Accelerating Offshore Wind-to-Hydrogen Energy Systems in the Netherlands

A Technological Innovation System Analysis

Robert Blauw

MSc Environmental & Energy Management
University of Twente, The Netherlands

1st supervisor: Lisa Sanderink
2nd supervisor: Steven McGreevy

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Preface

The motivation for this thesis topic stems from my personal experiences and interests. Over the last year, I frequently travelled across the Afsluitdijk for work. During these trips, I passed by Windpark Fryslân, a wind park situated in the IJsselmeer consisting of 89 wind turbines producing 4.3 MW each. It was during these commutes that I first became acquainted with the concept of wind curtailment. I noticed that on numerous windy days, many of the turbines were not operational. While aware of the net congestion issues prevalent in the Dutch energy grid, it startled me to think about the amount of potential renewable energy being unused.

With a background in chemical engineering and experience in electrochemistry, I recognized the potential of using excess wind energy for hydrogen production. After some Google searches, I came across a scenario analysis by TNO. The analysis described how the Dutch government's ambitious goals for offshore wind development would be untenable without viable energy conversion solutions. This insight inspired me to contribute to this critical area of research.

Through this research, I aim to contribute to accelerating the adoption and diffusion of offshore wind-to-hydrogen energy systems, hoping to see the wind turbines stand still a little less often.

Acknowledgements

I would like to express my gratitude to my supervisors, Lisa Sanderink and Steven McGreevy, for their invaluable guidance and support throughout this research. In particular, I am immensely grateful to Lisa Sanderink, my primary supervisor, for her dedication to enhancing my thesis. Her insightful feedback and active involvement in the development of my work have been instrumental to its success. I am also thankful to Lisa for arranging my participation in the opening event of the PosHYdon pilot, an experience that not only deepened my understanding of the topic but also made the thesis process more enjoyable. I extend my sincere thanks to the PosHYdon crew for facilitating this opportunity.

I would also like to thank all the interviewees for their willingness to share their valuable insights.

Finally, I owe a special debt of gratitude to my future wife for her incredible support throughout this journey. Her understanding and encouragement, especially while managing the planning of our wedding during my master's program, have been a source of immense strength and motivation for me.

Abstract

In the effort to address climate change, it is imperative to transition to renewable energy sources. Wind energy stands out as a cost-effective option with minimal environmental impact. The Netherlands, ideally positioned for offshore wind development, has set ambitious targets to substantially increase offshore wind capacity in the coming years. However, the inherent intermittency of renewable energy sources imposes additional stress on the already constrained Dutch electricity grid. Energy storage solutions can enhance grid flexibility as the share of offshore wind energy rises. One promising method is converting electricity to hydrogen through electrolysis, which also aids in decarbonizing heavy industry.

Integrating offshore wind energy with electrolysis requires significant innovation, as large-scale systems of this nature do not yet exist. Research in this area, particularly from a systems thinking perspective, is limited. Understanding the current progress and the supportive landscape of this innovation can provide valuable insights. While previous studies have focused mainly on either offshore wind or green hydrogen innovation, there is a gap in innovation research on the integrated system.

This study comprehensively explores the development of offshore wind-to-hydrogen energy systems in the Netherlands, identifying barriers to diffusion and proposing policy measures. The Technological Innovation Systems (TIS) framework was operationalized to achieve this, providing both qualitative and quantitative insights through interviews and document analysis. Additionally, this research contributes to the field by applying Social Network Analysis (SNA) in a novel context and quantitatively represents the financial infrastructure dimension of the TIS framework.

The study finds that accelerating the diffusion of offshore wind-to-hydrogen energy systems requires enhanced knowledge development on the value of system balancing services and the environmental implications of such systems. Projects and research specifically focused on offshore electrolysis and system integration are underrepresented and should be prioritized. Legislation can help create a market for green hydrogen, while subsidy programs should include more demand-side funding, and the stringency of existing permit procedures should be reduced.

Table of contents

List of Tables

List of Figures

List of abbreviations

CCS	Carbon Capture and Storage
CEF	Connecting Europe Facility
CO2	Carbon Dioxide
DOI	Diffusion of Innovation
EU	European Union
EZK	Ministerie van Economische Zaken en Klimaat (Dutch Ministry of Economic Affairs and Climate Policy)
FID	Final Investment Decision
GW	Giga watt
IEA	International Energy Agency
IPCC	International Panel on Climate Change
IPCEI	Important Project of Common European Interest
IS	Innovation System
MLP	Multi Level Perspective
MW	Mega watt
NGO	Non Governmental Organization
NWP	Nationaal Waterstof Programma (National Hydrogen Program)
OWE	Opschaling volledig hernieuwbare Waterstofproductie via Elektrolyse (Scaling up fully renewable Hydrogen production via Electrolysis)
PEM	Proton Exchange Membrane
R&D	Research and Development
RE	Renewable Energy
RED	Renewable Energy Directive
RVO	Rijksdienst voor Ondernemend Nederland (Dutch Enterprise Agency)
SME	Small and Medium-sized Enterprises
SNA	Social Network Analysis
SNM	Strategic Niche Management
TIS	Technological Innovation System
TM	Transition Management
TOE	Technology Organization Environment
TSO	Transmission System Operator

1 | Introduction

The transition to renewable energy (RE) sources is fundamental in the global effort to address climate change, a point strongly emphasized in the most recent report from the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2023). According to the report, the impacts of climate change could surpass previous predictions, suggesting that to avoid irreversible and catastrophic effects, it is crucial to limit the rise in global temperature to 1.5°C. The Paris Agreement, in which world leaders formally committed to reducing greenhouse gas emissions and making efforts to keep global warming well below 2°C, with efforts to limit it to 1.5°C, was a pivotal moment in the global effort to combat climate change.

The European Union (EU) has been at the forefront of adopting measures to align with the Paris Agreement. The adoption of the 'Green Deal' by the EU in 2019 marked a significant commitment to reducing carbon dioxide (CO_2) emissions, with targets set at a 49% reduction by 2030 and 95% by 2050, relative to 1990 levels (Fetting, 2020). Recognizing the urgency of escalating climate challenges, the EU further advanced its ambitions with the 'Fit for 55' package in 2021. This initiative seeks to achieve a 55% reduction in emissions by 2030, setting a clear path towards a carbon-neutral economy by 2050, reflecting the intensified commitment to decarbonization (European Commission, 2021).

In achieving these ambitious climate targets, it is imperative to step away from fossil fuels to more sustainable energy sources, with electrification playing a key role in this transition. Projections indicate that by 2050, electricity will evolve from its 2020 share of 22% to become the primary energy source (IEA, 2023c). In this context, wind energy can be found to play a crucial role, with expectations for global wind energy capacity to increase 11-fold to 8000 GW. This expansion positions wind power as the leading electricity generator, anticipated to contribute 28% to the total global electricity mix (IEA, 2021a). The reason for this significant growth can be attributed to the ongoing recognition of wind energy's minimal environmental impact, significant technological advancements, and steadily declining costs. These factors have made wind energy an increasingly preferred option for meeting the global demand for clean and sustainable electricity (Kaygusuz, 2009). Despite its advantages, the intrinsic variability and uncertainty of wind energy pose considerable challenges for integration into power systems. Although grid operators have long managed fluctuations on the demand side, the rapid expansion of RE sources now requires grid operators to also deal with variations in supply, making it increasingly difficult to maintain grid stability and ensure efficient power system operations (Holttinen, 2012).

In addressing the challenges posed by the intermittency of renewable energy (RE) sources, it is critical to focus on innovative solutions that enhance grid flexibility and stability. Grid flexibility refers to the ability of a power system to maintain reliable operations amidst the variability and unpredictability inherent in RE generation. Grid system operators are equipped with several methods for enhancing grid flexibility, however, scenarios can still exist where grid transmission capacity is constrained as a result of an oversupply of RE and a too-large share of inflexible base-load generators (Lund et al., 2015). In these instances, system operators might opt to reduce the intake of renewable energy, a practice known as curtailment (Bird et al., 2016). While wind curtailment can be carried out for a variety of reasons, it is often done to alleviate grid constraints brought on by moments of high wind penetration. Curtailment in essence implies losing renewable electricity. As the share of variable RE has increased, the International Energy Agency (IEA) has observed a trend in the amount of curtailment (IEA, 2023a). In Germany and the UK for example, wind curtailment rates increased from around 0.4% and 0.7% in 2012 to 4.4% and 5.6% in 2016 respectively, placing significant financial burdens on the countries for balancing acts (Joos & Staffell, 2018).

To prevent RE losses, storage can be applied, which is considered essential to manage the impact of RE sources on the electricity grid (IEA, 2023b). Energy storage has the potential to increase both the energy and economic efficiency of RE systems. By storing energy during periods of low demand, baseload power production can continue operating at high efficiency, and during times of high demand, the stored energy can be utilized to meet peak needs without resorting to less efficient peaking power plants (Lund et al., 2015). This approach not only contributes to smoothing out the variability of RE sources but also reduces the need for curtailment, ensuring that a higher proportion of generated RE can be utilized efficiently. Among the energy storage solutions pumped hydroelectric power stands out as currently the most applied with battery storage experiencing a remarkable 14-fold increase in application over the last seven years (IEA, 2023b). However, pumped hydro's feasibility is geographically limited, and large-scale battery storage raises concerns due to its environmental impact (Blakers et al., 2021; Dehghani-Sanij et al., 2019).

It is within this context, that the role of green hydrogen as a versatile energy carrier presents significant opportunities (Sgobbi et al., 2016). Within the broader scope of decarbonization, green hydrogen emerges as a key solution, offering both short-term storage capabilities comparable to those of batteries and efficient long-term energy storage (Carmo & Stolten, 2018). This can be understood as the concept of power-to-hydrogen, a technique that uses an electrolysis process to transform electricity into hydrogen. This process can not only enhance grid flexibility and increase energy security, but also holds the potential to decarbonize traditionally fossil fuel-dependent sectors such as transportation, shipping, and heavy industry through the adoption of this energy carrier. Hydrogen is anticipated to account for 14% of global final energy consumption by 2050, highlighting its critical role in the energy transition (IRENA, 2023).

As the energy landscape changes to incorporate more variable wind energy the integration of it with green hydrogen production is key to accelerate the energy transition (Won et al., 2017). Specifically, in the Netherlands, this integration strategy can significantly aid in achieving the nation's ambitious climate goals. The Netherlands already has a strong commitment to creating a hydrogen economy and acknowledges hydrogen's crucial role in the energy transition (Gigler et al., 2021). When it comes to wind energy, the Netherlands is not ideal for onshore wind due to spatial constraints and social acceptance issues (Bilgili et al., 2011; IEA, 2021b; Ryberg et al., 2019). Conversely, the Netherlands is ideally positioned to exploit offshore wind energy, thanks to excellent weather conditions, shallow waters and the sandy sea bed of the North Sea (Macquart et al., 2023). This strategic advantage, coupled with the integration of green hydrogen production, paves the way for the cost-effective development of offshore wind farms (Durakovic et al., 2023).

1.1 Problem statement

Acknowledging wind energy's potential, the Netherlands has set ambitious goals to expand its wind energy capacity significantly, aiming for a sevenfold increase in offshore capacity to reach 21 GW by 2030 and 70 GW by 2050 (RVO, 2021b). This initiative is central to the energy transition in the Netherlands and could significantly contribute to meeting its climate targets. However, this ambitious expansion faces a critical challenge due to the existing grid constraints in the Dutch electricity system. The capacity constraints of the current grid infrastructure have become a pressing issue, indicating regions where the grid is unable to accommodate additional electricity generation or demand without substantial upgrades (Netbeheer Nederland, n.d.; RVO, 2021a).

The resulting economic implications of these grid constraints are substantial. Grid balancing efforts by the Dutch transmission system operator (TSO) Tennet to ensure grid stability have incurred substantial costs, with taxpayers bearing an expense of 340 million euros in 2021 (Pauw, n.d.). These costs underscore the urgency of addressing the grid's limitations to avoid further economic burdens and facilitate a smoother transition to renewable energy sources.

Furthermore, a recent report by TNO discusses the feasibility of the Netherlands' offshore wind energy ambitions under the current grid conditions (Gonzalez-Aparicio et al., 2022). The report states that, with the planned increase in offshore wind capacity, an estimated 13% of the generated wind energy would have to be curtailed due to the inability of the grid to accommodate this surge in production. This level of curtailment would not only undermine the economic viability of offshore wind projects but also signify a substantial loss in potential renewable energy that could be harnessed to meet the country's climate goals. Conversely, the TNO report found that achieving electrification in heavy industries could offer a solution to these grid constraints, enabling full utilization of renewable energy capacity. By elevating electricity demand through the electrification of high-energy-consuming sectors, the grid can accommodate the increase in renewable energy production. To achieve this electrification the production of green hydrogen is suggested to increase flexibility and reduce the risks of wind energy projects.

Hydrogen production, especially offshore hydrogen production, is still in its early stages. Many steps of innovation are still required to enable large-scale offshore hydrogen production (TNO, 2022). It necessitates the development of integrated systems where hydrogen production is flexibly managed based on the demand for either hydrogen or electricity. To realize the Netherlands' ambitious targets, significant efforts are needed to accelerate green hydrogen production and its integration with offshore wind energy systems.

1.2 Knowledge gap

It is clear from the above description that significant efforts need to be made to accelerate the diffusion of offshore wind-to-hydrogen systems. A deeper understanding of this technology from a systems perspective could be instrumental in facilitating its diffusion. The fundamental work of Carlsson and Stankiewicz (1991) introduced the concept of the technological innovation system (TIS) which they 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 utilization of technology". This perspective highlights the importance of considering the network of actors, institutions, and policies that collectively influence the development and diffusion of new technologies. In this context, 'diffusion' refers to how an idea or technology is adopted by and spreads across markets and the broader social system following its introduction (Rogers, 1962). TIS is part of the broader field of innovation system (IS) research focussing on technology as the unit of analysis.

Despite the significant body of research on the integration of green hydrogen production with offshore wind energy systems, a distinct knowledge gap persists in understanding the diffusion of these integrated systems within the Netherlands from an IS perspective. Current literature has explored various facets of this integration, ranging from operational preferences (Weimann et al., 2021) and technical barriers (Rabiee et al., 2021; Ramakrishnan et al., 2024) to economic implications (Durakovic et al., 2023) and barriers to project development (Wu et al., 2022). Looking more broadly at hydrogen in general, future scenarios for a hydrogen economy have been described using modelling approaches (Hanley et al., 2018; Mulder et al., 2019; Remko et al., 2020), IS analyses in offshore wind (Sawulski et al., 2019; Wieczorek et al., 2013a, 2015), and the diffusion of hydrogen technologies (Da Silva et al., 2022), have provided valuable insights. Furthermore, TIS studies for hydrogen in different geographical contexts have contributed to understanding the broader hydrogen TIS (Asna Ashari et al., 2023, 2024; Broekstra, 2023; Laarhoven, 2023; Suurs et al., 2009). Therefore, most of these TIS studies have taken a broader approach by focusing either on hydrogen in general or specifically on offshore wind, without delving into the integration of the two. While Decourt (2019) explored the TIS surrounding power-to-X systems, this study approached the topic from a European perspective and remained broad in scope, considering multiple energy sources and various conversion pathways, including but not limited to hydrogen. Consequently, the specific dynamics of integrating offshore wind with hydrogen production in the Dutch context remain underexplored. Conducting such an analysis can accelerate the diffusion of these systems in the Netherlands by identifying existing barriers within the TIS and proposing strategies to overcome them.

1.3 Research objective

This study aims to analyse the TIS surrounding offshore wind-to-hydrogen energy systems in the Netherlands. By identifying the actors, networks, institutions and infrastructure relevant to the innovation, and assessing the functionality of the TIS, this research aims to reveal the existing barriers in the TIS and suggest strategies for relieving them.

Centered around this goal, the research is guided by the main research question:

"How can the diffusion of wind-to-hydrogen energy systems in the Netherlands be accelerated?"

To address this overarching question, the study is structured around three sub-questions, each designed to uncover certain aspects of the TIS:

SRQ 1: *"What are the key actors, networks, institutions and infrastructure relevant to the offshore wind-to-hydrogen technological innovation system?"*

SRQ 2: *"What are the systemic barriers that currently impede the diffusion of offshore wind-to-hydrogen energy systems?"*

SRQ 3:*“What policy measures can be formulated to overcome the barriers and accelerate the diffusion of offshore wind-to-hydrogen energy systems?"*

The first subquestion explores the configuration of the offshore wind-to-hydrogen innovation system, focusing on the key actors, interactions, institutions, and infrastructure. This analysis aims to understand not only the ecosystem making up the TIS and help to identify shortcomings.

The second subquestion identifies the systemic barriers that currently impede the diffusion of offshore wind-to-hydrogen energy systems. By highlighting these barriers the research aims to provide a clear understanding of the obstacles to diffusion. To achieve this, the functioning of the TIS must be assessed in relation to its structure to identify the structural cause of the barrier. This analysis is essential for recognizing the areas where intervention is needed to support the technology’s development and adoption.

The third sub-question aims to identify opportunities that could potentially accelerate the adoption and diffusion of offshore wind-to-hydrogen energy systems. Through this analysis, the study seeks to offer policy goals that target the development and diffusion of offshore wind-to-hydrogen systems in the Netherlands.

2 | Literature review

The section presents an overview of hydrogen energy systems, with a specific focus on the concept of green hydrogen, its production process, the Dutch hydrogen economy, and an analysis of IS studies on the topic. Following this, it provides context for offshore wind energy systems, examining the state of these systems in the Netherlands and a review of studies of its TIS. Finally, it will discuss the plans to integrate these systems into a wind-to-hydrogen energy system and explain previous findings of such a system from an innovation systems perspective.

2.1 Hydrogen energy systems and TIS

Hydrogen is the simplest and most abundant element in the universe, yet it rarely exists in its pure form on Earth. The element was first described in the 1800s by the British scientist and chemist Henry Cavendish, who determined that burning the gas produced only water. The French chemist Antoine Lavoisier later named the element hydrogen from the Greek words 'hydro' (water) and 'genes' (forming), meaning "water-former," reflecting its property of forming water when burned (West, 2014). This quality also makes the fuel an attractive alternative to CO_2 emitting fossil fuels. Unlike oil, coal or gas, hydrogen is a secondary energy carrier falling in the same category as e.g. gasoline, heat or electricity. Meaning it first has to be produced from a primary energy source (Edwards et al., 2007).

The conventional way to produce hydrogen is through steam methane reforming. While this technique is efficient for generating large quantities in today's context, this process emits CO_2, categorizing it as a non-renewable method and earning it the label 'grey' hydrogen. An alternative, more environmentally friendly approach involves combining hydrogen production with carbon capture and storage (CCS). Although this method reduces the environmental impact relative to grey hydrogen, it continues to depend on fossil fuels and involves extra costs and energy for capturing carbon, thus referred to as 'blue' hydrogen (Newborough & Cooley, 2020).

For hydrogen to be considered 'green', it must be derived from renewable energy sources such as solar, wind, geothermal, biomass, and hydro. While biological and thermochemical processes for producing green hydrogen exist, electrolysis is considered the most basic method, using renewable electricity to split water into hydrogen and oxygen (Dincer, 2012). Among the different methods of electrolysis, alkaline electrolysis is characterized by its maturity and economic efficiency. Nonetheless, Proton Exchange Membrane (PEM) electrolysis is often the method of choice for its compatibility with renewable energy sources, owing to its ability to operate at higher currents, produce high-purity gas, and greater flexibility in responding to fluctuating energy inputs (Mucci et al., 2023; Shiva Kumar & Himabindu, 2019).

The diffusion of hydrogen into society can not be considered a function of the development of its production method. Achieving widespread adoption of hydrogen necessitates the establishment of a market and the development of public infrastructure (Gigler et al., 2021). This introduces the concept of a hydrogen economy which suggests that looking from a broader perspective, hydrogen will replace fossil fuels to become the major energy carrier. The analysis of potential scenarios within a Dutch hydrogen economy highlights the critical prerequisites for establishing such an energy framework, including the alignment with global energy trends, the formulation of supportive policies, and the adaptation of regulatory frameworks, as highlighted by (Mulder et al., 2019). Moreover, the role of market development is underscored, requiring industrial applications to be tailored to utilize hydrogen, the application of hydrogen in bunker fuels, and the requirement of the development of new storage and transport systems (Remko et al., 2020). Hanley et al. (2018) offer an international perspective on the drivers and barriers to a hydrogen economy, identifying decarbonization targets, high renewable electricity penetration, high abatement costs, infrastructure availability, and potential to decarbonize hard-to-abate sectors as key drivers. Furthermore, the role of bioenergy within a region is complex, acting simultaneously as a competitor to hydrogen and as a potential source of sustainable hydrogen production, when the conversion of biogas to hydrogen is coupled with CCS.

Furthermore, research has been devoted to understanding the TIS surrounding hydrogen. Asna Ashari et al. (2023) studied the TIS around hydrogen from a more international perspective, studying publications, patents and standards. The study suggested that the international TIS surrounding hydrogen is still in its formative phase with showing signs of moving toward the growth phase. Asna Ashari et al. (2023) further argue there is more need for developing international standards around hydrogen, which could accelerate the TIS. Suurs et al. (2009), offer an early examination of the TIS around hydrogen and fuel cell technologies in the Netherlands, with findings indicating the lack of market formation, lack of networks, lack of institutions providing coordination, and lack of policies. The core facilitators at that time were the push by the science and technology sector and the entrepreneurial motor. More recent work of Broekstra (2023) studied the TIS of hydrogen in the Netherlands and found that while there is an increased policy involvement of the Dutch government influencing system dynamics the system function guidance of the search was lacking, negatively affecting resource mobilization and market formation. Laarhoven (2023) studied the TIS of green hydrogen in the Netherlands and found the TIS was mainly hampered by a lack of market formation and a lack of regulations to guide innovation.

2.2 Offshore wind energy systems and its TIS

Humanity has been harnessing the power of wind energy since the late 19th century. British electrotechnical engineer James Blyth was a pioneer in this field, operating the first wind turbine to generate electricity in 1887 (Price, 2005). Initially, wind turbines were only capable of generating electricity at the kilowatt scale. This changed dramatically when Denmark installed its first megawatt-scale wind turbine in 1978. By 2016, the average capacity of wind turbines had increased to 7.58 MW (Enevoldsen & Xydis, 2019). This increase in capacity naturally led to larger turbines. As a result, some of the largest modern wind turbines now reach heights of up to 252 meters (Cuthbertson, 2023), highlighting the significant advancements in wind energy technology over time.

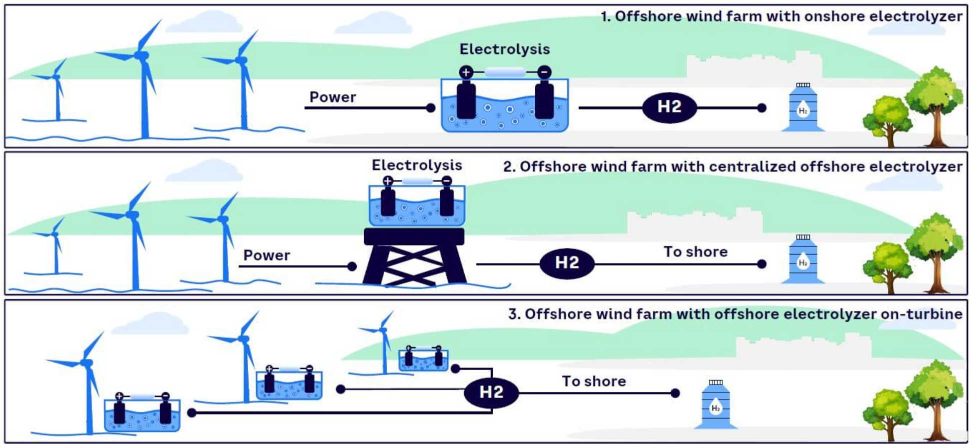
Along with increased height, several social issues emerge in wind energy projects. Common objections include visual impacts, noise pollution, and perceived health hazards. In this context, offshore wind energy often becomes the preferred choice over its onshore counterpart due to its minimal visual and noise impacts, achieved by situating turbines far off the coast (Konstantinidis & Botsaris, 2016). Additionally, offshore wind is favoured for its increased efficiency, which is attributed to more consistent and higher wind speeds available at sea. This geographical advantage is further underscored by the fact that offshore wind projects face fewer spatial constraints and do not compete with other land-based infrastructure projects, thereby facilitating the development of high-capacity wind farms. However, wind energy projects, particularly offshore, also face significant challenges, notably in terms of high capital and operational costs (Desalegn et al., 2023).

Wind energy has seen rapid development over the years which should again not just be seen from the perspective of one actor. The complexity of these systems underscores the crucial role of the TIS surrounding offshore wind energy systems. Key aspects of this development include the engineering of foundations and the installation of increasingly large wind turbines in offshore environments, which necessitate careful project management (Díaz & Guedes Soares, 2020; Thomson, 2014). Several studies sought to understand the TIS surrounding offshore wind energy. A study of Wieczorek et al. (2013a) confined its focus to the Netherlands, Denmark, the UK, and Germany. During that time they concluded the system functions of resource mobilization, market formation, and legitimacy creation needed improvement. Notably, the national policy and legislation were strongly different between the countries, hindering international collaboration for the development of a more European-centered TIS. Further research by Wieczorek et al. (2015) sought to expand on the concept of international TIS dependency by examining the interactions among different national TIS. They found that barriers to TIS were mostly country-specific, however, their findings also emphasized that technological innovation often transcends national borders, with several challenges proving internationally relevant. Sawulski et al. (2019), studied the case of Poland, which they consider a following country as opposed to leading countries such as the Netherlands. Findings indicate the TIS was mainly hampered by a lack of legitimacy resulting from political indecisiveness favouring the established practice. They further argue that the knowledge development function seems to be dependent on the ability of a country to accommodate a leading country's knowledge.

Looking at more recent studies on the Netherlands specifically show the substantial evolution the Netherlands TIS surrounding offshore wind has gone through. Initially, offshore wind in the Netherlands experienced a slow start. However, the decline of the oil and gas sector has had a positive impact on the offshore wind TIS. Consequently, market development has accelerated, and the TIS has gained significant legitimacy, largely due to the Dutch government's recent initiatives to expand offshore wind energy capacity. These developments have send the Dutch offshore wind TIS into the take-off phase (van der Loos et al., 2020, 2021).

2.3 Offshore wind-to-hydrogen energy systems and its TIS

Offshore wind-to-hydrogen energy systems refer to the integration of the two systems as outlined above. Wind-to-hydrogen falls under the umbrella term power-to-x, referring to the production of any energy carrier or chemical from a renewable energy source. The fact remains that hydrogen is the necessary precursor. The versatility of hydrogen makes it difficult to describe a standard layout for these systems as they can have diverse operational modes. Wind-to-hydrogen systems can be implemented through hybrid integration, allowing for the simultaneous production of hydrogen and electricity based on demand. Alternatively, some systems may operate solely to convert all generated electricity into hydrogen. Furthermore, the electrolysis component, crucial for hydrogen production, can be situated offshore—potentially on an existing structure like a decommissioned oil rig or new jacket-or integrated into the wind turbine itself—or onshore, where electricity is transmitted via cables to the shore (Carlot et al., 2023; Mucci et al., 2023).



Source: Arthur D. Little

Figure 1: Models for hydrogen and offshore wind energy systems integration (Carlot et al., 2023).

Figure 1 illustrates three different models for hydrogen and offshore wind energy systems integration. The choice of a model and operation mode depends on several factors. A country can for example, prioritize decarbonizing industry over providing carbon-neutral electricity. In such a situation, wind farms would only produce hydrogen. Carlot et al. (2023), however, find that a hybrid approach, where hydrogen is only produced when curtailment occurs, decreases the levelized cost of hydrogen. Additionally, the geographical location of the wind farm significantly affects the choice of model. Wind farms located far from the coast tend to favour offshore electrolysis since transporting hydrogen via pipelines is more efficient and cost-effective than transmitting electricity through undersea cables.

The integration of offshore wind-to-hydrogen systems introduces entirely new challenges and necessitates a distinct body of knowledge, making it clear that the TIS specific to this integration cannot be fully understood by examining the systems separately. Research on the development of these systems is limited. Wu et al. (2022) utilized a modelling approach to identify the obstacles hindering the development of offshore wind-to-hydrogen projects. Their findings highlight the complicated planning and design, lack of technical specifications, high initial investment, immature business model and lack of high-matching modelling technology as the five most critical barriers that hamper its development. Decourt (2019) studied the TIS of power-to-x from a European perspective and found that its TIS is growing but is mainly hampered by a lack of market formation and underlying conflict of interest across the wide basis of actors.

From the above literature review, it can be concluded that certain aspects of offshore wind energy systems and hydrogen energy systems are likely to intersect within the TIS of offshore wind-to-hydrogen. Specifically, the barrier of market development, a common issue identified in both the power-to-x case and within the TIS related to hydrogen, is expected to be a significant challenge for offshore wind-to-hydrogen as well since all these systems operate within the same market. Furthermore, the TIS surrounding offshore wind looks to be more developed than the one for hydrogen energy systems suggesting that more hampering is expected from that side of the innovation system.

3 | Analytical framework

The analytical framework for this research was selected following a review of transition framework literature conducted via Scopus and Google Scholar. The review identified several possible frameworks: Transition Management (TM), Strategic Niche Management (SNM), The Multilevel Perspective (MLP), the Diffusion of Innovation (DOI) theory, the Technology-Organization-Environment (TOE) framework, and the TIS framework. Among these, TM was excluded due to its, governance-focused approach that might be applicable for more broad sustainability transitions but less for this specific innovation which involves a network of actors (Markard et al., 2012). SNM can be valuable for studying innovation trajectories and involves creating protected spaces for innovations to develop. This also applies less to the context of the integration of two relatively matured systems by a large group of actors. The MLP was found to be less fitting due to its broad focus rather than a detailed, systemic analysis required to understand this technological innovation (Geels, 2019). Similarly, the DOI focuses predominantly on how technologies are adopted by societies. While this research acknowledged this aspect as important, it can be argued to be less relevant for wind-to-hydrogen systems. These systems are primarily adopted by organizations rather than directly by societal end-users (Rogers, 2005). The TEO was not selected because it focuses on how technologies, such as new software, are adopted by organizations (Baker, 2011). Consequently, the TIS emerged as the most suitable framework, offering a comprehensive and systematic approach for analyzing the development and diffusion of offshore wind-to-hydrogen energy systems.

The TIS framework is an evolution of the IS concept, which has its foundations in industrial economics of the 1980s (Freeman, 1987). The IS concept captures how innovation is a process to be seen as both individual and collective actions, bound by a network of actors. Over time, this systems thinking approach has evolved into various specialized iterations, including national, regional, sectoral, and technological perspectives, with the latter applied best to study wind-to-hydrogen energy systems (Carlsson et al., 2002). The notion of TIS, as introduced by Carlsson and Stankiewicz (1991), provide a structured approach to examine the development and diffusion of emerging technologies within society. Carlsson and Stankiewicz (1991) define a technological system as "a dynamic network of agents interacting within a specific economic/industrial context, underpinned by a particular set of institutional arrangements, and engaged in the creation, spread, and application of technology" (p. 93). The TIS framework gained popularity in the study of emerging technologies and sustainability transitions. Since its introduction, the framework has faced some criticism from scholars, particularly regarding its limited consideration of external influences such as pressure from dominant regimes or broader socio-economic landscapes, as well as its treatment of spatial factors. However, over the last decade, the TIS framework has undergone significant conceptual development, addressing many of these concerns and expanding its applicability (Markard et al., 2015).

3.1 Structural components

Central to the TIS framework are three core elements—actors, networks, and institutions—that collectively contribute to the development and diffusion of specific technologies (Bergek et al., 2008; Carlsson & Stankiewicz, 1991). Within this framework, 'actors' encompass the entities integral to the innovation value chain, including firms, universities, research institutes, government agencies, and financial organizations. These actors are technically, financially or politically capable of influencing the process of innovation diffusion. Following actors, 'networks' comprise the channels in which information, resources, and support, are shared, enabling the collaborative effort necessary for innovation (Bergek et al., 2008, 2015; Markard & Truffer, 2008). Wieczorek and Hekkert (2012) broaden this concept by distinguishing the element 'interactions' as they argue networks can be seen as a higher form of an organization while interactions don't necessarily have to occur within networks. 'Institutions', in the context of TIS, refer to both the formal and informal rules that shape interactions among the actors. This encompasses laws, regulations, standards, and cultural practices that collectively influence the process of innovation (Bergek et al., 2008; Wieczorek & Hekkert, 2012). Although not a core element of the TIS framework, some studies report infrastructure as an element shaping innovation systems with divergent interpretations. Wieczorek and Hekkert (2012) specifically categorizes infrastructure into three domains: physical, financial, and knowledge-based, each as structural components in shaping the innovation system. Table 1 summarises all the structural components of the TIS framework.

Table 1: Structural components of the TIS framework. Adopted from Wieczorek and Hekkert (2012).

Structural dimensions	**Subcategories**
Actors:	• Civil society • Companies: start-ups, SMEs, large firms, multinational companies • Knowledge institutes: universities, technology institutes, research centres, schools • Government • NGOs • Other parties: legal organisations, financial organisations/banks, intermediaries, knowledge brokers, consultants
Institutions:	• Hard: rules, laws, regulations, instructions • Soft: customs, common habits, routines, established practices, traditions, ways of conduct, norms, expectations
Interactions:	• At level of networks • At level of individual contacts
Infrastructure:	• Physical: artefacts, instruments, machines, roads, buildings, networks, bridges, harbours • Knowledge: knowledge, expertise, know-how, strategic information • Financial: subsidies, financial programs, grants etc.

3.2 System functions

Innovation systems can have similar structural components but function in a totally different way. Therefore it is necessary to study the systems functions to critically assess the performance of an innovation system. Functions are the critical activities or processes that need to occur for the TIS to perform well and foster the development, diffusion, and use of new technologies. The development of a conceptual framework around system functions was thought to be a pivotal moment in TIS research (Hekkert et al., 2011). Hekkert et al. (2007) and Bergek et al. (2008) have significantly contributed to the conceptualization of functions and currently dominate the field with their interpretations (Bergek, 2019). This study adopts the conceptualization of Hekkert et al. (2007), as detailed in table 2.

Table 2: The system functions adopted from Hekkert et al. (2007).

The system function	**Description**
F1: Entrepreneurial activities	Turns the potential of new knowledge, networks, and markets into concrete actions to generate – and take advantage of – new business opportunities.
F2: Knowledge development	Encompasses R&D and knowledge development in the form of learning by searching' and 'learning by doing'.
F3: Knowledge diffusion through networks	Exchange of information in networks. Includes 'learning by interacting' and 'learning by using' (if user-producer networks are concerned).
F4: Guidance of the search	Those activities within the TIS that can positively affect the visibility and clarity of specific wants among technology users. Represents the process of selection among various technological options.
F5: Market formation	Creation of protected space for new technologies.
F6: Resource mobilisation	Allocation of sufficient resources, both financial and human capital.
F7: Creation of legitimacy/counteract resistance to change	Creation of legitimacy for a technological trajectory by advocacy coalitions putting the new technology on the agenda and lobbying for resources and favourable tax regimes.

3.3 The phase of development

According to Bergek et al. (2008) it is a common mistake of scholars to assess a TIS in its formative phase on criteria relevant to its growth phase. The extent to which system functions need to be fulfilled depends on the phase of development of the innovation. A TIS can require different forms of functionality across different phases of development, underscoring the importance of identifying the system's current phase before evaluating its functionality (Bergek et al., 2008; Hekkert et al., 2011).

Wieczorek and Hekkert (2012) define four stages: pre-development, development, take-off, and acceleration. The pre-development stage is characterized by a high degree of uncertainty in which a prototype might be produced, and knowledge development is seen as the most critical system function. This function can be negatively influenced by the other system functions knowledge exchange, guidance of the search and resource mobilization. In the development stage, experimentation starts, characterised by pilot projects that need to showcase the innovation's practicality. In this stage, all system functions are seen to positively or negatively affect each other, which is why all system functions are found to be critical. In the take-off phase, knowledge development and knowledge diffusion through networks become less relevant, while entrepreneurial activities and the creation of legitimacy to counteract resistance to change become critical. In the final acceleration phase, the focus shifts to market formation, supported by ongoing entrepreneurial activities, resource mobilization and, guidance of the search. The phase of development is completed when saturation and stabilization occur. Figure 2 shows the functional dynamics across phases: the black arrows show current relationships; the grey arrows, show past ones that still advance technology into later phases. This illustrates how system functions evolve and reinforce each other, driving the innovation system's growth (Hekkert et al., 2011).

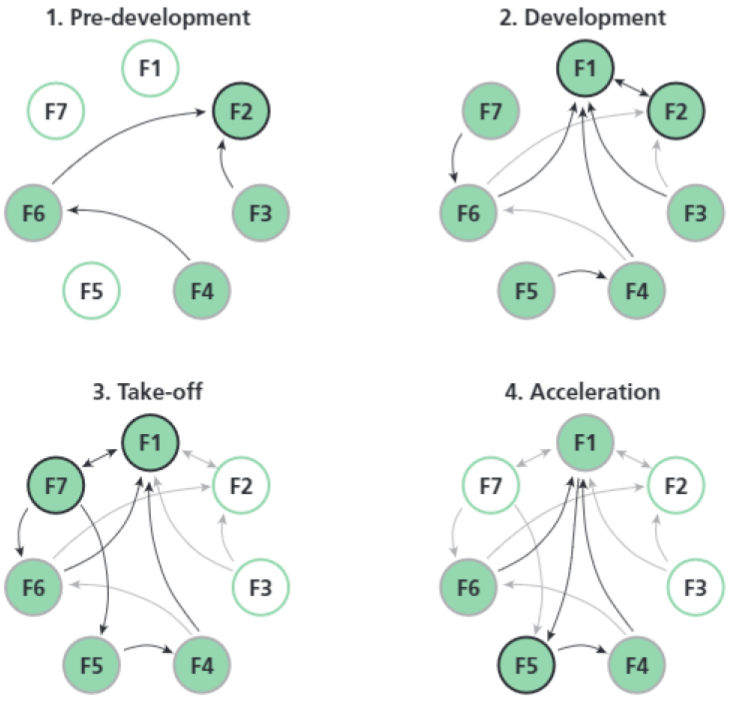


Figure 2: Functional patterns per phase (Hekkert et al., 2011).

3.4 Systemic problems and systemic instruments

The functionality or diffusion of a TIS may encounter hindrances for a variety of reasons. Through an analysis of structural components and system functions, these hindrances can be identified and addressed. In the literature, the malfunctioning of a system is commonly attributed to either systemic problems or blocking mechanisms (De Oliveira et al., 2020). Despite the varied terminology used, there is a common ground between the two. Bergek et al. (2008) refers to these obstacles as blocking mechanisms and evaluates them based on the system functions. Wieczorek and Hekkert (2012) made an effort aimed at connecting the conceptual gap between system functions and the system elements, stating that an improvement in a systems function cannot be made without changing the structural components, a connection that Bergek et al. (2008) does not explicitly establish in their typology. This makes the typology of Wieczorek and Hekkert (2012) a more established one, enhancing the understanding of the TIS dynamics.

Carlsson et al. (2002) define a system through its components, relationships, and attributes, with attributes considered as properties of components. However, Wieczorek and Hekkert (2012) argue that relationships, too, can have attributes, broadening the perspective on system composition. Here the components are the structural components of a system as delineated in Section 3.1.

Carlsson et al. (2002) further argue that a system's functionality is compromised if any issues arise within its components or their respective attributes. Such issues could range from the absence of any of the structural components to the existence of either too-strong or too-weak interactions (networks), all of which can adversely affect the system's overall performance. Building upon this, Wieczorek and Hekkert (2012) introduce a framework for identifying systemic problems, categorizing them based on: I) The presence or capabilities of the actors. II) The presence or quality of the institutional setup. III) The presence or quality of the interactions. IV) the presence or quality of the infrastructure.

They label this approach a functional-structural analysis, a full overview of which can be viewed in Table 3

Table 3: Categorization of an innovation system's systemic problems based on a functional-structural analysis, adapted from Wieczorek and Hekkert (2012).

Systemic problem	**Type of systemic problem**	**Explanation of the systemic problem**
Actors' problems	Presence related	Relevant actors may be absent
	Capacity related	Actors may lack competence, capacity to learn or utilise available resources; articulate their needs; and develop visions and strategies
Institutional problems (hard and soft)	Presence related	When specific institutions are absent
	Capacity related	When there is a problem with their capacity/quality (too stringent or too weak)
Interaction problems	Presence related	Interactions are missing because of the cognitive distance between actors, differing objectives, assumptions, capacities, or lack of trust
	Quality related	If there is a problem with the quality or intensity of the interactions. Interaction quality problems can be either strong or weak. Strong network problems may be caused by influential actors misguiding others, hindrance of knowledge exchange due to internal focus, excessive involvement of established actors, absence of beneficial weak ties, and dependency on dominant partners for assets. Weak network problems are caused by weak connectivity between actors, which hinders interactive learning and innovation
Infrastructure problems	Presence related	When specific type of infrastructure is absent
	Quality related	When infrastructure is inadequate or malfunctioning

The above systemic problems can be addressed by applying certain strategies or tools that target the systemic problems and thus improve the functionality of the TIS. Smits and Kuhlmann (2004) introduced such strategies or tools as 'systemic instruments' and suggested five strategies that policies should apply to relieve systemic problems. Wieczorek and Hekkert (2012) later improved these strategies and put them into the context of a TIS by formulating eight goals which policies or systemic instruments should aim to achieve. Table 4 provides an overview of these goals and the systemic problems they relate to.

Table 4: Goals for systemic instruments for each type of systemic problem, adopted from Wieczorek and Hekkert (2012).

Systemic problem	**Type of systemic problem**	**Goals of systemic instruments (policy)**
Actors' problems	Presence related	Stimulate and organise the participation of various actors (NGOs, companies, government etc.)
	Capacity related	Create space for actors' capability development (e.g. through learning and experimenting)
Institutional problems (hard and soft)	Presence related	Secure the presence of (hard and soft) institutions
	Capacity related	Prevent institutions from being too weak or too stringent
Interaction problems	Presence related	Stimulate the occurrence of interaction among heterogeneous actors (e.g. by managing interfaces and building a consensus)
	Quality related	Prevent ties that are either too strong or too weak
Infrastructure problems	Presence related	Stimulate the physical, financial and knowledge infrastructure
	Quality related	Ensure that the quality of the infrastructure is adequate

3.5 Operationalization of the TIS framework

The sections above have conceptualized the TIS framework, the following section will explain the operationalization of the framework to study the TIS surrounding wind-to-hydrogen energy systems in the Netherlands. Several studies describe a scheme of analysis for studying a TIS (Bergek et al., 2008; Hekkert et al., 2011; Wieczorek & Hekkert, 2012). The analytical approach developed by Hekkert et al. (2011) is primarily adopted, supplemented by insights from additional frameworks by Bergek et al. (2008) and Wieczorek and Hekkert (2012). Similar studies have taken the same methodological approach (Sawulski et al., 2019; Wieczorek et al., 2015).

The first step is to provide a clear definition of the TIS surrounding wind-to-hydrogen energy systems in the Netherlands. This initial step, as suggested by Bergek et al. (2008), sets the foundation by determining the focus (knowledge field or product/service), scope (breadth or depth), and spatial boundaries of the study. This step is essential to address a common critique and pitfall of TIS studies, where failing to clearly outline the context of the TIS can lead to overlooking important relationships or interactions (Markard et al., 2015). This is particularly important given the complexity of offshore wind-to-hydrogen energy systems, which integrate multiple fields of expertise.

According to Hekkert et al. (2011) and Bergek et al. (2008), the way a TIS should be structured and function depends on the phase of development the technology is in. In a system that is still in its early stages, some type of structure and certain functions are more relevant than those of a mature technology. More on this is explained in Section 3.3. Therefore, to properly assess an innovation system's functionality the phase of development first has to be determined. Hekkert et al. (2011) describes several diagnostic questions that ought to be answered to determine the phase of development, if the answer to the question is yes, the phase of development moves up to the next stage:

Pre-development phase: is there a working prototype?
Development phase: is there a commercial application?
Take-off phase: Is there a fast market growth?
Acceleration phase: Is there market saturation?

Following the system definition, the next step is to identify the structural components of the TIS, as highlighted in Section 3.1. This starts by determining the key actors involved in the TIS. Bergek et al. (2008) propose four approaches for identifying key actors within the TIS: reviewing industry associations, company directories, and catalogues; conducting patent analysis to determine technological activity; performing bibliometric analysis to measure publication volume; and, interviewing experts. Furthermore, the relevant interactions or networks can be identified. Some networks are easily recognized by for example co-publishing or co-patenting, joint ventures or consortia. Other networks are harder to recognize and will involve discussion with industry experts, this again will be done after the later interviews. Institutional factors, encompassing cultural norms, laws, and regulations, can be analysed through document review, or interviews with industry experts. Lastly, the identification of relevant infrastructure, whether physical, knowledge-based, or financial, can also be accomplished through both document review and expert interviews.

The third step is the functional analysis, which is an assessment of how the TIS is performing in terms of the key processes (system functions). More on what these system functions entail is described in Section 3.2. This step should be guided by semi-structured interviews with industry experts. A set of diagnostic questions is conveniently provided in the research scheme of Hekkert et al. (2011).

Hekkert et al. (2011) further explains that after the assessment the system functions can be assigned a score on a five-point likert scale (1 = very weak and 5 = very strong). In their scheme, these points are assigned by the researcher based on the answers given by the experts. This is a method also evident in the empirical research of Sawulski et al. (2019) and Wieczorek et al. (2015). However, a different approach as was taken by Edsand (2017), who asked the experts themselves to rate the performance of the system functions. This method, while potentially yielding more accurate results by leveraging expert judgement instead of the interpretation of the researcher, does introduce the risk of subjective bias in the responses. Furthermore, Edsand (2017) also provided more linguistic expression to the likert scale by allowing the experts to rate the functions as "very bad" (1 point), "bad" (2), "acceptable" (3), "good" (4), "very good" (5 points), and "not applicable" (N/A). After data collection, Edsand (2017) presents the combined averages based on the responses of all actors.

The fourth step entails a comprehensive analysis of the data collected in the third step to pinpoint which system functions are impeding innovation development. As detailed in Section 3.4, it is critical to trace the root causes of the malfunctioning. This involves mapping the malfunction back to its structural components and establishing a clear link between the underlying cause and the resultant barrier. The analysis must determine whether these barriers stem from a lack of structural components or their quality (Hekkert et al., 2011).

The analysis as described above can offer policymakers valuable insights into the primary policy measures necessary for fostering the growth of innovation systems. By concentrating on remedying the poor functionality of the TIS, introducing inducement mechanisms and eliminating existing barriers, policy measures can effectively target and mitigate the root causes of TIS malfunctioning (Bergek et al., 2008; Hekkert et al., 2011). Therefore, the final step aims to interpret the findings to formulate policy measures. This requires establishing a connection between the outcomes of the functional-structural analysis and the normative outlook on the TIS. These policy measures can come in the form of policy goals (or systemic instruments). The barriers should be ranked to offer targeted policy recommendations (Hekkert et al., 2011).

4 | Methodology

The following section will describe the methodological approach used to research the TIS surrounding offshore wind-to-hydrogen energy systems in the Netherlands.

4.1 Research design

This research operationalised the TIS framework following the analytical steps as described in section 3.5. Document analysis, database analysis and semi-structured interviews were used as data collection methods. The first step of the research was to describe the TIS and set the system boundaries by describing the spatial and knowledge field boundaries, as well as clarify the breadth and depth of the study. For the structural analysis step, the study performed an analytical (top-down) identification of the actors and networks via database analysis and document analysis of grey literature. Later, a reconstructive (bottom-up) method was employed via the interviews whereby the interview data enhanced the initial structural analysis. This strategic approach ensured a comprehensive analysis of the structural elements, in line with the guidelines proposed by Bergek et al. (2008). The functional analysis was performed using semi-structured interviews. The structural and functional analysis was coupled and used to determine the systemic barriers and draw up policy measures. Figure 3 shows a schematic representation of the research scheme in chronological order from top to bottom.

A mixed-method approach was employed for this research, combining qualitative and quantitative techniques. The qualitative aspect included interviews and document analysis, both of which were evaluated qualitatively. The document analysis also produced quantitative insights that were primarily utilized for structural analysis.

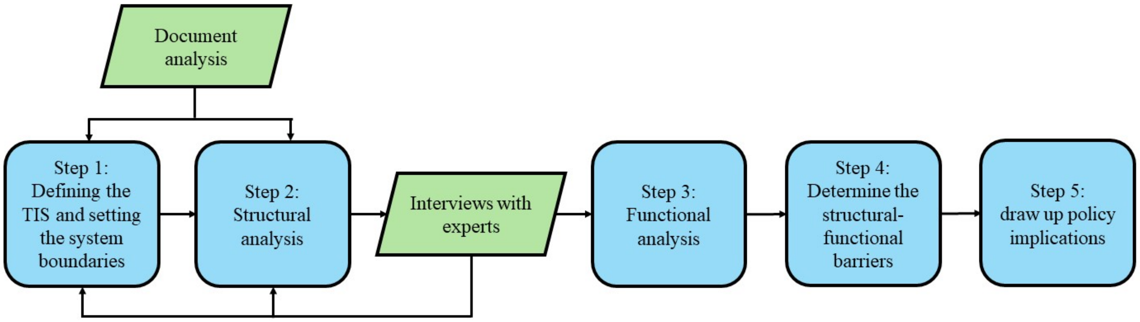


Figure 3: Schematic representation of the research framework.

4.2 Data collection

A literature review was conducted prior to the research activities, the approach of this review is discussed below. For the rest of this study document analysis and interviews were used as data collection methods. A data collection matrix is shown in Table 5.

Table 5: Data collection matrix.

Research questions	**Step of the analysis scheme**	**Sources**	**Data access method**
"What are the key actors, networks, institutions and infrastructure relevant to the offshore wind-to-hydrogen technological innovation system?"	1/2	Primary: Literature Secondary: Industry experts	document analysis Interviews
"What are the systemic barriers that currently impede the diffusion of offshore wind-to-hydrogen energy systems?"	1/3/4	Primary: Industry experts Secondary: Literature	Interviews document analysis
"What policy measures can be formulated to overcome the barriers and accelerate the diffusion of offshore wind-to-hydrogen energy systems?"	1/3/4/5	Primary: Industry experts Secondary: literature	Interviews document analysis

4.2.1 Literature review

For the literature review (Section 2), a search for scientific literature was conducted on the Scopus and Google Scholar search engines. The literature review first provides context and history of hydrogen energy systems, offshore wind and wind-to-hydrogen. The review begins by providing the context and history of hydrogen energy systems, offshore wind, and wind-to-hydrogen technologies. It then discusses previous TIS studies on offshore wind, green hydrogen, and offshore wind-to-hydrogen systems. For this, *Wind-to-hydrogen*, *offshore hydrogen*, *green hydrogen* and *power-to-x were* used as key search words along with the terms *Technological Innovation System*, *Innovation System*, *TIS* and *IS*. Literature was selected based on relevance and publication date to ensure the inclusion of the most current and pertinent insights, resulting in a total of 12 relevant studies.

4.2.2 Data survey

The structural analysis of this research employed document analysis of databases, grey literature, and online sources. Utilizing online data portals, all relevant projects were systematically collected and organized. The relevance to the offshore wind-to-hydrogen TIS was considered. A comprehensive map of hydrogen-related initiatives in the Netherlands exists which is maintained and regularly updated by MissieH2 (MissieH2, n.d.). Furthermore, databases of publicly funded projects are accessible on the websites of Topsector Energie (TopSector Energy, n.d.) and RVO (RVO, n.d.). European-funded projects were sourced from the European Commission's database (The European Commission, n.d.).

These databases served as primary repositories for gathering data on the projects and organizations contributing to the offshore wind-to-hydrogen innovation system. Project titles, associated organizations, and funding details were compiled from these sources. To ensure data fidelity, cross-referencing was performed with technical reports and company websites to verify the project status and identify all collaborating organizations [1].

4.2.3 Interviews

The data collection for this research relied heavily on semi-structured interviews with industry experts. A list of diagnostic questions was conveniently provided by Hekkert et al. (2011), which was adopted and added upon with

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[1] Data surveying was performed throughout May and June 2024.

insights gained from Wieczorek et al. (2015) and Edsand (2017) and can be found in Appendix A. The interviews were conducted online via Microsoft Teams and took between 30-60 minutes.

Table 6, provides a list of all the industry experts that have been interviewed. This research prioritized interviews with industry experts and knowledge institute representatives over public sector stakeholders or NGOs. While public sector and NGO perspectives are crucial for understanding regulatory frameworks and social impacts, they are indirectly involved with the TIS, while industry experts provide specific insights that are more directly aligned with the functioning of the TIS.

Table 6: List of interviewees and the ID assigned for easy reverence in the later analysis.

ID	Organization	Name	Role	Date
1	Topsector Energie ǀ TKI Nieuw Gas	Jörg Gigler	Managing Director	28-5-24
2	Ørsted	Request for anonymity	Manager	28-5-24
3	Dutch Marine Energy Centre (DMEC)	Request for anonymity	Advisor	30-5-24
4	Neptune Energy	Rene van der Meer	Head of New Energy	30-5-24
5	TNO	Rene Peters	Business Director Gas Technology	3-6-24
6	TNO	Joris Koornneef	Sr Consultant System Integration & Storage	6-6-24
7	TU Eindhoven	Request for anonymity	Professor	14-6-24

4.3 Data analysis

Figure 3 shows the different analysis steps that were done during this work. For steps one two and three, data had to be analysed while steps four and five used and combined this data to formulate the structural functional barriers and draw up the policy measures. Steps four and five are thus part of the discussion.

4.3.1 Document analysis

Step one was to divine the TIS and set the system boundaries. For this, grey literature was used. Document analysis yielded a comprehensive list of projects, encompassing all entrepreneurial activities pertinent to the TIS. This facilitated an understanding of the current development phase of the TIS and identified the involved actors. This list also facilitated part of the structural analysis (step two) by identifying all the relevant actors and interactions. Beyond those actors engaged in entrepreneurial activities, the analysis also included actors who contributed to relevant policy documents or other grey literature related to the TIS. Further document analysis yielded information about the relevant institutions and infrastructure relevant to the TIS. Lastly, the online databases detailed in section 4.2.2 offered data on public funding received by various entrepreneurial activities, research programs, and knowledge-sharing consortia relevant to the TIS. This data was used for a quantitative analysis of the TIS's financial infrastructure.

4.3.2 Network analysis

As part of the structural analysis, the interactions between the different actors were visualized using a social network analysis (SNA). The data from the document analysis produced an extensive list of projects and their involved actors. These projects facilitate interactions between actors. To illustrate how the different projects (or joint research programs) are connected, an SNA was performed. A SNA can reveal certain social structures. In an SNA, nodes and ties represent the network's elements. In this context, a node is a group of actors collaborating on a project related to offshore wind-to-hydrogen or a network in which actors cooperate, such as a joint research program. A tie is the relationship between nodes, which occurs when one or more actors are involved in multiple nodes (co-occurrences). This connection enables the flow of knowledge and experience from one node to another. The SNA follows from a network adjacency matrix where the projects or networks are listed in the top row and the leftmost column. Using this adjacency matrix, the data can be visualized with Gephi (Borgatti et al., 2013; Metz, 2024).

Table 7: Example adjacency matrix for a SNA. Note a project can involve an entrepreneurial activity but also a joint research program. The numbers in the matrix are a weight that can be assigned to a tie. This weight is given by the number of actors that co-occur in two nodes (adapted from Metz (2024)).

	Project A	Project B	Project C
Project A	-	2	0
Project B	2	-	5
Project C	0	1	-

4.3.3 Interview analysis

The functional analysis employed interviews with experts. These interviews were transcribed using the built-in transcription function of Microsoft Teams. The data was later coded, whereby the list of functions served as deductive labels for the coding. Furthermore, thematic coding was applied, categorizing various features of the transcripts within a function. The coded interviews were used to describe key qualitative insights descriptively. A list of all the labels that were used is provided in Appendix B. The interviewees' assessments of the system function, based on their Likert scale ratings, were collected and averaged to form a radar chart. Besides supplying the data for the functional analysis, the interviews were also used as a reference to cross-check the data resulting from the document analysis for steps one and two.

4.4 Ethical consideration

As this research involves human participants, this study strictly adhered to the ethics guidelines provided by the BMS Ethics Committee of the University of Twente. Prior to their participation, all interviewees gave their consent to participate in the study. They were informed about the intended use of the information they would be provided and about their right to decline or withdraw from the research at any time. For review, a copy of the consent form can be found in Appendix C.

5 | Results

5.1 Defining the TIS

Before analysing the TIS structure and functions, this section will provide a clear picture of what will be captured in this study by describing the scope of the analysis. Following this, the section will detail the current state of offshore wind-to-hydrogen systems in the Netherlands, providing an overview of entrepreneurial activities and their current status.

5.1.1 Scope

This study specifically focuses on the TIS of offshore wind-to-hydrogen energy systems. As such, it does not delve into the specific components or functions of electrolysers or wind turbines. Instead, the study emphasizes the TIS of integrated offshore wind and hydrogen energy systems, acknowledging the unique knowledge development they necessitate. This implies a narrow level of aggregation, where the knowledge field is highly specialized in comparison to the broader field of hydrogen innovation.

According to Little (2023), hydrogen can be integrated with offshore wind energy in three primary ways: through an offshore wind farm with an onshore electrolyser, an offshore wind farm with a centralized offshore electrolyser, or an offshore wind farm with an electrolyser located on the turbine. The optimal approach depends on several factors, including the distance to shore. Generally, offshore electrolysis is considered the preferred option because transporting energy to shore via hydrogen pipelines is more cost-effective than using cables. This study focuses on offshore wind-to-hydrogen energy systems but acknowledges that before offshore electrolysis at scale can be realized, onshore activities are required. An important example of such activities is producing hydrogen flexibly based on wind patterns. The actual offshore production would necessitate distinct knowledge development, but without considering the onshore projects and experimentation, the TIS would be incomplete as it would overlook the knowledge developed onshore. For this reason, the TIS analysis will also capture the components focusing on utilizing offshore wind energy for the production of hydrogen offshore and onshore.

The spatial boundaries have been set to the Netherlands. However, some initiatives may involve international actors or intergovernmental collaborations. These were not excluded from the analysis, but the geographical focus remained on the Netherlands. Only projects and initiatives based in the Netherlands were considered. The institutional components focused are all those relevant to the country. As the Netherlands is part of the European Union, it is subject to supranational laws or may receive EU funding for certain projects.

5.1.2 The current phase of development

To describe the current phase of development of offshore wind-to-hydrogen energy systems in the Netherlands, it is essential to review the entrepreneurial activities, including commercial, pilot, and research projects, and their current status. An overview of all projects can be found in Appendix D, which was compiled based on desk research and insights from interviews.

Currently, there are two pilot projects focused on offshore hydrogen production: Baseload Power Hub and PosHYdon. Both projects have made significant progress towards realizing their plans. Posydon started onshore testing in May 2024 and is soon starting to test their system offshore. However, larger commercial offshore production projects such as NortH2 and H2opZee have not yet reached a Final Investment Decision (FID). Similarly, most onshore green hydrogen projects, which intend to use offshore wind, are still awaiting FID or are in the initial engineering and design phases. The notable exception is Shell's Holland Hydrogen 1, which has started construction of its 100 MW green hydrogen facility.

In addition to the private initiatives listed in Appendix D, the Dutch government has committed to advancing offshore wind-to-hydrogen systems by announcing tenders for two demonstration projects. The motivation behind the government's involvement is articulated in a letter to the cabinet by Jetten (2023): "The goal is to have approximately 21 GW of offshore wind energy operational by around 2030. ... This involves large amounts of energy that need to be transported to land efficiently and safely, especially as wind farms are located increasingly farther from the coast. For several reasons, including the costs and spatial impact of cables at sea and the limited space on the onshore electricity grid, the electrical landing of wind farms is becoming increasingly complicated. Therefore, after 2030, it is anticipated that the transportation of offshore wind energy will occur in the form of both electricity and hydrogen. ... Offshore hydrogen production can provide this in addition to onshore electrolysis and imports" (p. 1). This statement clearly shows the commercial application of offshore hydrogen production, showing technical and economic benefits over onshore production. The first project the government announced, Demo 1, involves a 30-50 MW electrolyser to be installed at a wind park near the Hollandse Kust. The project is scheduled for realization in 2030. The second, Demo 2, plans for a 500 MW electrolyser at a yet-to-be-commissioned wind park near the Frisian Islands and is scheduled for realization in 2033 (Jetten, 2024). The tender documents for these projects outline specific learning objectives aimed at enhancing the technical, financial, and environmental aspects of the technology (RVO, 2023b).

In conclusion, while the TIS of offshore wind-to-hydrogen energy systems shows promising advancements, particularly in pilot projects, they have not yet transitioned fully into a rapid market expansion phase. Despite the realization of pilot projects like Baseload Power Hub and PosHYdon, and the initiation of larger projects like Shell's Holland Hydrogen 1, the lack of FID in larger-scale commercial projects reflects caution from the industrial sector. Furthermore, the Dutch government's strategic commitment, articulated in their recent tenders for two large-scale demonstration projects, reflects an understanding of the logistical and economic complexities involved in scaling offshore hydrogen production and the need for government interference to drive development. Thus, applying the diagnostic framework as described in section 3.5 the TIS positions itself on the brink of the take-off phase but remains embedded within the development phase, pending broader commercial validation and market diffusion.

5.2 Structural analysis

5.2.1 Actors

The actors in the TIS surrounding offshore wind-to-hydrogen are the organizations that are integral to the value chain of the innovation, capable of influencing its diffusion. Appendix E provides a list and categorization of these key organizations. This list combines the entities involved in related projects (as described in Appendix D), those participating in knowledge-sharing platforms and joint research projects (outlined in Section 5.2.2, excluding the HEROW platform), as well as entities identified based on the interviews or document analysis. Figure 4 presents a pie chart illustrating the distribution of different categories of actors. The chart also shows the breakdown of these actors by their affiliation: public, private, public/private partnership, or civil society.

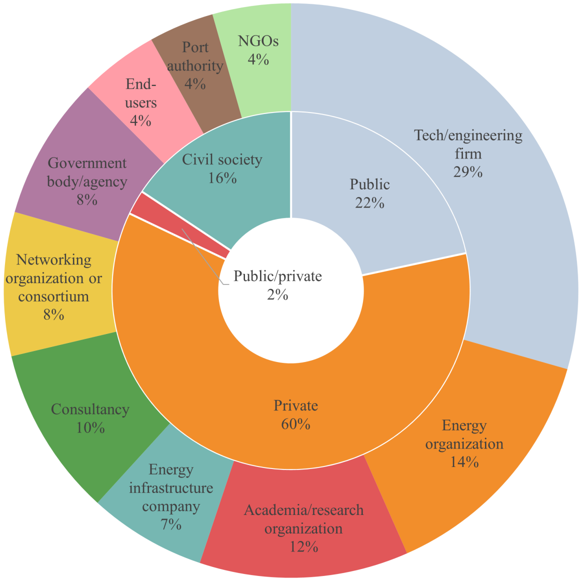

Figure 4: Graphical overview of types of actors in the TIS and its distribution. The chart presents data from the entrepreneurial activities in Appendix E and the networks of Section 5.2.2.

A total of 136 different actors have been identified, with technology and engineering firms constituting the largest segment. This group includes offshore engineering specialists like Van Oord and Sif, as well as electrolyser specialists such as Plug and Nel. Another significant portion involves energy organizations, including oil and gas companies (e.g. Shell, Total Energies) and electricity generators (e.g. Eneco, RWE). These organizations are often the main developers of the commercial projects detailed in Appendix D. Academia and research organizations also play a vital role, represented by universities such as TU Delft and research institutes like TNO and ISPT, adding value through their research and pilot projects.

Energy infrastructure companies like Gasunie and Tennet are crucial to the system, providing and maintaining critical infrastructure. Additionally, consultancies such as Deloitte, which was engaged by the Dutch Ministry of Economic Affairs and Climate Policy (EZK) to research necessary infrastructure developments, play an important role (Deloitte, 2024). Other consultancy firms contribute value through their involvement in various projects and knowledge-sharing platforms. Actors dedicated specifically to knowledge sharing are also central to the TIS. For instance, Topsector Energie aims to foster collaboration among organizations and works with RVO on subsidization initiatives, while the New Energy Coalition focuses on knowledge sharing within the energy sector.

Several governmental organizations have been identified. The EZK provides strategic direction through policy, while RVO supports initiatives and distributes subsidies. The Ministry of Agriculture, Nature and Food Quality, and the Ministry of Infrastructure and Water Management are also involved in developments around the North Sea (Overlegorgaan Fysieke Leefomgeving, 2021). The European Commission offers policy guidance and subsidies, and provincial governments participate in various projects.

Key end-users, primarily chemical and process industry organizations, aim to use green hydrogen for products such as ammonia or methanol (e.g., OCI, Yara) or for steel production (Tata Steel). Several Port Authorities are involved in the projects by hosting the initiatives. The Port of Rotterdam, for example, has dedicated seven sites to commercial green hydrogen projects (Port of Rotterdam, 2024). NGOs are also active in this context. Environmental conservation organizations like Natuur en Milieu and Stichting de Noordzee have expressed their interest in participating in discussions surrounding offshore infrastructure projects such as energy islands and have reported on their concerns (Stichting de Noordzee & Natuur & Milieu, 2021). Greenpeace is also involved in discussions on North Sea developments, generally supporting wind energy, and was, together with other NGOs, involved in the Noordzee Akkoord on the future of wind energy and offshore hydrogen in the North Sea (Overlegorgaan Fysieke Leefomgeving, 2021). Recently the Noordzee Akkoord saw withdrawal from Greenpeace as a result of the continuing natural gas exploitation in the North Sea (Palmen, 2024). Lastly, NEN, a foundation focusing on standardization, is included in the North Sea Energy network.

Figure 5, shows which actors occur most frequently in the entrepreneurial activities or networks of the TIS. The knowledge institute TNO has the highest number of occurrences followed by the private organization's Shell and HyCC and state-owned gas infrastructure company Gasunie. Energy organization Eneco is involved in five activities or networks together with the port authority of Rotterdam which hosts several of the offshore wind-to-hydrogen initiatives.

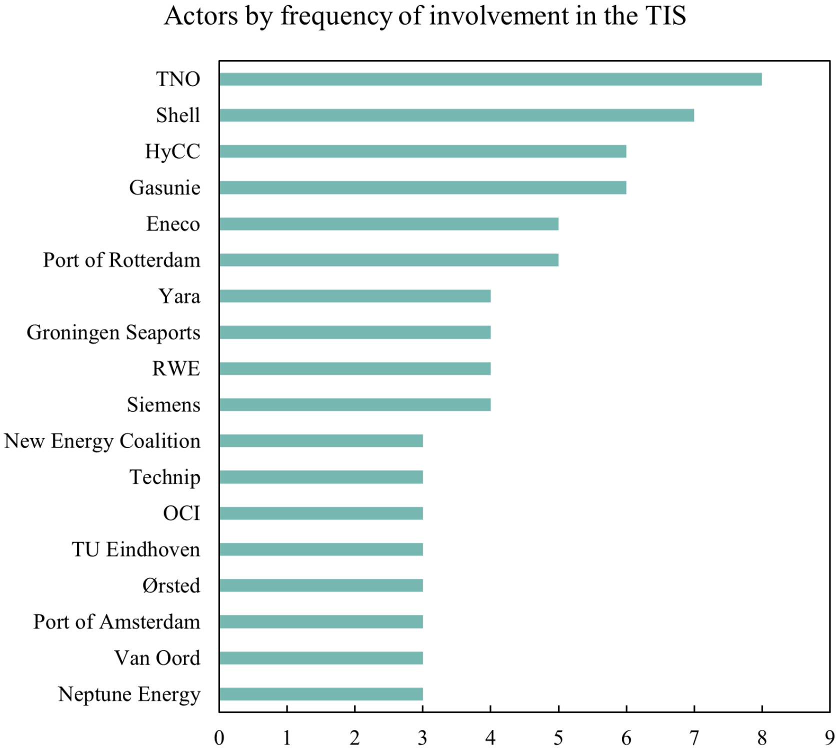

Figure 5: Frequency of actor involvement in the entrepreneurial activities as listed in Appendix E or the networks in Section 5.2.2. Actors with a frequency of less than three were excluded from the chart.

5.2.2 Interactions

For the interactions involved in the TIS surrounding offshore wind-to-hydrogen, this research considers two types of interactions: collaborations through joint research programs or knowledge-sharing platforms, and the collaborative efforts in project consortia or groups of actors working together on the specific projects listed in Appendix D. Both types of interactions were identified through desk research and insights from interviews.

North Sea Energy

The North Sea Energy program is a collaborative network that includes companies, knowledge institutions, and government entities focused on integrating energy systems in the North Sea. This network comprises nearly 40 companies working together to develop innovative solutions for utilizing the North Sea's power to decarbonize the Netherlands. The consortium focuses on developing roadmaps for transition pathways, emphasizing the exploitation of wind energy, the production of green hydrogen, and the use of the North Sea for CCS. Over the years, the consortium has collectively addressed safety and legal challenges and has worked to establish industry standards. A list of the actors included in the network is provided on the North Sea Energy Website (North Sea Energy, n.d.).

North Sea Wind Power Hub

The North Sea Wind Power Hub is a consortium comprising the Dutch gas infrastructure company Gasunie, TSO Tennet, and the Danish TSO Energinet. The consortium has focused on developing knowledge about offshore energy hubs, where energy can be generated, converted, and shared among countries. Their accomplishments include gaining insights into the regulatory, economic, and technological aspects of these systems. This network is highly relevant to the TIS of offshore wind-to-hydrogen, as it also considers the integration of wind energy and hydrogen production in these hubs (North Sea Wind Power Hub, n.d.).

Hydrohub MegaWatt Test Center

The Hydrohub MegaWatt Test Center, located in Groningen, is a research facility that provides a space for companies to collaborate on designing, validating and up-scaling technologies for hydrogen production through water electrolysis. This network is relevant to the TIS of offshore wind-to-hydrogen because a significant portion of its research activities focuses on testing and validating advanced process control systems that effectively manage the flexible load from renewable energy sources on electrolysers. HyCC, Shell, Nobian, Yara, Yokogawa, Hanze University of Applied Sciences, TNO, Rijksuniversiteit Groningen, Groningen Seaports, and ISPT work together in this test centre (ISPT, n.d.; Topsector Energie, n.d.-a, n.d.-c).

HEROW

HEROW (Hydrogen Empowering Revolutionary Offshore Wind) is a collaborative knowledge platform established by TKI Wind op Zee, TNO, and DOB Academy. It aims to advance and disseminate knowledge essential for developing offshore hydrogen production as a method for transporting renewable energy to end users. This platform serves as a hub for developers to exchange insights from pilot projects and to generate innovative ideas. Additionally, the network is dedicated to creating educational materials (Topsector Energie, n.d.-b). Unfortunately, the details about the participants are not publicly accessible, as membership is by invitation only. According to interviews, the network comprises approximately 50-70 companies (ID1).

Network analysis

Figure 6 provides a visualization of the interactions and relationships within the offshore wind-to-hydrogen TIS in the Netherlands. The SNA highlights the connections between different initiatives and the flow of knowledge and experience among actors. Knowledge-sharing is more likely when the actors are involved in initiatives that are centrally positioned and have a large number of connections to other initiatives. The North Sea Energy program stands out in this graph due to its large number of actors and extensive ties. This program is situated in a cluster primarily consisting of demonstration/research pilots or feasibility study/concept design initiatives. However, some demonstration/research pilots, such as Sea2H2, OFFSET, and AmpHytrite, are located outside this cluster. Notably, many commercial projects are positioned at the outer edges of the network. Additionally, it is important to mention that the HEROW network, an important network identified by numerous interviewees, could not be included in the analysis due to the unavailability of public data on the involved actors.

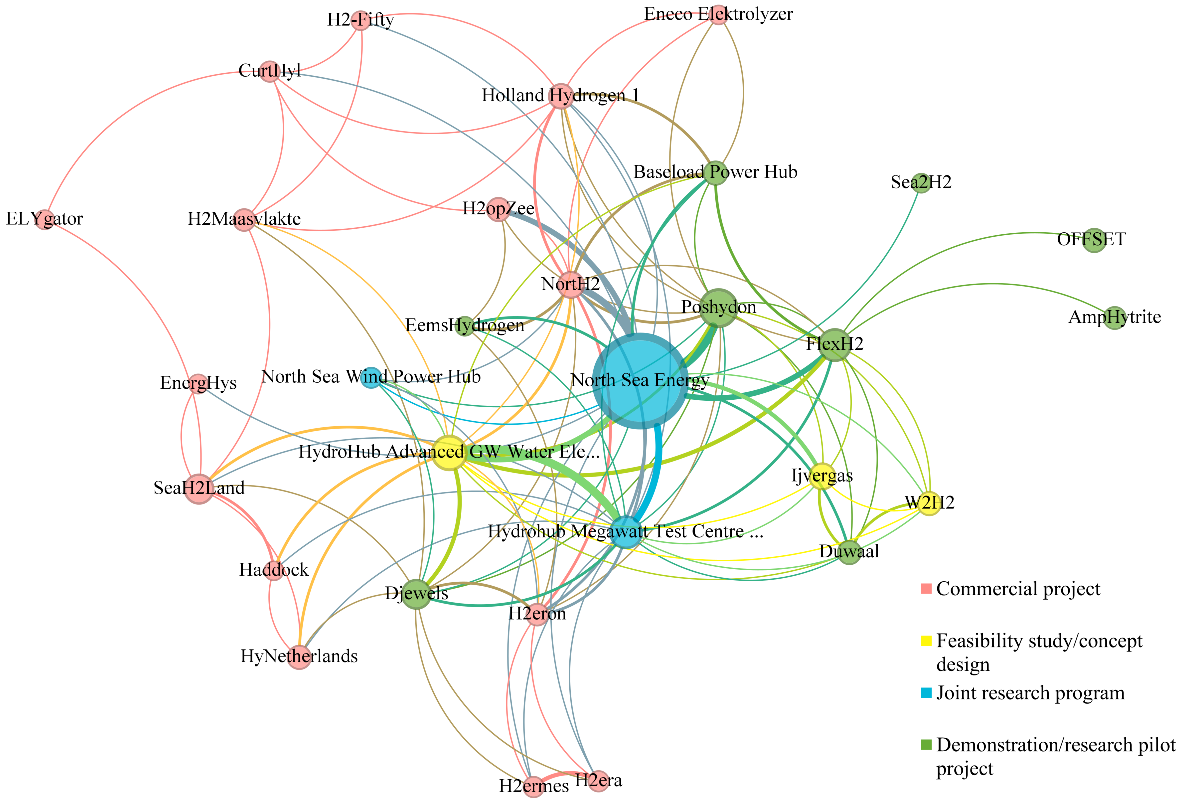

Figure 6: SNA showing the interactions in the offshore wind-to-hydrogen TIS in the Netherlands. The nodes present the different entrepreneurial activities or joint research programs, while the size of the node corresponds to the number of actors involved in the activity. The edges show the different ties between the interactions, the edge size is related to the number of actors co-occurring in two nodes. The figure was created in Gephi software using the data listed in Appendix D and in Section 5.2.2.

5.2.3 Institutions

Institutions such as laws, regulations, customs, and expectations can significantly influence the development of innovation (Carlsson & Stankiewicz, 1991). The institutional framework relevant to the TIS of offshore wind-to-hydrogen in the Netherlands is largely shaped by EU directives. The Netherlands, being an EU member, must transpose these directives into national legislation.

European institutional framework

A key overarching framework is the 2019 European Green Deal, followed by the 'Fit for 55' package, which set a target for a 55% reduction in greenhouse gas emissions by 2030 compared to 1990 levels. This target was enforced by the 2021 European Climate Law, legally binding member states to take necessary measures to meet this goal (European Hydrogen Observatory, 2024). As part of the European Green Deal, the European Commission formulated a strategy for promoting system integration, linking energy carriers with each other and with end-users. The strategy proposes policy and legislative measures to create a more integrated energy system in the EU. This strategy runs in parallel to the EU's Hydrogen Strategy, which sets clear goals for the role of hydrogen in such an integrated system (European Hydrogen Observatory, 2024). The

The Renewable Energy Directive (RED) sets binding targets for the share of renewable energy in the energy mix of EU member states. Initially enacted in 2008, RED established a target of 20% renewables by 2020 (European Commission, n.d.). This target was later revised to 32% by 2030 in the 2018 RED II package. RED II also set clear rules for what qualifies as green hydrogen, which includes additionality, geographical, and temporal criteria. Additionality ensures that hydrogen is produced using renewable energy that is not diverted from other purposes. Geographical criteria require that the electrolyser is located in the same bidding zone (the area where producers and consumers trade energy). Temporal criteria dictate that hydrogen must be produced within the same time period as renewable electricity under the power purchase agreement. Currently, the regulation allows for a one-calendar-month time period, but starting in 2030, all hydrogen must be produced within a one-hour period (European Parliament & Council of the European Union, 2018). Recently, the RED III package was adopted, which further increased the target renewable electricity target to 42.5% by 2030. Additionally, RED III mandates that at least 42% of the hydrogen used in industry for energy or non-energy purposes must be sourced from renewable sources. The RED III package also continued to refine definitions of green hydrogen (European Parliament & Council of the European Union, 2023).

Dutch national institutional framework

Initially, the Netherlands set its emission reduction target at 49% by 2030 in the 2019 Climate Agreement (Klimaatakkoord). However, following the 2021 Coalition Agreement (Coalitieakkoord), the Netherlands revised its target to 55% in 2023 to align with the updated European objectives (Rijksoverheid, 2022a, 2023). The climate agreement also stated the goal to achieve 500 MW electrolysis capacity for the Netherlands by 2025 and 3-4 GW by 2030 (Rijksoverheid, 2019). Supporting this goal is the 'Nationaal Waterstof Programma' (National Hydrogen Program) that produced a roadmap together with industry on how to get to this goal (Nationaal Waterstof Programma, 2022). The Netherlands has produced more of these roadmaps in their policy framework, one in which they draw up the role of energy storage in the future energy system. It sets out action points for energy storage in the form of hydrogen that are necessary before 2035. The Netherlands' ambitious plans for offshore wind energy development are set out in the 'Routekaart wind op zee' (Roadmap offshore wind), envisioning 70 GW of offshore wind capacity by 2050 (RVO, 2021b)

Currently, the Netherlands is in the process of transposing the EU's RED III into national law, with an 18-month deadline from its adoption in October 2023 to complete this process (Heijnen, 2024). This means the necessary legislative and regulatory measures must be in place by mid-2025 to comply with the new directive's requirements.

In the 'Akkoord over de Noordzee' (North Sea Accord), a policy agreement was established between the Dutch government and various participating organizations, including energy cooperatives, fisheries, and NGOs. This agreement, which extends until 2030, outlines policies that influence activities in the North Sea. Relevant aspects of the accord include reducing oil and gas extraction and promoting the development of hydrogen energy in the region (Overlegorgaan Fysieke Leefomgeving, 2021). Further details and specific plans for wind energy development and the role of hydrogen in the North Sea are extensively discussed in the subsequent policy document, 'Programma Noordzee 2022-2027' (Rijksoverheid, 2022b).

The further relevant legislation for offshore wind-to-hydrogen energy systems in the Netherlands includes the 2015 Wet Wind Energie op Zee (Offshore Wind Energy Act), which was amended in 2021 to accommodate other energy carriers besides electricity. Additionally, the Waterwet (Water Act), wet Natuurbescherming (Nature Conservation Act), and the Omgevingswet (Environmental and Planning Act) are pertinent (Noordzeeloket, n.d.). Recently, the Netherlands passed a new bill replacing the old Energiewet (Energy Act), enhancing provisions for energy storage and flexibility (Rijksoverheid, 2024; Tweede Kamer, n.d.-a). Lastly, the Mijnbouwwet (Mining Act) was revised in 2020 to facilitate the repurposing of oil and gas rigs for sustainable energy uses, including hydrogen (Tweede Kamer, n.d.-b).

5.2.4 Infrastructure

Physical infrastructure

Key infrastructure required for the offshore wind-to-hydrogen TIS includes a hydrogen transportation network to connect supply and demand. The Dutch gas infrastructure company, Gasunie, through its subsidiary HyNetwork Services, is responsible for creating and maintaining this network. The network will comprise both repurposed gas pipelines and newly constructed ones, with plans to eventually extend into the North Sea to facilitate offshore electrolysis. With a general network at sea, there is no need for individual connections to shore. Initially, the focus will be on developing onshore infrastructure to support projects that bring electricity onshore for hydrogen production. The network also prioritizes development in industrial clusters to ensure the timely decarbonization of these areas (Gasunie, 2022).

Electricity infrastructure is also relevant to the innovation system. In the early stage, the high-capacity transmission lines are essential for transporting electricity generated by offshore wind farms to onshore facilities, where it can be converted into hydrogen. In later stages, the electricity infrastructure should be ready to deal with the hybridity of offshore wind-to-hydrogen. This is envisioned through the idea of energy hubs, where electrical connections come together with electrolysis and gas infrastructure (North Sea Wind Power Hub, 2022). The duality of electricity production and conversion to hydrogen in offshore wind-to-hydrogen energy systems calls for collaboration between Tennet, Gasunie and project developers to develop cohesive infrastructure.

Knowledge infrastructure

Large-scale development of offshore wind-to-hydrogen in the Netherlands requires a certain amount of knowledge infrastructure, implying the skills and expertise that exist in public and private organizations that contribute to the development of the innovation system. The Netherlands is a leading country when it comes to offshore wind development. In 2023, the Netherlands installed the most capacity of offshore wind among the European countries, with 1.9 GW of offshore wind developed that year. This shows there exists a strong framework of organizations and individuals that have expertise in developing offshore infrastructure (Costanzo & Brindley, 2023; RVO, 2023a).

The Netherlands was also one of the first countries to exploit natural gas as an energy source with the discovery of the Groninger gas field in 1959 eventually leading the Netherlands to be an energy hub of Europe. However, the current energy transition forces the sector to adapt to alternative energy scenarios to maintain its position as an energy hub (Energiebeheer Nederland, 2023). Additionally, the exploitation of natural gas in Groningen has led to significant social challenges due to earthquakes, prompting the Dutch government to accelerate the phase-out of natural gas exploitation in the region (Tweede Kamer, 2023).

Hydrogen production and use are not new to the Netherlands, as it is already produced and utilized on a large scale. However, it is primarily used as a feedstock for the chemical industry and is not produced renewably (Weeda & Segers, 2020). The adoption of offshore wind-to-hydrogen technologies can leverage the existing knowledge infrastructure within these sectors, supporting the TIS.

Financial infrastructure

Online databases provide detailed information on the funding received by the projects listed in Appendix D and the networks discussed in Section 5.2.2 (RVO, n.d.; The European Commission, n.d.; TopSector Energy, n.d.). A total of 1.2 billion euros in public funding has been allocated to support initiatives within the offshore wind-to-hydrogen TIS. The largest share of this funding comes from the Netherlands through the Netherlands Enterprise Agency (RVO) across five subsidy schemes.

The Important Project of Common European Interest (IPCEI) subsidy scheme is funded by the Netherlands and authorized by the European Commission. The subsidy was made possible after the EU revised state aid rules for the priority areas climate, energy, and environment (European Hydrogen Observatory, 2024). This enables certain projects to receive more substantial funding than is normally allowed under regular state aid regulations. Another notable scheme, ’Opschaling volledig hernieuwbare waterstofproductie via elektrolyse’ (OWE), finances electrolyser projects with capacities ranging from 0.5 to 50 MW, covering both investment and operational costs for 7 to a maximum of 15 years. The TSE subsidies provide funding for feasibility and environmental studies. The DEI+ scheme supports pilot and demonstration projects. Additionally, the Top Consortium for Knowledge and Innovation (TKI) supports networking activities and collaborative initiatives.

The EU has also contributed significantly through three key schemes: the European Innovation Fund, the Connecting Europe Facility (CEF), and Horizon2020. The European Innovation Fund focuses on large-scale demonstration projects for innovative low-carbon technologies, while the CEF supports the development of trans-European networks and infrastructure in the energy sector. Horizon2020, the EU’s research and innovation program, funds various projects aimed at fostering scientific excellence and innovation.

Lastly, the Waddenfonds is a public funding body dedicated to supporting projects that enhance the ecological and economic value of the Wadden Sea region. The fund is managed collaboratively by the three provinces of Noord-Holland, Friesland, and Groningen (Waddenfonds, n.d.).

Figure 7 illustrates the distribution of public funding through various subsidy schemes to the projects listed in Appendix D and networks described in Section 5.2.2. The largest share of funding was allocated nationally through the IPCEI subsidy scheme, primarily benefiting large-scale commercial projects. Notably, the ELYgator and Holland Hydrogen 1 projects received significant funding from both national sources and the EU's European Innovation Fund. Smaller-scale pilot and demonstration projects, as well as feasibility studies, were mainly funded through the DEI+ and TSE subsidies.

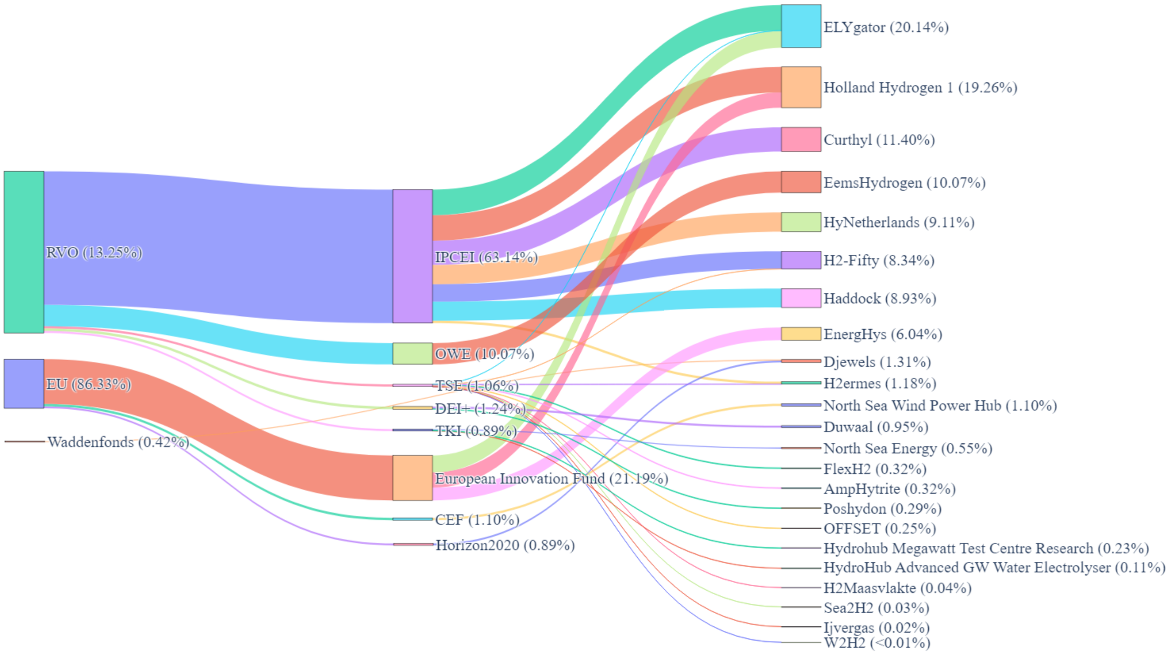

Figure 7: Sankey diagram illustrating the public funding allocated through different subsidy schemes to the projects listed in Appendix D and networks described in Section 5.2.2. The figure depicts the percentage of the total amount of funding allocated. Data for this diagram can be found in Appendix F.

5.3 Functional analysis

5.3.1 Entrepreneurial activities

The rapid development of offshore wind underscores the need to accompany this technology with hydrogen production at sea, this development would benefit from increased entrepreneurial activities (ID5). Currently, there is a large number of actors working on the development of this type of technology (ID4) and the level of engagement appears adequate for the current stage of innovation (ID3). There is not only a lot being done on the technical side, a lot of effort has gone into how these systems would work commercially (ID2).

However, several financial factors are impeding entrepreneurial activities. The current economic climate, characterized by high interest rates and labour costs, makes it challenging for companies to close the business case for hydrogen projects (ID5). Companies can be found to be stuck on an FID investment decision hinting the current market conditions are not conducive to investments, hindering the experimentation and innovation with these systems (ID2).

There is some ambiguity and contrast regarding which type of activities most effectively contribute to the TIS of offshore wind-to-hydrogen. While there is a general consensus about the need for offshore electrolysis, there is little focus on the activities that focus on offshore electrolysis specifically (ID4 & ID7). Many of the entrepreneurial activities access offshore wind energy for electrolysis via certificates of origin and use off-the-shelf technology. Moreover, the intraday market is often used to produce hydrogen at the right moments. These initiatives contribute little to innovation on the systems integration level (ID7)[1]. However, onshore pilots and experiments still offer valuable insights that do not necessarily need to be conducted offshore. Onshore electrolysis helps mitigate technical risks, enhance operational reliability, and build capacity (ID2, ID6 & ID7).

5.3.2 Knowledge development

A lot of knowledge is being developed for offshore wind-to-hydrogen energy systems, but there is room for improvement (ID5). The development not only occurs within commercial companies but also through smaller government-funded projects (ID2). However, the type of knowledge developed has not adequately focused on the specific requirements for offshore wind-to-hydrogen systems. Research has not sufficiently addressed offshore production (ID4), and there is a lack of research on a true system integration level (ID7), as earlier described in Section 5.3.1.

Additional insights highlight the need to focus more on environmental and economic aspects rather than purely technical ones (ID3 & ID6). These environmental implications can include the release of brine, heat, or potential noise (ID3 & ID4). One key point raised is the insufficient understanding of the actual value of offshore hydrogen. Its value extends beyond energy-carrying capacity and market price. Offshore production requires fewer cables, reduces curtailment, and minimizes the need for grid-balancing efforts. These social and system values can be quantified to fully demonstrate the full value of offshore hydrogen (ID6).

5.3.3 Knowledge exchange

Knowledge exchange within the TIS of offshore wind-to-hydrogen is catalyzed by several key networks and facilitators. The HEROW platform stands out as a prominent network where substantial information sharing occurs. Additionally, the North Sea Energy program hosts numerous companies, fostering a collaborative environment for knowledge exchange (ID1, ID3, ID4, ID5 & ID6). The Netherlands is regarded as having state-of-the-art knowledge exchange practices compared to other countries (ID1 & ID6). The public-private entity Topsector Energie is noted for its role as a networker, effectively connecting individuals to the right networks and working closely with the funding body RVO (ID1).

An issue regarding knowledge exchange is the discrepancy between academia and industry regarding the economic aspects of technology. Peer-reviewed papers often present different figures compared to those shared by companies within these networks, indicating a flaw in the knowledge exchange between science and industry (ID6).

The effectiveness of knowledge exchange is debated, particularly due to the commercial sensitivity of the information. While knowledge exchange among companies is relatively strong during the pre-competitive stage, companies remain cautious about sharing technical details to maintain their competitive edge (ID5). This reluctance to share information is primarily observed among commercial companies, a concern echoed by various experts (ID1, ID2, ID3, ID4, ID5, ID6 & ID7). Conversely, public organizations such as TNO and ISTP are highly valued for their role in disseminating knowledge with fewer reservations (ID1 & ID2).

Another key point is the value of working in consortium projects. Consortia like Poshydon operate through work packages, allowing companies to develop their own intellectual properties while contributing to the collective knowledge gained in the process (ID4).

5.3.4 Guidance of the search

The Dutch government, particularly the EZK and RVO, play a crucial role in directing the development of offshore wind-to-hydrogen initiatives (ID1, ID2, ID3 & ID5). This guidance is exemplified by the commissioning of advisory reports. Notably, the EZK and RVO enlisted Deloitte to produce an advisory report outlining the necessary infrastructure developments to achieve offshore wind targets from 2030 to 2050 (ID5). Central to this report is the development

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[1] For more information on what is implied with innovation on a true system integration level this study refers to literature on grid ancillery services or grid forming services that electrolysers can provide to prevent delving into extensive technical details. Example studies are Jain et al. (2023) or Tavakoli et al. (2023)

of hydrogen production, storage, and transport capacity (Deloitte, 2024). The government have set clear targets for the intended direction of this type of technology in the Energy scenarios (ID6). Other guidance is given in the form of tenders for demonstration projects (ID5, ID3, ID6), as further described in section 5.1.2.

Furthermore, the direction of the search is reinforced through networks like North Sea Energy, where participating companies collaborate to build a shared vision for offshore hydrogen production (ID5). This unified vision is crucial, as public authorities require a cohesive and well-articulated narrative to formulate effective rules and legislation (ID2). While there is a general consensus on the main direction for innovation (ID1), the specifics of how to achieve these goals vary among companies, each advocating for their own interests (ID1, ID3, ID4, ID6 & ID7). A key topic of discussion is whether hydrogen production should be centralized or decentralized—whether it should occur at a central point on top of a jacket or be integrated near the wind turbine itself (ID6 & ID3). It may take time for these technicalities to be fully resolved. Currently, different approaches are being developed simultaneously, each with its own pros and cons, making it premature to settle on a definitive method at this stage (ID4). Comparing the Netherlands to countries like China, it is generally more difficult to achieve alignment. China is seen as being more coordinated and advanced in certain aspects, while European countries need to make an effort to align (ID7).

5.3.5 Market formation

The market size for offshore wind-to-hydrogen projects in the Netherlands is substantial (ID2). This is evidenced by the Dutch government's ambitious plans to develop 70 GW of offshore wind capacity by 2050, in which offshore hydrogen production plays a significant role. The Netherlands is strategically positioned in a region with high demand for both electricity and hydrogen (ID3 & ID5). Within this context, the market for offshore wind-to-hydrogen is projected to reach tens of gigawatts (ID7).

Currently, the market for green hydrogen is still under development, and the willingness of companies to pay a higher price for green hydrogen is disappointing. The price gap between green and grey hydrogen remains too large, deterring companies from committing to the offtake of large quantities (ID5 & ID2). As a result, the current market is technology-driven rather than market-driven. Moreover, the market is highly dependent on subsidies, ultimately, the offtake of hydrogen must yield a favourable business case for it to create a sustainable market.

It is unlikely that the costs of green hydrogen will decrease sufficiently in the short term to compete with grey hydrogen (ID5 & ID7). However, the value of offshore wind-to-hydrogen systems extends beyond the offtake market. These systems also provide significant, albeit harder to quantify, benefits in terms of system balancing. Clarifying who will pay for these balancing services could potentially improve the market for these systems (ID6).

Regulation plays a pivotal role in market formation (ID5 & ID7). When markets do not develop within a desired timeframe on their own, regulation can be utilized to expedite the process. In the European Union, for instance, the Revised Renewable Energy Directive (RED III) mandates that 42% of hydrogen used in industry must be sourced from renewable energy by 2030. This regulatory intervention aims to drive market development, but this policy is yet to be transposed into the Dutch national law. Historical examples, such as chlorofluorocarbons legislation and the implementation of catalytic converters, illustrate the effectiveness of such regulatory measures (ID5).

5.3.6 Resource mobilization

The financial aspect of resource mobilization can present some challenges. Securing capital is difficult due to customer reluctance to pay high prices, which hinders project development (ID5). Consequently, the sector is heavily subsidized, with significant public funding issued to hydrogen projects. Billions of Euros have been designated for production, infrastructure, and storage (ID1, ID2), but there are some comments on the effective allocation and use of these funds. Instead of spreading the funding across numerous projects, it may be more effective to allocate resources to the most feasible projects (ID2). Additionally, funds should be directed towards research that yields the most favourable outcomes for the innovation system, focusing more on system integration research rather than capacity building (ID7). Moreover, it might be beneficial to subsidize both the supply side (production) as well as the demand side of the market (offtake) (ID4, ID6). Subsidizing the offtake market means providing financial incentives to end-users and companies that purchase and use green hydrogen. This approach can stimulate market demand, making green hydrogen more attractive and competitive compared to grey hydrogen.

Due to its commitment to establishing a national hydrogen backbone that links producers and end-users, the Netherlands is regarded as a leading country in developing the necessary infrastructure relevant to the TIS (ID1). This infrastructure is critical for all green hydrogen initiatives in the country. While there is general positivity about the network being commissioned, concerns exist about potential delays in this project (ID2, ID4 & ID6). To prevent these delays from significantly impacting green hydrogen initiatives, it is crucial to focus on establishing more localized networks and collaborating with local end-users (ID2). Additionally, blending hydrogen into the existing natural gas infrastructure can keep the development of this technology progressing without being entirely dependent on the completion of the hydrogen backbone (ID4).

Another critical infrastructure component is the jackets for offshore electrolysis. Scaling up centralized offshore electrolysis is currently constrained by the installation capabilities of available ships. The largest jacket that can be installed today can support an electrolysis capacity of up to 400 MW. Larger jackets would face mechanical challenges and are not feasible with current installation technology (ID7).

For offshore wind-to-hydrogen systems, PEM electrolysis is often the preferred choice. However, this technology relies on physical resources such as rare earth metals like platinum and iridium. This dependence could pose challenges as the technology expands, particularly if the costs of these metals increase or their supply diminishes (ID5). Additionally, wind parks, along with many other renewable energy solutions, require significant amounts of copper for transformers. Sourcing this resource may become increasingly difficult in the future (ID7).

5.3.7 Creation of legitimacy

Overall, there appears to be strong social and political support for green hydrogen initiatives in the Netherlands (ID1, ID2, ID3, ID5). However, the application of the produced hydrogen is somewhat controversial. While there is general support for using hydrogen in industrial decarbonization, its use in the mobility or residential heating sectors garners less enthusiasm (ID1). In terms of production, resistance to offshore wind-to-hydrogen projects is presumed lower compared to projects like CO_2 sequestration, which have faced forms of societal opposition (ID6). Nonetheless, resistance can still be anticipated, primarily due to environmental implications (ID3, ID6). Although these systems are less visible to the general public, increased resistance can be expected from NGOs, who are likely to raise concerns about their environmental impact (ID3). Other concerns over the technology come in the form of safety (ID1).

The regulatory environment surrounding offshore wind-to-hydrogen projects in the Netherlands presents some challenges. One significant issue is the need to transpose the European Commission's renewable energy directives into Dutch national law, which would provide more clarity for project developers (ID2). The novelty of the technology necessitates specific legislative changes. For instance, the repurposing of oil and gas wells for hydrogen production conflicts with the Mijnbouwwet (Mining Act), which was originally designed for oil and gas operations (ID5). Another legislative challenge is related to blending specifications. Utilizing existing pipelines and blending hydrogen with natural gas can reduce costs during the early stages of technology development. However, the current regulatory framework permits only minimal levels of blending (ID4). For offshore wind projects, the Offshore Wind Energy Act provides a regulatory framework. A cohesive regulatory framework is necessary for the system integration. The current lack of harmonization between these regulatory areas could either form a barrier or act as a catalyst, depending on how the policies are formulated and implemented (ID7). The government is presumed to be aware of what needs to change and is working hard to make the necessary changes (ID5 & ID6).

The permitting process for offshore wind-to-hydrogen projects in the Netherlands is not expected to result in outright denials, but it is often a lengthy and bureaucratic procedure (ID2). This complexity arises in part due to the novelty of the technology, which introduces challenges for permitters who may lack the necessary expertise to make informed decisions (ID1).

5.3.8 Performance of TIS functions

Figure 8 presents a radar chart depicting the performance scores of seven TIS functions. These scores, assigned by interviewees and subsequently averaged, represent the perceived performance of each function of the TIS. Note that this chart does not act as a quantitative representation of the functionality of the TIS. It should be seen as a quantitative representation that was created based on the scores of the seven interviewees. Higher scores indicate functions that are perceived to perform better. According to the chart, knowledge development and knowledge diffusion through networks are the top-performing functions. Conversely, market formation is identified as the lowest-performing function, followed by resource mobilization and guidance of the search.

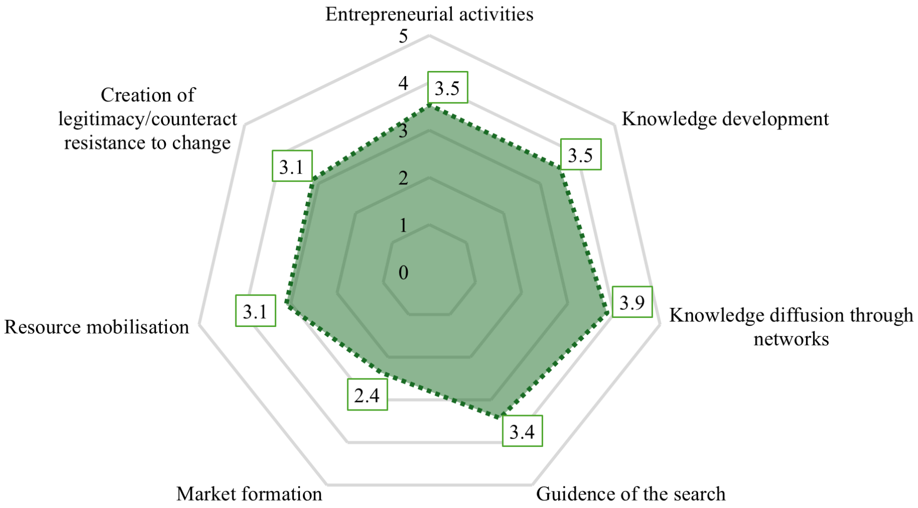

Figure 8: Radar chart representing the average score assigned by the interviewees to the TIS functions. The scores assigned per interviewee are presented in Appendix G.

6 | Discussion

The following section will first discuss the results by coupling the functional and structural analysis to draw up systemic problems. For this Table 3 is applied and a distinction is made between presence-related and quality-related systemic problems. The systemic problems can be addressed through targeted policies or 'systemic instruments'. Consequently, the section will outline policy implications by formulating goals that policy should aim to achieve by applying Table 4 (Wieczorek & Hekkert, 2012). Additionally, it will briefly discuss the development phase and the radar chart. Finally, the section will reflect on the research limitations and offer implications for future research.

6.1 Systemic barriers of the TIS

For entrepreneurial activities, financial constraints prevent actors from making substantial investments. Given this, the entrepreneurial activities function seems to be hindered by its supportive function of resource mobilization as the systemic barrier relates to financial infrastructure. The entrepreneurial activities are also subject to bad market conditions causing reluctance to make the FID. A well-functioning market formation function provides actors with financial certainty which is why the function supports entrepreneurial activities through the guidance of the search function in the development stage (Hekkert et al., 2011). Also, the performance of this function is impeded by a shifted focus from activities that would be of the most value for the TIS. Entrepreneurial activities specifically focussing on offshore electrolysis or research at a true system integration level have fallen short compared to activities that apply off-the-shelf technology. This issue both relates to the capability of the actors and the presence of certain knowledge infrastructure, as know-how about offshore electrolysis and system integration is still missing or under development.

This finding is echoed in the analysis of the knowledge development function, where the type of knowledge being developed is not perceived as fitting the needs of the TIS, necessitating more knowledge of offshore electrolysis and system integration. Additionally, more knowledge should be generated on the environmental implications related to offshore wind-to-hydrogen and the social and system value of offshore hydrogen should be quantified.

Knowledge exchange is emphasized as a strong function by the interviewed experts. This is also evident from the network analysis (see Figure 6) which shows some strong networks with a large numbers of actors and ties. However, there exists some reluctance among commercial companies to share information. This is also visible in the network analysis, which shows several (mainly commercial) initiatives excluded from the cluster where knowledge sharing is concentrated. This deficiency can be seen as a quality type of systemic problem related to the interactions.

The Netherlands has laid out clear targets and roadmaps about offshore wind development and the role of hydrogen in the future energy system (see Section 5.2.3). Furthermore, the Dutch government's proactive approach to supporting offshore wind-to-hydrogen by releasing tenders for demonstration projects shows a strong commitment to innovation. Still, discrepancies exist in the actors' views on how these targets can be achieved. Different approaches to offshore wind-to-hydrogen such as centralized or decentralized electrolysis are advocated by the actors. This is not inherently negative as only time will tell what the best approach is.

The potential market size for offshore wind-to-hydrogen energy systems is substantial, but the offtake market for green hydrogen is still developing. Currently, customers are reluctant to pay the high price for green hydrogen. The cost of hydrogen produced by offshore wind-to-hydrogen systems could be reduced if the value of the system balancing services they provide are quantified. This constitutes a presence-type knowledge infrastructure problem. Given the unlikelihood of a significant cost reduction in the short term, market formation is likely to rely on market intervention.

Institutions play a critical role in this context. Legislation such as RED III, which mandates that member states source 42% of hydrogen used in industry from renewable energy by 2030, can be crucial in compelling end-users to adopt green hydrogen. The Netherlands is still trying to incorporate the framework into national law, therefore this is still a presence-type institutional problem.

As mentioned earlier, a systemic barrier exists in the financial infrastructure, negatively affecting entrepreneurial activities. Looking at the extensive public funding schemes outlined in Section 5.2.4, the problem seems more quality-related than it is presence-related. Substantial investments have been allocated to commercial-scale projects while they are still pending a FID. Interviews suggest that the quality of the financial infrastructure can be improved by subsidizing the demand side. Most subsidies are allocated to the supply side, primarily covering capital expenditures. Notably, only the OWE subsidy explicitly covers both capital and operational expenditures, which can reduce long-term financial uncertainty. Furthermore, the quality of the financial infrastructure could be improved by prioritizing the most feasible projects and those with the highest value to the TIS. In addition to financial considerations, there is a significant concern regarding the availability of skilled personnel to support innovation development. This issue can prove to be critical if the innovation is to enter the take-off phase, representing a presence-type systemic problem within the knowledge infrastructure. Furthermore, critical infrastructure for the TIS includes hydrogen pipelines. Some delays are expected in this project although the focus on developing localized networks, such as those by HyNetworks in industrialized areas, aligns with the needs expressed by interviewees. Improving the quality of other critical infrastructure, such as ships capable of installing larger jackets for offshore electrolysis, is essential. Finally, ensuring a reliable and affordable supply of relevant rare metals can be crucial for the later stages of development.

For the creation of legitimacy, social support is currently sufficient but can be assured in the future if knowledge of the environmental implications is gathered. The rapid developments in the green hydrogen sector, more specifically in the offshore wind-to-hydrogen sector, desire legislative changes. The cohesivity of this framework is presumed essential. According to Section 5.2.3, the past few years have witnessed necessary legislative changes within the innovation system, a view supported by interviewees who noted the government's diligent efforts. Lastly permitting processes for initiatives are presumed lengthy, which suggests a quality-related institutional problem.

6.2 Policy measures

Reflecting on the development phase described in Section 5.1.2, the innovation is currently in the development stage while showing signs of transitioning to the take-off phase. According to Hekkert et al. (2011), entrepreneurial experimentation is crucial in this phase and is influenced by all other system functions. Therefore, specific emphasis should be placed on supporting entrepreneurial experimentation. However, since all system functions impact this process, it is essential to recognize the importance of each function (see Figure 2). The radar chart including the scores assigned by the experts on the different functions of the TIS (see Figure 8) shows how policy that supports market formation should be prioritized, followed by resource mobilization and the creation of legitimacy.

A barrier impacting the resource mobilization function and entrepreneurial activities indirectly, is the quality of financial infrastructure, particularly in the form of subsidies. Currently, the public funding focuses primarily on subsidizing capital expenditures. Providing subsidies for both capital and operational expenses, or supporting the offtake market, could create a more favourable business case for actors. Enhancing the quality of financial infrastructure within the resource mobilization function could thus drive entrepreneurial activities. Notably, this improvement is already evident in the 2023 OWE subsidy provided by RVO. This approach is already reflected in the 2023 OWE subsidy provided by RVO, which should be continued and expanded in future funding schemes.

To promote specific entrepreneurial activities and knowledge development, particularly on offshore electrolysis and true system integration, this specific knowledge infrastructure needs to be developed and the capabilities of the actors in this context can be improved. To do this, policy can focus on creating space for the actors' capability development, and the specific knowledge infrastructure should be stimulated. Interestingly, this could create a positive feedback loop as entrepreneurial activities and knowledge development are functions that support each other and are particularly relevant in the development phase (Hekkert et al., 2011). Other specific knowledge infrastructure that should be stimulated is knowledge about the environmental implications and the true social and system values of offshore wind-to-hydrogen. Notably, knowledge development of the environmental implications could also add to the creation of legitimacy function, where it can help foster social support thus counteracting resistance to change if environmental implications can be prevented. This supportive function was not highlighted by Hekkert et al. (2011). From a normative perspective, the development of specific knowledge could be effectively supported by the public-private entity Topsector Energie, identified by interviewees as a key networking facilitator. This support could be implemented through platforms such as HEROW or North Sea Energy, which were highlighted as the most important networks.

The knowledge exchange function faces a systemic barrier due to the reluctance of commercial companies to share information. To address this, policy efforts should focus on strengthening weak ties within the network. Additionally, connections can be encouraged between actors involved in initiatives on the outer edges of the network graph (see Figure 6) and those more centrally positioned. This would foster greater collaboration and information sharing across the network. Topsector Energie can again facilitate this through its role as a networker.

The Dutch government has developed numerous policy documents to guide the development of innovation towards specific targets. However, various actors often advocate for their own interests, favouring specific technological details. It remains unclear how policy can effectively intervene in this context, as these technological details will need to be refined and established over time.

In addition to enhancing knowledge and financial infrastructure as previously discussed, the market formation function will benefit from specific legislative changes. Regulatory interventions, such as the RED III directive, are expected to stimulate the market for green hydrogen. The Dutch government is actively working to ensure the necessary institutional change by transposing this directive into national law.

To prevent a lack of human resources from hindering TIS development, policies should aim to ensure a sufficient supply of skilled workers. There already exists a labour pool with skills and know-how relevant to the TIS (see Section 5.2.4). The human capital agenda of NWP serves as an example of a policy aimed at assuring a healthy supply of human capital in the broader context of the green hydrogen sector. Further barriers in the resource mobilization function are related to the physical infrastructure. Policy should assure the timely development of hydrogen pipeline infrastructure, stimulate the development of ships with large carrying capacity for the instalment of jackets for electrolysers and assure a stable supply chain of rare earth metals such as platinum, iridium and copper. The timely development of the hydrogen pipeline infrastructure falls in the hands of HyNetworks. The responsibility for the timely development of hydrogen pipeline infrastructure primarily lies with HyNetworks. While the development of a national hydrogen network might be overly ambitious in the short term, focusing on establishing local networks first appears to be the most practical approach. The development of larger ships can be advocated by Topsector Energie, with potential backing from the national government through subsidies. Ensuring a stable supply of rare earth metals presents a significant challenge, as this issue extends beyond national borders and may require coordinated international efforts.

Lastly, the function of creation of legitimacy can be improved by continuing the efforts made in making the necessary legislative changes with the goal of creating a cohesive institutional framework. The current status quo involves multiple legislative acts that simultaneously impact the development of offshore wind-to-hydrogen systems. The Dutch government should streamline these legislative acts into a unified framework to enhance clarity and reduce regulatory complexity for the actors. Furthermore, the lengthy permitting process looks to be a case of too stringent institutions which policy should aim to prevent.

6.3 Reflection on the literature review

Reflecting on the literature review, TIS of offshore wind in the Netherlands has achieved substantial legitimacy due to the government's commitment to expanding offshore wind capacity (van der Loos et al., 2020, 2021). This commitment extends to the TIS for offshore wind-to-hydrogen systems, as the government recognizes their crucial role in advancing offshore wind development goals. Although the TIS for hydrogen has experienced increased policy involvement (Broekstra, 2023), it remains constrained by the performance of the guidance of the search function. In contrast, the offshore wind-to-hydrogen TIS benefits from relatively strong policy guidance and a consensus among actors regarding the primary direction of the search, with debates limited to technological details.

Research by Laarhoven (2023) identified that the TIS for green hydrogen in the Netherlands faces significant challenges due to a lack of market formation, which negatively impacts resource mobilization and entrepreneurial activities. While this research also highlights market formation as a critical factor affecting entrepreneurial activities, it finds that resource mobilization is not directly impacted. Instead, market formation influences entrepreneurial activities independently. Consequently, the TIS studied by Laarhoven (2023) can be categorized in the pre-development phase, whereas the TIS for offshore wind-to-hydrogen exhibits a functional pattern more indicative of the development phase (see Figure 2). The distinct functional patterns between these TISs can be attributed to the varying effectiveness of the guidance of the search function. The TIS for offshore wind-to-hydrogen is more specific and can therefore be guided more efficiently than the broader TIS surrounding green hydrogen.

Decourt (2019) also found that the TIS of power-to-x technologies in Europe was significantly hampered by a lack of market formation. He further explained that the guidance of the search function was critical due to divergent interests regarding which type of power-to-x technology should be prioritized. In contrast, the TIS for offshore wind-to-hydrogen focuses on one specific technology, where the guidance of the search function is less critical. Here, the divergent interests are primarily related to technical details rather than competing systems, with the expectation that these details will become more defined over time. (Decourt, 2019) did not indicate a need for more specific knowledge development in areas such as system balancing, environmental impacts, or true system integration. This omission may be due to the broader technological scope of the study.

Wu et al. (2022) applied a modelling approach to identify the most significant barriers to offshore wind-to-hydrogen project development. Their findings highlight barriers that closely align with the challenges in the market formation function, specifically the immaturity of business model and high initial investment costs. Additionally, they identified other critical barriers, such as the complexity of planning and design, the lack of standardized technical specifications, and the challenges in matching modeling technologies. These factors contribute to a broader understanding of why many initiatives struggle to achieve true system integration. Instead of focusing on real-time balancing and coupling with the electricity grid, many projects opt for less complex solutions, such as purchasing electricity from the intraday market or relying on guarantees of origin of renewable energy to produce hydrogen. The technological complexity can drive actors to take this less riskfull route in their project development.

6.4 Reflection on the analytical framework and method

The TIS framework was selected for its comprehensive, systematic approach to analyzing the development and diffusion of offshore wind-to-hydrogen energy systems in the Netherlands. This theoretical framework successfully uncovered various facets of this specialized field.

The mixed-method approach, which integrated qualitative insights from document analysis and interviews with a quantitative representation of the networks using SNA and the analysis of allocated public funding, added significant value to this study and the research field as a whole. Looking at the previous literature, studies are either qualitative or mixed methods. Of the studies adopted in the literature review, only Wieczorek et al. (2013b) and Decourt (2019) applied SNA methodology from an international perspective to examine country-level collaboration within a TIS. This research applied the same method at the national level, providing new insights for national policy aimed at fostering increased collaboration. Additionally, the quantitative analysis of the public funding that was allocated to initiatives relevant to the TIS was not observed in previous research but can prove to be a valueable addition.

This study argues that this method is allows for a more accurate assessment of the financial structure by cross-referencing expert evaluations with quantitative data, helping to identify potential gaps or deficiencies in this structural component.

6.5 Limitations and implications for future research

This research prioritized interviewing industry experts and representatives from knowledge institutes over public sector stakeholders and NGOs. This decision was based on the expectation that these representatives would provide the most relevant knowledge. However, this focus may introduce bias into the research. The exclusion of policymakers, who might have different perspectives on the needs of the TIS, represents another potential limitation. Future research can consider including a broader range of stakeholders, including policymakers and NGOs, to capture a more comprehensive view of the TIS requirements and to mitigate potential biases.

Another limitation is the confinement of this TIS analysis within national geographical borders. Wieczorek et al. (2015) argue that although systemic barriers are often national, technological innovation frequently transcends borders.

Analyzing offshore wind-to-hydrogen systems from a broader geographical context could therefore provide different insights. Future research can focus on expanding the geographical scope of TIS analyses to include international perspectives.

Additionally, the functional analysis was based on a limited number of interviews, with only seven conducted. This small sample size may not fully capture the diversity of perspectives within the industry. The structural analysis relied mainly on publicly available data, which therefore may have missed certain elements. An example of a critical element that is missing is the data on the HEROW network.

Future research can build on this work by adopting a similar approach for Social Network Analysis (SNA) and financial infrastructure analysis, as these methods have yielded valuable insights. Specifically, the databases used in this study contain extensive data on funding allocated to a wide range of technologies, making them applicable to other TIS studies. Researchers can leverage these resources to explore financial dynamics in different technological contexts, potentially uncovering patterns and insights that contribute to the broader understanding of a TIS. SNA conducted on a national basis clearly reveals the flow of knowledge between entrepreneurial activities and identifies areas where additional interactions can be fostered and would be a great addition to any TIS study.

7 | Conclusion

This thesis set out to analyse the TIS surrounding offshore wind-to-hydrogen energy systems in the Netherlands. Through document analysis of various grey literature and consultation of online databases, the structure of the offshore wind-to-hydrogen TIS in the Netherlands was revealed. These findings were further reinforced with insights from experts in the field. The TIS structure involves the actors, interactions, institutions and infrastructure relevant to the TIS. The functional analysis was constructed based on interviews with experts and combined to identify the systemic barriers. Based on this, policy measures have been proposed.

Key government actors include EZK and RVO, which offer policy guidance and public funding for projects. Topsector Energy, a notable public-private entity, is recognized for its networking activities and close relationship with RVO. Several NGOs such as Stichting de Noordzee are politically capable of influencing the TIS. An analysis of the involvement of the actors in entrepreneurial and networking activities reveals other key participants, such as TNO, Shell, HyCC, Gasunie, and the Port of Rotterdam, each of which has participated in five or more activities related to the TIS. A network analysis indicates North Sea Energy as the most central interaction where a lot of knowledge sharing is expected to occur. Furthermore, the HEROW network, which could not be included in the network analysis, was identified by many of the interviewees as a highly relevant network for the TIS.

The Dutch institutional framework is to a large extent guided by the EU. The European Green Deal, along with subsequent hydrogen and system integration strategies and climate law, guides member states towards adopting green hydrogen. The RED packages provide clear goals and definitions for green hydrogen, with a crucial mandate targeting the end-use of hydrogen in industry. The Netherlands transposes these EU targets into its national law but has independently developed its own roadmap and targets in line with the EU strategy and goals. Notably, there is a significant focus on offshore wind development. Policy roadmaps for green hydrogen, along with the mention of offshore hydrogen in the North Sea Accord, provide further guidance for the TIS. The Netherlands is currently in the process of transposing the most recent RED. Furthermore, the Netherlands demonstrates its guidance by actively changing legislation relevant to the TIS, such as the Energy and Mining Acts.

Key physical infrastructure for offshore wind-to-hydrogen systems include hydrogen pipelines and electrical infrastructure. Gasunie subsidiary HyNetworks has initiated the construction of a hydrogen pipeline network, initially prioritizing industrial areas and eventually extending towards the North Sea. This expansion will facilitate cost-effective offshore electrolysis at scale. Furthermore, wind-to-hydrogen energy systems require ties with the electricity grid to ensure additionally by diverting only excess RE for the production of hydrogen. The existing expertise and know-how in offshore infrastructure development and gas handling in the Netherlands serve as relevant knowledge infrastructure for the TIS. Financial infrastructure is provided mainly by the EU and RVO, with significant contributions from the IPCEI and European Innovation Fund subsidy programs supporting commercial-scale projects. Additionally, TSE and DEI+ primarily fund pilot, demonstration, and feasibility studies. Altogether, a total of 1.2 billion euros has been allocated to entrepreneurial and network activities relevant to the TIS.

The entrepreneurial activities function is affected by the performance of the market formation, knowledge development and resource mobilization functions. To improve market development policy can focus on stimulating knowledge development on the value of the system balancing acts offshore wind-to-hydrogen energy systems provide. These values are still unquantified referring to a present-type knowledge infrastructure problem. Market intervention is also expected to improve market formation. Transposing the RED III directive to national legislation can be critical here, which remains a presence-type institutional problem. Currently, entrepreneurial activities focus too little on offshore electrolysis and true system integration, which presents a capability-type systemic problem regarding the actors. Also, knowledge on these two topics is limited, presenting a presence-type problem related to the knowledge infrastructure. Policy should aim to stimulate knowledge development on offshore electrolysis and system integration and create space for actors to develop capability on these topics. This would increase the performance of both entrepreneurial activities and knowledge development as these functions support each other. Additionally, the presence of knowledge of the environmental implications should be secured, which in turn would benefit the guidance of the search function. At the moment, resource mobilization affects entrepreneurial activities because of a quality-related systemic problem related to the financial infrastructure. Integrating more demand-side funding into subsidy programs can reduce the financial uncertainty for entrepreneurial activities, as is already being done in the recent OWE subsidy program. Development of critical physical infrastructure, such as the national hydrogen network, as well as securing an adequate supply of relevant rare earth metals and human capital is less crucial at the current stage of development. However, ensuring these elements are in place is essential for the TIS to smoothly transition to the next phase. Knowledge exchange is generally well-functioning but can be improved by improving the ties with the commercial initiatives. Lastly, the creation of legitimacy function is hindered by quality-type systemic problems relating to institutions. A cohesive legislative framework should be assured, and the permitting process was characterized as lengthy, serving as an example of too stringent institutions which should be prevented.

Therefore, to accelerate the diffusion of wind-to-hydrogen energy systems in the Netherlands, more knowledge needs to be created about the system balancing value they provide and the environmental implications related to offshore hydrogen. Entrepreneurial activities and research should focus on true system integration and offshore electrolysis. Furthermore, the market for green hydrogen should be forced using legislation. Subsidy programs should continue to integrate demand-side funding, and the stringency of existing permit procedures should be reduced.

In addition to these direct findings related to the research objective, this study made a significant contribution to the field by incorporating a quantitative analysis of the financial infrastructure into its methodology. Furthermore, the application of SNA proved to be a valuable tool for examining networks within the TIS. While SNA is not new to this area, its application at the national level offers a novel perspective, enabling networking actors to identify and integrate organizations and initiatives into the national knowledge network more effectively.

Bibliography

Air Liquide. (n.d.). Curthyl. Retrieved May 17, 2024, from https://nl.airliquide.com/energietransitie-de-benelux/waterstof-voor-industrie-en-transport/curthyl

Air Liquide (2022). *Publiek rapport van haalbaarheidsstudie-resultaten voor ELYgator*.

Asna Ashari, P., Blind, K., & Koch, C. (2023). Knowledge and technology transfer via publications, patents, standards: Exploring the hydrogen technological innovation system. *Technological Forecasting and Social Change*, *187*(November 2022). https://doi.org/10.1016/j.techfore.2022.122201

Asna Ashari, P., Oh, H., & Koch, C. (2024). Pathways to the hydrogen economy: A multidimensional analysis of the technological innovation systems of Germany and South Korea. *International Journal of Hydrogen Energy*, *49*, 405–421. https://doi.org/10.1016/j.ijhydene.2023.08.286

Baker, J. (2011). The Technology–Organization–Environment Framework In: *Integrated series on information systems*[(eds.)], pp. 231–245, https://doi.org/https://doi.org/10.1007/978-1-4419-6108-2_12

Bergek, A. (2019). Technological innovation systems: a review of recent findings and suggestions for future research. *Handbook of Sustainable Innovation*, 200–218. https://doi.org/10.4337/9781788112574.00019

Bergek, A., Hekkert, M., Jacobsson, S., Markard, J., Sandén, B., & Truffer, B. (2015). Technological innovation systems in contexts: Conceptualizing contextual structures and interaction dynamics. *Environmental Innovation and Societal Transitions*, *16*, 51–64. https://doi.org/10.1016/j.eist.2015.07.003

Bergek, A., Jacobsson, S., Carlsson, B., Lindmark, S., & Rickne, A. (2008). Analyzing the functional dynamics of technological innovation systems: A scheme of analysis. *Research Policy*, *37*(3), 407–429. https://doi.org/10.1016/j.respol.2007.12.003

Besteman, T. (2024, April). Energieleverancier Uniper stelt waterstoffabriek Rotterdam uit: 'Te duur, te veel onzekerheid'. https://www.telegraaf.nl/financieel/1459951827/energieleverancier-uniper-stelt-waterstoffabriek-rotterdam-uit-te-duur-te-veel-onzekerheid

Bilgili, M., Yasar, A., & Simsek, E. (2011). Offshore wind power development in Europe and its comparison with onshore counterpart. *Renewable and Sustainable Energy Reviews*, *15*(2), 905–915. https://doi.org/10.1016/j.rser.2010.11.006

Bird, L., Lew, D., Milligan, M., Carlini, E. M., Estanqueiro, A., Flynn, D., Gomez-Lazaro, E., Holttinen, H., Menemenlis, N., Orths, A., Eriksen, P. B., Smith, J. C., Soder, L., Sorensen, P., Altiparmakis, A., Yasuda, Y., & Miller, J. (2016). Wind and solar energy curtailment: A review of international experience. *Renewable and Sustainable Energy Reviews*, *65*, 577–586. https://doi.org/10.1016/j.rser.2016.06.082

Blakers, A., Stocks, M., Lu, B., & Cheng, C. (2021). A review of pumped hydro energy storage. *Progress in Energy*, *3*(2). https://doi.org/10.1088/2516-1083/abeb5b

Blot, J., Witvrouwen, K., & Bartholomé, G. (2022). *HyNetherlands 100MW: Final report ENGIE Energie Nederland*.

Borgatti, S. P., Everett, M. G., & Johnson, J. C. (2013). *Analysing Social Networks*. SAGE PUBN.

Broekstra, B. (2023). *Understanding how the hydrogen technological innovation system in the Netherlands can be accelerated* [Master's thesis]. Universiteit Utrecht.

Carlot, F., Klossa, A., Pluchet, J., Clauwaert, S., Viel, P., Blondeau, L., & Yoran, V. H. (2023). *Offshore Wind & Hydrogen Integration*. Arthur D. Little.

Carlsson, B., & Stankiewicz, R. (1991). On the nature, function and composition of technological systems. *Journal of Evolutionary Economics*, *1*(2), 93–118. https://doi.org/10.1007/BF01224915/METRICS

Carlsson, B., Jacobsson, S., Holmen, M., & Rickne, A. (2002). Innovation systems: Analytical and methodological issues. *Research Policy*, *31*(2), 233–245. https://doi.org/10.1016/S0048-7333(01)00138-X

Carmo, M., & Stolten, D. (2018). *Energy storage using hydrogen produced from excess renewable electricity: Power to hydrogen*. Elsevier Inc. https://doi.org/10.1016/B978-0-12-814251-6.00004-6

Costanzo, G., & Brindley, G. (2023). *Wind energy in Europe - 2023 Statistics and the outlook for 2024-2030*. WindEurope.

Crosswind. (2023). Presentation: We deliver, We innovate, We share. https://www.kivi.nl/uploads/media/651e7ce3a5163/kivi-nw-presentation-crosswind-04-10-2023.pdf

Cuthbertson, A. (2023). World's largest wind turbine breaks record for power generated in a single day. Retrieved April 12, 2024, from https://www.independent.co.uk/tech/wind-power-world-record-renewable-energy-b2406952.html

Da Silva, L. C., Schwabe, O., & Almeida, N. (2022). Speed of Innovation Diffusion in Green Hydrogen Technologies In: *Lecture notes in mechanical engineering*[(eds.)], pp. 101–111, https://doi.org/https://doi.org/10.1007/978-3-030-96794-9_10

De Oliveira, L. G. S., Subtil Lacerda, J., & Negro, S. O. (2020). A mechanism-based explanation for blocking mechanisms in technological innovation systems. *Environmental Innovation and Societal Transitions*, *37*(July), 18–38. https://doi.org/10.1016/j.eist.2020.07.006

Decourt, B. (2019). Weaknesses and drivers for power-to-X diffusion in Europe. Insights from technological innovation system analysis. *International Journal of Hydrogen Energy*, *44*(33), 17411–17430. https://doi.org/10.1016/j.ijhydene.2019.05.149

Dehghani-Sanij, A. R., Tharumalingam, E., Dusseault, M. B., & Fraser, R. (2019). Study of energy storage systems and environmental challenges of batteries. *Renewable and Sustainable Energy Reviews*, *104*, 192–208. https://doi.org/10.1016/j.rser.2019.01.023

Deloitte (2024). *Samenvattend adviesrapport ten behoeve van het Plan Noordzee 2050*. https://www2.deloitte.com/content/dam/Deloitte/nl/Documents/energy-resources/Energie%7B%5C_%7DInfrastructuur%7B%5C_%7DPlan%7B%5C_%7DNoordzee%7B%5C_%7D2050.pdf

Desalegn, B., Gebeyehu, D., Tamrat, B., Tadiwose, T., & Lata, A. (2023). Onshore versus offshore wind power trends and recent study practices in modeling of wind turbines' life-cycle impact assessments. *Cleaner Engineering and Technology*, *17*(November). https://doi.org/10.1016/j.clet.2023.100691

Díaz, H., & Guedes Soares, C. (2020). Review of the current status, technology and future trends of offshore wind farms. *Ocean Engineering*, *209*(April). https://doi.org/10.1016/j.oceaneng.2020.107381

Dincer, I. (2012). Green methods for hydrogen production. *International Journal of Hydrogen Energy*, *37*(2), 1954–1971. https://doi.org/10.1016/j.ijhydene.2011.03.173

Durakovic, G., del Granado, P. C., & Tomasgard, A. (2023). Powering Europe with North Sea offshore wind: The impact of hydrogen investments on grid infrastructure and power prices. *Energy*, *263*(September 2022). https://doi.org/10.1016/j.energy.2022.125654

Edsand, H. E. (2017). Identifying barriers to wind energy diffusion in Colombia: A function analysis of the technological innovation system and the wider context. *Technology in Society*, *49*, 1–15. https://doi.org/10.1016/j.techsoc.2017.01.002

Edwards, P. P., Kuznetsov, V. L., & David, W. I. (2007). Hydrogen energy. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *365*(1853), 1043–1056. https://doi.org/10.1098/rsta.2006.1965

Eneco. (n.d.). Eneco Elektrolyzer. Retrieved June 8, 2024, from https://www.eneco.nl/over-ons/wat-we-doen/inspiratie/groene-waterstof/enecoelectrolyzer/

Energiebeheer Nederland (2023). *Het energiesysteem van de toekomst: de II3050-scenario's*.

Enevoldsen, P., & Xydis, G. (2019). Examining the trends of 35 years growth of key wind turbine components. *Energy for Sustainable Development*, *50*, 18–26. https://doi.org/10.1016/j.esd.2019.02.003

European Commission. (n.d.). Renewable Energy Directive. Retrieved July 1, 2024, from https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-directive%7B%5C_%7Den%7B%5C#%7Dthe-revised-directive

European Commission. (2021). 'Fit for 55': delivering the EU's 2030 Climate Target on the way to climate neutrality. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%7B%5C%%7D3A52021DC0550

European Commission (2024). *INNOVFUND_Netherlands.pdf*. https://ec.europa.eu/assets/cinea/country%7B%5C_%7Dfactsheets/innovation%7B%5C_%7Dfund/INNOVFUND%7B%5C_%7DNetherlands.pdf

European Hydrogen Observatory (2024). *The European hydrogen policy landscape*.

European Parliament & Council of the European Union. (2018, December). Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast). https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32018L2001%7B%5C&%7Dqid=1719862408596

European Parliament & Council of the European Union. (2023, October). Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing Council. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=OJ:L%7B%5C_%7D202302413

Fetting, C. (2020). *The European Green Deal*. ESDN Report. December 2020. ESDN Office. Vienna.

FlexH2. (n.d.). The Project. Retrieved May 16, 2024, from grow-flexh2.nl/project

Freeman, C. (1987). *Technology Policy and Economic Performance: Lessons from Japan*. Frances Printer Publishers.

Gasunie. (2022). Gasunie onderzoekt waterstofnetwerk op Noordzee. Retrieved June 27, 2024, from https://www.gasunie.nl/nieuwsbrief/gasunie-update-3-2022/gasunie-onderzoekt-waterstofnetwerk-op-noordzee

Geels, F. W. (2019). Socio-technical transitions to sustainability: a review of criticisms and elaborations of the Multi-Level Perspective. *Current Opinion in Environmental Sustainability*, *39*, 187–201. https://doi.org/10.1016/j.cosust.2019.06.009

Gigler, J., Hooft Graafland, C., & Blokdijk, R. (2021). *The second gas revolution*. RVO, FME, Topsector Energie & TKI Nieuw Gas. https://www.fme.nl/hydrogen-guide-2023

Gonzalez-Aparicio, I., Vitulli, A., Krishna-Swamy, S., Hernandez-Serna, R., Jansen, N., & Verstraten, P. (2022). *TNO whitepaper Offshore wind business feasibility in a flexible and electrified Dutch energy market by 2030*. TNO.

Hanley, E. S., Deane, J. P., & Gallachóir, B. P. (2018). The role of hydrogen in low carbon energy futures–A review of existing perspectives. *Renewable and Sustainable Energy Reviews*, *82*(January), 3027–3045. https://doi.org/10.1016/j.rser.2017.10.034

Heijnen, V. (2024, April). Kamerbrief over voortgang implementatie RED-III vervoer. https://www.tweedekamer.nl/kamerstukken/moties/detail?id=2021D47333%7B%5C&%7Ddid=2021D47333

Hekkert, M. P., Negro, S., Heimeriks, G., & Harmsen, R. (2011). Technological Innovation System Analysis: A manual for analysts.

Hekkert, M. P., Suurs, R. A., Negro, S. O., Kuhlmann, S., Smits, R. E., & Hekkert, M. P. (2007). Functions of innovation systems: A new approach for analysing technological change. *Technological Forecasting and Social Change*, *74*(4), 413–432. https://doi.org/10.1016/j.techfore.2006.03.002

Holttinen, H. (2012). Wind integration: Experience, issues, and challenges. *WIREs Energy and Environment*, *1*(3), 243–255. https://doi.org/10.1002/wene.18

HyCC. (n.d.-a). H2-Fifty, Rotterdam. Retrieved May 16, 2024, from https://www.hycc.com/en/projects/h2-fifty

HyCC. (n.d.-b). H2era. Retrieved May 17, 2024, from https://www.hycc.com/nl/projecten/h2era

HyCC. (n.d.-c). H2ermes. Retrieved May 17, 2024, from https://www.hycc.com/en/projects/h2ermes

HyCC (2023). *Eindrapport TSE - H2Fifty*.

HyCC & Gasunie. (2024). Eindrapport DEI+ - Djewels: Pilotproject waterstoffabriek ter balancering van het elektriciteitsnetwerk.

HYGRO. (n.d.). Groene waterstof met HYGRO waterstofmolen. Retrieved June 8, 2024, from https://hy-gro.nl/nl/project/groene-waterstof-met-hygro-waterstofmolen

HYGRO, Energy Expo, ECN, Energy Valley, & Composite Agency (2018). *Wind-to-Hydrogen (W2H2): Openbaar Eindrapport TKI systeemintegratiestudie*. https://projecten.topsectorenergie.nl/storage/app/uploads/public/5b2/8ef/8a0/5b28ef8a04372977882948.pdf

IEA (2021a). *Net Zero by 2050: A Roadmap for the Global Energy Sector*. International Energy Agency. Paris. https://www.iea.org/reports/net-zero-by-2050

IEA. (2021b). Wind Energy in The Netherlands. Retrieved March 16, 2024, from https://iea-wind.org/about-iea-wind-tcp/members/the-netherlands/

IEA (2023a). *Renewable Energy Market Update: Outlook for 2023 and 2024*. International Energy Agency. Paris. www.iea.org/t%7B%5C&%7Dc/

IEA (2023b). *Tracking Clean Energy Progress 2023*. International Energy Agency. Paris. https://www.iea.org/reports/tracking-clean-energy-progress-2023

IEA (2023c). *World Energy Outlook 2023*. International Energy Agency. Paris. https://www.iea.org/reports/world-energy-outlook-2023

IPCC (2023). Sections In: *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*[Core Writing Team, Romero, J., & Lee, H. (eds.)], IPCC, Geneva, Switzerland, pp. 35–115, https://doi.org/10.59327/IPCC/AR6-9789291691647

IRENA (2023). *World energy transitions outlook 2022: 1.5°C Pathway*. International Renewable Energy Agency. Abu Dhabi. https://irena.org/Digital-Report/World-Energy-Transitions-Outlook-2022%7B%5C%%7D0Ahttps://irena.org/publications/2021/March/World-Energy-Transitions-Outlook

ISPT. (n.d.). Hydrohub MegaWatt Test Center. Retrieved July 2, 2024, from https://ispt.eu/projects/hydrohub-megawatt-test-centre/

Jain, R., Nagasawa, K., Veda, S., & Sprik, S. (2023). Grid ancillary services using electrolyzer-Based power-to-Gas systems with increasing renewable penetration. *e-Prime - Advances in Electrical Engineering, Electronics and Energy*, *6*(July 2022). https://doi.org/10.1016/j.prime.2023.100308

Jetten, R. (2023, June). Voorkeurslocaties demonstratieprojecten waterstof op zee. https://open.overheid.nl/documenten/d7de6323-5666-4922-b081-89b7ac2a4123/file

Jetten, R. (2024, June). Voortgang demonstratieprojecten waterstof op zee. https://www.tweedekamer.nl/kamerstukken/brieven%7B%5C_%7Dregering/detail?id=2024Z10151%7B%5C&%7Ddid=2024D24016

Joos, M., & Staffell, I. (2018). Short-term integration costs of variable renewable energy: Wind curtailment and balancing in Britain and Germany. *Renewable and Sustainable Energy Reviews*, *86*(August 2017), 45–65. https://doi.org/10.1016/j.rser.2018.01.009

Kaygusuz, K. (2009). Wind power for a clean and sustainable energy future. *Energy Sources, Part B: Economics, Planning and Policy*, *4*(1), 122–133. https://doi.org/10.1080/15567240701620390

Konstantinidis, E. I., & Botsaris, P. N. (2016). Wind turbines: Current status, obstacles, trends and technologies. *IOP Conference Series: Materials Science and Engineering*, *161*(1). https://doi.org/10.1088/1757-899X/161/1/012079

Laarhoven, M. (2023). *TIS analysis of green hydrogen in the Netherlands: identifying key gaps and opportunities* [Doctoral dissertation, Eindhoven University of Technology].

Lund, P. D., Lindgren, J., Mikkola, J., & Salpakari, J. (2015). Review of energy system flexibility measures to enable high levels of variable renewable electricity. *Renewable and Sustainable Energy Reviews*, *45*, 785–807. https://doi.org/10.1016/j.rser.2015.01.057

Macquart, T., Kucukbahar, D., & Prinsenn, B. (2023). Dutch Offshore Wind Market Report 2023. (April).

Markard, J., Hekkert, M., & Jacobsson, S. (2015). The technological innovation systems framework: Response to six criticisms. *Environmental Innovation and Societal Transitions*, *16*, 76–86. https://doi.org/10.1016/j.eist.2015.07.006

Markard, J., Raven, R., & Truffer, B. (2012). Sustainability transitions: An emerging field of research and its prospects. *Research Policy*, *41*(6), 955–967. https://doi.org/10.1016/j.respol.2012.02.013

Markard, J., & Truffer, B. (2008). Technological innovation systems and the multi-level perspective: Towards an integrated framework. *Research Policy*, *37*(4), 596–615. https://doi.org/10.1016/j.respol.2008.01.004

Metz, F. (2024). Lecture Notes: Network Analysis.

MissieH2. (n.d.). Waterstofkaart. https://waterstofkaart.missieh2.nl/nl/

Mucci, S., Mitsos, A., & Bongartz, D. (2023). Power-to-X processes based on PEM water electrolyzers: A review of process integration and flexible operation. *Computers and Chemical Engineering*, *175*(February 2022), 108260. https://doi.org/10.1016/j.compchemeng.2023.108260

Mulder, M., Perey, P., & Moraga, J. L. (2019). *Outlook for a Dutch hydrogen market*. https://www.rug.nl/ceer/blog/ceer%7B%5C_%7Dpolicypaper%7B%5C_%7D5%7B%5C_%7Dweb.pdf

Nationaal Waterstof Programma. (2022). Routekaart Waterstof, 1–152. www.nationaalwaterstofprogramma.nl

Netbeheer Nederland. (n.d.). Capaciteitskaart elektriciteitsnet. Retrieved February 27, 2024, from https://capaciteitskaart.netbeheernederland.nl/

Newborough, M., & Cooley, G. (2020). Developments in the global hydrogen market: The spectrum of hydrogen colours. *Fuel Cells Bulletin*, *2020*(11), 16–22. https://doi.org/10.1016/S1464-2859(20)30546-0

Noordzeeloket. (n.d.). Wet- en regelgeving, internationale verdragen en beleid. Retrieved July 2, 2024, from https://www.noordzeeloket.nl/functies-gebruik/windenergie/wet-regelgeving-internationale-verdragen-beleid/

North Sea Energy. (n.d.). North Sea Energy Roadmap 2050.

North Sea Wind Power Hub. (n.d.). Key concepts. Retrieved June 13, 2024, from https://northseawindpowerhub.eu/key-concepts

North Sea Wind Power Hub (2022). *Hubs and spokes - viable beyond theory*. https://northseawindpowerhub.eu/files/media/document/NSWPH%7B%5C_%7DHubs%20and%20spokes%20%E2%80%93%20viable%20beyond%20theory%7B%5C_%7Dnov.%202022%7B%5C_%7D1.pdf

NortH2. (n.d.). Nieuws. Retrieved May 16, 2024, from https://www.north2.eu/nieuws/

Ørsted. (2020). Ørsted and Yara seek to develop groundbreaking green ammonia project in the Netherlands. https://orsted.com/en/media/news/2020/10/143404185982536

Overlegorgaan Fysieke Leefomgeving (2021). *Het Akkoord voor de Noordzee*. OFL. https://open.overheid.nl/documenten/ronl-99d46f4b-1d45-49cd-a979-2ce8bf737e22/pdf

Palmen, A. (2024). Brief opzegging Noordzee Akkoord. https://www.greenpeace.org/nl/klimaatverandering/62421/brief-opzegging-noordzee-akkoord/

Pauw, M. (n.d.). Overschot groene stroom kost Tennet honderden miljoenen, burgers betalen. Retrieved February 27, 2024, from https://www.rtlnieuws.nl/economie/artikel/5312211/tennet-stroomnet-hoogspanning-congestie-kosten-honderden-miljoenen

Port of Rotterdam. (2022). In 2023 groene waterstofproductie bij SIF. Retrieved May 31, 2024, from https://www.portofrotterdam.com/nl/nieuws-en-persberichten/in-2023-groene-waterstofproductie-bij-sif

Port of Rotterdam. (2024). Green Hydrogen Production Starts at Dedicated Sites for Electrolysis. https://www.portofrotterdam.com/sites/default/files/2024-06/Hydrogen-Locations-Port-of-Rotterdam-2024.pdf

PosHYdon. (2024). PosHYdon: test op land succesvol van start. Retrieved May 16, 2024, from https://poshydon.com/nl/poshydon-test-op-land-succesvol-van-start/

Price, T. J. (2005). Britain's first modern wind power pioneer. *Wind engineering*, *29*, 191–200.

Rabiee, A., Keane, A., & Soroudi, A. (2021). Technical barriers for harnessing the green hydrogen: A power system perspective. *Renewable Energy*, *163*, 1580–1587. https://doi.org/10.1016/j.renene.2020.10.051

Ramakrishnan, S., Delpisheh, M., Convery, C., Niblett, D., Vinothkannan, M., & Mamlouk, M. (2024). Offshore green hydrogen production from wind energy : Critical review and perspective. *195*(October 2023).

Remko, D., Marcel, W., & Joost, v. S. (2020). *Hydrogen in the Netherlands A review of recent Dutch scenario studies*. TNO. https://repository.tno.nl/islandora/object/uuid%7B%5C%%7D3A83e918c3-4d9e-4319-ae82-bd3729726cdf

Rijksoverheid (2019). *Klimaatakkoord 2019*. Den Haag. https://www.rijksoverheid.nl/documenten/rapporten/2019/06/28/klimaatakkoord

Rijksoverheid (2022a). *Coalitieakkoord 2021-2025*. https://open.overheid.nl/documenten/ronl-f3cb0d9c-878b-4608-9f6a-8a2f6e24a410/pdf

Rijksoverheid (2022b). *Programma Noordzee*. Den Haag. https://www.rijksoverheid.nl/documenten/rapporten/2020/06/19/bijlage-ofl-rapport-het-akkoord-voor-de-noordzee

Rijksoverheid. (2023). Klimaatwet. Retrieved July 1, 2024, from https://wetten.overheid.nl/BWBR0042394/2023-07-22

Rijksoverheid. (2024). Brede steun voor nieuwe energiewet. Retrieved July 2, 2024, from https://www.rijksoverheid.nl/actueel/nieuws/2024/06/04/brede-steun-voor-nieuwe-energiewet

Rogers, E. M. (1962). *Diffusion of Innovations*. Free Press of Glencoe.

Rogers, E. M. (2005). *Diffusion of Innovations* (3rd ed.). Free Press of Glencoe.

RVO. (n.d.). Database - Ondersteunde projecten door RVO. Retrieved May 31, 2024, from https://data.rvo.nl/subsidies-regelingen/projecten?query-content=%7B%5C&%7Dundefined=Zoeken

RVO. (2021a). Netcapaciteit en netcongestie. Retrieved March 16, 2024, from https://www.rvo.nl/onderwerpen/zonne-energie/netcapaciteit

RVO. (2021b). Nieuwe windparken op zee. Retrieved July 2, 2024, from https://www.rvo.nl/onderwerpen/windenergie-op-zee/nieuwe-windparken-op-zee

RVO (2023a). *Dutch Offshore Wind Innovation Guide*.

RVO. (2023b). Interessepeiling: waterstofproductie op zee. Retrieved June 9, 2024, from https://www.rvo.nl/onderwerpen/waterstof/interessepeiling-waterstofproductie-op-zee

RWE. (n.d.). H2opZee. Retrieved May 16, 2024, from https://www.rwe.com/en/research-and-development/hydrogen-projects/h2opzee/

RWE (2024). *Persbericht: RWE ontvangt subsidie voor Eemshydrogen-project om elektrolyser van 50 megawatt te bouwen voor de productie van groene H2*. Geertruidenberg. https://benelux.rwe.com/-/media/RWE/RWE-Benelux/press/rwe-generation-se/2024/2024-04-29-rwe-ontvangt-subsidie-voor-eemshydrogen-project-om-elektrolyser-van-50-mw-te-bouwen.pdf

Ryberg, D. S., Caglayan, D. G., Schmitt, S., Linßen, J., Stolten, D., & Robinius, M. (2019). The future of European onshore wind energy potential: Detailed distribution and simulation of advanced turbine designs. *Energy*, *182*, 1222–1238. https://doi.org/10.1016/j.energy.2019.06.052

Sawulski, J., Gałczyński, M., & Zajdler, R. (2019). Technological innovation system analysis in a follower country – The case of offshore wind in Poland. *Environmental Innovation and Societal Transitions*, *33*(September 2018), 249–267. https://doi.org/10.1016/j.eist.2019.07.002

SeaH2Land. (2024). Summary. Retrieved May 18, 2024, from https://seah2land.nl/summary

Sgobbi, A., Nijs, W., De Miglio, R., Chiodi, A., Gargiulo, M., & Thiel, C. (2016). How far away is hydrogen? Its role in the medium and long-term decarbonisation of the European energy system. *International Journal of Hydrogen Energy*, *41*(1), 19–35. https://doi.org/10.1016/j.ijhydene.2015.09.004

Shell (). *Kick-Starting the Hydrogen Economy of the netherlands: Shell Holland Hydrogen 1.*

Shiva Kumar, S., & Himabindu, V. (2019). Hydrogen production by PEM water electrolysis – A review. *Materials Science for Energy Technologies*, *2*(3), 442–454. https://doi.org/10.1016/j.mset.2019.03.002

Smits, R., & Kuhlmann, S. (2004). The rise of systemic instruments in innovation policy. *International Journal of Foresight and Innovation Policy*, *1*(1-2), 4–32. https://doi.org/10.1504/ijfip.2004.004621

Stichting de Noordzee & Natuur & Milieu (2021). *Positie Positie energie-eilanden*. https://natuurenmilieu.nl/app/uploads/Positie-energie-eilanden-Stichting-De-Noordzee-en-Natuur-en-Milieu.pdf

Suurs, R. A., Hekkert, M. P., & Smits, R. E. (2009). Understanding the build-up of a technological innovation system around hydrogen and fuel cell technologies. *International Journal of Hydrogen Energy*, *34*(24), 9639–9654. https://doi.org/10.1016/j.ijhydene.2009.09.092

Tavakoli, S. D., Dozein, M. G., Lacerda, V. A., Mane, M. C., Prieto-Araujo, E., Mancarella, P., & Gomis-Bellmunt, O. (2023). Grid-Forming Services From Hydrogen Electrolyzers. *IEEE Transactions on Sustainable Energy*, *14*(4), 2205–2219. https://doi.org/10.1109/TSTE.2023.3270295

The European Commission. (n.d.). Database - EU Funded Projects. Retrieved May 31, 2024, from https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/projects-results

Thomson, K. (2014). *Offshore wind: A Comprehensive Guide to Successful Offshore Wind Farm Installation* (2nd). Academic Press.

TNO. (2022). Offshore hydrogen for unlocking the full energy potential of the North Sea. (November). https://energy.ec.europa.eu/system/files/2022-09/220912%7B%5C_%7DNSEC%7B%5C_%7DJoint%7B%5C_%7DStatement%7B%5C_%7DDublin%7B%5C_%7DMinisterial.pdf

Topsector Energie. (n.d.-a). Advanced Process Control Hydrohub. Retrieved June 13, 2024, from https://projecten.topsectorenergie.nl/projecten/advanced-process-control-hydrohub-36947

Topsector Energie. (n.d.-b). HEROW: Hydrogen empowering revolutionary offshore wind. Retrieved June 15, 2024, from https://topsectorenergie.nl/nl/maak-kennis-met-tse/tki-offshore-energy/herow/

Topsector Energie. (n.d.-c). HydroHub MegaWatt Test Centre Research phase 2.

TopSector Energy. (n.d.). Topsector Energie - Projecten. Retrieved May 31, 2024, from https://projecten.topsectorenergie.nl/projecten

Topsector Energy. (n.d.). PosHYdon. Retrieved May 7, 2024, from https://projecten.topsectorenergie.nl/projecten/poshydon-35973

TU Delft. (2023). MOOI grant for a floating green hydrogen and ammonia project. Retrieved May 31, 2024, from https://www.tudelft.nl/2023/h2-platform/mooi-grant-for-a-floating-green-hydrogen-and-ammonia-project

Tweede Kamer. (n.d.-a). Wetsvoorstel Energiewet. Retrieved July 2, 2024, from https://www.tweedekamer.nl/kamerstukken/wetsvoorstellen/detail?cfg=wetsvoorsteldetails%7B%5C&%7Dqry=wetsvoorstel%7B%5C%%7D3A36378%7B%5C#%7Dwetgevingsproces

Tweede Kamer. (n.d.-b). Wijziging van de Mijnbouwwet. Retrieved July 2, 2024, from https://www.tweedekamer.nl/kamerstukken/wetsvoorstellen/detail?id=2020Z08961%7B%5C&%7Ddossier=35462

Tweede Kamer (2023). *Groningers boven gas: Rapport parlementaire enquêtecommissie aargaswinning Groningen - Boek 1: Conclusies en aanbevelingen*. https://rapportaardgaswinning.tweedekamer.nl

Uniper. (2023). Uniper's H2Maasvlakte project selected by the European Commission for innovation grant. Retrieved May 18, 2024, from https://www.uniper.energy/news/unipers-h2maasvlakte-project-selected-by-the-european-commission-for-innovation-grant

van der Loos, A., Negro, S. O., & Hekkert, M. P. (2020). Low-carbon lock-in? Exploring transformative innovation policy and offshore wind energy pathways in the Netherlands. *Energy Research and Social Science*, *69*(November 2019). https://doi.org/10.1016/j.erss.2020.101640 van der Loos, A., Normann, H. E., Hanson, J., & Hekkert, M. P. (2021). The co-evolution of innovation systems and context: Offshore wind in Norway and the Netherlands. *Renewable and Sustainable Energy Reviews*, *138*(February 2020). https://doi.org/10.1016/j.rser.2020.110513

van 't Noordende, H., & Ripson, P. (2022). *A One-GigaWatt Plant*. ISPT. Amersfoort.

van Medevoort, J., Kuipers, N., & ten Hoopen, P. (2022). *SEA2H2 Hydrogen from seawater via Membrane Distillation and Polymer Electrolyte Membrane Water Electrolysis*.

Voulis, N., Rooijers, F., Scholten, T., Vendrik, J., van der Veen, R., Renz, M., van Schot, M., Jepma, C., Halter, M., Koorneef, J., Dijkstra, H., van Zuijlen, E., Westra, C., Klomp, W., van der Linden, F., & Asare-Bediako, B. (2020). *Eindrapport TES - Ijvergas: Feasibility of hydrogen generation on a multifunctional island at IJmuiden Ver*.

Waddenfonds. (n.d.). Projecten. Retrieved June 30, 2024, from https://waddenfonds.nl/projecten/

Weeda, M., & Segers, R. (2020). *The Dutch hydrogen balance, and the current and future representation of hydrogen in the energy statistics*. TNO.

Weimann, L., Gabrielli, P., Boldrini, A., Kramer, G. J., & Gazzani, M. (2021). Optimal hydrogen production in a wind-dominated zero-emission energy system. *Advances in Applied Energy*, *3*(April). https://doi.org/10.1016/j.adapen.2021.100032

West, J. B. (2014). Henry Cavendish (1731-1810): Hydrogen, carbon dioxide, water, and weighing the world. *American Journal of Physiology - Lung Cellular and Molecular Physiology*, *307*(1), 1–6. https://doi.org/10.1152/ajplung.00067.2014

Wieczorek, A. J., & Hekkert, M. P. (2012). Systemic instruments for systemic innovation problems: A framework for policy makers and innovation scholars. *Science and Public Policy*, *39*(1), 74–87. https://doi.org/10.1093/scipol/scr008

Wieczorek, A. J., Hekkert, M. P., Coenen, L., & Harmsen, R. (2015). Broadening the national focus in technological innovation system analysis: The case of offshore wind. *Environmental Innovation and Societal Transitions*, *14*, 128–148. https://doi.org/10.1016/j.eist.2014.09.001

Wieczorek, A. J., Negro, S. O., Harmsen, R., Heimeriks, G. J., Luo, L., & Hekkert, M. P. (2013a). A review of the European offshore wind innovation system. *Renewable and Sustainable Energy Reviews*, *26*, 294–306. https://doi.org/10.1016/j.rser.2013.05.045

Wieczorek, A. J., Negro, S. O., Harmsen, R., Heimeriks, G. J., Luo, L., & Hekkert, M. P. (2013b). A review of the European offshore wind innovation system. *Renewable and Sustainable Energy Reviews*, *26*, 294–306. https://doi.org/10.1016/j.rser.2013.05.045

Won, W., Kwon, H., Han, J. H., & Kim, J. (2017). Design and operation of renewable energy sources based hydrogen supply system: Technology integration and optimization. *Renewable Energy*, *103*, 226–238. https://doi.org/10.1016/j.renene.2016.11.038

Wu, Y., Liu, F., Wu, J., He, J., Xu, M., & Zhou, J. (2022). Barrier identification and analysis framework to the development of offshore wind-to-hydrogen projects. *Energy*, *239*. https://doi.org/10.1016/j.energy.2021.122077

A | List of interview questions

Table 8: List of interview questions (adapted from Hekkert et al. (2011)).

Functions	Diagnostic questions
F1: Entrepreneurial activities	• Are the actors in the structural analysis the most relevant? • Are there sufficient and suitable types of actors in the technological innovation system that contribute to experimentation with offshore wind-to-hydrogen energy systems and up-scaling the technology? • Does the experimentation and production by entrepreneurs form a barrier for the technological innovation system to move to the next phase? • How would you assess the performance of this function using the following scale: "very bad" (1 point), "bad" (2), "acceptable" (3), "good" (4), "very good" (5 points)?
F2: Knowledge development	• Is the amount and quality of knowledge development sufficient for the development of the innovation system? • Does the type of knowledge developed fit with the knowledge needs within the innovation system? • Does the quality and/or quantity of knowledge development form a barrier for the TIS to move to the next phase? • How would you assess the performance of this function using the following scale: "very bad" (1 point), "bad" (2), "acceptable" (3), "good" (4), "very good" (5 points)?
F3: Knowledge diffusion through networks	• Is there enough knowledge exchange between science and industry? • Is knowledge exchange forming a barrier for the IS to move to the next phase? • How would you assess the performance of this function using the following scale: "very bad" (1 point), "bad" (2), "acceptable" (3), "good" (4), "very good" (5 points)?
F4: Guidance of the search	• Do actors and institutions provide a sufficiently clear direction for the future development of the technology? • Are the visions and expectations of the actors involved sufficiently aligned? • If so, does this (lack of) shared vision block the development of the TIS? • How would you assess the performance of this function using the following scale: "very bad" (1 point), "bad" (2), "acceptable" (3), "good" (4), "very good" (5 points)?
F5: Market formation	• Is the current and expected future market size sufficient? • Does the market size form a barrier for the development of the innovation system? • How would you assess the performance of this function using the following scale: "very bad" (1 point), "bad" (2), "acceptable" (3), "good" (4), "very good" (5 points)?

F6: Resource mobilisation	• Are there sufficient human resources? If not, does that form a barrier? • Are there sufficient financial resources? If not, does that form a barrier? • Are there expected physical resource constraints that may affect technology diffusion? • Is the physical infrastructure developed well enough to support the diffusion of the technology? • How would you assess the performance of this function using the following scale: "very bad" (1 point), "bad" (2), "acceptable" (3), "good" (4), "very good" (5 points)?
F7: Creation of legitimacy/counteract resistance to change	• Is there a lot of resistance towards the new technology, the set up of projects of permit procedures? • If there is resistance, does that form a barrier? • Do actors, formal and informal institutions sufficiently contribute to legitimacy? • How would you assess the performance of this function using the following scale: "very bad" (1 point), "bad" (2), "acceptable" (3), "good" (4), "very good" (5 points)?

B | Interview codes

Table 9: List of labels and sublabels used for coding the interview transcripts.

Label	**Sublabel**
Entrepreneurial activities	Market challenges and financial barriers Development and type of experimentation Stage of innovation
Knowledge development	Current programs and initiatives Technological and ecological knowledge
Knowledge diffusion through networks	Network initiatives Effectiveness of knowledge sharing Value of consortium type projects
Guidance of the search	Government role and vision Industry perspectives
Market formation	Market size and potential Market challenges and development Institutional role in market formation
Resource mobilization	Human resources Financial resources Infrastructure and physical resources
Creation of legitimacy/counteract Resistance to change	Societal and political acceptance Regulatory and legislative challenges

C | Consent form

Research Fact Sheet ’Technological Innovation System Analysis for Offshore Wind-to-hydrogen Energy Systems’

Purpose of the study
This research is led by Robert Blauw to write his master’s thesis for the Environmental & Energy Management programme at the University of Twente. The aim of this research is to investigate the Technological Innovation System (TIS) behind offshore wind-to-hydrogen systems. Research on TIS is part of the scientific approach to systems thinking, in which innovation is seen as the product of a network of collaborating organisations, rather than developments within a single entity. By mapping the TIS of offshore wind-to-hydrogen, I hope to be able to provide valuable insights to policy officers to support this innovation in a targeted manner.

How do we work?
You will participate in a study in which we will gather information through a semi-structured interview with an audio recording. A transcript of the interview will also be worked out.

During the interview, questions will be asked specifically designed to obtain your assessment of the functionality of the Technological Innovation System (TIS). The qualitative data collected will be used to describe the current state of the TIS in the form of a master’s thesis and to investigate possible policy measures.

Potential Risks and Inconveniences
There are no physical, legal, or economic risks associated with your participation in this study. You don’t have to answer questions you don’t want to answer. Your participation is voluntary, and you can stop your participation at any time.

Compensation
You will not receive any compensation for participating in this study.

Confidentiality of data
Before we publish our research data, your personal data will be anonymized as much as possible. Only a general description of your position, such as ’manager’, and the name of your organisation will be mentioned. Your full name will only be used if you give explicit permission for this in our consent form, for example when quoting your statements.

The audio recordings, forms, and other documents created or collected as part of this study will be stored on an encrypted SSD of the investigator and destroyed after the study is completed.

Finally, this research was assessed and approved by the ethics committee of the BMS faculty (domain Humanities & Social Sciences)

Voluntary
Participation in this study is completely voluntary. As a participant, you can stop your participation in the study at any time, or refuse to allow your data to be used for the study, without giving reasons. Terminating participation will not have any adverse consequences for you or any compensation already received. If you decide to stop cooperating during the study, the data you have already provided will be used in the study until the moment of withdrawal of consent. Do you want to stop the study, or do you have questions and/or complaints? Please contact the research leader.

If you have any objections regarding the design and/or conduct of the study, you can also contact the Secretary of the Ethics Committee / Humanities & Social Sciences of the Faculty of Behavioural, Management and Social Sciences at the University of Twente via ethicscommittee-hss@utwente.nl. This research is carried out by the University of Twente, Faculty of Behavioural, Management and Social Sciences. If you have specific questions about the handling of personal data, you can also direct them to the UT Data Protection Officer by sending an email to dpo@utwente.nl.

Finally, you have the right to request inspection, modification, deletion or adjustment of your data from the Research Director.

By signing this consent form, I acknowledge the following:

1. I have been sufficiently informed about the research by means of a separate information sheet. I have read the information sheet and then had the opportunity to ask questions. These questions have been adequately answered.
2. I participate in this study voluntarily. There is no explicit or implicit compulsion for me to participate in this study. It is clear to me that I can terminate my participation in the research at any time, without giving any reason. I don't have to answer a question if I don't want to.

In addition to the above, it is possible below for various parts of the study to give specific consent. You can choose whether or not to give permission for each part. If you want to give permission for everything, you can do so via the checkbox at the bottom of the statements.

3. I consent to the processing of the data collected from me during the study as stated in the attached information sheet.
   YES ☐ NO ☐
4. I give permission to make recordings (sound) during the interview and to work out my answers in a transcript.
   YES ☐ NO ☐
5. I give permission to use my answers for quotes in the research publications.
   YES ☐ NO ☐
6. I give permission to mention my real name in the quotes referred to above.
   YES ☐ NO ☐
7. I consent to everything described above.
   YES ☐

Participant's name: ______________________

Signature: _____________________________

Date: ________________________________

Researcher's Name: ______________________

Signature: _____________________________

Date: ________________________________

D | List of entrepreneurial activities

Table 10: Entrepreneurial activities in the offshore wind-to-hydrogen knowledge field.

Project	**Description**	**Involved organizations**	**Type**	**Latest update** [1]
AmpHytrite	The AmpHytrite project aims to demonstrate offshore hydrogen production using wind turbines. An Electrolyser will be coupled to a 12 MW wind turbine and constructed on the Maasvlakte (Port of Rotterdam, 2022)	General Electric, KCI, Pondera, Sif	Demonstration/research pilot project	Realization
Baseload Power Hub	This pilot project, launched by the Crosswind consortium aims to balance the variability of wind energy. The initiative focuses on converting surplus wind energy into hydrogen at the Hollandse Kust Noord wind park. The process involves a 2.5 MW Electrolyser, which facilitates the storage of hydrogen. This stored hydrogen can then be converted back into electricity during periods of low or no wind (Crosswind, 2023).	Shell, Eneco, Siemens Gamesa, van Oord, Rosetti Marino	Demonstration/research pilot project	Realization
CurtHyl	The CurtHyl project is a 200 MW Electrolyser that is scheduled for operation in 2026. Although not limited to, the Electrolyser will be powered by offshore wind energy (Air Liquide, n.d.). The Electrolyser will be situated in the Port of Rotterdam on the Maasvlakte 2 area.	Airliquide, Siemens Gamesa, Port of Rotterdam	Commercial scale project	Scheduled for development after ELYgator

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[1] The latest updates were obtained by visiting company websites and reviewing news articles throughout May and June 2024.

Djewels	This project is created to establish a 20 MW electrolysis capacity at Chemiepark Delfzijl. The hydrogen produced will be used in the production of methanol. It is intended to function as an intermediary project, providing essential knowledge and insights for potentially expanding to larger offshore production facilities in the future (HyCC & Gasunie, 2024).	HyCC, De Nora, Hinicio, Gasunie, OCI, McPhy, Technip	Demonstration/research pilot project	pending FID
Duwaal	As part of a larger supply chain consortium project, this project integrates wind energy and hydrogen production by connecting a 4 MW electrolyser to a windturbine. Not specific to offshore wind this project does contribute to system integration research (HYGRO, n.d.)	HYGRO, ENERCON, TNO, New Energy Coalition, Ontwikkelingsbedrijf Noord-Holland Noord	Demonstration/research pilot project	Realization
Eemshydrogen	Eemshydrogen is a project that aims to develop a 50 MW Electrolyser in Eemshaven in the North of the Netherlands. The Electrolysers are said to be powered by a wind park Werstereems. It is planned for operation in 2027 (RWE, 2024).	RWE, Groningen Seaports	Commercial scale project	pending FID
ELYgator	In the ELYgator project AirLiquide aims to develop a 200 MW electrolyser in Terneuzen. It is said to be powered by offshore wind, among other renewable energy sources (Air Liquide, 2022; European Commission, 2024).	Airliquide, Smart Delta Resources	Commercial scale project	Pending FID
Eneco Electrolyser	Scheduled for construction in 2026 and operation in 2029, the Eneco Electrolyser project aims to realize 800 MW of hydrogen production capacity in the harbour of Rotterdam. The electrolyser is said to be powered by offshore wind parks but does not exclude other forms of renewable energy (Eneco, n.d.; Port of Rotterdam, 2024).	Eneco, Mitsubishi, Port of Rotterdam	Commercial scale project	pending FID
EnergHys	In the EnergHys project, Total Energies plans to build a 300 MW Electrolyser in the Vlissingen area powered by offshore wind farms (European Commission, 2024).	Total Energies, Zeeland Refinery	Commercial scale project	pending FID

FlexH2	The FlexH2 project aims to develop an integrated offshore wind and onshore hydrogen production system to enhance efficiency and power system flexibility. Announced in 2021, the project emphasizes on electrical engineering knowledge developmen required for flexible hydrogen production. It seeks to elevate the technological readiness level (TRL) to 6 through simulations and a demonstration system. Currently, the project has established functional specifications and optimal operation philosophies (FlexH2, n.d.).	GROW, Shell, General Electric, ABB, VONK, Van Oord, TNO, TU Delft, DNV, TU Eindhoven, Twentsche Kabelfabriek	Demonstration/research pilot project	Research ongoing
H2era	Scheduled for operation in 2027, the project H2era aims to realize a 500 MW Electrolyser in the Amsterdam Port area. The Electrolyser is intended to operate flexibly connected to an offshore wind park. The residual heat that is created in the electrolysis process is intended for use in district heating (HyCC, n.d.-b)	HyCC, Port of Amsterdam, Tata Steel	Commercial scale project	FEED studies
H2ermes	The H2ermes project aims to develop a 100 MW Electrolyser facility to produce hydrogen near Amsterdam to be used by Steel manufacturer TATA Steel and the Amsterdam Metropolitan Area. The installation is said to be located at the Dutch coastal region utilizing the power of offshore wind parks in the North Sea (HyCC, n.d.-c)	HyCC, Port of Amsterdam, Tata Steel	Commercial scale project	Pending FID
H2-Fifty	H2-Fifty is a hydrogen project envisioned for the port of Rotterdam area. The project has a 250 MW Electrolyser capacity and will be replacing the use of grey hydrogen in a large desulfurization refinery of BP among other applications in the port area. The Electrolysers are said to be connected to offshore wind farms (HyCC, n.d.-a, 2023; Port of Rotterdam, 2024).	BP, HyCC, Port of Rotterdam	Commercial scale project	Pending FID
H2Maasvlakte	The H2Maasvlakte project was announced in 2021 by Uniper and aims to develop 100 MW Electrolyser capacity in the Port of Rotterdam by 2027. They aim to make the 100MW system modular to in the end scale the system to a capacity of 500 MW by 2030. The latest news shows the plans to build the factory have been delayed. (Besteman, 2024; Uniper, 2023)	Uniper, Port of Rotterdam, Technip, Plug	Commercial scale project	Delayed

H2opZee	The H2opZee project aims to realize 300-500 MW electrolyser capacity for offshore hydrogen production by 2030. This initiative builds upon the insights gained from the PosHYdon pilot project. In 2022, H2opZee commenced with a feasibility study, which was projected for completion by the end of 2023. (RWE, n.d.).	RWE, Neptune Energy, Siemens Gamesa, H2SEA, Enersea	Commercial scale project	FEED studies
Haddock	The Haddock project aimed to develop 100 MW Electrolyser capacity powered by offshore wind from Ørsted's Borssele 1 and 2 wind parks that were commissioned in 2020. The produced hydrogen is intended for green ammonia. The project has since been transformed into a larger scale project involving more offtake companies and public parties (Ørsted, 2020)	Ørsted, Yara	Commercial scale project	Turned into SeaH2Land
Holland Hydrogen 1	Holland Hydrogen 1 is a 200 MW Electrolyser that is currently being built on the Maasvlakte area in Rotterdam. The Electrolyser will be powered by offshore wind energy from the wind park Hollandse Kust Noord. The plant is said to be operational in the second half of 2020s (European Commission, 2024; Shell, n.d.).	Eneco, Shell, Stork, Port of Rotterdam, ThyssenKrupp, Worley	Commercial scale project	Realization
HydroHub Advanced GW Water Electrolyser	Started in 2018 and finished in 2022 this consortium project set out to design a GW scale electrolysis plant powered by offshore wind energy on paper (van 't Noordende & Ripson, 2022).	DOW, ISPT, HyCC, Ørsted, Yara, Imperial College London, TNO, OCI, Utrecht University, TU Eindhoven, Shell, Gasunie, Plug	Feasibility study/Concept design	Completed
HyNetherlands	As part of a bigger project to create a hydrogen value chain, the HyNetherlands project aims to realize a 100 MW Electrolyser for the production of hydrogen for maritime applications mainly. The Electrolyser will be powered mainly by offshore wind coming directly from a contracted offshore wind farm or from the grid with guarantees of origin (Blot et al., 2022).	Engie, Technip, John Cockerill, OCI Methanol Europe, Energy from Waste (EEW)	Commercial scale project	Pending FID
Ijvergas	This feasibility study set out to study hydrogen generation on a multifunctional Island at Ijmuiden Ver. Different scenarios of integrating wind energy with hydrogen production were tested for their technical and economic feasibility (Voulis et al., 2020).	Offshore Service Facilities, TNO, New Energy Coalition, Ce Delft, Intecsea, Royal Haskoning, Hogeschool van Arnhem en Nijmegen	Feasibility study/Concept design	Completed

NortH2	As part of a broader initiative encompassing hydrogen transport, storage, and utilization, the NorthH2 consortium plans to achieve a hydrogen production capacity of 2-4 GW from offshore wind, with an aim to expand this capacity to 10 GW by 2040. After its introduction in 2020, NorthH2 completed its technical feasibility study in December 2022. It is said that the project will now focus on the preparations for the next phase (NortH2, n.d.; RWE, 2024).	Shell, Equinor, RWE, Eneco, Gasunie, Groningen Seaports, Provincie Groningen	Commercial scale project	Feasibility studies completed
OFFSET	The Offshore Floating Storage of Energy and Transfer (OFFSET) project aims to develop an offshore floating system where hydrogen and/or ammonia can be produced near offshore wind farms (TU Delft, 2023).	BW, Marin, Strohm, SwitcH2, TU Delft	Demonstration/research pilot project	FEED studies ongoing
Poshydon	In this pilot a consortium of 15 partners is working on repurposing an oil and gas well thirteen kilometres off the coast of Scheveningen in the Netherlands. On this platform an offshore hydrogen production pilot, integrating offshore wind, hydrogen, and natural gas technologies will be constructed. Wind energy harvested from a nearby wind farm will power an Electrolyser that operates flexibly to produce hydrogen. This hydrogen will then be transported to shore by blending it with oil and natural gas using the existing infrastructure. The primary goal of this pilot is to gather valuable experience in the integration of these diverse energy systems. The pilot plant has a capacity of 1 MW and started its onshore testing phase in May 2024 (PosHYdon, 2024; Topsector Energy, n.d.).	Nexstep, Hatenboer, Investa, IV, Nel, Neptune Energy, Noordgastransport, Nogat, TAQA, TNO, DEME, EBN, Eneco, Emerson, Gasunie	Demonstration/research pilot project	Realization
Sea2H2	The Sea2H2 is a finished pilot project that aimed to reduce the cost of offshore hydrogen by utilizing membrane distillation to desalinate seawater for hydrogen production. The pilot unit was coupled to an electrolyser with a capacity of 50KW (1kg/h) (van Medevoort et al., 2022)	Wageningen University & Research, Hydron Energy	Demonstration/research pilot project	Completed

SeaH2Land	Coupled to the Haddock project, SeaH2Land is a vision to create a 1 GW Electrolyser providing hydrogen for the Dutch-Flemish industry on the border of Zeeland and Belgium. The Electrolyser would be powered by a 2 GW wind park on the Dutch coast (SeaH2Land, 2024)	Ørsted, Yara, ArcelorMittal, DOW, Zeeland Refinery, North Sea Port, Smart Delta Resources, Provincie Zeeland, Provincie Oost-Vlaanderen	Commercial scale project	Feasibility studies ongoing
W2H2	Granted in 2016 and finished in 2018 this project worked on a feasibility study in the form of a techno-economic analysis to find the cost reduction that is created for hydrogen if it is combined with offshore wind energy (HYGRO et al., 2018).	TNO, Energy Expo, Energy Valley, Composite Agency, HYGRO	Feasibility study/Concept design	Completed

E | Innovation system actors

The actors in the TIS were identified by integrating the organizations listed in Table 10, the organizations involved in the networks described in Section 5.2.2, and the actors mentioned during interviews.

Table 11: Catagorization of the identified actors in the TIS.

Category	**Actors**
Tech/engineering firm	ABB, AirLiquide, Arcadis, BW Offshore, Bilfinger, Boskalis, Composite Agency, DEME, De Nora, Emerson, Enersea, H2SEA, Hatenboer, Huisman, Hydron Energy, Intecsea, IV, John Cockerill, Mitsubishi, Nel, Plug, Rosetti Marino, Sif, SkyNGR, Stork, Strohm, Subsea7, Technip, ThyssenKrupp, Van Oord, VONK, Worley, XKP, Yokogawa, sHYp, HYGRO, ENERCON, General Electric, McPhy, SwitcH2, Siemens, Twentsche Kabel Fabriek
Energy organization	BP, Dana Petroleum, EBN, EEW Energy from Waste, Eneco, Engie, Equinor, Gasterra, HyCC, NAM, Neptune Energy, one dyas, Ørsted, RWE, Shell, TAQA, Total Energies, Uniper, Wintershall
Academia/research organization	Deltares, Hanzehogeschool Groningen, Hogeschool van Arnhem en Nijmegen, Imperial College London, Investa, ISPT, Marin, Net Zero Technology Centre, Norce, Rijksuniversiteit Groningen, TNO, TU Delft, TU Eindhoven, University of Groningen, University Utrecht, Wageningen University & Research
Consultancy	Bureau Veritas, CE Delft, DMEC, Deloitte, Hinacio, HINT, KCI, Loyens & Loeff, MSG, Peterson, Pondera, Royal Haskoning, DNV
End-users	ArcelorMittal, DOW, OCI, Tata Steel, Yara, Zeeland Refinery
Networking organization or consortium	AquaVentus, Element nl, Energy Valley, Energy Expo, GROW, New Energy Coalition, Offshore Service Facilities, Smart Delta Resources, Smart Port, Topsector Energie, NWEA
Energy infrastructure	Eneginet, Gasunie, Nexstep, Noordgastransport, Tennet, HyNetwork
Port Authority	Groningen Seaports, North Sea Port, Port of Amsterdam, Port of Den Helder, Port of Rotterdam
Government body/agency	Ministry of Economic and Climate Affairs, The Ministry of Agriculture, Nature and Food Quality, Ministry of Infrastructure and Water Management, European Commission, Oil & Gas Authority, Ontwikkelingsbedrijf Noord-Holland Noord, Provincie Groningen, Provincie Oost-Vlaanderen, Provincie Zeeland, RVO, Waddenfonds
NGO's	Stichting de Noordzee, Stichting Natuur & Milieu, Waddenvereniging, Greenpeace, WWF, Vogelbescherming, NEN

F | List of allocated public funding

Table 12: List of public funding assigned to entrepreneurial activities including funding assigned to the networks as listed in section 5.2.2.

Project	Subsidy scheme	Amount of funding	Source
AmpHytrite	TSE	€3.968.952	(TopSector Energy, n.d.)
Curthyl	IPCEI	€141.445.837	(RVO, n.d.)
Djewels	Horizon2020	€10.999.999	(The European Commission, n.d.)
Duwaal	DEI+	€11.801.753	(TopSector Energy, n.d.)
EemsHydrogen	OWE	€124.900.000	(RVO, n.d.)
ELYgator	IPCEI	€150.755.858	(RVO, n.d.)
ELYgator	European Innovation Fund	€99.000.000	(The European Commission, n.d.)
ELYgator	TSE	€161.818	(TopSector Energy, n.d.)
EnergHys	European Innovation Fund	€75.000.000	(The European Commission, n.d.)
FlexH2	TSE	€4.000.000	(TopSector Energy, n.d.)
H2ermes	IPCEI	€14.397.026	(RVO, n.d.)
H2ermes	TSE	€293.735	(TopSector Energy, n.d.)
H2-fifty	IPCEI	€103.006.383	(RVO, n.d.)
H2-Fifty	TSE	€500.000	(TopSector Energy, n.d.)
H2Maasvlakte	TSE	€500.000	(TopSector Energy, n.d.)
Haddock	IPCEI	€110.804.896	(RVO, n.d.)
Holland Hydrogen 1	IPCEI	€150.000.000	(RVO, n.d.)
Holland Hydrogen 1	European Innovation Fund	€89.000.000	(The European Commission, n.d.)
HydroHub Advanced GW Water Electrolyser	TKI	€1.318.773	(TopSector Energy, n.d.)
Hydrohub Megawatt Test Centre Research	TKI	€2.909.885	(TopSector Energy, n.d.)
HyNetherlands	IPCEI	€113.090.000	(RVO, n.d.)
Ijvergas	TSE	€216.053	(TopSector Energy, n.d.)
North Sea Energy	TKI	€6.769.078	(TopSector Energy, n.d.)
North Sea Wind Power Hub	CEF	€13.684.500	(The European Commission, n.d.)
OFFSET	TSE	€3.048.078	(TopSector Energy, n.d.)
Poshydon	DEI+	€3.631.424	(TopSector Energy, n.d.)
Sea2H2	TSE	€397.795	(TopSector Energy, n.d.)
W2H2	TSE	€50.000	(TopSector Energy, n.d.)
Total		**€1.235.651.843**	

G | Assigned score to the system functions by the experts

Table 13 presents the scores assigned to the system functions by various interviewees. In some cases, interviewees assigned multiple grades to a single function, reflecting their evaluation of different components within that function. The table displays the average of these multiple grades.

Table 13: Table presenting the scores assigned to the system functions per interviewee.

Function	**ID1**	**ID2**	**ID3**	**ID4**	**ID5**	**ID6**	**ID7**	**Average**
Entrepreneurial activities	4	3.8	5	3	3.5	4	1.5	3.5
Knowledge development	5	5	3	2	4	3.8	2	3.5
Knowledge diffusion through networks	4	3.5	3	4	5	4	3.5	3.9
Guidance of the search	3	4	2.5	4	4	4.5	2	3.4
Market formation	2	2	2.5	1	5	2	2	2.4
Resource mobilisation	3.7	4	3	2	2.5	3.5	2.1	3.1
Creation of legitimacy / Counteract resistance to change	3	3	4	4	3	4	1	3.1