the REPowerEU initiative to decrease dependency on Russians energy supply (EB1). In this mandate, the EU increases the projected output of hydrogen (EB1). 'Initially, the goal was to create around five megatons of domestic hydrogen production to serve the market, that translate to few 10s of GWs. In the REPowerEU, that has been scaled to almost 15 megatons additionally. So, we are talking about almost 20 megatons of hydrogen -*annually*- that we would need by 2030. Out of the 20 megatons, at least 10 has to be imported, that has been made clear by the REPowerEU mandate' (EB1, 00:26). It remains unclear if the REPowerEU will be transposed in legislation or directives.

The proposed RED II and the REPowerEU mandate do provide a sense of direction and expectations on the use of hydrogen. However, since the directive and mandate entail a proposal and vision document, the need to still implement it in national policy of the different member states remains and thus the execution of those measures seems not apparent in the near future.

As a means to provide an impulse to sustainable technology development, the Dutch government has multiple subsidiary programs in place (PI/PM1). These programs are designed by the Ministry of EAC and implemented by the NEA (PI/PM1). The coming subsidiary programs have been mentioned in interview (PI/PM1) because they are deemed best applicable to the TIS.

The Dutch DEI+ subsidy is issued for innovations in lower Technology Readiness Levels (TRLs). The TRL scale is used to assess the level of maturity of a technology and ranges from one to nine (Sauser et al., 2006). A TRL of one correlates with the theoretic and basic notion of a principle, whilst a TRL of nine means a fully mature and commercialized technology (Sauser et al., 2006). The DEI+ offers means for innovative, small-scale pilot projects. In context of an electrolyzer, an application of a DEI+ subsidiary has become difficult since most electrolyzer technologies have past the lower TRLs (PI/PM1). However, for specific adjustments or creative implementations, it is a useful program (PI/PM1). The DEI+ is an investment support instrument, applicated to lowering the CAPEX necessary for running the pilot (PI/PM1).

The Dutch SDE++ subsidiary program entails a 'fund from the government to support climate neutral investments in the industry' (PI/PM1, 03:43). However, one of the prerequisites to obtain the subsidy is a maximum cost of 300€ per tonnes of CO_2 saved by the technology (PI/PM1). However, under current circumstances, CO_2 abatement by electrolyzers is more expensive than that (PI/PM1). Similar to the DEI+, the SDE++ subsidy is a direct financial investment, issued to lower the CAPEX (PI/PM1).

Another Dutch program is specifically designed for the upscaling of electrolyzer capacity and involves a subsidy which is meant to speed up the implementation of electrolyzers up to 50MW (PI/PM1). The subsidy has been announced but is not yet open for application. A maximum abatement cost of CO_2 is not applicable (PI/PM1), solving the issue with the SDE++ subsidy.

The European IPCEI subsidiary program is aimed at a GW scale of electrolyzer capacity and involves a fund with multiple billions of euros (PI/PM1). An additional benefit of the European subsidy program is the less strict rules and regulations, where national subsidiary programs are not allowed to back up a 'national champion' (PI/PM1), indicating an invested and incumbent company that has dominated the sector for a long period of time. The issue of these strict and limiting rules has also been emphasized in interview (PS2), also explaining the low participance of the Dutch government in most of the hydrogen projects from section 4.1.3.

Another European subsidiary program is REACT, with a budget of over 50 billion euros. The program is used to solidify and increase resilience of the European economy in the aftermath of the COVID-19 crisis. Part of the budget is reserved for sustainable initiatives, and whilst the exact requirements remain vague, the hydrogen project mentioned in interview (DSO/EC1) has made use of multiple millions of euros from the REACT fund.

The subsidy programs mentioned above can cover up to 50% of expenses (PI/PM1; PS2).

4.2 SQ 2 Functional analysis

The performance of the TIS of hydrogen electrolysis in the Netherlands is mapped by assessing seven system functions, which embody the key processes necessary for the development. The outcome of the label score of the expert interviews according to the indicators presented in section 3.2 is presented in Table 7. The data presented in Table 7 is a cumulation of the individual datasets per interview which are presented Appendix F.

Table 7: Data from labelling expert interviews

System function	Positive	Negative	Sum	Score
1	47	8	+39	4.3
2	28	4	+24	4.4
3	21	12	+9	3.2
4	51	35	+16	3.0
5	24	18	+6	2.9
6	35	33	+2	2.6
7	12	9	+3	2.9

However, due to the fact that certain statements presented by experts have a higher impact on the performance of the functions, a qualitative analysis is used to supplement the scores presented in Table 7. This will lead to the analysis score mentioned in the methodology.

4.2.1 Entrepreneurial activities

From the IEA database is derived that Dutch stakeholders are involved in 41 hydrogen electrolysis projects, out of 990 worldwide (IEA, 2021c). However, as is mentioned in interviews (KI1) and (GAS1), the lack of MW-scale projects limits the impact on the formation of the infrastructure, the development of a market and the overall trust in the system. Throughout the data analysis, four reasons concerning entrepreneurial activity were found that provide a plausible cause for the absence of these large-scale implementations.

System entry barrier
Economies of scale are necessary to eventually compete with the production of grey hydrogen (KI1; DSO/EC1; IND2), however, to create an economy of scale, a large amount of financial capital is required. Since the estimation that the CAPEX of an electrolyzer ranges between €1400/kW and €1800/kW depending on the specific approach (ISPT, 2020), multiple MW systems require millions of financial inputs. Even more, the OPEX of the system is estimated at an even higher strain on the investor (EM1). For these systems, financial capital is required that may be hard to come by for companies such as start-ups. That may also be an explanation to why all top 14 stakeholders are large, incumbent companies, as was found in the network analysis and no start-up appeared in the database. Entry barriers cause the need for large investments, bringing risk and reluctancy.

Complexity
Second, the implementation of an electrolyzer involves a complex process. The exact operations and responsibilities differ per project and specialisation is difficult. From the dataset used for the network analysis also led that 23 out of 41 projects conducted involved four or more stakeholders. As an illustrative example, the following case was found in the interviews: the DSOs and gas TSO are not allowed to trade or store energy, nor operate an electrolyzer (DSO/EC1; IEM/IND1; GAS1). Consequently, the complexity amongst the different stakeholders increases and an energy cooperation or trader must be involved (DSO/EC1). However, as amplified in the interview (DSO/EC1), some stakeholders 'cannot invest in the system themselves because it is too expensive, too large an investment for some local energy cooperation. So, it creates really complex system and stakeholder structures' (DSO/EC1, 17:43). And thus, additional investments are required by different stakeholders. The added complexity of different stakeholders poses additional transaction costs, whilst a higher level of trust will be required to develop a connection amongst multiple stakeholders.

Stakeholder standoff
Third, during the interviews, multiple times is mentioned that the stakeholders are looking at each other and are taking a wait and see attitude (EC2; EB1; IND2; GAS1). As a consequence of the entry barriers and the added complexity, the investment risks are high and unprecedented (IND2). The illustrative example mentioned in the previous paragraph is extended: only the DSOs and gas TSO are allowed to transport via the orchestrated hydrogen backbone. Since this network will possibly be the cheapest transportation means, involvement of those stakeholders is required. However, the construction is partly upheld due to the lack of contracts by producers of hydrogen (GAS1). In turn, these producers claim to invest in electrolyzer capacity once the infrastructure is finished (IND2). For these producers, the lack of conformation from the consumers also plays a role in the investment decisions (IEM/IND1; IND2).

Underrepresented stakeholder groups
Fourth, as was also remarked in the network analysis in section 4.1.3, the lack of NGOs and societal groups could have an impact on the interest and credibility of the system. These

stakeholders are considered to have an impact due to the fact that 'they are more like independent resources that are more reliable because they do not have a political agenda. Or they are not driven by such political agenda' (KI1, 30:47). An example was provided in interview (IND2) on green steel certificates. Certificates such as these, could be best uphold by transparent and non-political organisation such as NGOs, to increase the trust in the system (KI1). The impact of green certificates such as green steel, could push steel producers into investing in hydrogen electrolysis (IND2), increasing their activity.

Important players contribute

From the network analysis in section 4.1.3 led the insight that the industry sector is the most involved stakeholder group in previous and current hydrogen projects. That marks an important insight, since multiple experts amplified the necessity of the industry to experiment with the implementation of the technology (DSO/EC1; KI1; PS3; EB1; IEM/IND1; IND2; GAS1), with an emphasis on multinational petrochemical companies such as Shell, BP, and Chevron. A repetitive argument is that these actors 'have an immense amount of knowledge on chemical processes at scale.' (KI1, 28:20). Their involvement is most likely an important kick-starter for the further deepening and implementation of the technology. It marks the notion that the argued most important stakeholder group is also the most involved. Additionally, a petrochemical multinational also cooperates together with DNV GL, both on their own initiative (EC2). The aim of the collaboration is to create a framework with practical standards, since the lack of such issued by the government is holding up the implementation (EC2). The latter is elaborated on in guidance of the search, but the initiative shows the pro-active attitude of the industry and important certificate organizations such as DNV GL.

Score

The entrepreneurial activity is perceived as hesitant by certain stakeholders (KI1; PS1; EB1; GAS1). Four reasons plausible were mentioned why these stakeholders are reluctant towards investing on a larger scale. However, the relatively high number of demonstration projects conducted along with the notion that the most important stakeholders are invested in the system, provide a positive note. Additionally, with the exemption of Strukton Power (PS1; PS2; PS3), the stakeholders interviewed all had separate hydrogen departments, showcasing the initiative to contribute to the Dutch TIS. The labelling of the interviews resulted in a score of 4.3, but in light of the argumentation mentioned in this section, the performance of SF1 is settled at 3.

4.2.2 Knowledge development

High interest in knowledge development

First of all, insights from the two stakeholders highly involved with knowledge creation led to the notion of increasing research activity concerning hydrogen electrolysis (KI1; KI2). The high and increasing interest by research groups mentioned in interview (KI1) and (KI2) also correlate with the involvement of knowledge institutes and universities as was found in the network analysis in section 4.1.3.

Additionally, during interview (KI1) became clear that private stakeholder groups also show a willingness to contribute to the knowledge development, by financially contributing to research groups. During interview (PI/PM1) became clear that the Dutch government also funds learning trajectories focused on innovation in the sector. However, both the private sector and the government conduct different demonstration projects focused on learning. Said projects have been or currently are being conducted by DSOs (DSO/EC1) and industry (IND2). Other learning activities include safety tests (EC2), and the active influx of tacit knowledge from the formal natural gas sector (GAS1). With the use of demonstration and pilot projects conducted, the Dutch TIS entails an increasing activity in learning by doing. This led to a high performance of SF2 across different stakeholder groups. However, in interview (KI1) is mentioned that the lack of MW-scale pilots results in a data gap on the behaviour of the technology. As is also amplified in interview (EM1), the necessity to show reliability at different scales is underestimated by policymakers.

Articles

To assess the number of Dutch publications over the past 20 years, the database Web of Science is used along with the keyword 'hydrogen electrolysis'. By filtering on Dutch publications and counting the articles, a positive trend was discovered and depicted in Figure 8. The incline supports the high interest beforementioned. A similar incline in published articles is stated in Griffiths et al. (2021). From the same Web of Science search led that the Netherlands ranked 15th globally, concerning the number of publications on hydrogen electrolysis.

Figure 8: Scientific publications based on database Web of Science

Patenting

Private R&D expenditure could provide insights in future strategies of the actor. Therefore, it is assumed that such exact numbers are not made publicly accessible. To operationalize the R&D of private companies, the number of patents is regarded as an indicator for said investments. It is assumed that if a company invests in R&D, it will likely protect their insights and technology. Since the use of a patent allows for such protection and a patent has to be made public, the private R&D activity of a technology can be quantified. According to the most recent patent insight report from the European Patent Office (EPO) in collaboration with IRENA, the number of patents issued on hydrogen electrolysis has risen by an average of 18% annually between 2005 and 2020 (EPO & IRENA, 2022). According to the report, with 326 active patent strings on hydrogen electrolysis, the Netherlands ranks 6th worldwide, as is displayed in Figure 9.

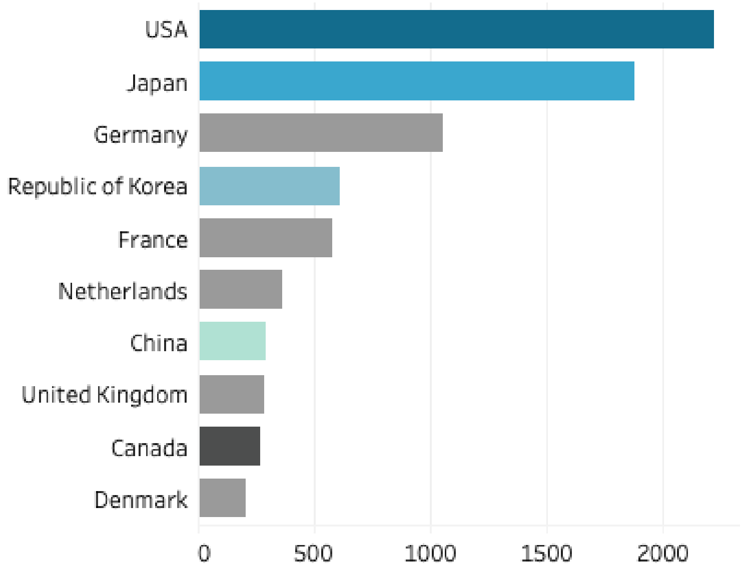


Figure 9: Top 10 patenting countries, based on IRENA database, accessed via report EPO & IRENA (2022, p. 9)

Lack of standards in knowledge development

The lack of clear standards either from the government or the industry itself has been named as a barrier by multiple stakeholder groups. Research by knowledge institutes and universities towards a more efficient system is dispersed due to the lack of specific design requirements, such as pressure, current densities, material use, overpotential, and safely operable and reliable material temperatures (KI1). This creates a disperse approach amongst researchers, with certain research groups building forth on adjustment A, whilst others focus their system on adjustment B (KI1). In the case a standard is set in place, one of those adjustments will be rendered obsolete, so it is partly wasted energy and resources (KI1).

Score

Although electrochemical synthesis of hydrogen has been conducted for decades, the multi-MW scale implementation proposed in policy documents brings new challenges. The high and increasing interest in the technology by either knowledge institutes and universities, as well as private actors, forge a fruitful basis for knowledge development. This fruitful basis also pays out in terms of increasing numbers of articles published and patents uphold. However, the lack of pilots on MW-sale creates a knowledge gap and limit the ability to show robustness and reliability on a larger scale. Another remark was made on the efficiency of the research due to a lack of standardization.

The high interest and efforts made by multiple stakeholders shows the power of the TIS. However, the lack of large-scale implementation limits the availability of data on robustness and reliance of the technology. The label score resulted in a 4.4, but in light of the argumentation mentioned in this section, the analysis score of SF2 is settled at 4.

4.2.3 Knowledge diffusion

As was described in the section above, the knowledge development of the TIS is performing well. However, not only the absolute knowledge of a technology has an impact, also the diffusion and availability of said knowledge is considered a key process. Interaction and coordination of the tacit knowledge accumulated during experiences with the technology could facilitate a higher performance of the TIS.

Conferences
By scanning through the agendas on websites from associates such as *Topsectoren Energie* and *Waterstofnet*, it became clear that hydrogen events are abundant. With the inclusion of online events, for the past half year, public accessible events focused on hydrogen have been organized more than once a week. Although differing in size, the events share a common commitment to distribute knowledge on the technology, organize network activities, and create awareness on the existing possibilities of green hydrogen. The direct effect of a conference is difficult to measure, but it is argued that the public events attribute to the diffusion of knowledge amongst involved professionals and the attending public. The effort also acts as an endorsement to the expectations of the technology, increasing the performance of the guidance of the search (SF4).

Low willingness to cooperate between private and public institutes
As mentioned in SF1 and SF2, the lack of multi-MW scale projects poses a barrier for certain implications and technological capabilities. It is partly caused by a low willingness to cooperate between public and private stakeholder groups (KI1). As mentioned in interview (KI1), certain knowledge cannot be created at the scale of which universities conduct experiments. The entry barriers mentioned in SF1 limit the implementation of expensive multi-MW scale systems (KI1). Financial injections from the private sector could help (KI2). However, during the data analysis, perceived downsides of collaboration with a knowledge institute or university were mentioned by private stakeholders. First, in case of a public issued project, 'involving a knowledge institute usually creates extra costs that will lose you the tender' (PS1, 26:32). This could be especially limiting, since these tender projects would likely be at a scale which universities cannot initiate, as described by (KI1). Second, in interview (PS2), the lack of a hands-on, practical approach is mentioned as a barrier to cooperate, stating that 'there can be a discrepancy between a practical solution and an academic challenge … between theory and real-world' (PS2, 45:38). So, besides the unwillingness or inability of funding, the objectives of the different parties also seem to differ from a fundamental point of view. Third, as indicated in interview (KI1) and mentioned in the institutional analysis and SF2, is the lack of clear standards. The lack of a standard leads to unrealistic expectations by the private sector over the outcome of research and project results, creating friction (KI1).

A consequence of the limiting knowledge diffusion through the system is mentioned in interview (DSO/EC1). As is also extensively mentioned in the institutional analysis, the Dutch SSM has not issued a permit to the DSOs and for the transport of hydrogen (DSO/EC1). According to the interview (DSO/EC1), this is a direct result in the lack of knowledge diffusion, since the supervisor is educated simultaneously to the DSO during the demonstration project mentioned. In turn, this also has an effect on the guidance of the search since relevant policymakers are not able to issue appropriate standards and permits.

An interesting notion is that from the network analysis conducted in section 4.1.3, could be derived that knowledge institutes and universities have been or are involved in 40 out of the 41 projects. So, even though multiple downsides were mentioned in the interviews, the activity among previous and current projects indicates a high interaction.

Educational arrangements
In interview (DSO/EC1) became clear that learning trajectories are being organized for mechanics with an interest in the applications of hydrogen. On their own initiative, DSOs contribute to knowledge diffusion with projects such as the hydrogen demo house (DSO/EC1). However, with 12 mechanics per cycle, still small in scale (DSO/EC1), the initiative of such learning trajectories aid in the diffusion of knowledge. In interview (GAS1) became clear that

the tacit knowledge from the former gas industry is incorporated in new hydrogen departments, diffusing knowledge from a similar subject into the system.

Score
It is made clear in interview (KI1) and (KI2) that private capital is necessary for a larger scale project. As mentioned in SF1 and SF2, these types of projects will boost the TIS. However, what resides from the analysis of SF3 are the multiple downsides of collaboration within a research project. The low willingness to cooperate could partly explain why these projects and activities seem to lack in reality. The low willingness causes a low performance of the knowledge diffusion, of which the direct consequence is mentioned in interview concerning the hydrogen transport permits (DSO/EC1). Learning trajectories and frequent conferences do contribute to the knowledge diffusion and may be seen as an effort to close the gap between private and public organization. Despite the multiple downsides mentioned, knowledge institutes and universities are involved in 40 out of 41 hydrogen projects. The labelling of SF3 showed a score of 3.2 and due to the arguments mentioned above, the analysis score is settled at 3.

4.2.4 Guidance of the search

Target setting
As was laid in design in the Dutch *Klimaatakkoord* of 2019, and imbursed in the Dutch coalition agreement of 2021, 500MW of hydrogen electrolysis should be installed by 2025 (Yesilgöz-Zegerius, 2021). By recent words of the Dutch minister of Climate and Energy, that capacity should be expanded to reach 8GW by 2030 (Stellinga & van der Walle, 2022). During the expert interviews, varying expectations on the feasibility of these plans were given. However, of those who questioned the reality of these numbers, all but one reimbursed the importance of setting high target goals (KI2; EB1; IEM/IND1; IND2; GAS1). By doing so, the government is providing a message to the stakeholders involved. The message is that hydrogen electrolysis can count on the support and endorsement of the Dutch government. It is argued that target setting issues trust in a technology, and with the endorsement of a central government, the investment risk decreases. By doing so, the performance of the function resonates back-and-forth to SF1 and SF6, where more trust leads to more entrepreneurial activity and resource mobilization.

The endorsement of the Dutch government is no stand-alone. The ECom targets for at least 40GW of electrolyzer capacity by 2030 within the EU (European Commission, 2020). Since the EC indirectly influences Dutch regulations via directives, this target also impacts the Dutch TIS. As is mentioned in interview (IEM/IND1; EM1; IND2), incumbent players in the petrochemical-, heavy-, and process industry also target to transpose their hydrogen generation via SMR towards electrolysis in the coming years.

Expectation of experts
Every expert interviewed in this thesis expects the technology to play a role in the future Dutch energy system. The level of capacity differs amongst the experts, but all expect an increase, nonetheless. As is strikingly captured in interview (KI2, 31:36): 'Part of the palette of solutions of that we will have in the future, is hydrogen'. All experts mentioned the application of hydrogen electrolysis for SC and as feedstock replacement for grey hydrogen. Endorsement as peak shaving utilization was mentioned in interview (DSO/EC1; PS1; PS2; GAS1).

The negative expectations mentioned in the interviews were caused by the long time-to-market of an electrolyzer, the effect of the electricity price on the OPEX, and the scale of operations. These negative expectations all related to the target of the Dutch government to have 500MW installed by 2025, not particularly on the prospect of the technology itself.

Absence of standards in design and operation
The lack of efficiency measuring standards could well be a consequence of a new technology, however, as was mentioned in interview (EC2), the Dutch government seems not to take an initiative to create them. Efficiency measurements and utilization of MW-scale electrolyzer installations are currently initiated by private instances (EC2). Standardization issued by the central government could streamline production and implementation of electrolyzers (EM1), decreasing time-to-market and focus the knowledge creation for higher efficiency (KI1). Organization of the standardization process befits the permitholder that is the central government and would align the stakeholders of the TIS.

Counterintuitive legislation and sluggish adjustment
The use of a hydrogen pipeline infrastructure could reduce the transportation costs and allow the creation of a commodity market (IND2) however, the DSOs and gas TSO are not permitted to transport hydrogen. In interview (DSO/EC1) was mentioned that the Dutch government is discouraging DSOs to partake in hydrogen projects up to 2030. Even though presently, the amount of electrolyzer capacity installed would not rationalize a large hydrogen infrastructure (GAS1), demonstration projects create and diffuse knowledge and potentially create a market pull. Especially since the DSOs and gas TSO are the only entities allowed to transport hydrogen via a public pipeline (DSO/EC1; GAS1). Including these stakeholders in future MW-scale projects seems rational.

A similar point was mentioned in interview (EC2) and confirmed in D-Vision & Ecorys, (2019). The pricing scheme with the use of a kWmax seems to originate from the time of a central energy system, and even though the legislation is up for debate (EC2), no change on the price structure has been made. This also decreases the competitive advantage of an electrolyzer installation, especially since electricity contributes most to the OPEX (EM1; ISPT, 2020).

European directives
With the Fit-for-55, the EU issues a directive to force the use of at least 50% green hydrogen by 2030 (PI/PM1; ECom directive 2021/803). The directive is still in proposition under the RED II adjustment, but if agreed upon, will serve as a boost to the development of the TIS. However, the uncertain situation of a certificate for the origin of green hydrogen limits the impact of the directive. With the leaked delegated act of the ECom, the origin of green hydrogen will likely be sorted (PI/PM1). The act will also provide rules on when to get a European or national subsidy (PI/PM1). The fact that such a draft is in the pipeline, provides a sense of guidance and direction. The delegated act will likely resolve around three rules to label hydrogen as green or renewable. The additionality of the RES, the use of the RES within the same bidding zone and the use of the RES within 15 minutes or with the use of a PPA. The latter would limit the electricity supply to 2000-3000 hours a year, since it scales with the percentage of RES in the energy mix. The act has yet to be published. From the interviews, there has been critique, especially on the additionality rule. That critique is mentioned under SF6.

Even though the most likely case that by 2030, such a certificate is used (PI/PM1), currently the uncertainty does not allow the industry to invest and participate to the directive. If 50% of the 100PJ worth of hydrogen used in Dutch industry needs to be replaced via domestic production or via imports, such large adjustments take many years of planning, commissioning, and construction (IEM/IND1).

With the Fit-for-55 package and the delegated act, the ECom seems to steer towards a mandatory use of green hydrogen in industry. However, since these directives will have to be implemented in Dutch law as well, the implementation of such mandates will not be issued in the near future. As mentioned in interview (PI/PM1), the Ministry of EAC wants to create a long-term goal but is waiting on European legislation. In the meantime, the industry upholds investment decision (PI/PM1; IND2), negatively impacting SF1 and SF6.

Low consumer incentive
Whilst the situation holds that electrolysis of hydrogen will be more expensive than via SMR, it is not rational for consumers to adopt the costlier hydrogen. As a result, investments in electrolyzers are put on hold, partly because the risk of not reaching at least the break-even point is too high (IND2). This negatively impacts the incentive to invest. The consumers are 'waiting for either subsidies or that it's going to be mandatory, and everyone has to do it so as not to be left behind' (IEM/IND2, 18:55). This has an impact on SF5, but since the government can incentivize consumers, it also effects the performance of SF4.

Score
Hydrogen is such a hot topic that it has been warned to become a hype (PS2; GAS1). However, the target setting in numbers by the Dutch government and EU, the entrepreneurial activity amongst stakeholders and the positive expectations from the experts, act as a driving force to the TIS. The Fit-for-55 directive will most likely provide the necessary legal means for the Dutch government to demand the use of green hydrogen, at least in industry (PI/PM1). However, as mentioned above, a transformation at such a scale takes many years. Due to the fact that currently the standards, legislation, subsidiary rules, and incentives do not provide the stimulation of the TIS, time is getting stringent. In the meantime, stakeholders remain reluctant to move forward with investment decision. The label score for SF4 is 3.0, and even though the experts endorse the technology, and governments and industries set high targets, the institutional guidance poses a large barrier. Therefore, the analysis score remains a 3.

4.2.5 Market formation

Market size
Regardless of the synthesis method, the physical properties of hydrogen do not alter, meaning the current market for the chemical could serve as a steppingstone for the electrolysis technology. However, since hydrogen has the potential to not only serve as feedstock, but also be utilized in energy storage, residential heating, and mobility (DSO/EC1), the access to the market also becomes strategic.

As mentioned in the introduction, 100PJ of hydrogen as a chemical feedstock is used by the Dutch process industry alone. According to insights from the interview with a current hydrogen producer, the demand is going to 'rise very much, we get a lot of extra requests, especially from processes now heated by natural gas, which are now really asking for hydrogen' (IEM/IND1, 23:02). An exact market size is hard to come by, especially since the import of hydrogen might oppose the Dutch domestic hydrogen production (EB1). However, the prospects made by an electrolyzer manufacturer are that 'in Rotterdam alone, you have already about way more than one GW potential of electrolysis' (EM1; 25:13). In interview (EB1), a prospect of an annual 20 megatons of hydrogen consumption is made for the European market. Given the rough estimation that a 10 MW electrolyzer capacity produces 4 tons of hydrogen per day (EM1), and 50% would need to be produced via electrolysis, that would result in a market potential of up to 74 GW for the European market.

Deregulated market

At the end of 2021, the Dutch State secretary of EAC published a document indicating the market regulation for electrolyzers (Yesilgöz-Zegerius, 2021). An important notion is that the Dutch government considers the market of hydrogen electrolysis as deregulated, meaning that the free-market principle of demand and supply is applicable (GAS1). The decision to allow third parties to enter the market is one of the first actual market formations of the Dutch government concerning hydrogen electrolysis. The deregulated market principle is regarded as a driver to the TIS, since it incentivizes market entry and internal competition, ingredients for increasing efficiency and decreasing the costs per tons of hydrogen (IEM/IND1).

Niche markets

With niche markets such as feedstock capabilities (IEM/IND1), high temperature industrial heating (PS1), residential heating and long-term storage (DSO/EC1), mobility on road and rails (PS2; EC2), production in remote or difficult to reach facilities (IEM/IND1), hydrogen could tap into multiple market potentials. For the storage in vehicles for example, the pressure needs to be increased heavily to become economically viable (EC2), however, the electrolysis process need not change. However, since hydrogen synthesized by electrolysis is multiple times as expensive as via SMR (EM1), those niche markets would need special arrangements to protect the entry of the innovation. One of those potential protections is the Emissions Trading Scheme (ETS) of the EU, where CO_2 emission rights need to be bought depending on the tons exerted (IEM/IND1). By annually increasing the price for each exerted ton of CO_2, the EU can decrease the competitive advantage of pollution processes in relation to clean methods, as is the case with SMR and hydrogen electrolysis. However, the current ETS price is too low for SMR to lose the cost benefit (IEM/IND1).

During the data analysis, multiple experts issued the effect of high supply and low demand of electricity, drastically decreasing the price (PS1; PS3; EM1). Electricity, as main feedstock for electrolysis, would become abundant at times. Partly due to the ETS, SMR will not fall beneath a certain price, and a relative advantage for electrolysis over SMR would be created. However, an interesting remark is made on the fluctuations of RES in interview (KI2). In the future scenario where these fluctuations increase in amplitude due to increased RES capacity, the business case for electrolysis increases. But due to the market mechanism, outside stakeholders would enter the system once it becomes clear that the electricity supply swings cause a break-even or profitable situation. Hence, these abundancies might occur in the near future, but basing the business case of hydrogen electrolysis on that mechanism would be a mistake since others will join and the abundancy would dissipate within years (KI2). In other words, a business case based on the abundancy of electricity is not economically sustainable.

Another protection could be made in the form of transportation. However, when the hydrogen backbone is finished, no discrimination can be made on the production method for hydrogen (GAS1). Meaning that grey hydrogen will flow through the pipeline without restrictions, neglecting the effect the large capacity transport would have on the price gap if only green hydrogen was allowed.

Further protection could be made from tax exemptions; however, no such arrangements were found during the data gathering. Subsidy trajectories favouring green hydrogen do stimulate the implementation. The subsidies mentioned in the institutional analysis only relieve the CAPEX, whilst the OPEX of hydrogen electrolysis is thus a multitude of that of SMR (EM1). The potential niche markets seem abundant, yet the protection required to penetrate these markets seems lacking.

Lack of public market
Unlike commodities such as oil and gold, there is currently no public market for hydrogen (EC2, EB1). As a consequence, actors who are willing to invest in the system are doubtful since they 'cannot set their price and calculate a business case. The only thing they know now are the investment costs' (EC2, 32:27). However, in interview (IEM/IND1) a free-market principle is mentioned, where the three main global suppliers of hydrogen interact with each other on the price, quantity, and quality (IEM/IND1). The hydrogen, mostly synthesized via SMR, is sold directly to the costumer in a point-to-point market, in quantities of cylinders or tube trailers (IEM/IND1). The apparent difference is in the availability to the market, and the use of an open transport network. The point-to-point market existing today in the Netherlands is supplied via private-owned infrastructure onsite or via tube trailers, as there is no public network yet (IEM/IND1). In the current market arrangement as mentioned in interview (IEM/IND1), every actor transports hydrogen via their own private transport system. It is argued that the lack of a public network like the prospected hydrogen backbone of Gasunie creates an exclusive hydrogen market. In this manner, new projects, or activities of green hydrogen production by new actors, cannot cope with the assets of these three global hydrogen providers. In conclusion, there is a point-to-point market, but due to the high entry barriers opposed by the private-owned network, the lack of an accessible network denies an open and public market. Without a public market, hydrogen is no commodity (IND2).

Market uncertainty
The reluctant attitude of stakeholders argued in SF1 and the performance of SF4 also resonate to SF5, since the market uncertainty is large. Such is also being experienced by experts already involved in the market (IEM/IND1; EM1; IND2). In turn, the market uncertainty also has an effect on the entrepreneurial activity, creating a negative loop. Summarized, the market uncertainty is caused by:

1) Large entry barriers due to requirements of large-scale implementation
2) Low performance of institutional guidance, lacking standards, permits, and labels
3) Reluctant activity of important stakeholders (IEM/IND1)
4) Lack of empirical robustness of large scale electrolyzers (EM1)
5) Long time-to-market of an electrolyzer (EC2)
6) Low consumer incentives to invest in electrolyzers (IND2)
7) Insufficient availability of green electricity (IEM/IND1)
8) Lack of a public market, no ability to accurately calculate the wholesaling price (EC2)

The high expert expectancy mentioned in SF4 might create trust in the system and potential of the technology, in the meantime, stakeholders seem reluctant to invest over the back of their own assets. Under the denominator market uncertainty, multiple barriers of different SFs reside, also illustrating the complex problem with kickstarting the market.

Score
The multiple niche markets, absolute market size and endorsement of the technology in SF4 creates a prosperous perspective. The fact that the Dutch government has created clarity on the Dutch market ordinance of electrolyzers serves as a driver to private parties. However, the price gap is hardly bridged by institutional protective measure, and the market uncertainty is large. The label score is issued at 2.9. From the perspective of the TIS, the current market formation does not incentivize stakeholders well enough to enter the system. The analysis score is settled at 3, due to the low incentive and arrangements but high potential and applications of hydrogen.

4.2.6 Resource mobilization

The resources are divided in three categories, the human, financial, and physical resources.

Human resources

The human capital entails the working fleet of professionals capable and willing to contribute to the Dutch value chain of the hydrogen electrolysis technology.

Tightness on the labour market
In interview (EC2) and (EM1), the issue is raised of a shortage in qualified personnel, especially mechanics for the assembly and installation of electrolyzers and other support technology. More generally speaking, the sectors concerned with the energy transition are experiencing a shortage of qualified personnel, limiting production (IEM/IND1). As is also illustrated in Figure 10, where a sharp rise in the number of vacancies in the energy generation and industry sectors complement the statement. The lack of practical personnel poses a barrier for the realisation of the targets mentioned in SF4.

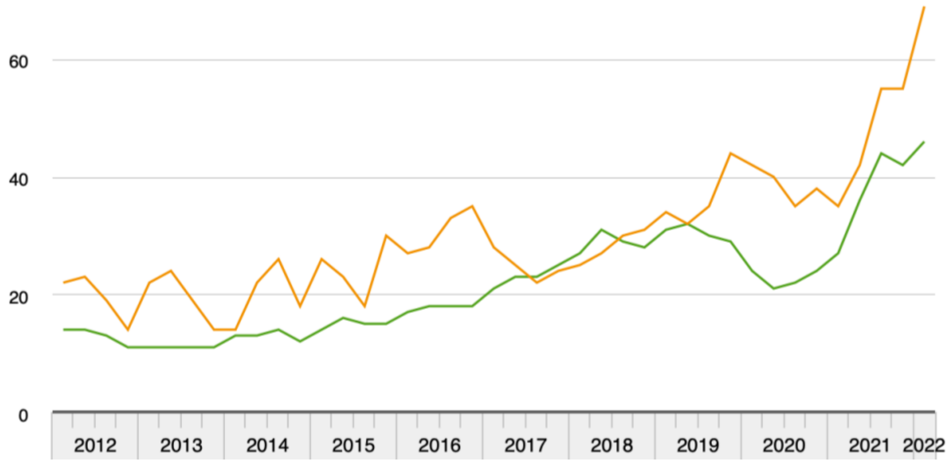


Figure 10: Dutch vacancies per 1000 jobs concerning the sectors energy generation (orange) and industry (green) (CBS, 2022)

Existing pool of technical personnel
From the pool of existing personnel employed by stakeholders, learning programs tend to educate technicians on the technology. For instance, the demonstration project mentioned in interview (DSO/EC1) is also used to educate mechanics on the properties of hydrogen. An interesting remark, however, is that the education is fully financed by the DSO itself, the Dutch government has not issued a specialized training program (DSO/EC1). The education of mechanics is in the context of the demonstration project, meaning that a group of approximately 12 mechanics are trained, from a pool of 400-500 mechanics in total (DSO/EC1). Therefore, the specific program implemented by the DSO is considered as small scale, but interest among mechanics is growing (DSO/EC1).

All in all, demonstration projects issued at the initiative of a stakeholder involved in the TIS is considered to be useful since it adds to the collective and tacit knowledge amongst people and organisations. However, the shortage of practical technicians and mechanics will likely require a more central approach and are part of a general labour market conjuncture.

Additionally, personnel formerly active in applications of natural gas are reenlisted to hydrogen projects (IND2; GAS1). This tacit knowledge is also mentioned as an advantage for the Dutch TIS on hydrogen electrolysis (PS1; EB1; ISPT, 2020). The problem seems not to reside at a management level, but on the personnel applicated with assembly, production, and installation. The tacit knowledge flowing from the natural gas sector benefits the influx of expertise, yet the shortage of technicians at lower levels partly upholds the execution of the targets set for hydrogen electrolysis and the general energy transition.

Financial resources

The mobilisation of financial means is necessary for the development and implementation of the technology and the contextual infrastructure. Financial injections also serve as a sense of trust in the TIS, since capital investments in low potential markets seem irrational. For instance, the allocation of public money assures stakeholders that the Dutch governments vouches for the technology.

Public funding

'Just as any other new technology or new product, if you want to introduce it in the market without a clear cost-efficient factor, that is the first place where public money or grants have to play a role' (KI2, 44:17). The mentioned lack of a cost-efficient factor is applicable to hydrogen electrolysis. Hydrogen produced via the electrolysis process in the Netherlands currently costs around 10€ per kg of hydrogen, where hydrogen via SMR remains at 1-2€ per kg (EM1). The increasing gas price due to the current crisis with Russia and uncertainty on the energy market is not included. Although SMR uses natural gas, the electricity price has also risen, partly neglecting the benefit of the electrolysis process (IEM/IND1). The cost difference could be compensated via the subsidiary trajectories mentioned in the institutional analysis in section 4.1.4. An exact calculation on the required subsidy and its impact on the CAPEX and OPEX of hydrogen electrolysis is not part of the analysis.

Last year, the Dutch government announced an additional 35 billion euros applicated to the Climate Funds (NOS, 2021). Of that additional funding, 15 billion euros are reserved for renewable energy carriers such as hydrogen, reportedly to partly gap the cost difference (NOS, 2021). The funding will be applicable via subsidiary trajectories mentioned in section 4.1.4, and up to 2030 (De Zeeuw, 2021). With that additional funding, the Netherlands ranks first among EU members in amount of capital subsidized per GW electrolyzer capacity, as is illustrated in Figure 11.

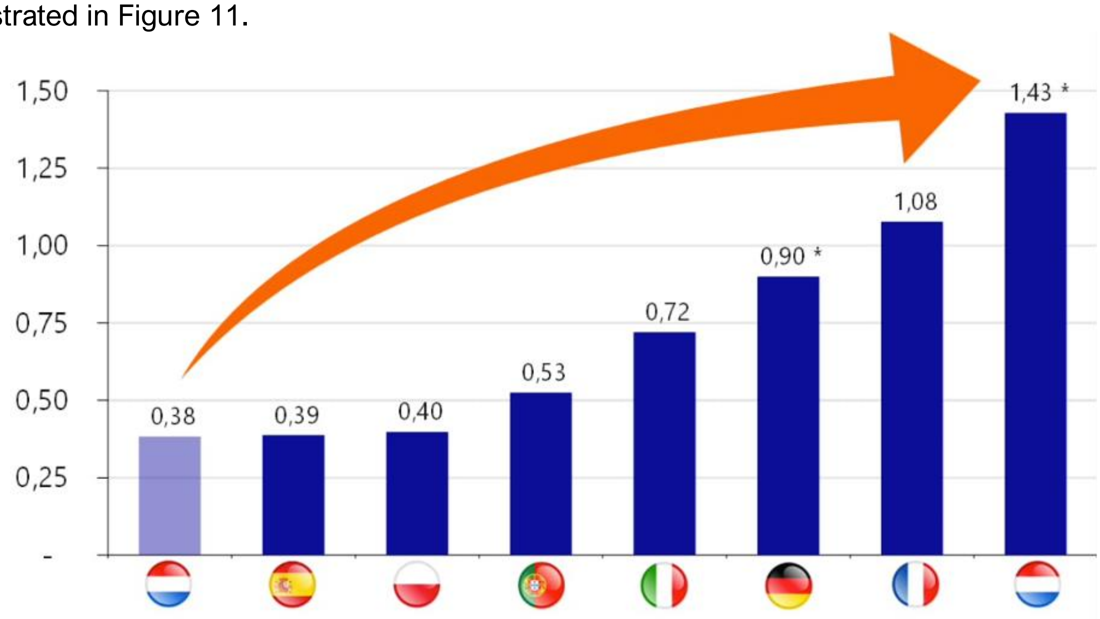


Figure 11: Billion euros of subsidy per GW of hydrogen electrolysis (De Zeeuw, 2021)

Private funding
Similar exacts number as for public funding were not acquainted during the data gathering, assumably since private stakeholders will not eagerly share their investment strategy. However, from the interviews, certain remarks can be derived that private investments are not prevalent, nor sufficient. First, there is the standoff situation described in SF1 and the lack of incentive for hydrogen consumers described in SF4. Second, in interview (EB1) is mentioned that 'we need to pull in private funding. We don't have enough private funding at this moment. Public funding can only go so far, for large scale development, you need to pull in massive private funding. And for that, there needs to be instrument put in place, especially in terms of policy' (EB1, 20:08). And third, private investments seem to require additional public funding, since 'if you go to large-scale you are still depended on a large subsidy' (IEM/IND1, 08:26).

Two of the reasons for a reluctant attitude towards private investments were given in interview (IEM/IND1) and (PI/PM1). First, no forced transition towards green hydrogen is in place yet, meaning that if consumer A would buy more expensive green hydrogen whilst consumer B does not, consumer A will lose its competitive position (IEM/IND1). Second, due to the complexity of the adjustments to an industrial plant, 'those investments have really long durations because the alterations are so large' (PI/PM1, 21:36). Whilst processes to make an investment decision are delayed, those funds are not put to use in the system.

In conclusion, exact numbers were not found, yet by scanning the data, an assumption is made that current private funding is not sufficient.

Physical resources

The physical resource mobilisation has been divided in three main subjects since these most prevailed during the interviews. These subjects are the electrolyzers, the electricity, and the pipeline transport infrastructure.

Electrolyzers
Electrolyzer manufacturers are massively investing in larger production facilities (EC2; EM1), but 'the current waiting times for an electrolyzer are up to one or two years already. And it is just going to get worse' (EC2, 34:17). The time-to-market of current electrolyzers has been increasing for the past years and puts a strain on the goal of the Dutch government to reach an electrolysis capacity of 500MW by 2025 (DSO/EC1). The current delivery issues of electrolyzers are increasing and in case of a mandate, that congestion will rise even further (IEM/IND1).

Besides the manufacturing capacity, the design has to be made fit for large scale application. 'Anytime you change scale, you scale up, you need to prove and demonstrate that your new design is able to be consistent and robust' (EM1, 02:39). The labour market tightness resonates to the production of electrolyzers as well since trained technicians are needed to assemble and install the systems (EM1).

Electricity
For sense of context, under current applications, 55 kWh of electricity is needed for one kg of hydrogen (EM1). With the Dutch targets for 2030, 50 PJ would need to be synthesized via electrolysis for the industry alone. Assuming an energy content of 120 MJ/kg for hydrogen, 50 PJ roughly relates to an annual production of 0.4 megatons of hydrogen. For such quantities, approximately 23 TWh of electricity will be needed annually. Assuming a capacity factor of 0.4 for RES, a capacity of 6.6GW of RES would suffice for the hydrogen consumption of 50% of the Dutch industry. That would nearly double the current total Dutch capacity of RES. In the

Klimaatakkoord, the Dutch government plans to have 11GW capacity of wind farms installed at sea by 2030 (Klimaatakkoord, 2019). In theory, 6.6GW seems applicable and reachable within the targets of the *Klimaatakkoord.*

However, an important remark has to be made. As mentioned before, the use of a subsidy is necessary to bridge the additional costs accompanied with hydrogen electrolysis. Once the European delegated act is installed, the first rule of a subsidy and the green hydrogen label will require a stakeholder to install additional RES for the electrolysis. In short, neglecting current installed electrolyzer capacity, 6.6GW of RES has to be installed in the coming years, solely for the production of green hydrogen. And according to the experts, that is where the bottleneck will be. Currently, there is not enough RES (PS1; EM1; IEM/IND1; IND2), and to build an additional 6.6GW of RES is a challenge. In interview (IND2) is mentioned that the appropriate lots at sea for that capacity worth of wind farms are not even issued. Additionally, the most suitable locations for RES and the locations of the industry clusters do not align (IEM/IND1), creating the necessity to transport the electricity via the Dutch electricity grid. In interview (IEM/IND1), the remark is made that network congestion will not allow an additional wind farm to connect to shore within five years. Another barrier concerns the return on investment when using the electricity for hydrogen synthesis. Capacity of RES will have to be installed and maintained, to feed a process, which also needs to be installed and maintained, which is in principle not profitable without a subsidy.

The expert in interview (PS1), believed there will be a surplus of electrical energy from the wind farms, however that is from the perspective that in those cases, hydrogen electrolysis becomes financially profitable. In the paragraph above, the perspective is reversed; for the targets of the Dutch government, that capacity of RES is required additional to the current installed capacity.

An example was made in interview (IND2), stating that lots for wind farms at sea are not dispensed in consultation with investors capable of building electrolyzer plants. The risk arises that third parties end up with the electrons and will sell it a wholesale price to the operators of the electrolyzers. As a consequence, the costs rise, and the market uncertainty and investment decision are again put under pressure.

The need for subsidy and the labelling of green hydrogen requires additional RES, which accounts for roughly 6.6GW by 2030. The Dutch government does plan to install 11GW of wind farms at sea by 2030, but experts doubt the feasibility. In the meantime, sufficient amounts of electrons are hard to come by and stakeholders are struggling with the network congestions and investment decisions. Counterproductive and outdated legal arrangements and permit allocations increase the risk and transaction costs, and limit the incentive to invest in RES.

Pipelines

The current infrastructure of natural gas pipelines has been mentioned as one of the advantages of the Dutch position of becoming an important player in the European green hydrogen market (EB1). With an existing transport infrastructure in place, high volumes of hydrogen can be transported at low costs after some relatively simple adjustments (EC2; GAS1). The use of the existing the local natural gas grid is also amplified in the project mentioned in interview (DSO/EC1). 'If the infrastructure is in place, the rest will follow' (PS1, 21:49) is an optimistic statement. However, Gasunie is reluctant since they also want contracts with hydrogen suppliers to make sure that enough hydrogen will flow through the backbone when the infrastructure is complete (GAS1). Again, the standoff described in SF1 seems to be upholding the process. However, the mandate of the Dutch government to finish the infrastructure by 2030 does provide clarity. Experts believe that the realization of the hydrogen backbone will create a market pull, driving costs down and imbursing the Dutch targets.

Score
Stakeholders have begun initializing learning programs to educate their personnel, however the small scale of it and the overall short-staffed industry and energy generation sector cause a barrier for the fast expansion of the electrolyzer market. Public funding has been readjusted and puts the Netherlands at the top, yet private funding is lacking. Physical materials cause the seemingly largest barrier. With the mandate to construct the hydrogen backbone, the Dutch government gives out a signal that the infrastructure will be realised. However, the scarcity of electrolyzers and increasing time-to-market along with the required additional RES under current network congestions act as a barrier to the TIS. The label score was set at 2.6, however, due to the inert barriers caused by the labour market and RES realisation, the analysis score is adjusted to 2.

4.2.7 Creation of legitimacy

Public opinion
No recent survey data on the reputation of hydrogen electrolysis in the Netherlands was found. However, during the expert interviews no statement was made on the negative attitude or low acceptance of the public. An explanation to the lack of survey data could be the low capacity of electrolyzers installed. A point made in interview (GAS1) was that if one does not live near a demonstration project or is employed in a sector involved with hydrogen, the technology might go unnoticed. During the demonstration project mentioned in interview (DSO/EC1), residents of the houses being altered for the use of hydrogen raise no concern on the safety issues, rather on the costs. It is assumed that technologies in aid of the energy transition are accepted more easily. To the public, hydrogen electrolysis may be seen as a solution for Russian dependency on fossil fuels and the climate crisis (GAS1). However, another explanation could be that the public is still unaware of the dangers of hydrogen. As amplified in interview (EC2), research is conducted on the safety hazards. As mentioned in interview (IEM/IND1), especially at pressures above 500 bars, the gas become difficult to handle since it no longer behaves like any other gaseous substance. Hydrogen is not without hazards, yet no sign of public unrest or worrying were found during the analysis. However, it may shift rapidly.

Stakeholder opinions
Concerning the attitude towards hydrogen electrolysis of the companies and organisations interviewed all responses displayed a high rate of approval amongst colleagues. As a remark, an electrolyzer manufacturer will unlikely employ people with a negative attitude towards the technology. Therefore, stakeholders highly invested in the technology are no representative sample group. However, a DSO or petrochemical company are less focused on hydrogen electrolysis yet declared similar rates of approval: ‘within our DSO, I think 80% is enthusiastic about hydrogen’ (DSO/EC1, 42:07). Yet, as was made clear in the same interview, was the reluctant attitude of the SSM towards the permits. The interviewee believed it could be the uncertainty of the hazards and risks of hydrogen amongst the supervisors that formed the counteractive attitude towards the transport via pipelines (DSO/EC1).

Lobby activities
As mentioned in interview (GAS1), the MissionH2 project of the Dutch government and industry stakeholders has resulted in an internal and external rise of approvement towards the technology. In interview (IND2), lobby activities in The Hague and Brussels are mentioned that increase legitimacy of the technology and aim to resolve the policy issues mentioned under

SF4. In interview (GAS1) a statement was made on the complex nature of the system and difficult to understand benefits of SC and the current revolution of RES. The multiple public events mentioned in SF3, and the presence of hydrogen associations are assumed as lobby activities as well. Other lobby activities, such as conversations between stakeholders and the Dutch government behind closed doors are important yet not possible to measure.

Score

The label score of SF7 is rated at 2.9, whilst the qualitative analysis of the data seems to display a better performance. The lower label score is partly explained by the low numbers of labels, creating an average score which is more easily influenced by a negative result. The seemingly high acceptance of the public and the social campaigning and stakeholder lobbying, rate a high performance. A remark has to be made that due to the complexity and low implementation of the technology, the public opinion could still easily shift once the development continues. Amongst the stakeholders, similar results to the public opinion imburse a high performance, yet the reluctant attitude of the Dutch SSM issuing the permits gives room for improvement. Due to the latter argument and the arguably easy change in public attitude, the analysis score is settled at 4.

Overall system performance

In Figure 12, the overall score is illustrated. The analysis score is the core of the analysis and forms the final assessment of the functioning of the SFs. The label score served as a benchmark during the analysis. By analysing Figure 12, a notion can be made on the relatively large difference in scores between SF1 and SF7. The analysis score of SF1 was deemed lower than the label score, since even though all stakeholders are actively involved in the TIS, the standoff and reluctant attitude limit the potential heavily. Since this gravely limits the development, the analysis score is decreased. The large deviation between the two scores of SF7 is attributed due to the lower quantity of labels. As a consequence, a negative label has a larger impact on the outcome of the label score, whilst the SF performed well after analysing the specific arguments made. The difference in scores of the remaining SFs is considered closely relatable, reimbursing the validating effect of the label score and the analysis score.

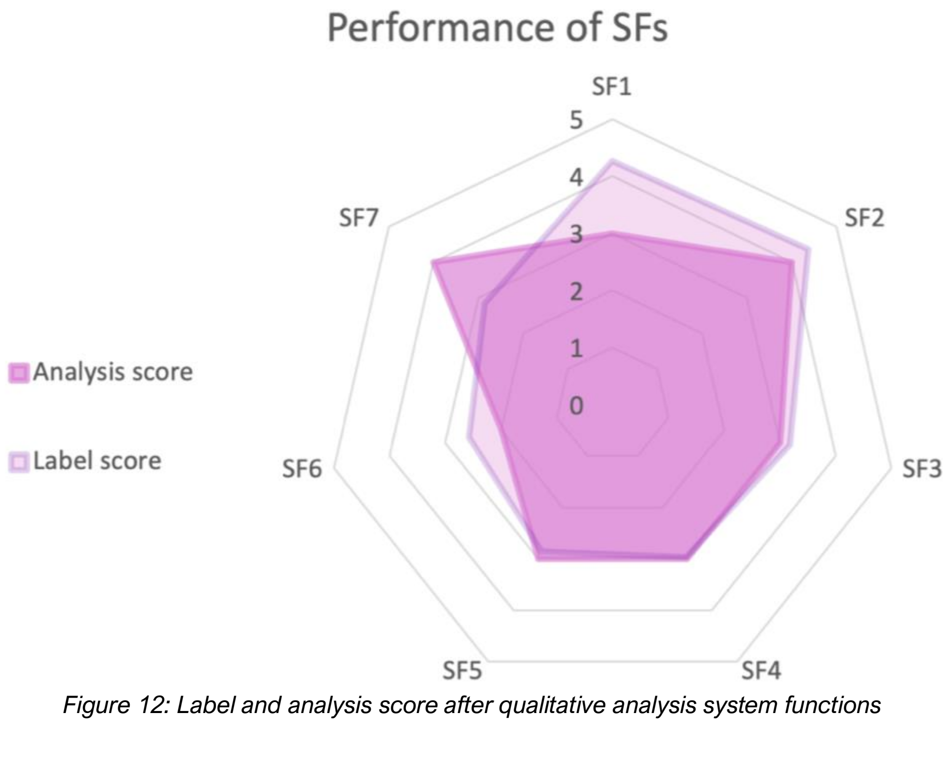


Figure 12: Label and analysis score after qualitative analysis system functions

4.3 SQ 3 Systemic problems

This section of the analysis focused specifically on the barriers that came up during the structural-functional analysis. The delineation of the barriers led to the systemic problems. In total, 36 systemic problems are found. Per SF, the main problem is given in Table 8. The full list of systemic problems is depicted in Table 26 in Appendix G.

Table 8: List of systemic problems

System function	Systemic problems
SF1: Entrepreneurial activity	Standoff created amongst stakeholders in the system, high risk for first mover. Creating a reluctant attitude towards investing in the system.
SF2: Knowledge development	Lack of multi-MW scale projects, insufficient data available on the operations.
SF3: Knowledge diffusion	Low diffusion of knowledge between public and private stakeholders, creating lack of understanding with state supervisors and unrealistic expectations.
SF4: Guidance of the search	Lack of efficiency standards for manufacturers, regulations for industry, and incentives for consumers to invest in the system, and contradictive legislation increases transaction costs, market uncertainty, and reluctancy towards investments.
SF5: Market formation	High market uncertainty due to lack of institutions, high entry costs and lack of public commodity market.
SF6: Resource mobilization	Insufficient technical personnel, electrolyzers, and available renewable electricity production.
SF7: Creation of legitimacy	Complicated technology and lack of campaigns do not prepare the public for the consequences of large-scale implementation of hydrogen synthesis.

4.4 SQ 4 Recommendations

In this section, recommendations are given to Strukton Power and subsequently to Dutch policy makers. As a closing remark, experiences of conducting this thesis project have been formulated in a recommendation for future researchers in regard of the TIS analysis.

4.4.1 Strukton Power

On the market side, Strukton Power should exploit the sector of hydrogen electrolysis and devote more resources to investigate where niche opportunities would arise in the future energy system. On the technical side, Strukton Power should consider what the specifications for power systems of electrolyzers are and at what relative ease these could be incorporated in the existing core business. They should do so regardless of the systemic problems found, because swerving as a red line throughout the different interviews and gathered data is the confidence that hydrogen electrolysis will become a contributor to the future energy mix. For one, the European and Dutch government weigh heavily on future hydrogen electrolysis in industry, and increasingly incorporate hydrogen in targets, directives, and legislative proposals. With the REPowerEU initiative to counter dependency on Russia, one can see the direction the EU is aiming for in assuring their own energy supply, and green hydrogen makes up a large portion of that plan. The Dutch government made close to 15 billion euros available for the development of hydrogen electrolysis in the near future, and the additional mandate to implement the hydrogen backbone by 2030, show their serious intentions. In comparison to other EU members, the Dutch government is financially backing the sector fanatically, as was found in section 4.2.6.

Second, the seemingly increasing effort put forward by stakeholders already active in the sector lead to similar conclusions as mentioned in the paragraph above. The attention hydrogen is getting, the increasing number of projects, and the relative ease to find and contact experts on hydrogen electrolysis show the activity of these private stakeholders. However, as was concluded under SF6, the private funding is considered low, and the standoff created between stakeholders is considered as a systemic problem. It is argued, however, that this also creates an opportunity. The fact that newly formed consortia are prevalent and experimenting through diverse projects, create a more fluid pattern that shows little characteristics of a systemic lock-in. In case Strukton Power would enter the system, a partnership with a stakeholder already active in the system would be most logical, according to the experts interviewed in (PS1) and (PS3). It is assumed that the relation to a partnership would currently be more equal than when the system is settled and matured, with heavy investments in place.

And third, the applications for hydrogen will most likely be more actively pursued once the initial infrastructure and institutional arrangement are in place. With the Fit-for-55 package, the focus of policymakers seems to be on industry, yet applications in peak shaving, mobility, and residential heating are explored as well. With the active pursuance of these applications in the future, the market size expands whilst the technology nor the chemical need not change. The point is made that experience of hydrogen electrolysis will be useful in other applications of hydrogen as well.

Currently, multiple stakeholders are waiting for the publication of the European delegated act that frame the origin of electricity and the requirements for a subsidy. According to the expert interviewed in (EC2), the act should become public near the end of the summer of 2022. Initial explorative talks could be held with potential partners before that, yet it is recommended to wait for the publication since it will clear the market structure and incentivize particular stakeholders, or the contrary, discourage certain others.

To benefit the TIS, particular systemic problems could be taken as a starting point. Two options are derived. In the first option the experience would be internalized. Since the TIS requires a large-scale pilot project, such a project could be funded. Especially in consideration with the lack of experience of electrolysis, Strukton Power could benefit from the collaboration with knowledge institutes, universities, and actors from the industry. They add expertise on electrical engineering and internalize the experience on the chemical process. The second option is to externalize their experience of electrical engineering and contact an electrolyzer manufacturer directly. Power systems show the largest potential in CAPEX reduction of an electrolyzer (ISPT, 2020), and the expertise of Strukton Power could be promoted as reaching such potential. This would benefit the TIS by increasing entrepreneurial activities and potentially reducing costs.

The first option to enter the system entails a long-term strategy: with the internalization of the experience, Strukton Power might become capable of implementing a turn-key operating electrolyzer by themselves. This would create the possibility to act as system integrator, entailing a larger market share. However, multiple stakeholders are already in front, and it is far from the core business. Internalizing the experience would take years. The second option is more short-term: leaving the chemical expertise to the electrolyzer manufacturer, whilst creating a business case in selling power units to these stakeholders. A remark was made in interview (EB1) and (EM1) concerning the turn-key solution provided in low capacity electrolyzers, with an internal power systems module inserted in the design. Large scale projects, 100MW and upwards, have no internal power system since it requires more expertise on power electronics and would serve the tacit knowledge of Strukton Power. The strength and size of the market position are less than with the first option, but the second option will arguably be easier to implement.

A final remark is made that the focus of this analysis is on hydrogen electrolysis. However, future needs to phase out of fossil fuels and increasing electrification of the energy system, might increase the production of other chemicals via electrolysis. Experience made during the explorative and implementing phase of hydrogen electrolysis could be applied to those future markets as well.

4.4.2 Dutch policymakers

In consideration of the systemic problems, recommendations for Dutch policymakers are constructed to increase the performance of the TIS. Eventually, for most systemic problems depicted in Table 26 in Appendix G, policy instruments could be designed that would potentially relieve or fully resolve the issue. However, due to time limitations, the SFs in which most marginal effects can be achieved are used to give policy recommendations. First, since SF4 is directly influenced by policymakers, and multiple barriers were found that were caused by a lack of institutional guidance, recommendations to increase SF4 are made. Second, the lowest performing SF is taken, SF6.

SF4
The inhibiting performance of SF4 is essentially based on three pillars: lack of efficiency standards, contra productive legislation, and lack of incentives.

First, the Dutch government should take the initiative to compose standards on efficiency measurements and RES utilization in collaboration with industry and knowledge institutes and universities, to decrease market uncertainty and transaction costs. Besides the existence of NEN-ISO 22734, multiple stakeholders still consider the lack of standards to inhibit the development (KI1; EC2). These new and clear standards should also serve the knowledge development without decreasing the innovative power. By combining the experience with large-scale chemical projects of the industry, the theoretical background of knowledge institutes and universities, and the legislative power of the government, standard setting could be in tune with reality and in range of certain targets.

Second, by involving governmental organizations such as the ACM and SSM on to the drawing board, contra productive legislation and discouragement of DSOs and Gasunie to cooperate in hydrogen projects should be put to an end. With involvement of these organizations, different viewpoints dissipate throughout the standard setting, increasing the likelihood that the end result is sufficient for most stakeholders. An additional benefit of initiative by the government in arranging such activities, is that is portrays an image to stakeholders in- and outside the TIS, that effort is being made to kickstart the implementation of hydrogen electrolysis. The direct involvement of the government on top of the targets set for 2025 and 2030 potentially create more trust in the development of the TIS, increasing entrepreneurial activity.

Third, by mandating or subsidizing the use of green hydrogen for large consumers, an incentive would be forced that also influences the creation of a market. Although the origin of green hydrogen is still disputed in the delegated act and the Dutch government is waiting on that. In the meantime, the Dutch policymakers could explore potential means of adding incentives to use green hydrogen once the delegated act is issued. By including multiple stakeholders in designing these measures, a fitting legislative package can be arranged that incentivizes consumers whilst not creation an insurmountable challenge that would compete Dutch industry out of the global market. By providing clarity and initiative, it is believed that trust in the system and technology is increased, indirectly benefitting SF1 and SF5.

SF6

To increase the performance of SF6, more specialized personnel should be attracted, and more RES should be planned and constructed. Concerning the first, the overall tightness on the labour market provides a difficult starting point yet instating specialized training programs and interest campaigns might increase the pool of mechanics able to attribute to the TIS.

The other systemic problem resided in the low availability of RES. Even though the Dutch energy system is deregulated, and market parties need to apply to tenders for wind parcs or solar fields, Dutch policy makers could incentivize said parties to include green hydrogen production in their tender proposal. For example, by instating that for every kWh fed into an electrolyzer, the government adds a fixed absolute fee of revenue, electricity generators are incentivized to include hydrogen electrolysis in their proposals. In case of high RES and low electricity prices, the absolute feed-in tariff towards electrolyzers becomes very attractive, whilst the low electricity price creates a more competitive position for green hydrogen. Additionally, the government should increase the available lots for wind parcs at the North Sea, since it is expected most RES will be produced there (IEM/IND1). Sufficient lots should also be reserved for stakeholders involved in hydrogen electrolysis projects.

4.4.3 Future analysts

In the past 5 months of executing this analysis, the experience led to two insights for future analysts. First, providing a heterogeneous notion on the actor component creates the opportunity to implement a sense of hierarchy amongst the stakeholders. In found TIS analyses, the stakeholders active in the system are regarded as entities with similar interests and motivations to develop the system. As a consequence, the entrepreneurial activity is mostly related to the quantity, yet the diversity and quality of the activities were not included. In this analysis, the delineation of the different responsibilities of the stakeholders allowed for a deepening of the functional analysis since these different responsibilities resulted in drivers and barriers otherwise undiscovered and should be considered.

Second, TIS analyses have been used to analyse and pinpoint if and where policy instruments should be implemented in order to increase the performance of the system. However, in this analysis, it also used to propose a recommendation to a private stakeholder exploring the possibilities of hydrogen electrolysis technology. In hindsight, the structural-functional analysis also lends itself well for creating an overview of the technology and the contextual innovation system. And by assessing the performance of the TIS and discovery of systemic problems, system entry can be argued for. With a future inclusion of a quantitative analysis on the business case, the TIS analysis provides a well-structured explorative approach.

5. Discussion

This section discusses the analysis conducted in the thesis and the interpretations of those results. The limitations of the data and analysis are delineated and the contributions to scientific literature are indicated. Suggestions for further research are made based on the limitations of the research and the findings of the analysis.

5.1 Interpretations of results

A remark has to be made on the outcomes of the functional analysis. The performance of the SFs is not to suggest the TIS is successful or failing, it is merely an effort to pinpoint which processes need additional support for a more optimal performance of the total TIS, and what are the specific barriers to resolve. Suggesting a success or failure of the system would not be accurate nor the purpose of the analysis, since the scores are relative: under current circumstances and stage of development, the performance of the processes is assessed. There is no blueprint that suggests which absolute scores would need to be reached for a successful TIS.

With the structural-functional TIS analysis, an effort is made to determine the impact of the SFs on the development of the hydrogen electrolysis technology in the Netherlands. The analysis score depicted in Figure 12 provides an overview of the performance of the key processes necessary to develop the technology. From the results led that SF6 is an inhibiting factor, and SF1, SF4, and SF5 perform mediocre with an analysis score of three. SF2, SF3, and SF7 act as accelerating factors since these processes were deemed an analysis score of four. Apart from the low performing processes, additional systemic problems are identified per SF. These systemic problems inhibit the development of the TIS and consist of re-occurring barriers originating from the system. With the mapping of the systemic problems, the results from the analysis allow for a clear delineation of the barriers of the TIS. In turn, these insights add depth to the discussion on the potential and direction of the hydrogen economy in the Netherlands. The overall results show what factors impact the development of the technology, both positively and negatively, from the perspective of the innovation system. By doing so, the impact of the innovation system on the development of the hydrogen electrolysis technology is assessed. This is in contrast to found literature mentioned in the literature review, filling the gap left by techno-economic literature. Those analyses have an engineering approach to explain the disadvantages of the hydrogen electrolysis, from the perspective of the technology. An advantage of analysing the system's accelerators as well, is that stakeholders active in the system can exploit these benefits, and policymakers can focus their resources on inhibiting processes. It may also attract new entries, stimulating entrepreneurial activity and resource mobilization.

By assessing the impact that the system has on the technology, an effort can be made to strengthen the innovation system and take away systemic barriers for the development of the technology. Additionally, showing which stakeholders are particularly active in the system, with whom they interact, and by delineating the different responsibilities they entail, the structural analysis provides an enabling overview for a starting point for system entries. This has proved particularly useful in the recommendation to Strukton Power.

5.2 Limitations

During the thesis, certain limitations were encountered by the researcher. The following section discusses these limitations, which are divided in the limitations related to the design of the structural-functional TIS analysis and in limitations encountered in the data gathering.

5.2.1 Limitations of TIS framework

Actor component

Initially, the actor component of the TIS is mapped with the use of desk research, as is prevalent in TIS literature such as Kushnir et al. (2020), Wieczorek et al. (2015) and endorsed by Hekkert et al., (2011). Subsequently, the diagram presented in Figure 3 was drafted. The diagram served as a preliminary benchmark to investigate the rough overall system stakeholders and their role in the TIS. It also aided in the search for potential experts. However, during the interviews became clear that the role pattern, responsibilities, and diversity of stakeholders vary heavily per project. The TIS is in a phase where stakeholders are not settled in, and institutional arrangements do not clearly delineate the regulations and responsibilities. Therefore, the so-called structural actor representation as presented in Figure 3 is not fully applicable to this TIS. The main issue can reside in the fact that the structural actor representation is a closed system, in which all the necessary processes of the supply chain are acquainted by a therefore responsible actor. However, with a heterogeneous stakeholder field, unclear responsibilities, and various technological components and trajectories creating a lack of a technical optimum, the Dutch TIS of hydrogen electrolysis can be considered volatile. The structural actor representation was not able to capture that. Also, the diagram presented in Figure 3 could potentially be properly filled in if a researcher is well embedded in the system and aware of the dynamics between stakeholders. Since this analysis was conducted without vast amounts of tacit knowledge on the subject at the start, the creation of such a diagram is deemed inaccurate. The actor diagram is prevalent in TIS literature yet proved little useful in this thesis and required a different approach to analyse the actor component.

In an effort to produce a workable actor analysis, Table 5 is created in which the stakeholders active in the TIS are delineated in stakeholder groups and responsibilities are attributed that truly are arranged under the current institutional landscape. In contrast, these stakeholder groups do not represent a closed system; system integrators or operators remain unpresented for instance, which is also the case in the actual TIS. With the delineation of the stakeholder groups, Table 5 provided a workable outcome for the further analyses, whilst representing reality. In addition, the provided overview of the stakeholder groups provides a more in-depth analysis, more fitting to the heterogeneous stakeholder field of the TIS. This is in contrast with TIS analyses performed in Decourt (2019) and Wesseling and Van der Vooren (2017), which do not create a clear distinction between the stakeholders. The recognition of the heterogeneous actor component of the TIS also aids policymakers in pinpointing institutional gaps, whilst it gives Strukton Power an overview of the different roles it may find befitting. With the creation of Table 5, the shortcomings of the actor analysis in the design of the TIS in this particular context is resolved.

SF4

After an initial analysis, the performance of SF4 seemed two-faced. On one side is the expressed believe that green hydrogen will become an important energy carrier or feedstock in the future Dutch energy system or industry sector. Every expert interviewed emphasized and endorsed the important role green hydrogen will play in a sustainable future. On the other side, the actual guidance of the system by institutional arrangements, is frequently named as lacking, incomplete or contradicting. Since both types of indicators influence the performance of the SF, the score evened out. However, this resulted in the inability of the analysis to show the extremes and highlight the high expectations with the low institutional guidance. The inability to differentiate between the prospects of a sustainable technology and the current institutional guidance results in a second large shortcoming in the design of the TIS framework.

To illustrate this issue and determine the impact, a division is made of SF4 in SF4A and SF4B. The former houses the expectations of experts and the target setting of industry and government. The latter indicates the institutional guidance, such as standard setting, regulations, and mandates. The same dataset is used, with the same method for assessing the label and analysis scores. The raw results are depicted in Appendix F.

The label score of SF4A resulted in a 4.3, but since the tempering expectations related to the speed of capacity realisation of the Dutch government, and not on the eventual feasibility of the technology, the analysis score is adjusted to a 5.

The label score of SF4B resulted in a 1.4. Policymakers have the right intention but seem to have started too late, providing little sense of direction. Due to the upcoming directives and mandates such as the Fit-for-55 package, the analysis score is adjusted to a 2, yet this score still illustrates the contrast with the expectations of the technology in SF4A.

Figure 13 provides the new overview if the analysis would have been conducted by splitting SF4. As it stands, SF4B would be a low performing and inhibiting process with a score of 2. All the while SF4A would perform highest with a score of 5 and considered as an accelerator.

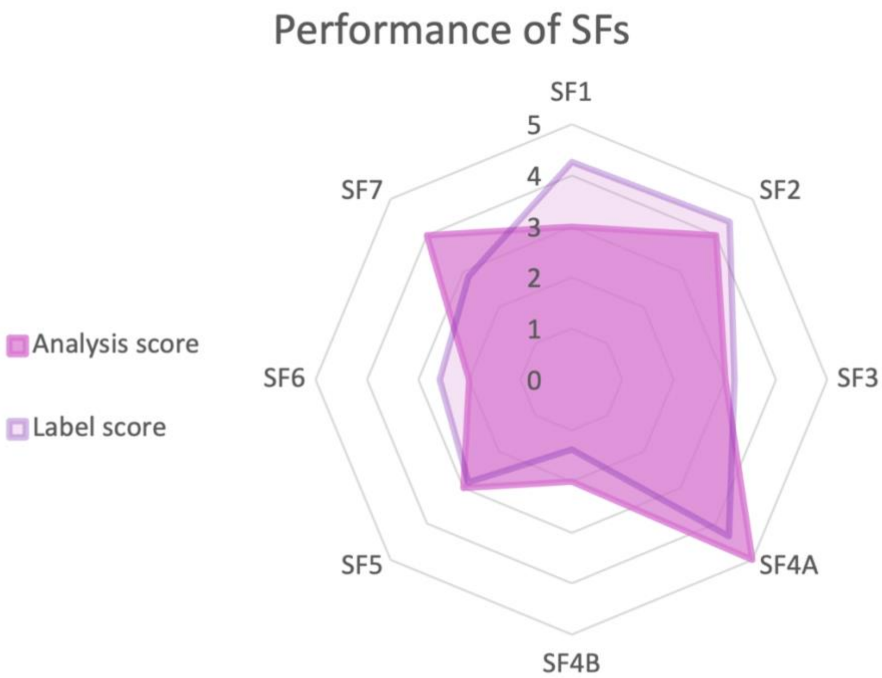


Figure 13: Label and analysis score after qualitative analysis system functions

Such a division within a SF is not prevalent in TIS literature. However, Figure 13 shows that the division is justified in the sense that relatively speaking, SF4A has the highest analysis score whilst SF4B has the lowest analysis score of the system. Therefore, by creating a division, the alteration of the analysis shows these extremes and not evening it out if it remained under the single denominator SF4.

Lack of substitutes
During the analysis conducted, solely electrolysis technology is considered to eventually replace the SMR process. Whilst in reality, governments might also consider blue hydrogen synthesis, with CCS, as a viable option to decrease GHG emission and support that TIS as well. Similar in the case of biogas, where biomass is gasified to form biomethane. Increased support for substitute technologies might pose as a threat to the TIS of hydrogen electrolysis. This is not accounted for.

Geographical isolation
Similar to the isolation of a single technological trajectory, the analysis did not include potential imports of hydrogen nor the performance of TIS' from neighbouring countries. Cost-efficient import from nations with lower RES prices such as Chili or Norway, could outcompete Dutch production. The indirect effect on the TIS would be that actors would remain reluctant to invest, leading to a drain in resources. The same goes for a strong neighbouring TIS. In case the German TIS for hydrogen electrolysis is outperforming the Dutch's, resources and investments are more likely introduced over the border. In such cases, it may also become irrational for the Dutch government to support the Dutch TIS, decreasing performance even further. This effect is not included in the analysis.

Level of technological complication
With the different trajectories and up- and downstream processes, hydrogen electrolysis is regarded as a complicated technology. With additional complications, the learning curve becomes flatter, upholding development, increasing investment uncertainty. The TIS framework does not include a rate for complicated technology, limiting this impact.

5.2.2 Data limitations

Even though the data gathering, and analysis are methodologically executed in line with relevant literature and verified where possible, the research encountered limitations which influence the impact of the results. By discussing these limitations, an effort is made to put the analysis in perspective.

The structural-functional analysis is based for the greater part on the expert interviews. In principle, this entails that the results of the analysis are based on the history, experience, and opinions of people, whilst being analysed by a single researcher. By assessing the label score, an effort is made to decrease the subjectivity of the researcher, yet these labels are also acquainted to the best efforts by that same researcher. Different experts could have resulted in a different outcome, as well as another researcher could have interpreted the data differently. Therefore, the results are formed subjective in nature and should be considered as such. Also, the interviews are all conducted by the researcher, and the researcher alone. This creates a conformation bias since the previous interviews have an unintentional effect on the sole researcher, potentially effecting the discussion in the interviews conducted later on. In an alternate order of conducting the interviews, other discussion points could have been iterated to stakeholders that were interviewed in an early stage.

Also, due to the time limitations, no more than 13 interviews have been conducted. During these interviews, time restrictions of appointments and availability of the experts also resulted in an abrupt ending of the discussion in some cases. The possibility to email the experts at a later stage of the analysis is used on certain occasions. This allowed asking additional questions and more time, however it did miss the dynamics of a live discussion plus not all emails were answered.

With the delineation of an expert in section 3.1.2, involvement in hydrogen was considered a prerequisite. However, in reality this means that the 14 experts questioned are all involved in hydrogen in some manner, increasing the likelihood these experts are positively biased in the utilization of hydrogen electrolysis. Also, since multiple experts are contacted via the direct network of previous interviewed experts, the likelihood increased they encountered similar problems or have a similar opinion since they could influence each other. However, to gain enough respondents in the limited time and resources reserved for data gathering, using these networks was deemed a necessary risk.

Another notion entails the sensitivity of information the experts might have not released. Either it be politically sensitive or giving price of a company strategy, certain data will likely be withheld from the discussion. All experts are anonymised in an effort to decrease the barrier, yet the notion the discussion is transcribed and appended in this publicly accessible thesis might have caused precaution, nonetheless. An example of such, is the data gathered for the network analysis in section 4.1.3, where the formal network is solely based on publicly funded projects since the strategy for private funding is not likely mentioned in such interviews.

The wide array of stakeholders interviewed resulted in a balanced data gathering. However, interviewees from Strukton proved to be not as equally useful as the other experts. Mainly because Strukton is not involved in the TIS, the statements of the technology are not directly derived from the actor's experiences. That goes for the analysis of the TIS, but they did prove more useful in generation a recommendation to Strukton Power. Concerning the addition of the other interviewees, from the network layout in Figure 7 led that 8 out of the 11 most active stakeholders were interviewed. Associations, energy generators, and ESCOs were not. However, associations mostly consist of a collection of spokespersons gathered from other stakeholders, which have been interviewed. Additionally, energy generators and ESCOs are considered to be involved with the supply of electricity including contracts and are therefore deemed as low contributing stakeholders, with low power in the decision-making processes or development of the TIS. Therefore, in consideration of the limited time for data gathering, these stakeholders were not interviewed.

A general notion applicable to all data is the fact that the data is gathered within a time slot of circa three months. Due to the volatile nature of the TIS, developments follow-up rapidly and certain statements could be outdated soon.

5.3 Contribution

By conducting the first structural-functional TIS analysis on hydrogen electrolysis in the Netherlands, the results contribute to new insights. By including technical, economic, institutional, and social aspects, the impact of the innovation system on the technology is considered in a broader perspective than in earlier techno-economic related literature. With this holistic approach, the outcome of the analysis also broadens the discussion on the drivers and barriers of the development of hydrogen electrolysis in the Netherlands. By delineating the different drivers and barriers originating from the innovation system, researchers, policy makers, and other related actors are able to adjust their strategy to resolve the systemic barriers or profit from the drivers. Stakeholders necessary for the development of the TIS could be urged or motivated to contribute, potentially accelerating the implementation of a sustainable technology. It is assumed that this thesis project has created clarity and direction on the systemic influence and appreciation towards the technological development of hydrogen electrolysis. Overall, the results from the structural-functional TIS analysis aid in partly answering the origin of the large discrepancy between targeted capacity and reality mentioned in the introduction.

Concerning the actor component, the notion is introduced in this thesis that without tacit knowledge on the inner relations of a system, or a strict demarcation of the different actor roles, the actor analysis requires a creative delineation. By creating different stakeholder groups, this issue was resolved whilst adding heterogeneity between the stakeholders involved. Additionally, with the delineation of the stakeholder groups interwoven in the network layouts presented in the structural analysis, it became clear which stakeholders intervene with whom and which are underrepresented. In the case of previous TIS analyses, such as Decourt (2019), Wesseling and Van der Vooren (2017), Wieczorek et al. (2015), these components are described but not interconnected as such. The method used in this thesis also provides an overview for stakeholders considering system entry to assess which roles are under- and overrepresented.

As is expressed and iterated on in section 5.2, the splitting of SF4 resulted in the two most extreme scores of all SFs. In innovation literature, the seven system functions were first delineated fully by Hekkert et al. (2007) and have been the norm since. However, for future TIS analyses on sustainable technologies, specifically the combination within SF4 might be outdated. Due to the increasing activities to counter climate change, sustainable technologies are more and more pushed through. That argument was also often heard during the data gathering. 'No matter what, we must meet those climate targets later … So, at one point those electrolyzers have to be installed, one way or another' (GAS1, 13:45), and similar statements. Under such prospects, experts are eager to endorse their confidence in the technology, not because it outcompetes the current one, but because society will demand it in time. Such emotional argumentation potentially results in high expectations of sustainable technologies, upping the score. Yet the institutional guidance can still underperform, as is the case in this TIS analysis. One could argue said climate targets provide institutional guidance, yet the analysis in this thesis showed that those general targets do not necessarily promote a specific technology. It might be useful to consider such a splitting in future TIS analyses which involve similar prospects, since the current delineation of the seven SFs proved to be rather tight.

The list with indicators presented in Table 4 and used for labelling the dataset builds forth on previous literature presented in Negro et al. (2007, Table 1), Suurs and Hekkert (2009, Table 3) and Vasseur et al. (2013, Table 1). By empirically adding indicators based on the findings in the interviews, Table 4 provides a new base for further related TIS analyses.

With the use of a label- and an analysis score, the performance is rated in a more balanced method. The combination led to the inclusion of weight of arguments, whilst reducing the influence of the subjectivity of the researcher.

5.4 Further research

The experience of the analysis conducted in this thesis project led to three insights for further research.

First, in relevant TIS literature, the stakeholders analysed in the actor component are not delineated on level of power or interest. For instance, a municipality could have a different motive to undertake in a system than a commercial party has. It can be argued that these perspectives give way to the effort and interest an actor has in the TIS, and thus, should be considered. Especially since the effort and interest could correlate with the perseverance and resource availability, potentially resulting in altering projections or mobilizations of resources of the TIS.

Second, institutional economists could use the list of systemic problems derived in SQ3 to present workable and effective policy measures. By analysing historical TIS analyses on sustainable technologies such as solar panels and electric vehicles, similarities in systemic problems could be investigated. In such cases, a closer analysis of policy measures that resolved those problems could be implemented in the TIS for hydrogen electrolysis as well. Particular research could standardize a set of policy measures evidently useful for systemic problems, aiding other TIS'.

Third, as argued in section 4.4.3, the structural-functional TIS analysis provides useful outcomes for stakeholders interested in system entry. With the combination of adoption theory, such as the Diffusion of Innovations by Rogers, attributes of the technology important to adopters can be analysed. With insights which attributes of the technology influence adoption, the TIS analysis can be conducted to conclude if the current system is able to pursue those attributes in a qualitative manner. By combining these perspectives, benefits of the product are linked to the capabilities of the innovation system and both the technology as well as the system are examined. By doing so, analysts can develop a well-informed investment decision, more in-depth than solely a business case analysis.

6. Conclusion

By means of a structural-functional TIS analysis mainly based on 13 expert interviews, this thesis has provided insights in the four structural components of the innovation system concerning electrochemical synthesis of hydrogen in the Netherlands.

The four structural components of the TIS for hydrogen electrolysis consists of at least 108 stakeholders, active in 18 different stakeholder groups. A stakeholder group represents a responsibility or role in the functioning of the TIS. Three different electrolysis approaches were considered, AEL, PEM, and SOEC respectively. The preference of a specific approach highly depends on the use-case, yet the PEM technology is currently implemented most in European electrolysis projects. The formal network analysed showed that the system is highly interconnected. The industry and knowledge institutes and universities are most active in Dutch electrolysis projects, whilst the government and DSOs only attribute slightly. The institutional arrangements for the TIS consists of different legislative packages, including the Dutch gas law. Specific efficiency measures, transport permits, and certifications for multi-MW electrolysis installations are not present. The Dutch and European government both attribute with public fundings via subsidiary trajectories.

The seven key processes delineated by innovation literature necessary for the development of the technology are assessed with the use of two scoring mechanisms. By doing so, the impact of the systemic functions is given. The resource mobilization scored a 2, the entrepreneurial activity, knowledge diffusions, guidance of the search, and market formation a score of 3, and knowledge development and creation of legitimacy a score of 4.

Re-occurring barriers concurring from the system which were mentioned in the dataset are labelled as systemic problems. In total, 36 systemic problems arose from the analysis. The systemic problems concentrate around the market uncertainty, lack of institutional guidance and incentives, reluctant attitude of stakeholders, and insufficient resource availability. Systemic problems occurred in all system functions of the TIS.

Strukton Power is recommended to further explore opportunities of the technology, with a focus on large scale electrolyzer projects with a capacity over 100MW. Two strategies are suggested. One in which knowledge on the electrolysis process is internalized to eventually act as system integrator, and one where the current experience on electrical engineering is externalized to electrolyzer manufacturers as supplier of power systems. Dutch policymakers are advised to focus on the additional supply of RES and tightness of technical personnel and impose hydrogen synthesis in tender projects for RES realisation from now on. Future analysts can include a structural-functional TIS analysis in the orientation of new markets or investment decisions.

From the analysis led that resource mobilization inhibits, the entrepreneurial activity, guidance of the search, and market formation can be considered neutral, and the knowledge development, knowledge diffusion, and creation of legitimacy drive the development of the technology. The system would benefit most from more private funding and investments, more physical resource mobilization, market certainty, and institutional clarity. Incremental improvements on these topics would likely increase the performance of the TIS.

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Appendix A – List of system stakeholders

Table 9 provides a non-exhaustive listing of stakeholders active in the Dutch supply chain of hydrogen electrolysis, accumulated per stakeholder group.

Table 9: non-exhaustive list of stakeholders active in Dutch TIS of hydrogen electrolysis, divided per stakeholder group

Stakeholder group	Actors
Associations	Connectr
	Deltalinqs
	DWG
	FCH JU
	FME
	Hydrogen Europe
	Hydrogreen Platform
	ISPT
	Kiemt
	Nationaal Waterstofprogramma
	New Energy Coalition
	Netherlands Hydrogen & Fuel cell Association NWBA
	TKI New Gas
	WSP
DSO	Coteq
	Enduris
	Enexis
	Liander
	Rendo
	Stedin
	Westland Infra
Electricity TSO	TenneT
Electrolyzer manufacturers	Aquahydrex
	Asahi Kasei
	Arevah$_2$
	Carbotech
	Cockerill Jingli
	Cummins-Hydrogenics
	Denora
	Enapter
	Giner ELX
	Green Hydrogen Systems
	Haldor Topsoe
	Hitachi Zosen
	Honda
	Hydrogenpro
	Hydrogen energy
	iGas
	ITM Power
	Kobelco
	Kumatec
	McPhy
	NEL Hydrogen
	Peric
	Plug Power
	Shanghai Zhizhen
	Siemens Energy
	Solidpower

	Sunfire Tianjin Teledyne Thyssenkrupp Uhde Toshiba
Energy consultancy	DNO GL Qirion
Energy generation	Engie GasTerra Orsted RWE Vestas
Engineering bureau	Bos Witteveen KiWa Royal HaskoningDHV Sweco
ESCOs	Eneco Engie Essent Pure Energie Qurrent Vandebron Vattenfall Zelfstroom
Gas TSO	Gasunie
Governmental agencies	Netherlands Entrepreneurship Agency (RVO)
Industry sector	Dow Chemicals K+S ICL Fertilizers Linde Nouryon OCI Nitrogen Port of Amsterdam Port of Rotterdam Rosier Nederland Vopak Westfalen YARA
Industrial equipment manufacturers	AEG Ansaldo Thomassen Antonius Bronkhorst Conpacksys Demaco Demcon Howden HyEt Hydrogen Klinger Linde Mammoet Neles Westfalen
Knowledge institutes and universities	&Flux FME

	Hanzehogeschool Groningen School of applied sciences of Arnhem and Nijmegen TNO TU Delft TU Eindhoven
National government, ministries, and municipalities	Dutch government Ministry of Economic Affairs and Climate (EAC) Municipality of Delft Municipality of Groningen Province of Zuid-Holland
NGOs	Cenex Greenpeace
Power systems	ABB ABC Techniek AEG Power Solutions Alfen Alstom General Electric Greener Power Solutions General Electric Siemens Strukton Power Vonk
Society	Dutch citizens
Water provision	Aqua Solid Bleko Chemie Evides Evilem ie Houweling Logisticon North Water ViVochem Waterplus

Appendix B – Expert interviews

An overview of the interviewees is presented in Table 10.

Table 10: Overview interviewees

#	Actor	Stakeholder group	Code in text
1	Dutch DSO (anonymized)	DSO and energy consultancy (EC)	DSO/EC1
2	Strukton Power	Power systems (PS)	PS1
3	TU Delft	Knowledge institutes and universities (KI)	KI1
4	Strukton Power	Power systems	PS2
5	TU Delft	Knowledge institutes and universities	KI2
6	DNV GL	Energy consultancy	EC2
7	Strukton Power	Power systems	PS3
8	NEA & Ministry of EAC	Policy implementor (PI) and policy maker (PM)	PI/PM1
9	Royal HaskoningDHV	Engineering bureau (EB)	EB1
10	Chemical producer (CP) and plant constructor (anonymized)	Industrial equipment manufacturer (IEM) and industry (IND)	IEM/IND1
11	Electrolyzer manufacturer (EM) (anonymized)	Electrolyzer manufacturer	EM1
12	Petrochemical multinational (anonymized)	Industry	IND2
13	Gasunie	Gas TSO	GAS1
14	Province of Zuid-Holland*	Policy maker	PM2

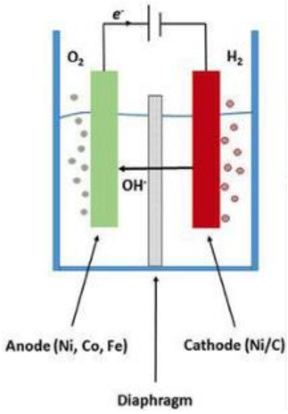
*Attempts were made to interview policy makers from provinces with industrial clusters, such as the province of Zuid-Holland. But due to time restrictions from the interviewee, the contact was limited to personal contact via email. This resulted in answers partly via mail exchange and via existing reports and attachments. The corresponding contact are depicted under ‘personal contact 1’.

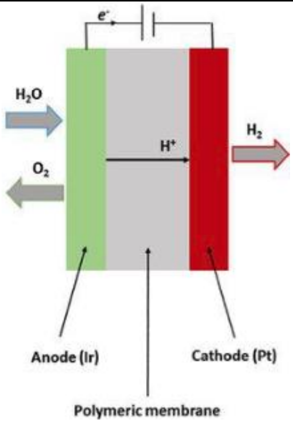
The transcriptions are available upon request, send to the author or first supervisor.

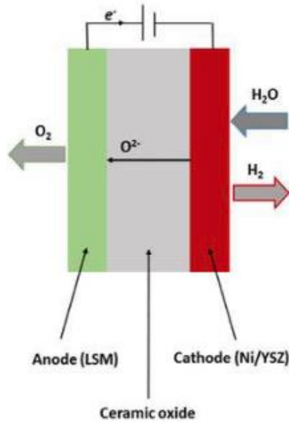
Appendix C – Electrolysis technology

Table 11: Technological overview of electrolysers

Schematics







	AEL	PEM	SOEC
Applied potential (V)	1.8-2.4	1.6-2.2	0.9-1.3
Charge carrier	OH^-	H^+/H_3O	O^{2-}
Pressure (bar)	1-30	30-70	1-10
Start-up time	Minutes	Minutes	Minutes-hours
Response time	Seconds-minute	Milliseconds	Minutes
Cell temperature (ºC)	40-90	20-100	500-1000
Electrolyte	Liquid (alkaline)	Polymer (solid)	Ceramic (solid)
Advantages	Commercially available Large scale application Lowest capital costs Low component costs Medium response time, mostly applicable for intermittent energy sources Most mature electrolyzer, experienced supply chain	Commercially available Large scale application Almost immediate response time, applicable for intermittent energy sources and grid stability purposes Highly flexible in operation Higher current density than AEL Compact design	Highest efficiency Highest current density No fluids allow for high operating temperatures, increasing kinetics Less extensive balance of plant (BoP) Waste heat relatively simple integrated into heat network
Disadvantages	Lowest current density Lowest efficiency Electrolyte pollution requires extra filtering sequence	Use of precious metals like platinum or iridium catalysts increases component costs Use of toxic metals decreases sustainability in supply chain	High start-up costs, only viable when running continuously Long response time, hardly applicable for intermittent energy sources and not applicable for grid stability purposes

	Medium response time, not applicable for grid stability purposes Corrosive alkaline electrolyte increases maintenance costs Low operational pressure	Ultra-pure water needed for process, extra step in water feedstock process	Not sustainable when high temperatures are reached by burning of fossil fuels High capital costs Not as commercially available as AEL and PEM No guaranteed lifetime expectancy Need for energy intensive compression due to low pressure hydrogen output

Appendix D – Project data network analysis

Number	Source	Consortia																			
1	Databases	ISPT	Dow Chemica	Eurest Service	Gasunie	TNO	Nobian Indust	OCI	Orsted		Yara										
2	Databases	TNO	Dutch centre	FUJIFILM Eurc	Hydron Energ	Polymer Technology Group Eindhoven															
3	Databases	HyCC	Nobian Indust	TU Eindhoven																	
4	Databases	Nouryon Indu	Nobian Indust	TU Eindhoven																	
5	Databases	NOGAT	NOGAT																		
6	Databases	TNO	Dutch centre	Frames Energy	Hydron Energy																
7	Databases	HyMatters	H2Consultanc	HyMatters	School of applied sciences of Arnhem and Nijmegen																
8	Databases	HyMatters	H2Consultanc	HyMatters	School of applied sciences of Arnhem and Nijmegen																
9	Databases	DENS	DENS Power																		
10	Databases	Hydron Energ	Hydron Energ	TNO																	
11	Databases	Air Liquide	Air Liquide																		
12	Databases	Shell	Enexis	Enexis	Shell																
13	Databases	TNO	Dutch centre	Hydron Energy																	
14	Databases	Offshore Servi	CE Delft	INTECSEA	TNO	Offshore Servi	School of appl	New Energy Coalition													
15	Databases	Frames Energy	Dutch centre	Frames Energy	Hydron Energ	Hanzehogeschool Groningen															
16	Databases	DENS	DENS Power																		
17	Databases	ISPT	Dow Chemica	Dutch centre	Frames Group	Gasunie	Imperial Colle	Nobian Chemi	OCI	Shell	ISPT	University of l	Yara								
18	Databases	Ch Energy Zer	CH Energy Zer	Solution 2 Nature																	
19	Databases	Deltalinqs	Air Liquide	BP	Deltalinqs	ENGIE	GasTerra	Port of Rotter	Linde	Gasunie	TNO	OCI	Shell	Statoil	TAQA Offshore	Uniper	Vopak				
20	Databases	Nouryon Indu	BP	Nobian Industrial Chemicals																	
21	Databases	Nouryon Indu	Port of Amste	Nobian Indust	Tata Steel																
22	Databases	Ansaldo Thom	GETEC	Nobian Indust	Opra Turbines	TU Delft	Thomassen En	Vattenfall													
23	Databases	Hydron Energ	Hydron Energ	Wageningen Research																	
24	Interview DSO/EC1	Alliander	Royal N.I.O.Z.																		
25	Databases	ISPT	Danieli Corus	Delft IMP	Eurest Service	Frames Group	Fraunhofer-G	Hydron Energ	MTSA Techn	TNO	Nouryon Industrial (	SALD	Hanzehogesch	ISPT	TDVG	Teijin Aramid	Van Swinden I	VDL Energy	Veco	Society FME-C	ZEF
26	Databases	TNO	Hydron Energ	MAGNETO spe	TNO	O3 Systems Energy															
27	Databases	TNO	Delft IMP	TNO	Polymer Technology Group Eindhoven																
28	Databases	Nouryon Indu	Gasunie	Nobian Industrial Chemicals																	
29	Databases		CE Delft	Gasunie	Vattenfall																
30	Databases	Gasunie	Gasunie	Nobian Industrial Chemicals																	
31	Databases	Sitech Manufa	Chemelot Can	Royal N.I.O.Z.	TNO	OCI	Sitech Manufa	University of Maastricht													
32	Databases	Hygear	Hygear																		
33	Databases	Vereniging Ne	EBN	TNO	Dutch oil com	Neptune Ener	TAQA Offshore	TOTAL	Society Nexstep												
34	Databases	Hyox			HYOX																
35	Interview DSO/EC1	Alliander	GroenLeven																		
36	Databases	Prodrive Tech	Prodrive Tech	ISPT																	
37	Databases	KWR Water	Allied Waters	Aveco de Bon	KWR Water	PitPoint.H2	Waternet	TU Delft													
38	Databases	TechMaCon	Composite An	Dutch centre	Energy Expo	Energy Valley	TechMaCon														
39	Interview DSO/EC1	Stedin	Municipality (	DNV GL	Bekaert Heati	GasTerra	Remeha														
40	Interview DSO/EC1	TU Delft	European Uni	Province of Zu	Municipality (	RVO	GasTerra	Alliander	Stedin	Engie	DNV GL										
41	Interview HS1	Province of Gr	Shell	Gasunie	Equinor	RWE	Eneco														

Figure 14: List of hydrogen projects and actor consortia

Name	Stakeholder group
Air Liquide	Industrial equipment manufacturer
Alliander	DSO
Allied Waters	Water provision
Ansaldo Thomassen	Industrial equipment manufacturer
Aveco de Bondt	Engineering bureau
Bekaert Heating	Industrial equipment manufacturer
BKS Verkoop en Advies	Engineering bureau
BP	Industry
CE Delft	Energy consultancy
Ch Energy Zernike	Industry
Chemelot Campus	Industry
Composite Analytica	Engineering bureau
Danieli Corus	Engineering bureau
Delft IMP	Industrial equipment manufacturer
Deltalinqs	Association
DENS	Electrolyzer manufacturer
DNV GL	Energy consultancy
Dow Chemical	Industry
Dutch centre for energy research	Knowledge institute and universities
Dutch oil company	Industry
EBN	Energy generation
Eneco	ESCO
Energy Expo	Association
Energy Valley	Association
Enexis	DSO
ENGIE	ESCO
Equinor	Energy generation
Eurest Services	Other
European Union	Government
Frames Energy Systems	Industrial equipment manufacturer
Fraunhofer-Gesellschaft	Knowledge institute and universities
FUJIFILM Europe	Energy generation
GasTerra	Industry
Gasunie	Gas TSO
GETEC	ESCO
Green Hydrogen Systems	Electrolyzer manufacturer
GroenLeven	Energy generation
H2Consultancy	Knowledge institute and universities
Hanzehogeschool Groningen	Knowledge institute and universities
Hartevelt Stomerij	Other
HyCC	Electrolyzer manufacturer
Hydron Energy	Electrolyzer manufacturer
Hygear	Electrolyzer manufacturer
HyMatters	Electrolyzer manufacturer
Hyox	Industrial equipment manufacturer
Imperial College London	Knowledge institute and universities
INTECSEA	Industrial equipment manufacturer
ISPT	Association
KiWa	Knowledge institute and universities
KWR Water	Water provision
Linde	Industrial equipment manufacturer
MAGNETO special anodes	Industrial equipment manufacturer
MTSA Technopower	Industrial equipment manufacturer
Municipality of Delft	Government
Municipality of Rotterdam	Government
Neptune Energy Netherlands	Energy generation
New Energy Coalition	Association
Nobian Industrial Chemicals	Industry
NOGAT	Industry
Nouryon Industrial Chemicals	Industry
O3 Systems Energy	Energy generation
OCI	Industry
Offshore Service Facilities	Other
Opra Turbines International	Industrial equipment manufacturer
Orsted	Energy generation
PitPoint.H2	Energy generation
Polymer Technology Group Eindhoven	Knowledge institute and universities
Port of Amsterdam	Industry
Port of Rotterdam	Industry
Prodrive Technologies	Industrial equipment manufacturer
Province of Groningen	Government
Province of Zuid Holland	Government
Remeha	Other
Royal N.I.O.Z.	Knowledge institute and universities
RVO	Government
RWE	Energy generation
SALD	Other
School of applied sciences of Arnhem and Nijmegen (HAN)	Knowledge institute and universities
Shell	Industry
Sitech Manufacturing Services	Industrial equipment manufacturer
Society FME-CWM	Association
Society Nexstep	Association
Solution 2 Nature	Energy consultancy
Statoil Petroleum As	Industry
Stedin	DSO
TAQA Offshore	Industry
Tata Steel	Industry
TDVG	Other
TechMaCon	Other
Teijin Aramid	Industrial equipment manufacturer
Theo Pouw Secundaire Bouwstoffen	Other
Thomassen Energy	Industrial equipment manufacturer
TNO	Knowledge institute and universities
TOTAL	Industry
TU Delft	Knowledge institute and universities
TU Eindhoven	Knowledge institute and universities
Uniper	Energy generation
University of Maastricht	Knowledge institute and universities
University of Utrecht	Knowledge institute and universities
Van Swinden Laboratorium	Knowledge institute and universities
Vattenfall	ESCO
VDL Energy Systems	Industrial equipment manufacturer
Veco	Industrial equipment manufacturer
Vopak	Industry
Wageningen Research	Knowledge institute and universities
Waternet	Association
Westfalen	Industry
Woonstichting Ressort Wonen	Other
Yara	Industry
ZEF	Association

Figure 15: List of actors and corresponding stakeholder group used in network analysis

Appendix E – Network diagrams

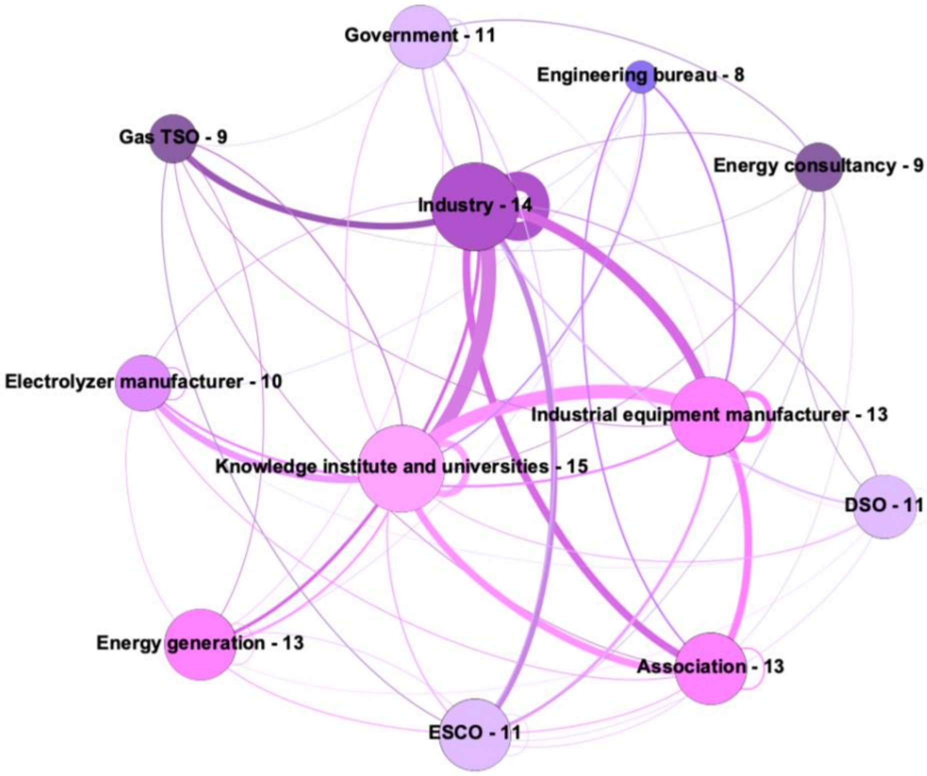


Figure 16: Network layout of stakeholder groups based on degrees between consortia

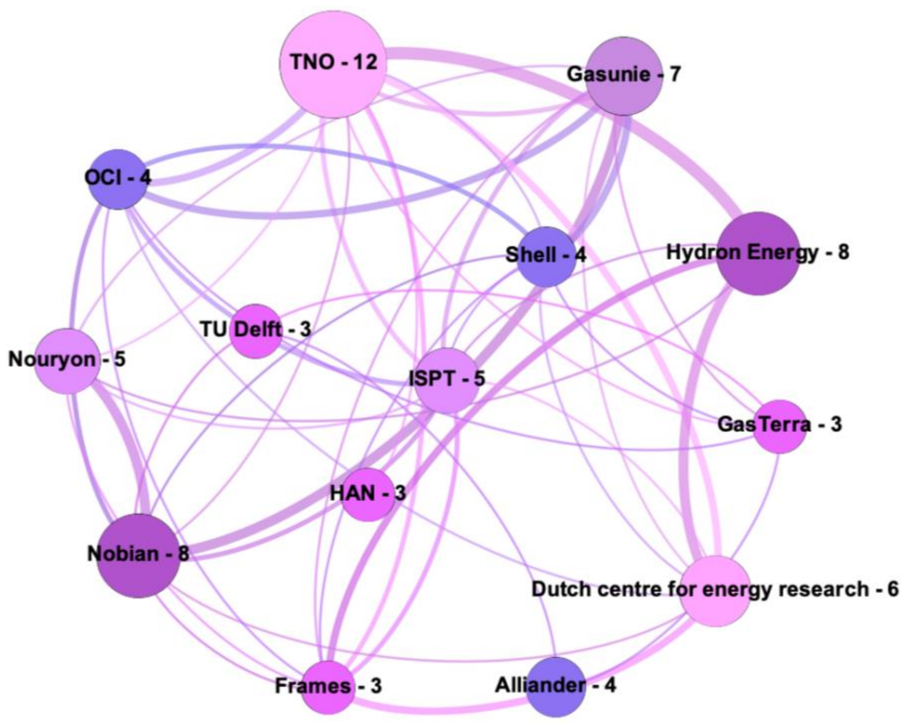


Figure 17: Network layout of individual stakeholders based on involvements in hydrogen electrolysis projects

Appendix F – Raw score interviews

Table 12: System score interview 1 (DSO/EC1)

System function	Positive	Negative	Total
1	3	2	+1
2	5	1	+4
3	3	5	-2
4A	3	1	+2
4B	0	2	-2
5	4	2	+2
6	4	1	+3
7	2	1	+1

Table 13: System score interview 2 (PS1)

System function	Positive	Negative	Total
1	3	0	+3
2	1	0	+1
3	0	1	-1
4A	3	0	+3
4B	1	0	+1
5	4	0	+4
6	4	2	+2
7	1	0	+1

Table 14: System score interview 3 (KI1)

System function	Positive	Negative	Total
1	1	2	-1
2	4	2	+2
3	3	3	0
4A	2	0	+2
4B	1	2	-1
5	1	1	0
6	1	0	+1
7	0	1	-1

Table 15: System score interview 4 (PS2)

System function	Positive	Negative	Total
1	4	0	+4
2	0	0	0
3	2	3	-1
4A	4	0	+4
4B	1	2	-1
5	0	0	0
6	1	1	0
7	1	1	0

Table 16: System score interview 5 (KI2)

System function	Positive	Negative	Total
1	3	0	+3
2	3	0	+3
3	3	0	+3
4A	2	0	+2
4B	1	0	+1
5	2	1	+1
6	3	0	+3
7	1	0	+1

Table 17: System score interview 6 (EC2)

System function	Positive	Negative	Total
1	4	0	+4
2	3	0	+3
3	2	0	+2
4A	1	0	+1
4B	2	5	-3
5	2	5	-3
6	2	3	-1
7	1	0	+1

Table 18: System score interview 7 (PS3)

System function	Positive	Negative	Total
1	2	0	+2
2	0	0	0
3	1	0	+1
4A	3	0	+3
4B	0	1	-1
5	0	1	-1
6	1	1	0
7	0	0	0

Table 19: System score interview 8 (PI/PM1)

System function	Positive	Negative	Total
1	1	0	+1
2	1	0	+1
3	1	0	+1
4A	2	1	+1
4B	1	2	-1
5	0	1	-1
6	3	4	-1
7	0	1	-1

Table 20: System score interview 9 (EB1)

System function	Positive	Negative	Total
1	6	1	+5
2	4	0	+4
3	0	0	0
4A	7	0	+7
4B	1	6	-5
5	1	1	0
6	3	6	-3
7	0	1	-1

Table 21: System score interview 10 (IEM/IND1)

System function	Positive	Negative	Total
1	5	2	+3
2	1	1	0
3	2	0	+2
4A	5	1	+4
4B	1	2	-1
5	5	2	+3
6	1	6	-5
7	1	1	0

Table 22: System score interview 11 (EM1)

System function	Positive	Negative	Total
1	6	0	+6
2	4	0	+4
3	2	0	+2
4A	5	2	+3
4B	1	1	0
5	2	0	+2
6	6	6	0
7	0	2	-2

Table 23: System score interview 12 (IND2)

System function	Positive	Negative	Total
1	6	0	+6
2	0	0	0
3	1	0	+1
4A	0	1	-1
4B	1	4	-3
5	2	2	0
6	2	2	0
7	2	0	+2

Table 24: System score interview 13 (GAS1)

System function	Positive	Negative	Total
1	4	1	+3
2	2	0	+2
3	1	0	+1
4A	3	0	+3
4B	0	2	-2
5	1	2	-1
6	4	1	+3
7	3	1	+2

Table 25: Overall system score

System function	Positive	Negative	Total
1	47	8	+39
2	28	4	+24
3	21	12	+9
4	51	35	+16
4A	40	6	+34
4B	11	29	-18
5	24	18	+6
6	35	33	+2
7	12	9	+3

Appendix G – Systemic problems

In Table 26, the full list of systemic problems is given. The systemic problems are classified in the SF in which they pose an issue. The structural component concerning the systemic problem is mentioned as well, in order to specify which component is influenced by or contributes to the problem. Often, multiple components were affected in some manner by one systemic problem.

Table 26: List of systemic problems

System function	Systemic problem	Structural component
SF1: Entrepreneurial activity	The lack of multi-MW scale electrolysis projects and implementations result in weak insights of the robustness and efficiency of the system. As a consequence, the rate of return on an investment is more difficult to calculate, adding reluctancy to invest.	Actors/ Technology
	Society is not sufficiently involved in electrolysis projects, lacking the ability for this stakeholder group to voice their interest and concerns. This could potentially result in unforeseen resistance once large-scale implementation accelerates.	Actors/ Network
	NGOs are not sufficiently involved in electrolysis projects, lacking the controlling power of non-political and independent organisation. This potentially a lack of trust in the system and higher reluctancy to invest.	Actors/ Network
	High entry barriers due to the necessity to create a large-scale system and transportation system require heavy investments to be remotely economically feasible, adding to the reluctancy to invest.	Actors/ Technology
	Complex stakeholder relations and responsibilities, which alter per project, add to the notion of a chaotic system in transition and hamper the development of a specialisation.	Actors/ Institutions
	Low active involvement of the government in electrolyzer projects, resulting in a poor insight in required institutions and other policy instruments.	Actors/ Institutions
	Low active involvement of DSOs in electrolyzer projects, partly caused by discouragement of the government, results in low cooperation and ability to utilize the existing natural gas network for cost reduction.	Actors/ Institutions
	Stakeholder standoff creates a reluctant attitude towards investing. Stakeholders are looking at each other and since a large risk could be on the first mover, they thread careful. Adding to the long investment decisions, lack of multi-MW scale electrolysis projects, and realisation of the infrastructure.	Actors
SF2: Knowledge development	The lack of multi-MW scale electrolysis projects and implementations result in a lack of data of the behaviour of such systems. Studies and R&D can contribute less to improving robustness and reliability of multi-MW scale systems.	Technology
	Multi-MW electrolysis projects involve high investment costs, usually not covered by universities. The lack of the possibility to implement a multi-MW project, limits the knowledge development and creates a dependency on other stakeholders	Actors/ Technology
	Lack of standards for design requirements of electrolyzers for researchers result in a scattering resource allocation.	Technology

SF3: Knowledge diffusion	Funding rate of a subsidy of 50% at best, create a reluctant attitude of knowledge institutes and universities to participate in learning projects unless another consortium members fill the gap.	Actors/ Institutions
	The inclusion of a knowledge institute or university results in a less practical approach than private stakeholders desire, whilst the latter bare a larger financial portion due to the funding rate of the subsidy.	Actors
	Knowledge institutions and universities and private stakeholders seem reluctant in cooperating in learning activities, resulting in a lack of practical knowledge of implementation and misaligned expectations.	Actors/ Technology/ Network
	Electrolyzer manufacturers mostly invested with knowledge institutes and universities, indicating that the technology is in the lab development phase and lack a focus on practical implementation.	Actors/ Technology/ Network
	Lacking knowledge diffusion towards supervisors and regulators hamper the process of acquainting permits.	Actors/ Network/ Institutions
SF4: Guidance of the search	Absence of standards in efficiency and RES application, and the lacking initiative of the government or other regulators to dictate them, decrease the streamlining of manufacturing and research. As a direct consequence, the full potential of the technology is difficult to monitor and the time-to-market increases. Both increase the market uncertainty and a reluctant attitude to invest in an electrolyzer system.	Actor/ Technology/ Institutions
	The Dutch government limits the involvement of the DSOs and gas TSO in hydrogen projects, whilst these entities are the only one permitted by law to transport hydrogen via public pipelines.	Actors/ Institutions
	The SSM has not issued a permit for the transport of hydrogen via public pipelines.	Actors/ Institutions
	The ACM apprehends a pricing scheme which does not incentivize users to consume electricity at full capacity, whilst network congestions and abundancy of RES create the necessity and opportunity to synthesize hydrogen at reduced costs via electrolysis.	Actors/ Institutions
	Delayed publication of European delegated act on rules for green hydrogen and subsidies create market uncertainty and reluctant investment decisions.	Actors/ Institutions
	Lack of consumer incentive to use green hydrogen. Results in a standoff and the reluctancy to invest early in the system.	Institutions
	The performance of the process of institutional guidance of the TIS is low, resulting in a lack of direction and incentives towards a high capital investment.	Institutions
SF5: Market formation	Sluggish increase of ETS results in little incentive to switch towards green hydrogen, since carbon tax can be incorporated in SMR production costs whilst keeping a cost advantage.	Institutional
	Hydrogen via electrolysis multiple times as expensive as hydrogen via SMR.	Technology
	No public market since infrastructure is owned by private stakeholders, entry barriers are high, and hydrogen is no commodity. As a results, producers cannot estimate their offset and business case.	Institutional
	High market uncertainty caused by multiple intertwined systemic problems, mentioned in section 4.2.5. The uncertainty adds to a reluctant attitude towards system entry or investment.	Actors
SF6: Resource mobilisation	Overall tightness on the labour market increase vacancies and increase time-to-market of e.g., electrolyzers, new RES, network connections.	Actors/ Technology

	Lack of private financial investments do not create the resources necessary to implement multi-MW electrolyzer systems. Contributing to a lack of understanding of reliance and robustness, in turn increasing reluctancy to invest.	Actors/ Technology
	Lack of materials and components for the assembly of electrolyzer increase the time-to-market of up to two years. In case the demand for electrolyzers increases due to policy measures, that number will sharply rise. The prospect of not being able to install an electrolyzer in time also creates a reluctant attitude to invest in up- and downstream processes, infrastructure, contracts etc.	Technology
	Increasing network congestions decrease ability to connect to the electricity grid.	Technology
	Insufficient RES available for large scale implementation of electrolyzers.	Technology
	Delegated act most likely forces additional construction of RES to feed the electrolyzer if a project wants to apply to a subsidy or gain a green hydrogen label, adding complexity to the system and increasing investment risk.	Actors/ Institutional
	Insufficient lots available in the Netherlands for the placement of RES.	Institutional
	The gas TSO wants production contracts to assure enough hydrogen will flow through the hydrogen backbone once completed, whilst producers do not commit to said contracts until the backbone is nearly completed. The standoff increases investment decision time and increases reluctant attitudes.	Actors
SF7: Creation of legitimacy	The complex system, low implementation, and seemingly low effort to educate the public on the applications of hydrogen or the hazards might result in a public misalignment of the risks. As a consequence, a relatively small setback or accident might overturn the public opinion towards the technology or hydrogen in general.	Actors/ Network