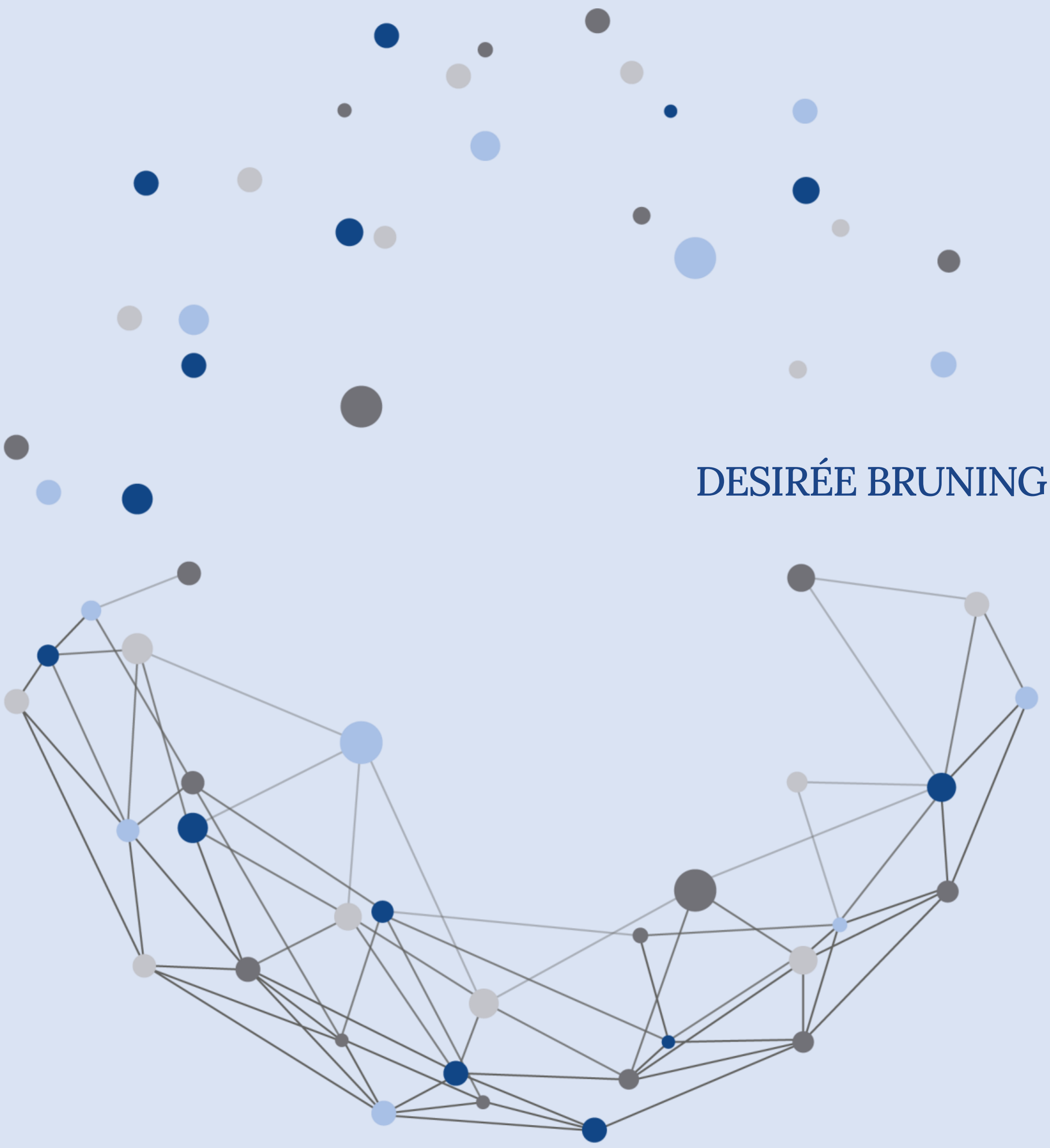
CONNECTING HYDROGEN

Exploring the Formation of Small-scale Hydrogen Networks in the Netherlands



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Connecting Hydrogen

Exploring the Formation of Small-scale Hydrogen Networks in the Netherlands

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"It's worth remembering that it is often the small steps, not the giant leaps, that bring about the most lasting change."

— Queen Elizabeth II, 2019

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Executive Summary

The current Dutch energy system requires a transformation to deal with the increasing issues associated with climate change. In recent years, the focus has been on decentralisation and the emergence of innovative technologies to help facilitate this shift towards a fossil-free future. Hydrogen energy technologies can potentially play an essential role in this future energy system and provide value on all levels of society.

This study focuses on defining one emerging phenomenon in particular: the formation of small-scale hydrogen networks (SHNs). In general, this encompasses a localised system or infrastructure that serves a specific region or community rather than a large-scale national or international network. For example, this can mean a local hydrogen production project with a regional attitude regarding storage, distribution and end-uses.

Amidst large-scale projects and influential actors, smaller endeavours are often overlooked. However, they are paramount for the energy transition to come to fruition. Understanding these unknown socio-technical systems proves to be a challenge as the hydrogen transition is still in its early stages of development. There is limited research regarding the integration of hydrogen on a small scale into our current energy system. How it can enhance the capabilities of the system remains to be explored. The diverse range of technologies, actors, and institutional rules adds another layer of complexity to hydrogen developments, integration, and eventual operationalisation within this framework.

In this thesis, a predominantly qualitative interpretive research approach is used to understand the contextually relevant factors that influence SHN formation. The research follows a problem-focused design science research strategy, which lends itself well to complex challenges with undefined issues. Steps include explicating the problem, defining its requirements and outlining the artefact, which in this case is an SHN. The concept of SHNs is explored by analysing the three pillars (technology, actors and institutional landscape), after which the interrelations of these dimensions are discussed. The case of Goeree-Overflakkee is zoomed in on to aid in outlining the artefact of SHNs within the energy system at large. The objective is to gain insights into the barriers and enablers to be addressed to successfully form SHNs.

The value chain is elaborated upon following the broad categorisation division of upstream (production), midstream (storage and transportation), and downstream (usage or application), according to Ma et al. (2023). For the actor analysis, three steps were conducted based on the stakeholder analysis typology proposed by Reed et al. (2009). It consists of (1) identification and (2) categorisation of stakeholders followed by (3) an analysis of their roles and interrelations. Finally, Williamson's four-layer model was employed to explore what institutional landscape these actors operate in (Williamson, 1998).

The results revealed significant barriers, including regulatory voids, negative business cases, and limited capacities. Navigating complex actor interactions, financial constraints, and a shortage of specialised expertise further impeded progress. Enablers included an innovative organisational culture, synergy creation, and crucial support from local governments. The study underscores the importance of smaller transitional steps, adaptive management, and flexible legal frameworks to facilitate the formation and integration of SHNs within the energy system.

Examining these new socio-technical configurations through the lenses of technology, actors, and the institutional landscape has proven conducive to understanding and identifying SHN enablers and barriers within the Dutch context. The insights are relevant for similar cases across Europe, particularly the North-West. Further research opportunities lie in comprehensive case comparisons of operational SHNs, examining missing institutional rules, agent-based modelling of the effects of legislative procedures, conducting Commercial Readiness Index analyses to evaluate projects, analysing the implications of financial agreements, reviewing subsidy system efficiencies or lack thereof, exploring stakeholder dynamics more deeply, and dissecting ownership and governance structures within SHNs. In-depth analysis and mapping of high-potential areas for SHN formation can further diversify and strengthen the energy landscape.

Acknowledgement

Embarking on this last journey to put an end to the two-year Master program of Industrial Ecology, I finally found solace in a simple yet profound question: “*What would it look like if it were easy?*” This question guided me through the labyrinth of inquiry and discovery that defined this thesis. It gently reminded me that complexity isn't always synonymous with progress, and that sometimes, the most enlightening answers lie in simplicity. In the end, it encouraged me to seek the paths of least resistance amidst the array of challenges that arose, dispelling the notion that difficulty is the sole measure of effort.

This thesis is the result of the last eight months of hard work, but more importantly of collaboration with many wonderful people that helped me to complete this final “sprint”. First and foremost, I would like to thank Sine, Amineh and Mahshid for their guidance and support. I’m grateful for your contributions that have taken my work to the next level and for the warm words of encouragement I needed to hear from time to time.

Second, I would like to thank all interviewees for their time and willingness to share their experiences with me. Your insights were of great value, and although emphasizing the difficulty of the topic, you still tried to help me to the best of your abilities. Your drive and enthusiasm for creating a more sustainable energy future were a true inspiration.

Finally, I am most grateful to my friends and family for their daily support. You have been an incredible source of strength and joy throughout this challenging period. Thank you for unconditionally believing in me and putting up with my most low and stressful moments. I can not express how grateful I am to have you all in my life and for consistently reminding me of what truly matters.

— Desirée Bruning
Delft, October 2023

- Chapter 1 –
Research Introduction

Hydrogens potential and conducive developments are introduced shortly (section 1.1), leading to a discussion of the identified research problem (section 1.2). Additionally, the research objective stating the main research question and sub-questions (section 1.3), the societal relevance of the study (section 1.4), and the thesis outline (section 1.5) are presented.

“We are just at the first chapter of a very thick book we are reading whilst also still writing the rest. “

— Allard Castelein, CEO Port of Rotterdam, 2023
Hydrogen Research & Innovation Day TU Delft

1.1 Background

"Hydrogen Hope or Hype" reads the title of Chapter 17 in the book "The Hydrogen Energy Transition" (Sperling & Cannon, 2004). The authors state that the gas "*is unlikely to succeed on the basis of environmental and energy advantages at least for the foreseeable future*" (p. 236). Now, almost 20 years later, this debate is still ongoing, or more so, has been revitalised (Seethamraju et al., 2023; Vaughan, 2021; Wollschläger, 2020). However, many are optimistic that the attention given to hydrogen is different this time. International organisations such as the International Energy Agency and the International Renewable Energy Agency have acknowledged hydrogen's role as the "*missing link*" or "*missing piece of the puzzle*" in the energy transition towards climate neutrality (IEA, 2018; IRENA, 2022). This renewed discourse and recognition of hydrogens' potential signifies a shift in perception and a re-evaluation of its role in combating climate change.

Addressing the climate crisis is essential for human society. The recently renewed Synthesis Report from the Intergovernmental Panel on Climate Change summarises "*the state of knowledge of climate change, its widespread impacts and risks, and climate change mitigation and adaptation*". Once again, it highlights that global warming, through the emission of greenhouse gases, has undeniably been caused by anthropogenic drivers (Calvin et al., 2023). Nonetheless, demand for energy is still on the rise, calling for decarbonisation efforts at all levels of society: global, national, regional, and local (Ritchie et al., 2022).

The challenges associated with widespread decarbonisation have spurred an increase in the deployment and installation of renewable energy technologies (Seetharaman et al., 2019). Additionally, the Nord Stream-1 gas pipeline closing following Russia's invasion of Ukraine has accelerated a sense of urgency to become more energy-independent and resilient. Especially within Europe, many countries are looking for alternatives to Russian gas and have substantially increased their infrastructure investments in renewables (IEA, 2023; Ivanova, 2023). Moreover, the growing consequences of climate change fuel concerns and conflicts over the availability and distribution of resources in the near future (Sovacool, 2021). Therefore, the European Union has committed itself as a global leader in transitioning from a fossil-based society towards an emission-free economy and to meeting the Paris Agreement objectives of limiting global warming to 1.5 degrees Celsius.

1.2 Research Problem

In the pursuit of a sustainable energy future, harnessing the potential of hydrogen on a smaller scale is a critical consideration. However, creating the necessary preconditions for this endeavour is a complex challenge. This section delves into the analysis of key components required to facilitate the integration of hydrogen technologies, addressing issues surrounding infrastructure, flexibility, and regional adaptation.

1.2.1 Analysis

We need electrolysers as real-time sinks for an oversupplied renewable energy system. Currently, the high-voltage grid in the Netherlands is severely struggling with congestion problems. Issues on the mid-and low voltage grid are also increasing and raising concerns (*Landelijk Actieprogramma Netcongestie*, 2022).

Expanding the electricity infrastructure through traditional means, such as cables and transformers, is costly, requires additional (limited available) space, and takes years to realise on a national scale. Nevertheless, despite this expansion, more than the existing electricity grid will be required to accommodate the necessary increase in the supply of electricity from solar and wind energy sources in the foreseeable future. Moreover, large amounts of electricity are not suitable for long transport (Robinius et al., 2018).

Besides upgrading the infrastructure, alternative solutions include creating flexibility in the demand for energy and exploring energy storage. Batteries are an option, but hydrogen offers advantages over electricity as a more easily storable form of energy on a larger scale and over more extended periods. However, transitioning away from natural gas, which currently provides significant flexibility, raises concerns about replacing that flexibility effectively (Crotogino, 2022; Elberry et al., 2021).

At the local and regional levels, initiatives are being undertaken to integrate local generation with hydrogen production, storage, and use. Hydrogen is not a goal in itself but rather a means to attain a CO_2-free society. This approach could address congestion issues in the electricity network, increase flexibility in the transportation and distribution of energy, and expand opportunities for integrating locally and regionally produced renewable energy.

However, we need a lot more elements to get there. These developments must be created simultaneously, especially within the scattered ownership of the hydrogen value chain. Between supply, infrastructure and demand, multiple chicken-egg problems are present. Investments require a certain amount of security, such as procuring future demand and implementing non-obstructive regulations. Innovating in uncertain times is a risk not many are willing to take the lead in.

On a large scale, the priorities are more apparent. However, a case-by-case format is required in the regions based on local factors, barriers and opportunities. Questions about scale arise: What do you do locally, what regionally and what nationally? What are the alternatives and best choices? As highlighted by Devine-Wright (2017), deep-rooted beliefs regarding the advantages of large-scale, centralised infrastructures could influence policymakers' perspectives on the feasible technological paths for hydrogen. This inclination may lead to a preference for policies that align with extensive deployments at the national level, potentially overlooking the potential benefits of smaller-scale solutions. Additionally, we are dealing with an overall capacity problem in knowledge and skills.

The Gartner Hype Cycles (Figure 1) provides a framework to understand the typical trajectory of emerging technologies like hydrogen, capturing the initial hype, subsequent challenges, and the eventual realisation of their potential. It can be argued that we are just about to start the Slope of Enlightenment. We are aware of the practical implementations, infrastructure requirements, and cost-effectiveness obstacles we face. However, hydrogen integration gradually progresses with further advancements, increased investments, and pilot projects providing feedback from reality. Practical use cases, technological improvements, and successful step-by-step deployment become more evident.

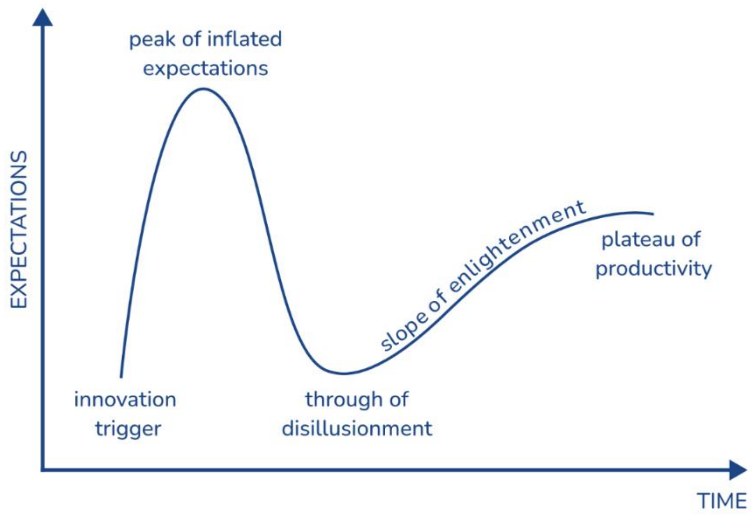

Figure 1 - The Gartner Hype Cycle framework

A Short Definition of SHN

The scale of a small-scale hydrogen network (SHN) can vary. When discussing decentralised energy systems, often micro (e.g. within a building) or meso (e.g. within a city) are referred to (Devine-Wright, 2019). This thesis defines small-scale as a localised system or infrastructure that serves a specific region or community rather than a large-scale national or international network. E.g. this can mean a local hydrogen production project with a regional attitude regarding storage, distribution and end-uses. This depends on the exact scale of resources, relations and expertise available in the specific area. Additionally, participatory and economic elements are significant features of these networks to turn a negative business case into a positive one, meaning they play a crucial role in converting what might initially be perceived as a challenging business proposition into a financially viable and socially beneficial venture (Heldeweg & Séverine Saintier, 2020).

Time will tell whether hydrogen in smaller-scale operational networks languishes in the "*trough of disillusionment*" because other energy transition pathways and technologies prove to be more cost-effective. Or whether it climbs to the "*plateau of productivity*" as hydrogen becomes the flexible fuel of the future energy system on all levels of society.

1.2.2 Knowledge Gap

Hydrogen networks are just at the initial stages of formation. How they successfully operate and practically benefit society on a small scale remains unknown.

Existing literature on hydrogen has mainly concentrated on technical and natural science aspects. They mainly focus on narrow technological affairs, and although gaining traction, its practical integration into energy systems remains little studied (Yue, 2021). Furthermore, less attention is paid to regulatory and policy considerations. Recent developments indicate a shift towards international and national plans and the establishment of technical standards and certifications (Machado, 2022). Nevertheless, there is a dearth of research exploring the formation and operationalisation of small-scale hydrogen networks.

The recent rise in publications and reports on hydrogen-related developments also highlights this "pre-formation" stage (IRENA, 2021). The majority of projects and collaborations are just starting up. In doing so, no "right way" of formation can be derived yet (e.g. comparing a successful implementation versus a non-successful one). How to mediate processes of change between scales (e.g. national-local) is understudied. In other words, unfolding hydrogens' potential would require a coordinated effort across multiple diverse actors in a competitive and fragmented energy sector basking in future uncertainty. More specifically, different energy consumption profiles, distribution options, social preferences, and technical functionalities make the implementation of hydrogen very complex.

We need to better understand the challenges or opportunities this poses for smaller-scale initiatives on the road to forming small-scale hydrogen networks. It can be concluded that current literature is lacking a systemic understanding of this concept.

1.3 Research Objective

In line with the knowledge gap stated above, the main research question is:

What are the barriers and enablers of small-scale hydrogen networks in the Netherlands?

The scope of the research is limited to the decentral developments of small-scale hydrogen networks (SHNs) in the Dutch context. The process of formation is in its infancy and subsequent long-term functioning of SHNs has yet to be determined. Therefore answering the main research question can give key insights into the conditions to be addressed for the successful establishment of such small-scale hydrogen networks and aims to provide clues on how to sustain them in the future.

These network infrastructures are socio-technical systems that deal with dual coordination issues (Künneke, 2018). The predominant focus in the literature on these socio-technical transitions has been on highlighting the interdependent relationship between institutions and technologies (Groenewegen et al., 2021). Recently social science studies are increasingly highlighting the integration of involved actors and their (mediating) roles. In their study on transformations in the Australian urban water sector, Fuenfschilling & Truffer (2016) assess the importance of agency processes in social-technical systems. They highlight the interplay between institutions, actors and technologies.

Similarly, Goulet (2021) analyses the alignment mechanisms involved in socio-technical transitions with a case study on biological alternatives to agricultural pesticides in Brazil. They present three pairing processes for successful *alignments* during this transition: a pairing between existing and future technologies, a pairing between potential users and converging issues the alternative can address, and organisational pairings between public and private organisations. Moreover, Elzen et al. (2012) proposed the concept of *anchoring* (vulnerable connections) as a stepping stone towards the formation of future (more robust and durable) links in a network. They identified three types in their study on the transition process of alternative energy approaches in the Dutch glasshouse horticulture sector: technological, actor network and institutional anchoring.

To answer the main research questions, the following sub-questions have been formulated to elaborate on the concept of small-scale hydrogen networks. They are based on the dynamic interplay of the above-identified three pillars (technological innovation, actors and institutions) that form new social-technical configurations.

1. What would be the technical specifications, the limitations, and potential applications of an SHN?
2. Who would be the actors involved and what are their objectives, potential roles and interrelations in an SHN?
3. What is the current institutional landscape that may shape or hinder the emergence and subsequent functioning of an SHN?
4. What are the interrelations of these three dimensions – technologies, actors, institutions – within SHN formation?

1.4 Societal Relevance

The research aimed to explore the formation of small-scale hydrogen networks in the Netherlands, which is a parallel development to incorporating green hydrogen into our energy systems. Developments in this area are interesting because the energy sector is undergoing a transformation and re-design process, posing opportunities for emerging technologies, such as hydrogen energy technologies.

Since hydrogen as an energy carrier is exceptionally versatile, it is seen as a possible medium to offer sustainable solutions to the wicked problems that need to be addressed in the current and future energy system (Griffiths et al., 2021; Martin et al., 2020). However, the integration of hydrogen poses several socio-technical and environmental challenges.

This research contributes to the current literature on energy systems integration, process management and policy/design implications related to the hydrogen discussion on a local/regional scale. It sheds light on why, when, and in what form hydrogen is a (good) option to enhance the energy ecosystem.

Accordingly, this topic seems applicable in the field of Industrial Ecology. This scientific discipline has been defined by the International Society for Industrial Ecology (n.d.). as "*the study of systemic relationships between society, the economy, and the natural environment. It focuses on the use of technology to reduce environmental impacts and reconcile human development with environmental stewardship while recognising the importance of socioeconomic factors in achieving these goals*."

The complexity of the formation of a hydrogen network is evident due to its dependence on other systems, e.g. the (renewable) energy market, infrastructure developments, and community initiatives. While at the same time, it can help make other systems redundant, e.g. the fossil fuel-based industry and centralised power plants. It becomes a system of systems for which Industrial Ecology provides a perspective or lens that goes beyond the dominant technical aspect of this energy transition.

Therefore, this thesis's contribution is a combined social, techno-economic, and institutional approach that can give insights into key areas to help push forward policy and system design for the formation of a hydrogen network. All in all, in the effort to show how the use of green hydrogen has the potential to significantly contribute to the Dutch transition towards renewable energy sources, assist in decarbonisation efforts, and help ensure a stable and reliable energy supply to society as a whole.

1.5 Thesis Outline

This thesis embarks on an exploratory journey into the formation of SHNs in the Netherlands, addressing a critical juncture in the country's energy transition. Chapter 1 sets the stage with a concise Research Introduction, delving into the background of the SHN phenomenon and identifying the research problem, knowledge gap and underscoring the societal relevance of the study. The subsequent chapters form the analytical backbone of the thesis. Chapter 2 delves into the Literature Background, providing a foundation for understanding SHNs within the broader energy landscape. Chapter 3 reports on the Research Approach & Methods, outlining the chosen approach and justifying the selection of the case study. This chapter also details the methods employed for data collection and analysis, including primary interviews and secondary desk research. In Chapter 4, a Conceptual Overview of Small-scale Hydrogen Networks in the Netherlands is presented, offering a comprehensive definition and dissecting the various elements of SHNs, from technical exploration, to an actor analysis, to institutional exploration. Chapter 5 dives into the Goeree Overflakkee case, providing an analysis of this particular region's SHN developments and discussing factors specific to the broader Dutch context. Finally, Chapter 6 synthesizes the thesis' main findings, discussing the broader implications of SHNs beyond the case study, and offering practical recommendations. Acknowledging its limitations, the thesis concludes by highlighting avenues for further research in this dynamic and evolving field.

- Chapter 2 -
Literature Background

This chapter provides a general overview of the international-scale to smaller-scale developments of the current energy landscape. Hydrogen developments, the concept of small-scale hydrogen networks and their potential are elaborated upon.

"Stability, in any form, is an illusion. It's an illusion that we actively cultivate and desperately hold onto, but an illusion nonetheless. "

— Chris Cow, 2016

2.1 Multi-level Hydrogen Developments

This section delves into the intricate landscape of multi-level hydrogen developments, examining the interplay between European policies and national measures, while also highlighting the evolving role of smaller-scale initiatives in this dynamic transition.

2.1.1 European Action

The European Green Deal established in 2019 provides a tangible roadmap to living up to the ambition of becoming the first climate-neutral continent (European Commission, 2019). Moreover, its goals have been laid down in the European Climate Law, binding the objectives legally (European Commission, 2021a). Europe's current energy policy agenda also stresses the importance of "*energy system integration*" (Figure 2), as presented in their strategy report in 2020 (European Commission, 2020). This report lays the foundation for transforming the fossil-fuel-based centralised energy system to a more decentralised energy system based on flexibility and efficiency. In synergy with this, the "*EU strategy on hydrogen*" was adopted simultaneously (European Commission, 2020). It is seen as a key priority to develop renewable and low-carbon fuels, such as hydrogen, in addition to renewable electrification and to reach a more circular energy system with resource efficiency at its centre.

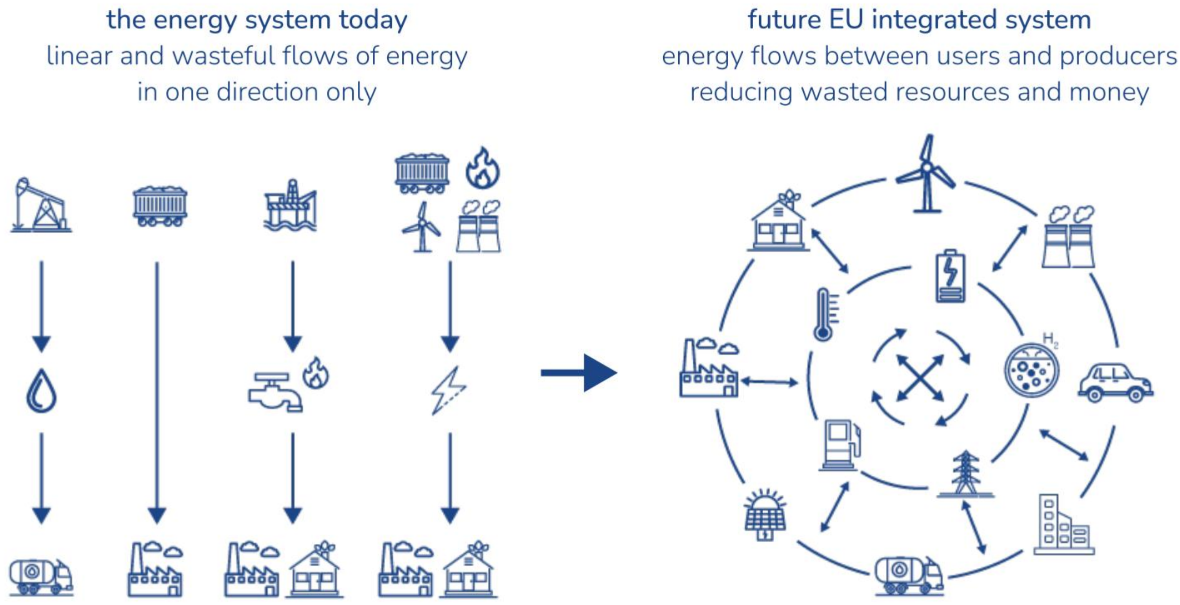

Figure 2 - System integration, figure adapted from (European Commission, 2020b)

Subsequently, the Fit for 55 packages, referring to the EU's target to reduce greenhouse gas emissions by 55% by 2030 compared to 1990 levels, aim to align, revise and update legislation to reach these obligations (European Council, 2021). One of these packages is the "*Hydrogen and decarbonised gas market*" package, which includes two proposals the European Council agreed upon in March 2023 (European Council, 2023b). One on regulations and one on directives, aiming to create a regulatory framework to set standard internal market rules for hydrogen and renewable gases and create a dedicated infrastructure (European Council, 2023a).

International Research

Alongside these developments, international-focused studies have been conducted on the (re-)start of this hydrogen economy in Europe (Dou et al., 2023; Falcone et al., 2021; Genovese et al., 2023; Van Der Spek et al., 2022); on the progress and outlooks of hydrogen energy systems (Parra et al., 2019; Yue et al., 2021), on optimisations and changes needed in renewable energy systems to include electricity-based hydrogen (Egeland-Eriksen et al., 2021; Khan et al., 2022), on the decarbonisation of hydrogen production in line with the EU's vision (Kakoulaki et al., 2021; Lux & Pfluger, 2020) and on the increasingly important role of energy storage (Victoria et al., 2019; Zsiborács et al., 2019). Research on this scale is valuable in understanding the broader perspective of the energy transition, including factors such as cross-border trade, geopolitical factors, international standards or investment flows (Lebrouhi et al., 2022; Van de Graaf et al., 2020).

2.1.2 National Measures

Nonetheless, the majority of research has concentrated on the national level. These national case studies contribute to the broader understanding of the energy transition by providing insights into different countries' unique contexts and circumstances. Such as sector coupling options in Germany (Gils et al., 2021), prospects of hydrogen-based transportation in Denmark (Apostolou & Welcher, 2021) or supply chain infrastructure pathways in France (Tlili et al., 2020). Despite this, the interconnectedness of the energy system and, subsequently, common European drivers can still be derived from national case studies, as a study by Reigstad et al. (2022) highlights.

In line with this, nearly all European Union (EU) member states have included hydrogen in their 2030 National Energy and Climate Plans (NECPs), which serve as mandatory frameworks for outlining energy and climate policies (Wolf & Zander, 2021). Complementary, the majority have issued their own national hydrogen plans or strategies by now. However, there are differences in the scale, ambition, and sophistication of these plans (Machado et al., 2022).

Dutch Efforts

The Netherlands is one of the countries aiming high in the field of hydrogen. After discovering natural gas reserves over 60 years ago and developing one of the world's most extensive and sophisticated gas grids, hydrogen is dubbed the "*second gas revolution*" (RVO et al., 2021). The Dutch government announced a billion-euro investment into this re-emerging technology (EZK 2022; Gasunie, 2021). As the global interest in hydrogen energy technologies is gaining momentum, huge market potential lies in being a frontrunner in this field (Van de Graaf et al., 2020). Currently, the Dutch are already the second-largest producer of hydrogen in Europe after Germany (RVO et al., 2021). However, this hydrogen is "*fossil-based*" or "*grey*": around 10% of Dutch natural gas is utilised for hydrogen production, resulting in notable CO_2 emissions (EZK, 2020).

As stated in the Dutch National Climate Agreement "*het Klimaatakkoord*" (2019), the objective is to transition to green "*carbon-free*" hydrogen production as much as is feasible in the short term. However, in the process of developing this system, the use of blue "*low-CO2*" hydrogen can be employed. Nonetheless, the Agreement clarifies that ambitious targets for hydrogen are set and supported by many stakeholders in varying sectors. Reasons for this are, e.g. the current and potential uses of hydrogen in the extensive processing industry; the geographical advantages of the Netherlands as a central hub in Northwest Europe, including the various large ports available for trade and transport; its knowledge and expertise with gas infrastructure, and the significant potential to link production with (upcoming) offshore wind energy in the North Sea (*Climate Agreement*, 2019).

In line with this, the government put out a "*government strategy on hydrogen*" (EZK, 2020). As previously mentioned in the Climate Agreement, the hydrogen program will focus on "*unlocking the supply of green hydrogen, the development of the necessary infrastructure and collaboration with various sectoral programmes, as well as the facilitation of ongoing initiatives and projects*" (p.181). This "*Nationaal Waterstof Programma*" (NWP) aims to contribute to reaching the goals of 500 MW of electrolyser capacity by 2025 and at least 3-4 GW in 2030[1] (*Nationaal Waterstof Programma*, n.d.). The first outline of a national plan for a new Dutch energy system, "*Nationaal plan energiesysteem*" (NPE), has been drafted alongside these objectives. The final plan will be presented at the end of 2023 (NPE, 2021).

Similarly, Gasunie, TenneT, and regional grid operators are collaborating on the second version of the Integrated Infrastructure Outlook "*Integrale infrastructuurverkenning*" 2030-2050 (II3050). This initiative aims to clarify the choices that need to be made for a resilient and climate-neutral energy system in 2050 to become a reality (Den Ouden et al., 2020). In April this year, they published an intermediate report on four different future scenarios explaining societal considerations and underlying choices. The final edition will also be published at the end of 2023. In short, these scenario alternatives are Decentral Initiatives, National Leadership, European Integration and International Trade as presented in Figure 3 (Netbeheer Nederland, 2023).

[1] This target was recently doubled to 6-8 MW of electrolyser capacity (Losson, 2022)

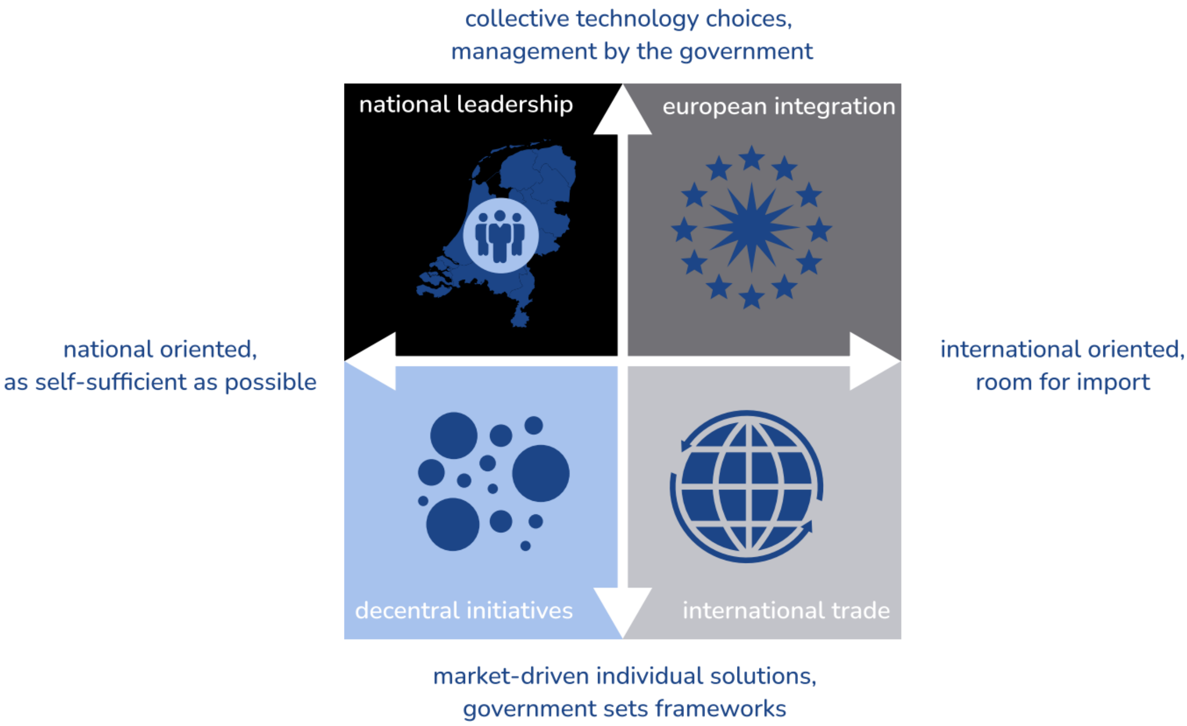

Figure 3 - Visual of the scenario alternatives adapted from Netbeheer Nederland (2023)

2.1.3 Hydrogen Integration

The four scenarios emphasize differences in scale sizes and steering during the transformation of the energy system (Netbeheer Nederland, 2023). The gas, electricity and heat networks must be overhauled to reach a more integrated system. As an energy carrier, these trajectories are equally relevant to hydrogen developments. The National Hydrogen Program also distinguishes in scale: between large-scale developments for the industry clusters and harbours and smaller-scale development at a decentral level in the regions (CSWW, 2021). The differences in speed of development, impact and visibility are discussed. However, in practice, these developments will be interrelated, influenced and reinforced by each other. Namely, the energy infrastructure is at the basis of transformations of all sectors: industry, mobility, built environment and agriculture (Netbeheer Nederland, 2023).

As mentioned above, large-scale developments are taking place. Gasunie will connect all five industrial clusters via a national hydrogen network, "*the hydrogen backbone*" (Figure 4), largely reusing existing pipelines (Gasunie, n.d.-b). Complementary hydrogen storage facilities, production locations and infrastructure to neighbouring countries to form a European hydrogen network will be realised (Tezel & Hensgens, 2021). One of the drivers is a target set by the EU to ensure that 50% of all hydrogen used in the industry is green by 2030. However, the demand for green hydrogen is expected to exceed its production capacities (Leguijt et al., 2022). In the Netherlands, several medium-sized to large-scale production projects are being set up in response: Cuthyl (200MW), Holland Hydrogen (200MW), H2era (500MW), H2ermes (100MW), HyNetherlands (100MW), SeaH2Land (1GW), VoltH2

(25MW-100MW 3x), and H2opZee (300-500 MW). In addition, a subsidiary of Gasunie, Hystock, is building up experience with hydrogen storage in underground salt caverns and depleted fields, most currently in use for natural gas. This storage will play an essential role in contributing to the future energy systems' changing demands concerning stability, flexibility and adequacy (security of supply) (Groenenberg et al., 2020).

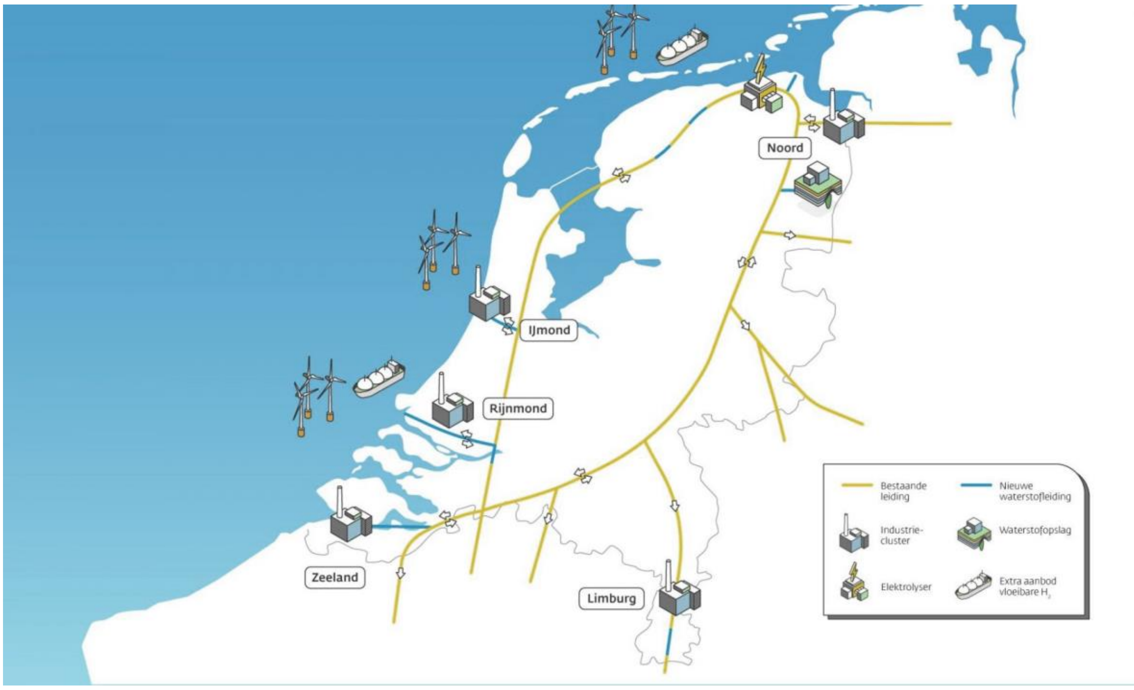

Figure 4 - The national hydrogen backbone plan as presented by Gasunie (2021)

One of the main origins of this need for flexibility is the previously emphasised increase in intermittent renewable energy sources. The Dutch government has even set a target of reaching 35TWh of renewable energy sources by 2030 (*Climate Agreement*, 2019). A national plan of regional energy strategies, "*Regionale Energie Strategie*" (RES), covering 30 regions (Figure 5), is rolled out to set in motion the realisation of these and several other goals in the Climate Agreement. In RES 1.0, the regions investigated the possibilities and shared choices to be made on electricity, heat and (green) gas (NPRES, 2021). Every two years, a progress document will be shared; RES 2.0 has been released July 2023.

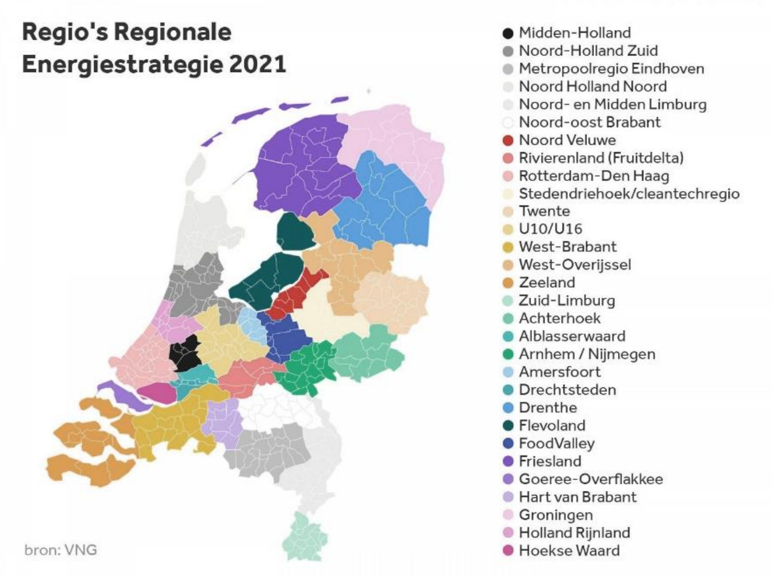

Figure 5 - The 30 RES regions in the Netherlands

An important aspect is using, e.g. locally generated electricity locally as well. In this process, the Dutch Climate Agreement states that we must strive for 50% local ownership. The key reason is that local participation is essential to ensure the success of these energy projects as the RESs deal with subjects that significantly impact our living environment.

2.1.4 Smaller-scale Steps

Amidst the backdrop of capitalistic projects, the significance of smaller-scale action cannot be overstated (Kirkegaard et al., 2023). As such, the concept of local participation is nothing new for the many energy cooperations in the Netherlands, helping the transition to a more decentralised and just energy system. More local collective action in the form of different types of energy initiatives has received increased attention in facilitating this shift (Hasanov & Zuidema, 2022). As outlined by Koirala et al. (2016), examples include microgrids, virtual power plants, energy hubs, prosumer community groups and (integrated) community energy systems. The Netherlands alone counts almost 700 initiatives in the form of energy cooperatives comprising 120,000 members (Schwenck, 2022).

Cooperatives are "*autonomous associations of persons united voluntarily to meet their common economic, social, and cultural needs and aspiration through a jointly owned and democratically-controlled enterprise*" (Hentschel et al., 2018). Energy cooperatives can be classified according to several purposes; the largest share, about 75%, works towards an integrated approach of producing and selling energy together (Schwenck, 2022; Yildiz et al., 2015). Their emergence is strongly motivated by environmental concerns, increasing energy security, and building resiliency to unforeseen circumstances (Hicks & Ison, 2018). National and even Europe-wide subsidies have supported the development of these initially small-scale energy projects, e.g. by helping with initial costs or priority access to the grid (Koirala et al., 2016). Additionally," *The European Green Deal*" and the "*Clean Energy for All Europeans*" package emphasises the need for empowering such energy communities (European Commission, 2019).

Energy Communities

"*Energy communities*" is the umbrella term most commonly used in literature (Gregg et al., 2020). The EU distinguishes between *renewable* and *citizen* energy communities. However, the evolving nature of the concept has led to diverse interpretations and a variety of compound terms used to capture the different aspects and contexts (Blasch et al., 2021). These include, e.g. "*local*" (Bartolini et al., 2020; Otamendi-Irizar et al., 2022), "*sustainable*" (Romero-Rubio & de Andrés Díaz, 2015), "*net-zero*" (Liu et al., 2021; Ullah et al., 2021), "*clean*" (Gui & MacGill, 2018; Mazzeo et al., 2021), "*integrated*" (Abdalla et al., 2021), or "*virtual*" energy communities (Divshali et al., 2020; Plewnia & Guenther, 2021). Additionally, a framework developed by Walker & Devine-Wright (2008) and adapted by Candelise & Ruggieri (2017) provides a structured way to understand the variation of energy communities across a process dimension, i.e. "*which actors the project is developed and run by*" and outcome dimension, i.e. "*who the project is for and benefits in economic and social terms*" (Figure 6).

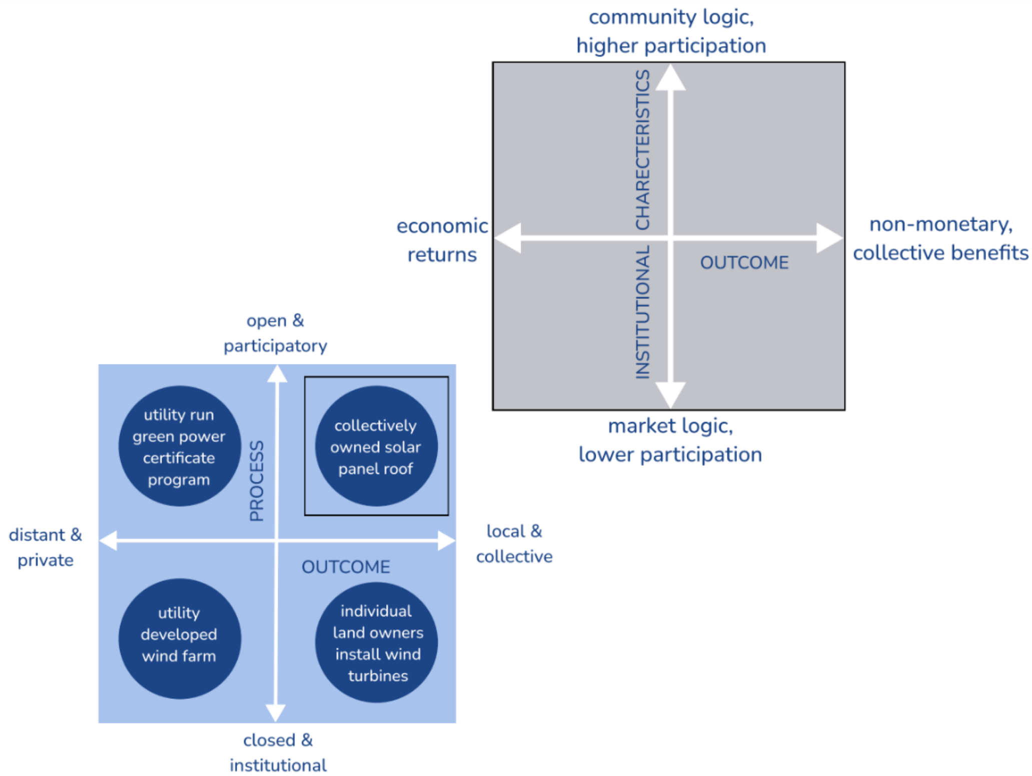

Figure 6 - The community energy framework adapted from Walker and Devine-Wright (2008) and Candelise and Ruggieri (2017)

2.1.5 Scale Interrelations

As the energy landscape changes and the complexity of the task becomes ever more evident, so is the importance of considering the different actors involved as well. Community energy initiatives often prioritise the local community's interests and context while recognising the importance of engaging with the larger energy system and seeking opportunities for collaboration and knowledge-sharing beyond their immediate boundaries (Devine-Wright, 2019). Until now, most initiatives focused on collective solar and wind power (Akerboom & Van Tulder, 2019; Schwenck, 2022), and studies on these renewable electricity sources highly dominate literature. However, there are limits to their growth and innovation is needed in the context of our current climate and energy crisis. As such, experimenting with and deploying geothermal or district heating, hydro-power, energy storage (e.g. batteries), and hydrogen has been gaining attention in recent years.

The Emergence of Large-scale Scattered Developments and Partnerships

This increase in complexity beyond the capabilities of these initiatives, in terms of capital, technical knowledge and entrepreneurial skills, has spurred an increase in (institutional) partnerships, company-led investments or other consortiums or coalition-like arrangements that often collaborate across sectors (Devine-Wright, 2019). Eitan et al. (2019) identified that these partnerships cooperate at governmental, private, or community levels to engage in experimentation and deployment. However, the study stresses that local community-private sector partnerships have received little academic attention, although having been identified as critical drivers of the energy transition towards a low-carbon society. Blasch et al. (2021) agree that there still needs to be a more comprehensive understanding of the types of actors involved and their respective roles in these varying configurations.

Hydrogen Developments in the Netherlands

Hydrogen development projects in the Netherlands are clearly characterised by these cross-sectoral and multi-level partnerships ranging from the supply side to the demand side and involving the public and private sectors, communities, and civil society. As hydrogen's value chain can be divided into upstream (production), midstream (storage and transportation), and downstream (usage or application), it becomes a multi-actor and multi-system undertaking (Ma et al., 2023). A network connects these different systems' interconnected components or parts into an interconnected entity. As a result, large-scale but also smaller-scale hydrogen networks can emerge (Figure 7).

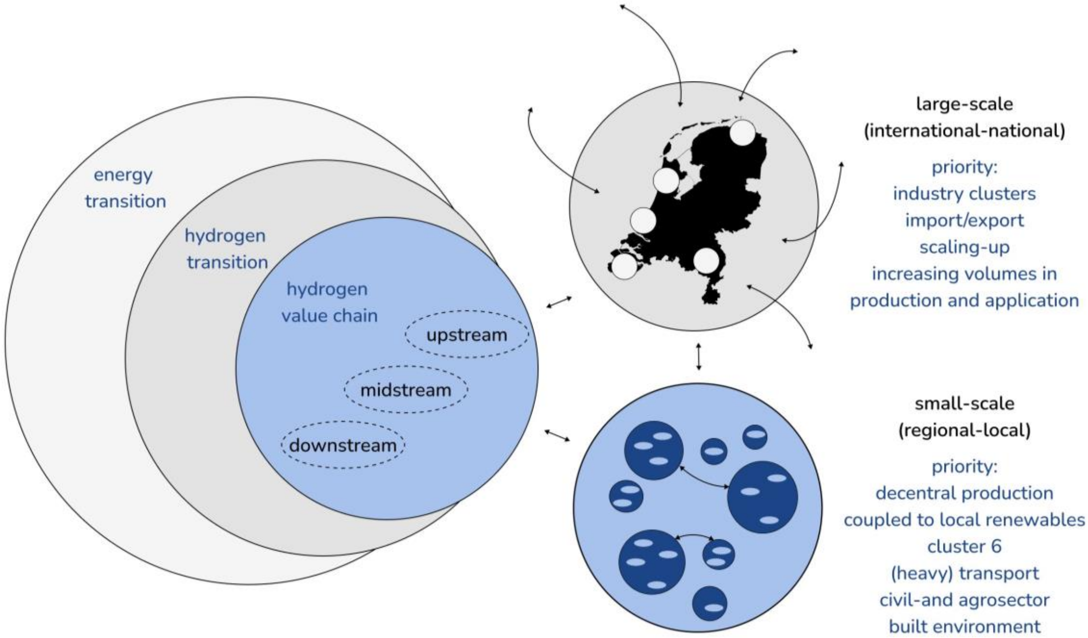

Figure 7 - A distinction in focus between large-scale and small-scale hydrogen developments

As smaller-scale energy systems gain prominence in energy transitions, we need to expand from having a central, large-scale, and electricity-dominated focus towards defining, characterising and understanding alternatives such as these smaller-scale hydrogen networks.

- Chapter 3 -
Research Approach & Methods

This chapter details the research design approach (section 3.1), followed by a discussion of the data collection methods (section 3.2). The final section (3.3) elaborates on the methods and frameworks used to scope and streamline data analysis.

"To make your unknown known – that's the important thing. "

— Georgia O'Keeffe, 1923

3.1 Research Approach

This research bases itself on an interpretive research approach. This allows for pre-dominantly qualitative data collection that aids in uncovering contextually relevant beliefs that influence the socio-technical transition. This approach "*is based on the assumption that social reality is not singular or objective, but is rather shaped by human experiences and social contexts, and is therefore best studied within its socio-historic context by reconciling the subjective interpretations of its various participants*" (Bhattacherjee, 2012, p.104). As Scovell (2022) pointed out, these might be overlooked when starting from a pre-defined framework or a positivist approach: one that starts with hypotheses formulation, testing and drawing conclusions from the empirical data. This approach might fail to generate interesting insights or new knowledge.

However, to structure the process, this research predominantly follows a problem-focused design science research strategy (Figure 8). This research paradigm is increasingly acknowledged for its potential to aid innovation processes and contribute to transformations towards a more sustainable society. This approach lends itself well to explorative research into complex challenges with undefined issues. A brief explanation of the stages to arrive at answering the main research questions can be found in Table 1, following the Method Framework for Design Science Research developed by (Johannesson & Perjons, 2014).

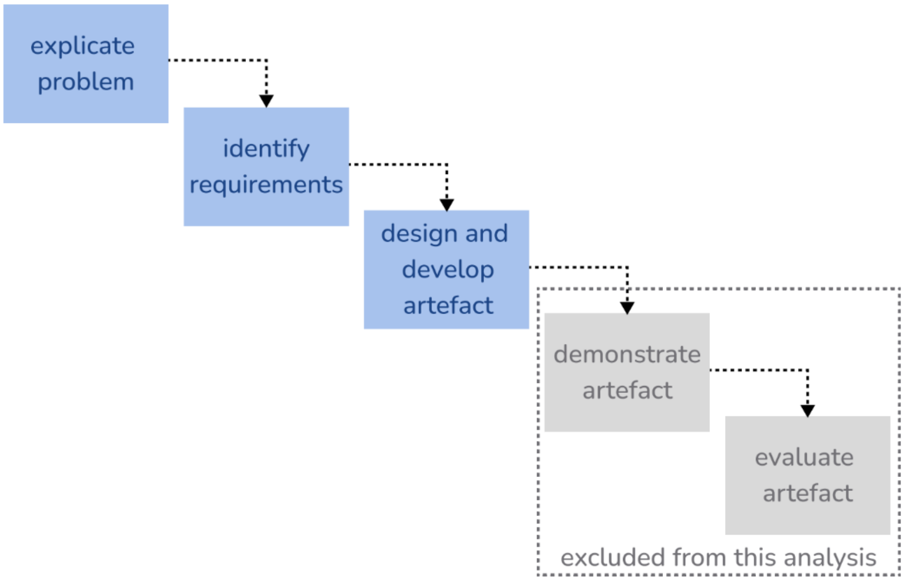

Figure 8 - Stages of the design science process, adapted from Johannesson & Perjons (2014)

Tabel 1 - Explanation of research steps according to the Method Framework for Design Science Research

Stage	Explanation	Section
Explicate problem	The initial challenge is to be investigated. In this case, the recognition of hydrogen's potential and the re-evaluation of its role in combating climate change and contributing to a more sustainable society on all levels. The key is to maintain a broad scope before zooming into the problem of interest and showing its significance within the bigger context. This research aims to establish insights into the deliberation of forming small-scale hydrogen networks.	Chapter 1 & 2 Primary & secondary data analysis
Define requirements	Important aspects of the socio-technical setting need to be defined. These are based on the interplay of the three pillars: technology, actors and institutions that constitute these dynamic configurations. This will form the basis of the innovation space to address the transformations necessary.	Chapter 4 Addressing the sub-questions
Design and develop artefact	In this stage an artefact is created that addresses the explicated problem and fulfils the requirements to establish it within the socio-technical setting. Within the context of this thesis, an artefact is not purely material, but the entirety of the concept of a small-scale hydrogen network is considered the artefact (see figure 9). These socio-technical systems "*have been purposely designed to address a practical problem or enable some human endeavour. However, they are, at the same time, emergent phenomena that evolve due to spontaneous and unforeseen interactions among the humans in the systems.*" (Johannesson & Perjons, 2014, p.12)	As this research is problem-focused and SHNs are not yet operational: "*The design of the artefact is only outlined, and neither demonstration nor evaluation is carried out. Projects of this kind often have a strong social science flavour, and the design element is downplayed. However, they can provide essential understanding of a problem, upon which subsequent design science projects can build.*" (Johannesson & Perjons, 2014, p.79) Chapter 5 Zooming in on developments
Demonstrate artefact	Out of scope / To be determined	Future studies
Evaluate artefact	Out of scope / To be determined	Future studies

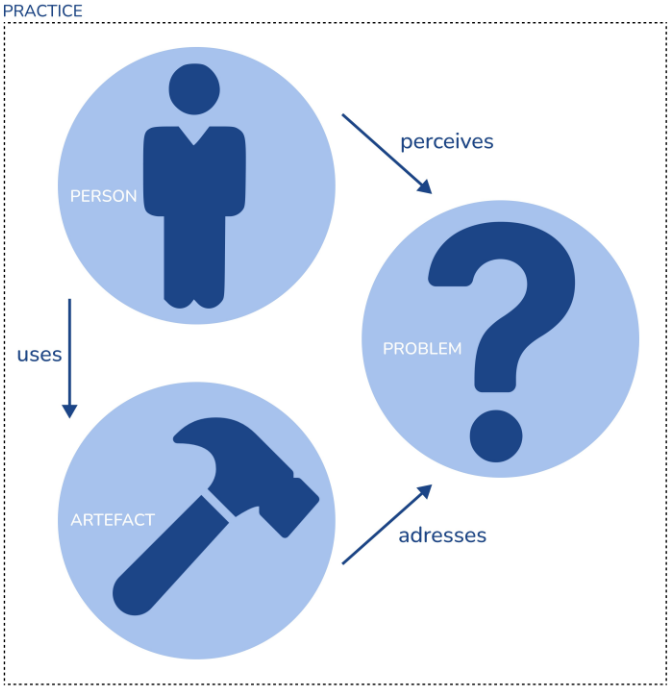

Figure 9 - Simple example of the relation in practice, adapted from Johannesson & Perjons (2014)

3.1.1 Case Study

As mentioned in the literature background, national case studies are essential to contribute to the broader understanding of the energy transition by providing insights into different countries' unique contexts and circumstances. Within the leading developments in Europe, the Netherlands has been chosen to be analysed for several reasons. First, because of its high ambitions regarding hydrogen developments. Moreover, it is one of the countries with the largest number of energy communities, representing the smaller-scale focus of this thesis. In addition, the evident limits of the current Dutch system pressure the exploration of alternatives and innovative solutions.

However, due to the infancy of the transition and the lack of practical applications in the Netherlands of small-scale hydrogen networks, a choice was made to employ a theoretical sampling strategy and subsequently zoom in on one particular case. Goeree-Overflakkee was found to fit the nature and purpose of the study. This case is one of the earliest initiatives and furthest in their development of *ideas* infrastructure-wise and scale-integration-wise (local-regional-national connection) and can thus provide a potentially good starting point in outlining the artefact of small-scale hydrogen networks within the energy system at large.

The case study serves a dual purpose: to serve as an illustrative example and to offer practical insights into the integration of hydrogen. It also aims to provide an empirical understanding of the factors that either hinder or facilitate the formation of a small-scale hydrogen network. The choice of a case study is particularly advantageous in situations where there is a need to comprehend the intricacies of a complex phenomenon by addressing questions related to "how," "what," and "why" (Gamme et al., 2020).

3.2 Data Collection Methods

This section delineates the methodologies employed for data collection in this research, encompassing both primary and secondary approaches to construct a robust and well-rounded analysis of the formation of small-scale hydrogen networks.

3.2.1 Primary Data Collection - Interviews

The primary data collection for this study involved semi-structured interviews with individuals selected for their pivotal roles in (hydrogen-related) innovation projects and their capacity to challenge prevailing norms within the energy transition landscape. This included interviewees mainly holding positions such as program managers, directors or in business development. See Tables 2 and 3 for a complete overview. Additionally, participants were selected from a spectrum of experience levels, encompassing both seasoned professionals deeply entrenched in the energy transition and individuals newly embarked on this transformative journey. This diversity ensured a rich array of perspectives, ranging from those immersed in established practices to fresh insights unencumbered by convention. Moreover, the regional and local scales were represented to a greater extent, which can be expected given the nature of this research.

Qualitative interviews are commonly employed in exploratory studies aiming to understand complex contexts or areas in which issues are not yet well defined (Bullock, 2016). The interviews were conducted using a semi-structured approach, allowing for a nuanced exploration of specific topics while affording room for open discussion (Adams, 2015). The semi-structured format strikes a balance between predefined questions and the flexibility to delve deeper into emerging themes (Adeoye-Olatunde & Olenik, 2021). Individual online interviews using Teams were conducted to enhance convenience and scheduling flexibility, ensuring that each participant's perspectives were gathered independently. This approach also provided a neutral environment for respondents, potentially fostering more open responses (Gray et al., 2020). Additionally, a recording of the interview was generated, complemented by an automated transcript to streamline the subsequent analysis process. The interviews were held in Dutch and took between 30 minutes and 1 hour on average. This language choice was based on the fact that both the interviewer and the interviewees were primarily fluent in Dutch.

Out of the twelve interviewees, eight were, to differing extents, directly involved in the case study, bringing insider's perspective to the discussions. The interviews were strategically divided into two rounds. The initial round comprised eight sessions conducted during April and May, offering a comprehensive foundation of insights. Subsequently, a second round of interviews took place in August, involving four additional participants, providing additional in-depth insights. For further reference, the interview guidelines can be found in Appendix I & II. These comprehensive guidelines were instrumental in structuring the interviews and ensuring consistent coverage of key topics essential to gaining insights into the dynamic landscape of hydrogen integration in the Netherlands and the potential formation of small-scale hydrogen networks, as this is one of the main research gaps in the literature.

Tabel 2 - First round of interviews overview

Number	Description	Date
1	Energy transition specialist	04-2023
2	CEO energy cooperation advocacy organisation	04-2023
3	Project developer energy cooperation	04-2023
4	Director energy cooperation	04-2023
5	Program manager energy transition	04-2023
6	Business developer energy systems grid operator	05-2023
7	Program manager energy cooperation	05-2023
8	Senior new energy developer energy service company	05-2023

Tabel 3 - Second round of interviews overview

Number	Description	Date
9	Business development specialist innovation company	08-2023
10	Energy transition analyst grid operator	08-2023
11	Director of operations innovation company	08-2023
12	Business developer energy service company	08-2023

3.2.2 Secondary Data Collection – Desk Research

The secondary data collection for this thesis was conducted through a comprehensive and multifaceted approach. It commenced with an extensive literature review, encompassing scholarly articles, research papers, and academic texts relevant to the energy transition and hydrogen developments in general. Industry reports, government publications, and research studies were also rigorously analysed to gain a holistic view of the subject matter. Additionally, scholarly databases were searched to identify peer-reviewed academic material, ensuring the inclusion of high-quality sources. Grey literature, comprising non-peer-reviewed reports, policy papers, informational websites, and confidential documents provided by some interviewees, were integrated, offering diverse perspectives and valuable insights or implications from practical standpoints. This approach to secondary data collection provided a robust foundation for the subsequent analysis and interpretation of the research findings.

3.3 Data Analysis Methods

This section describes the theoretical background used for data analysis. It describes the steps undertaken to distil insights from the interviews, the approach utilised to dissect the pivotal roles and interactions within the examined system of actors, and finally introduces the framework employed for the institutional underpinnings of the study.

3.3.1 Process of Interview Data Analysis

Initially, the interview transcripts were cross-referenced with the recordings for accuracy and completeness. After that, the analysis of the interview data followed a grounded theory approach (Figure 10) as founded by Glaser & Strauss (1967), starting with a thorough review of the transcripts to gain an overall understanding and establish "*units of significance*" that authentically reflected participants' opinions and experiences (Bhattacherjee, 2012). The coding process involved assigning specific labels to passages in the interview transcripts, creating a systematic framework for exploration. The codes encompassed a range of categories, including e.g. enablers, barriers (social, technical, economic, political etc.), opportunities, concerns, sustainable system needs, actors, ideal landscape visions, and various classifications related to the expectations of the energy transition (infrastructures and investments) and roles of hydrogen (see Appendix III). This inductive approach to qualitative analysis allowed for the emergence of patterns and themes directly from the data rather than imposing a predetermined framework (Timmermans & Tavory, 2012). The coding was conducted using ATLAS.ti, ensuring consistency in the treatment of significant units across the interviews.

The initial list of codes was refined and adapted during the coding process to capture the nuances of the data better. However, it's important to acknowledge potential limitations. Maintaining both inter- and intra-code reliability proved to be a challenge, as codes needed to remain consistent not only within themselves but also over time (Bryman, 2016). Additionally, guarding against biases in interpretation was crucial. While qualitative analysis aids in exploration, it's imperative to be vigilant against unconscious predispositions that may influence the coding process. The potential for pre-formed opinions to impact the interpretation of codes underscores the need for an open-minded approach to data analysis, ensuring the identification of truly relevant and novel insights (Skjott Linneberg & Korsgaard, 2019). Lastly, to maintain fidelity to the original responses, all interview quotes used in this thesis were translated from Dutch to English as closely as possible.

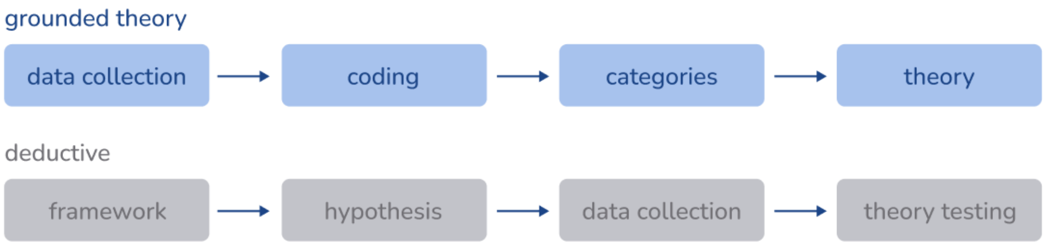

Figure 10 - Grounded theory approach versus a deductive approach

3.3.2 Method for Actor Analysis of the System

Stakeholder analysis is a recognised method or approach to gather insights about "*relevant actors*", comprehending their behaviour, objectives and agency or resources that impact decision-making processes (Brugha & Varvasovszky, 2000). Numerous contemporary definitions of stakeholders are rooted in Freemans (1984) groundbreaking stakeholder theory founded in the strategic management realm, which differentiated between individuals who impact or are impacted by decisions or actions. This classification is sometimes termed active versus passive stakeholders within the context of natural resource management (Grimble & Wellard, 1997). Following this distinction, this research explored actors that are active parts of an SHN and actors that enable or affect its formation.

Three steps were conducted based on the stakeholder analysis typology proposed by Reed et al. (2009) and adjusted for this work. It consists of (1) identification and (2) categorisation of stakeholders followed by (3) an analysis of their roles and interrelations.
An initial inventory of stakeholders in the emerging Dutch hydrogen sector was made through examining secondary data consisting of academic and grey literature, policy documents, industry publications, and research institute reports. The collected data was partly added upon and validated using primary data from the semi-structured interviews.

A broad definition of stakeholders was used. While this approach is valuable for creating an initial comprehensive list of actors, it's crucial to streamline the analysis by subsequently constraining this number (Grimble & Chan, 1995: 119). Three general guidelines as suggested by Enserink et al. (2010) were used to keep the remainder of the analysis feasible:

- Ensure that the identified actor-network is in line with the chosen level of analysis.
- Ensure that the identified actors cover a balanced set of interests and roles.
- Strive to include between ten and twenty distinct actors in the stakeholder analysis to enhance the credibility of analysis outcomes. Fewer than ten may lead to the omission of relevant actors while exceeding twenty could dilute the analysis's focus. A division was made between the core and the shell of actors related to SHN formation.

Additionally, the geographical scope was set to the Netherlands (not excluding international stakeholders significantly impacting SHNs) and the temporal scope encompassed the formation and subsequent functioning of an SHN. The identification and categorisation of actors involved in this system was an iterative process (Reed et al., 2009). The rainbow diagram proposed by Chevalier & Buckles (2008) was used to help classify stakeholders accordingly (Figure 11).

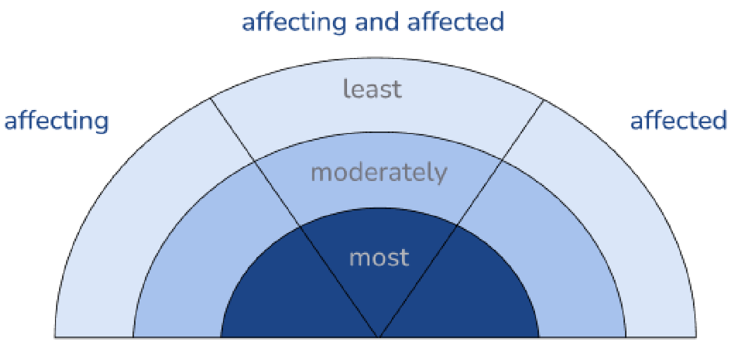

Figure 11 - The rainbow diagram, adapted from Chevalier & Buckles (2008), ranging from affecting to affected and distinguishing between core actors and outer shell actors

3.3.3 Williamson's Four-Layer Model for Institutional Exploration

Williamson's four-layer model (Figure 12) is considered a valuable foundational framework for comprehensive social or institutional analysis (Joskow, 2004; Künneke & Fens, 2007). It distinguishes between four interrelated levels that govern behaviour, each operating at its own pace (Ghorbani et al., 2010; Williamson, 1998).

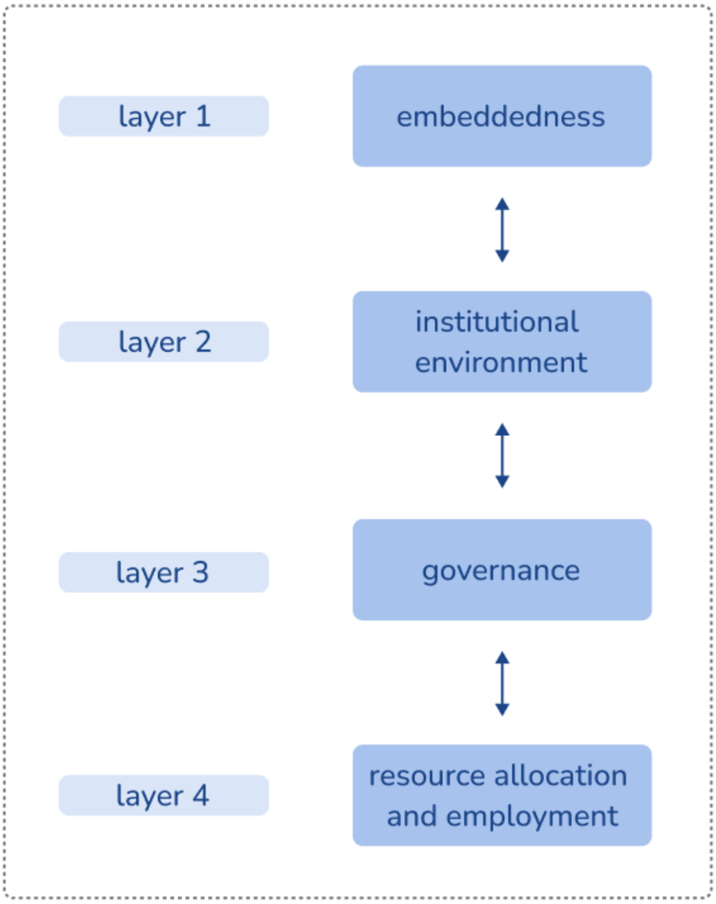

Figure 12 – The four-layer model of Williamson

Layer 1: Embeddedness

The top layer emphasizes the embedded nature of economic activities within a broader social and cultural context. This includes "*norms, customs, mores, traditions, etc*." (Williamson, 1998, p.27). It highlights the influence of informal social networks, trust and shared values in interactions that go beyond rational market considerations (Koppenjan & Groenewegen, 2005). These institutions are emergent from the lower layers and can inhibit or support them (Ghorbani et al., 2010). This evolves very slowly and exerts a lasting grip on societal behaviours (Williamson, 1998).

Layer 2: Institutional Environment

The second layer comprises the political, legal and governmental formal arrangements and is best understood by looking at the economics of property rights (Ghorbani et al., 2010; Williamson, 1998). It provides the formal rules of the game that structure economic activity, i.e. the mechanisms available to actors to coordinate their interactions (Koppenjan & Groenewegen, 2005). When (re)designing socio-technical systems, this layer is crucial to "*get the institutional environment right*" (Williamson, 1998, p27). Significant alterations to the established rules often take place during pivotal moments, such as wars or economic breakdowns. Nevertheless, system change (e.g. through rewriting laws) usually occurs in periods of decennia and results from lengthy negotiations, partially constrained by a slow rate of adaptation to the first layer (Ghorbani et al., 2010; Joskow, 2004).

Layer 3: Governance

The third layer describes Williamson (1998) as: "*the play of the game*" (p.29). It refers to the institutional arrangements or governance structures that affect how decisions are made, certain transactions are coordinated, and responsibilities are allocated (Koppenjan & Groenewegen, 2005). It encompasses a range of organisational modes ranging from market-based mechanisms, hierarchical structures and complex network relationships (Ghorbani et al., 2010). Agreements and contractual arrangements are at the centre of this layer and are heavily influenced by the attributes (opportunities or restrictions) of the institutional environment of layer two (Joskow, 2004). The timespan for change within these structures and transactions typically ranges from one year to a decade (Künneke & Fens, 2007).

Layer 4: Resource Allocation and Employment

The last layer of the model switches from structural to individual analysis (Ghorbani et al., 2010). It refers to spontaneous transactions and the day-to-day allocation of resources by actors related to supply and demand (Joskow, 2004). It entails continuous operations and management responding to changing (market) conditions. Individuals consider the costs and benefits of actions to get marginal conditions right (Williamson, 1998). Therefore, it is the fastest changing and developing institutional level.

Although the model is visually divided, it reveals that different categories of institutions do not exist in a vacuum but interact in a top-down and bottom-up manner (Koppenjan & Groenewegen, 2005; Künneke & Fens, 2007). "*The lower layers, entirely operational and most flexible, are influenced, either constrained or facilitated, by the layers above [...] nevertheless, developments in the lower layers may affect the higher layers, by means of deliberate attempts of actors, policy makers and politicians to alter the institutions, in response to all kinds of developments*" (Broekhans & Correljé, 2008, p. 71).

Moreover, the model makes essential observations on the notion of speed. Changes are perceived at different time scales, with large-scale adaptation generally being considered a slow but steady (i.e. incremental) process. In contrast, exogenous developments can require much-needed rapid changes, although simultaneously destabilising arrangements on all layers (Joskow, 2004). It is then vital that institutions are quickly re-aligned and congruent with each other; otherwise, the system will not function adequality (Koppenjan & Groenewegen, 2005).

In conclusion, the qualitative characterisation of the model is helpful in providing an understanding of the institutional influence on the formation of SHNs. It is sufficiently generic to be applied to this socio-technical system as its evolution is highly intertwined on all levels of society and across sectors.

- Chapter 4 -
A Conceptual Overview of Small-scale Hydrogen Networks in the Netherlands

This chapter provides an in-depth analysis of the concept of small-scale hydrogen networks by elaborating on the main components of the socio-technical system in section 4.1, followed by a synthesis of the key elements in section 4.2.

"Complex solutions are needed for the simplest of elements."

— Raffaella Gerboni, 2016
Compendium of Hydrogen Energy, Volume 2

4.1 Definition

Each section delineates one of the three principal constituents of SHNs (technological innovation along the value chain, actors involved in the system, and the institutional landscape) as explained in section 1.3, answering sub-questions 1, 2 and 3, respectively.

4.1.1 Technical Exploration

This section aims to introduce the technology components of (small-scale) hydrogen networks by addressing the first sub-question: *What would be the technical specifications, the limitations, and potential applications of an SHN?* First, the basic properties of hydrogen and its role as an energy carrier are discussed. After which, the value chain is elaborated upon following the broad categorisation division of upstream (production), midstream (storage and transportation), and downstream (usage or application), according to Ma et al. (2023).

4.1.1.1 The Basic Properties

Hydrogen is the lightest and most abundant chemical element in the universe. It has an atomic mass of 1.008 and is represented by the symbol "H" in the periodic table. At standard temperature and pressure, it is a colourless, odourless, tasteless, non-toxic, but highly flammable gas (Bahman, 2019). Hydrogen as a single atom is not a naturally existing energy resource on Earth because it readily forms bonds with other elements, such as oxygen or carbon, to form compounds (H_20, CHn). Therefore, to obtain hydrogen, it must be extracted from these other sources, making it a secondary energy source, also known as an energy carrier (Ball & Wietschel, 2008). In scientific and everyday usage, "hydrogen" is commonly used to refer to both the element (H) and the gas (H_2).

There are two main advantages of the use of hydrogen. First, it has the highest theoretical mass-energy density (120MJ/kg) among various types of fuels in terms of its Low Heat Value (LHV). This means it contains a large amount of energy per unit *mass*, making it a potentially efficient and compact energy carrier. Secondly, hydrogen can have a clean combustion process. It only produces pure water vapour as a byproduct when it is burned with oxygen. This makes it an attractive option for reducing carbon dioxide or other greenhouse gas emissions (Dou et al., 2023).

4.1.1.2 Molecular and System Role

In general, the role of hydrogen in the energy transition is two-fold: it has a molecular role and a system role. Its molecular role mainly revolves around using CO_2-neutral hydrogen in making a range of market segments more sustainable (Detz et al., 2019):

- Used as a raw material: Hydrogen has a significant molecular role in the production of various chemicals and materials used in the (petro)chemical industry. This industry is already one of the largest consumers and producers of hydrogen. Two of the most prominent examples are the production of ammonia (NH_3), a crucial component of the production of fertilisers, and methanol (CH_3OH), an important feedstock for the synthesis of various chemicals (van Wijk, 2017; Araya et al., 2022).

- Used for high temperatures: Hydrogen has a significant molecular role in some industrial processes that rely on extreme heat, e.g. glass manufacturing, ceramic production, or metal refining. Its high energy density and combustion properties can provide the heat or power required for these high-temperature industrial furnaces that would be difficult to obtain through electrification. Moreover, it can be used as a direct reduction agent in the production of iron and steel, replacing carbon-based reducing agents (Carmona-Martínez et al., 2023)
- Used as fuel for transport: Hydrogen has a significant molecular role in heavy and long-distance transport where direct electrification (use of batteries) may not (yet) be feasible due to factors like weight, range or infrastructure limitations. Hydrogen-powered fuel cell electric vehicles (FCEVs) might offer solutions for buses, trucks or other speciality vehicles because of their extended range and quick refuelling time. Additionally, it can be indirectly used as a raw material for producing biofuels or synthetic fuels employed in aviation or maritime industries (Detz et al., 2019).
- Used for low temperatures: Hydrogen has a significant molecular role in providing heat for various purposes, such as space heating for residential, commercial, and industrial buildings, as well as in certain industrial processes that require moderate heat levels. Hydrogen can either be used in the gas networks, pure or mixed with other gases, or its (rest)heat from combustion in burners and boilers can be used to fulfil the built environment's heat demand (Böhm et al., 2021).

In addition to hydrogens' role in these particular market segments, CO_2-neutral hydrogen may include wider energy system functions to tackle the problems as outlined in 1.2.1.

- Used to increase flexibility: Hydrogen has a significant system role in the integration of intermittent renewable energy sources, e.g. as a buffer to non-dispatchable renewable energy generation (Capurso et al., 2022). It can be employed as a demand response over different time scales, contributing to rapid adjustments in power balancing markets, providing frequency control within seconds or minutes, or this can be extended to days or months as large-scale, long-term seasonal storage, converting the overproduction in summer using power-to-X technologies back during winter (Detz et al., 2019; Schlund, 2022).
- Used to increase reliability: Hydrogen has a significant system role in safeguarding the reliability of the energy system. Through the coupling of various market segments or energy sectors, it improves system integration and enhances the overall system. Strong elements in one system can counteract weaker ones in another. Through its flexibility and storage mechanisms, it serves as a much-needed backup of the current electricity, gas and heat networks (Barreto et al., 2003; Sorrenti et al., 2022).
- Used to increase resiliency: Hydrogen has a significant system role in increasing the energy systems' long-term resiliency. It can provide cost-effective transportation and distribution of energy in areas where, e.g. the electricity transmission network reaches its limits. Moreover, using hydrogen as a strategic reserve strengthens energy security to satisfy energy demand when no alternatives are available, e.g. during

natural disasters or emergencies when used in microgrids that can operate even when the main power grid is down (Shahbazbegian et al., 2023; IRENA, 2022).

Research and advancements in hydrogen technologies are ongoing to unlock its full potential as a clean and versatile energy carrier across these different applications.

4.1.1.3 Upstream - Sources & Production

Hydrogen distinguishes itself as an unparalleled and inexhaustible energy source. However, as previously mentioned, to obtain hydrogen, it must be extracted from other sources. This happens during substantial resource-intensive harnessing processes (Zohuri, 2018). To distinguish between these different hydrogen synthesis processes, colour codes are utilised. The current state of hydrogen production, as reviewed by Hermesmann & Müller (2022), addresses four main developments: green (carbon-free), turquoise (CO_2-free), blue (low-CO_2), and grey (conventional) hydrogen. Whereas green hydrogen is produced from renewable energy, blue uses carbon capture and storage (CCS), and turquoise produces solid carbon as a by-product, grey hydrogen heavily depends on fossil fuels.

Additional colour codes used in the industry as outlined by Ma et al. (2023) are:

- White: refers to subsurface geological hydrogen that occurs naturally but at present is not exploited
- Black and brown: refer to hydrogen generated from black coal or lignite (brown coal) and is the most environmentally damaging
- Pink: refers to green hydrogen made using nuclear energy
- Orange: refers to green hydrogen made using wind energy
- Yellow: refers to green hydrogen made using solar energy

Figure 13 presents a comprehensive overview of various hydrogen production technologies and the corresponding resources utilised in the process. For extensive discussions of the different classifications, see Osman et al. (2021), Younas et al. (2022), Ishaq et al. (2022), Hermesmann & Müller (2022) or Ma et al. (2023). Among all these technologies, steam methane reforming (SMR) dominates hydrogen production in the Netherlands. High-temperature steam (700–1000°C) is used to react with natural gas to produce H_2 (Cioli et al., 2021). As mentioned in the introduction, we can see a trend going towards the other end of the spectrum (Figure 14). Additionally, as previously highlighted in Figure 6, one of the focus areas on a small scale is the decentral production of hydrogen coupled to local renewables: onshore wind and solar. Due to this growth potential, the main technological focus of this thesis is directed at the production of *green* hydrogen. Moreover, as electrolysis is the most mature, well-established and effective approach among its alternatives, it is taken as the main technological component of SHNs in this research (Ma et al., 2023).

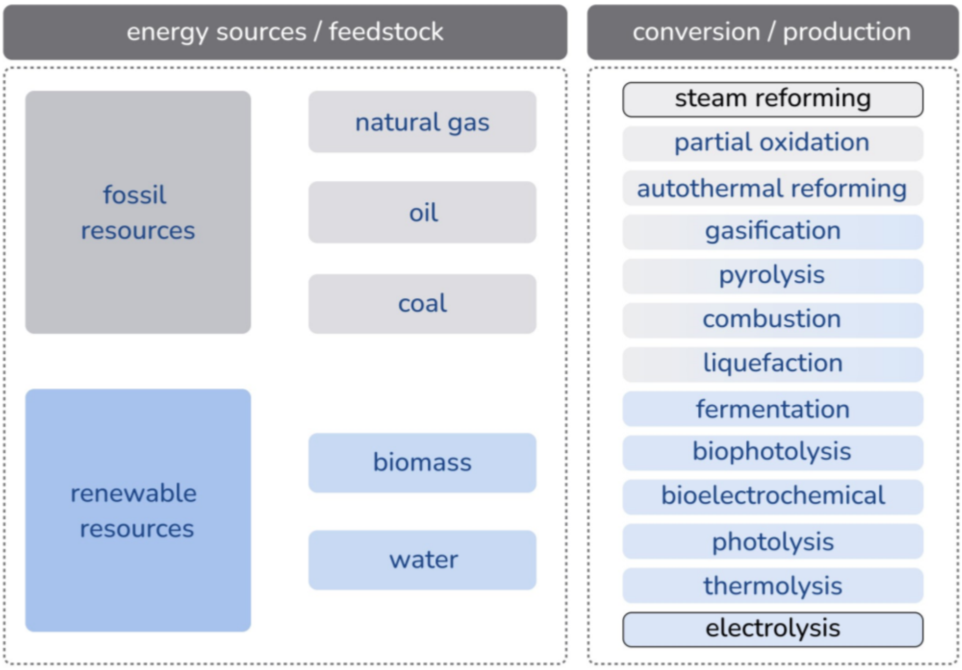

Figure 13 - Overview of various hydrogen production technologies

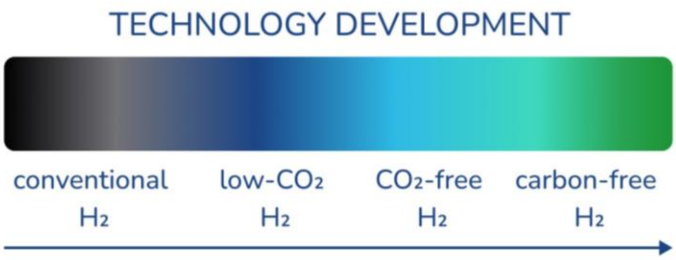

Figure 14 - Hydrogen colour spectrum

Electrolysis is a chemical process that uses a significant amount of electricity (electric current) to split water into its constituent elements: hydrogen and oxygen (1). This process takes place in an electrolyser, often interchangeably referred to as a hydrogen plant or "*waterstoffabriek*" in Dutch (Port of Rotterdam, 2022).

$$2H_2O(l) \rightarrow 2H_2(g) + O_2(g) \tag{1}$$

The three most commonly used technologies are alkaline, PEM (proton exchange membrane) and solid oxide electrolysers (IEA, 2023). Their operating principles are illustrated in Figure 15.

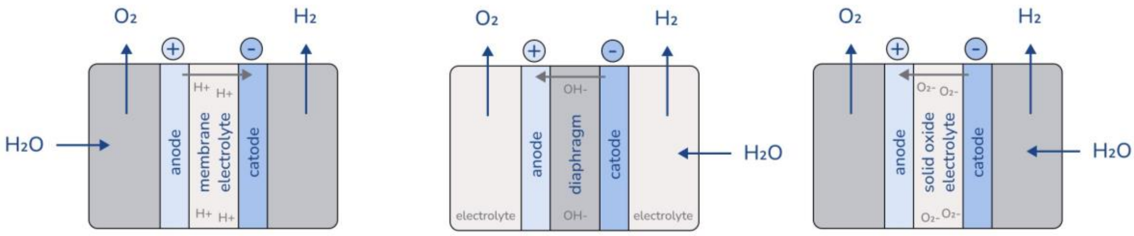

Figure 15 - Schematic of the main types of electrolysers a) PEM b) Alkaline c) Solid oxide adapted from Araya et al. (2022)

The main differences are in terms of (1) development stage (see figure 16), (2) electrolyte type and charge carrier used, (3) operating temperature/conditions, (4) suitability for dynamic operation, e.g. varying electric input or demand fluctuations, and (5) scalability and suitability for various applications (Hermesmann & Müller, 2022). See Araya et al. (2022), Sorrenti et al. (2022) or Faye et al. (2022) for a more detailed comparison of these electrolysis technologies and their key advantages or disadvantages. The most suitable type per SHN will depend on local conditions, e.g. alkaline and PEM are more suitable for direct coupling with renewable while solid oxide electrolysers might be a better choice where waste-heat is available as their operation requires higher temperatures (Pavan, 2023).

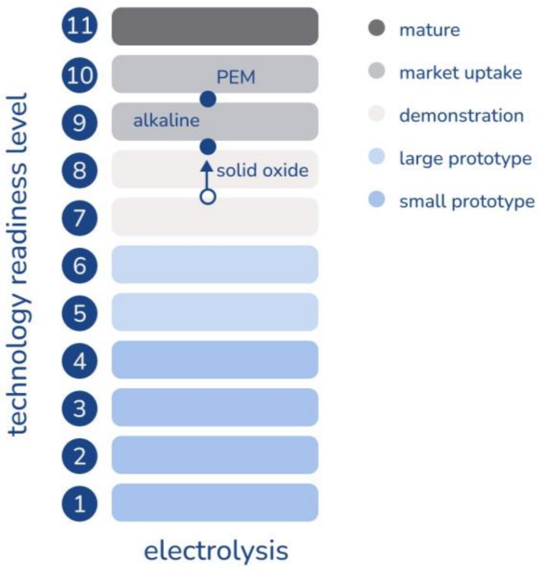

Figure 16 - Technology Readiness Level adapted from IEA (2023).

At the moment, the commercial exploitation of electrolysers still needs significant investment. As outlined in a report by HyDelta on *the drivers of renewable hydrogen production in the Dutch integrated energy system*, it is expected that different scales of electrolyser capacity will emerge (van Zoelen et al., 2023). They differentiate between:

- Small-scale: range of about 1 MW to several MWs,
- medium-sized: range between some tens to some hundreds of MWs,
- and large-scale electrolysers: ranging from about 250MW to several GWs.

Along the lines of this order of magnitude, this Thesis defines small-scale as an electrolyser with a capacity under 50 MW. This is in line with the recently introduced OWE subsidy for hydrogen production through electrolysis with installation capacities in between 0.5 and 50 MW (RVO, 2023).

Furthermore, the HyDelta report highlights the importance of electrolysers' locations and their impact on the total energy system. The alignment of the business value and the system value of electrolysers needs to be ensured, as this can prevent a lot of insignificant investments. Nonetheless, there is limited research into the potential future division between central and decentral electrolysis and their location. The maps in Figure 17 illustrate the overall potential of specific regions in general. However, the success of small-scale electrolyser investments largely hinges on a combination of very specific local driving forces. These factors can either create a favourable environment for investment or hinder its viability.

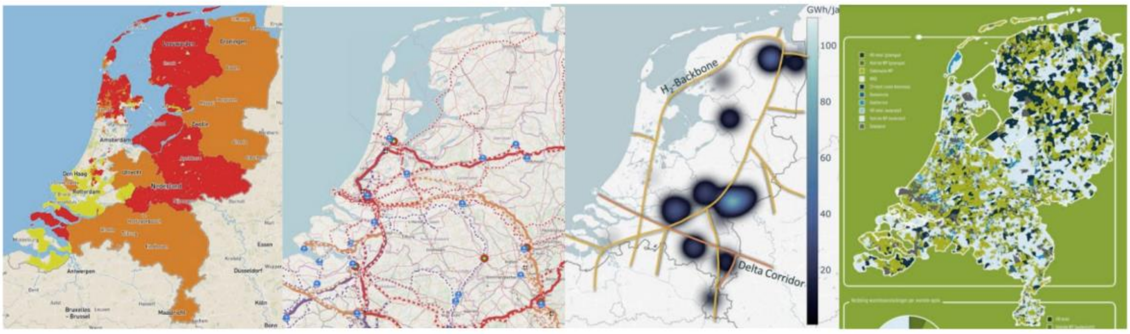

Figure 17 - Four maps showing decentral electrolysis area with high potential: from left to right (1) electricity grid congestion map (red), (2) transportation corridors via road, water and rail, (3) hydrogen demand 6th cluster industry (blue), (4) built environment potential (light blue) (van Zoelen et al., 2023)

Overall, water electrolysis represents an environmentally friendly method for hydrogen production, as it does not depend on fossil resources and does not directly emit CO_2 or other greenhouse gases during the process. Nevertheless, it is crucial to acknowledge that significant environmental implications may arise from various stages of the electrolysis life cycle. These implications primarily stem from plant manufacturing, additional infrastructure developments, and the intricate supply chains associated with sourcing water and electricity (Hermesmann & Müller, 2022).

These installations are the most cost-effective if they can operate continuously. As wind and solar are intermittent energy sources, this will only be possible if a connection to the main electricity grid is established. This additional purchasing of renewable energy might be necessary as a back-up and/or to lower initial capital expenses per amount of hydrogen generated (Hoogervorst, 2020).

4.1.1.4 Midstream - Transport & Storage

Besides hydrogen generation, its (re)distribution methods and infrastructure are essential components that must be addressed (Faye et al., 2022). Moreover, developments of hydrogen storage technologies are critical in addressing this phase's challenges which are often closely linked to potential mismatches between supply and demand (Hu et al., 2020). The midstream part of the value chain consists of the technologies responsible for this safe and efficient use of hydrogen anywhere, anytime (Tarhan & Çil, 2021).

Storage Technologies Overview

As mentioned in 4.1.1.1, hydrogen has the highest energy content per unit *mass* among commonly used fuels. However, in contrast, its *volumetric* energy density is very low at standard temperature and pressure. As a result, a significant volume of space is required to store a given amount of hydrogen gas. To overcome this limitation, various strategies are being pursued for hydrogen storage. These technologies can broadly be divided into physical and material-based (chemical) storage methods, as illustrated in Figure 18. Table 4 briefly describes the main storage methods that can be applied. For more extensive reviews of each currently available method, see Usman (2022), Tarhan & Çil (2021), Yang et al. (2023), Elberry et al. (2021) or Faye et al. (2022).

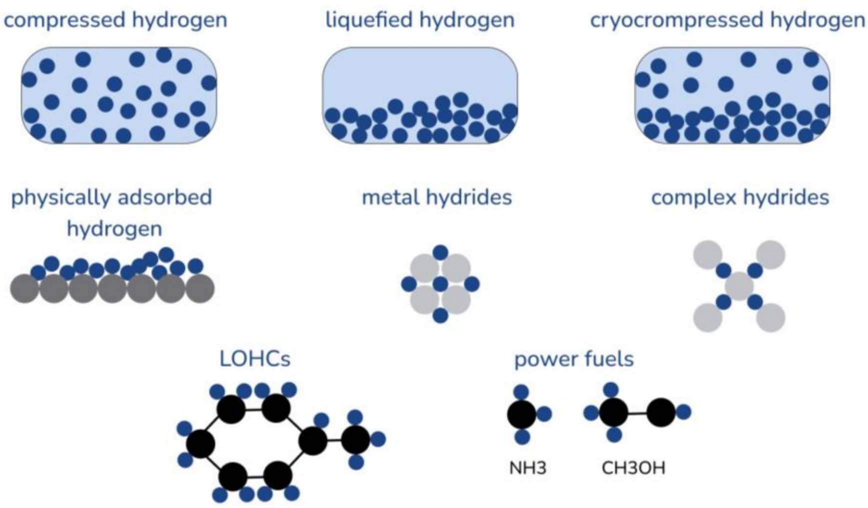

Figure 18 – Visual representation of hydrogen storage methods

Tabel 4 – Overview of storage methods

Compressed hydrogen	Hydrogen is compressed to a higher pressure (up to 700 bar) to achieve a lower volume. This is a well-developed technology and utilises various types of storage vessels. Compressed hydrogen can also be stored in underground geological storage. See Elberry et al. (2021) or Tarkowski & Uliasz-Misiak (2022) for further analyses of (large-scale) underground hydrogen storage (UHS).
Liquified hydrogen	Hydrogen gas is cooled to very low temperatures (around -253°C or 20K) to become liquid. This is a well-established technology and enhances hydrogens' energy density.
Cryocompressed hydrogen	This is a new method that combines elements of both compressed and liquified hydrogen storage. Hydrogen is compressed (to 250-350 bar) and then cooled to its boiling point, which heightens its energy density and storage capacity.
Physically adsorbed hydrogen	Hydrogen is adsorbed onto the surface of a solid material due to van der Waals forces or dispersion forces. Suitable materials include activated carbons, zeolites and metal-organic frameworks.
Metal hydrides	Hydrogen is chemically bonded with metals to form solid compounds. These can store hydrogen at moderate pressures and temperatures and offer the potential for reversible hydrogen storage. Additional research needs to be conducted to improve its loading and release properties under different circumstances.
Complex hydrides	Hydrogen is chemically bonded with lighter elements, such as alkali metals or alkaline earth metals. This increases its storage density. They can be broadly classified into alanates, borohydrides, and amides-imides.
Liquid organic hydrogen carriers (LOHCs)	Hydrogen is chemically stored by reacting with liquid organic compounds that are initially hydrogen-deficient. This results in hydrogen-rich compounds which can be transported efficiently without extensive pressurisation or cryogenic storage. This technology is still in its early stages of development but has demonstrated significant potential.
Power fuels / E-fuels	Hydrogen gas reacts with nitrogen to form ammonia at high temperature (300-500 °C) and pressure (20-35MPa) or it is hydrogenated with carbon dioxide to form methanol (200-300°C, 5-10MPa). These can be used as fuels.

Storage technologies are undergoing fast-moving developments, making new opportunities or challenges unclear. For example, material-based hydrogen storage still has relatively low technology readiness levels (TRL). However, it can highly increase the future application of hydrogen and provide alternative, more safe modes of transport. Currently, extra measures need to be taken to deal with hydrogens' high diffusivity causing embrittlement effects, heightening leakage concerns or resulting in added complexities, e.g. affecting pressure needs or conversion necessities (Kovač et al., 2021).

As the majority of the material-based storage technologies are still in their development and demonstration phase, this Thesis focuses on the more mature physical storage technologies that have been directly developed from other gas and chemical industries (Yang et al., 2023).

Hydrogen Transportation

The transportation of hydrogen varies based on the type of storage method employed (Kim et al., 2023). However, three primary classifications are defined concerning established and operational gas transportation systems: road transport, pipeline transport, and shipping (Yang et al., 2023).

Shipping

As shipping concerns itself with hydrogen trade between countries or continents (connecting "*renewable exporters*" and "*renewable importers*"), it is not considered as this research focuses on the formation of smaller-scale networks in the Netherlands itself. Moreover, hydrogen supply chains based on shipping hydrogen in its elemental or compound form are not yet well established. A few pilot projects are running as a global green hydrogen economy is expected to emerge. For further discussion on the long-distance transport of hydrogen(carriers), see Lee et al. (2022), Johnston et al. (2022) or d'Amore-Domenech et al. (2023).

Road

As mentioned, compressed gaseous hydrogen storage (CGH_2) utilises different types of vessels; tests have even been done to store the gas inside windmills (Elberry et al., 2021). However, a so-called tube trailer[2] or gas cylinder bundles[3] are specifically designed for CGH_2 transportation on roads. These are especially suitable for smaller hydrogen demands that need to travel relatively short distances (<300km) (Kim et al., 2023). Alternatively, liquid hydrogen (LH_2) can also be transported in special trailers via road. However, they require specialised equipment to maintain a low temperature to keep the hydrogen in its liquid state. This mode of transport is particularly suitable for medium/large-scale supply and medium/long-distance transport (> 160 km) and is therefore considered to be out of scope for this Thesis (Kim et al., 2023).

Pipeline

Lastly, pipeline transport can be considered. Similar to the natural gas network, for continuous large-scale supply over long distances, this is the most economically suitable way (Yang et al., 2023). However, investing in a completely new pipeline system is capital-intensive. As mentioned in the introduction, the Netherlands is on its way to repurposing a large amount of its natural gas pipelines for hydrogen transport to connect large industrial clusters to a national hydrogen backbone, which will eventually expand into a Europe-wide backbone (RVO et al., 2021). In contrast, pipelines can also be employed for continuous supply for smaller-scale purposes over shorter distances. E.g. connecting local green hydrogen generation to a close by refuelling station, or placing an electrolyser on-site /close to a smaller industrial facility that requires hydrogen for its processes.

[2] Tube trailers are elongated, cylindrical containers of which multiple can be stacked and mounted on a trailer chassis

[3] Gas cylinder bundles are also cylindrical containers typically smaller in size and under higher pressure

Necessary in the context of hydrogen pipeline transmission is ensuring hydrogen purity (Yang et al., 2023). When using a repurposed or, sometimes even a newly constructed, hydrogen pipeline, there might be challenges in delivering the gas with the required purity levels suitable for e.g. fuel cell applications (typically requiring a purity of 99.5% to 99.9%). Depending on the subsequent hydrogen processing and intended application, an additional purification process might be necessary at the endpoint. This aligns with a division made by Hu et al. (2020) between the option to directly distribute hydrogen, convert and then redistribute it, or opt for end-user purification.

Additionally, it is important to note that the classification of distances can be relative and can vary based on the available infrastructure, regional considerations, and the specific technologies used for transportation. For instance, what might be considered a long distance for road-based tube trailers could be considered a medium distance for national pipeline transportation. The Dutch national hydrogen backbone will cover approximately 1200 km (de Wit, 2023). A pipeline connecting two chemical companies in Zeeland is about 12 km long, and the pipeline network in Rotterdam about 30 km (Gasunie, n.d.a). Therefore, this thesis defines pipeline transport below 30km to be small-scale.

Figure 19 - Overview of hydrogen transportation modes, CG = compressed gas, NG = natural gas

All in all, tube trailers are the first choice on a small scale: they are highly mobile and thus offer flexibility. Hydrogen suppliers can adapt to changing or temporary market demand more easily, they can be deployed quickly, and distribution networks can be adjusted or redirected accordingly. Furthermore, they can be more cost-effective, purity levels can be better maintained, and they can better support the early stages of market formation when a widespread infrastructure is not in place (yet). This is especially relevant for decentral developments, as these encounter significant "last-mile" transportation costs (van Zoelen et al., 2023).

As the hydrogen market develops, a combination of tube trailers (also occasionally referred to as "*discontinuous* pipelines") and pipelines can effectively form a comprehensive transportation network that meets various small-scale storage and distribution needs (Figure 19). Ensuring the technologies' safety and reliability is vital for widespread adoption.

4.1.1.5. Downstream - Usage or Application

(Green) hydrogen adoption is also highly dependent on its possible end-uses. As the focus shifts towards practical implementations of the gas, exploring its utilisation when arriving at the point of consumption sheds light on the potential for contributing to a carbon-free future, as outlined in the discussion on its molecular and system role in 4.1.1.2.

Although hydrogen's use in the (petro)chemical industry is widely established, its use in, e.g. the transport sector, in power generation, or for grid balancing is negligible (Conrad & Reinhardt, 2020). Moreover, it is competing with other low-carbon solutions that tackle similar applications, as most hydrogen-based solutions are not yet competitive with traditional solutions. Therefore, *potential* is an important word here.

In demonstrating this potential, a few distinctions can be made for diverse downstream applications: e.g. demand for pure or mixed hydrogen, connected to the electricity grid or a direct line, mobile or stationary, and again the scale of hydrogen utilisation. For an up-to-date overview of hydrogen projects in the Netherlands, see waterstofkaart.missieh2.nl.

From this overview, the *Nationaal Waterstof Programma*, and verified during the interviews, it can be derived that small-scale usage or applications in the Netherlands will mainly be focused on the following:

- 6th cluster industry
- (Heavy) transport and mobility on road or on water
- The agricultural-sector
- The construction sector
- The built environment
- Storing local renewable energy (over)production

Examples

Given the significant number and varying levels of technology readiness associated with potential end-use applications and services within these sectors, this section aims to provide a general impression of the demand side of the chain. This overview is achieved by touching upon a few project examples that are currently operational or under development.

Hydrogen chain Kappele region: Concept – The project aims to establish a regional intricate hydrogen distribution infrastructure from a hydrogen backbone, benefiting regional medium-sized businesses through enabling them to take significant steps towards energy sustainability as well. These local hydrogen chains enable convenient, cost-effective access to hydrogen, facilitated by above- and below-ground transport and storage networks (Missie H2, 2023a).

Duwaal: Realisation – The goal of the project is creating a regional hydrogen production and distribution network in the safety region North Holland North. Establishing three hydrogen refuelling stations, two hydrogen trucks, a hydrogen-powered sweeper, and an integrated hydrogen storage, transport, and distribution system. This will be coupled to a 4 MW hydrogen turbine (Missie H2, 2023b).

H2-Agri Stadskanaal: Investment decision – The aim is establishing a regional hydrogen chain in Stadskanaal. An electrolyser powered by solar energy is placed at a farm. Hydrogen is transported via a plastic pipeline to the local bakery Borgesius and the Monuta crematorium, replacing natural gas usage. The goal is to have the first hydrogen flowing through the pipes by Q2 2024. Additional green electricity from the grid could enable the electrolyser to operate during nights and dark days (Missie H2, 2023c).

Generator on hydrogen: Operational – This project focused on a solution for eco-friendly, odourless, and noise-free energy supply for projects without access to grid power, e.g. (construction) sites and events. The units from Volta Energy's hydrogen power generators harness solar energy and feature a backup generator powered by a fuel cell, converting hydrogen into electricity. In 2023, the setup was tested at the Demo Field in Arnhem's IPKW (Missie H2, 2023d).

Stad Aardgasvrij: Investment decision – Stad aan 't Haringvliet is transitioning to green hydrogen for heating its 600 homes through a local hydrogen system developed within the natural gas free neighbourhoods program "*Programma Aardgasvrije Wijken*". Using the existing gas network negates the need for new infrastructure. Following a positive referendum response of 77.6% in June 2023, the conversion plan from natural gas to hydrogen will be developed by the winter of 2024, with the expectation to switch existing natural gas connections to hydrogen by summer 2025 or at the latest by 2030, pending municipal approval (Missie H2, 2023e).

Sinnenwetterstof: Operational - A 1.4 MW electrolyser has been installed in Oosterwolde on a 50 MW solar park to balance the grid and supply hydrogen for mobility. Instead of reducing generation during peak times, the electrolyser converts electricity from the adjacent solar park into hydrogen, preventing grid overload. The produced high-quality hydrogen is compressed to 300 bar and stored in tube trailers for future use in hydrogen vehicles. The Oosterwolde hydrogen facility has been in operation since late 2022 (Missie H2, 2023f).

4.1.2 Actors - System Analysis

This section aims to explore the actors involved in the formation of the socio-technical system of SHNs in the Netherlands. First, existing academic publications regarding stakeholder analysis related to the hydrogen sector are touched upon. Secondly, the identification, categorisation, and stakeholder roles and interrelations are presented. The structure follows the typology proposed by Reed et al. (2009) as explained in section 3.3.2 and answers the second sub-question: *Who would be the actors involved and what are their objectives, potential roles and interrelations in an SHN?*

4.1.2.1 Background

Few publications have determined and analysed stakeholders related to hydrogen integration. The most recent and comprehensive systematic analysis are by Schlund et al. (2022) comprising insights into the emerging German hydrogen market ramp-up and Hasankhani et al. (2023) on the complexities of hydrogen integration in the Dutch context. Furthermore mainly sector or country specific preliminary research has been conducted. e.g. Enevoldsen et al. (2014) on the Danish hydrogen electrolysis industry and Chantre et al. (2022) or Murray et al. (2008) on transitioning to a hydrogen economy in Brazil and Poland respectively. Furthermore research has touched upon social acceptance perspectives of stakeholders (Emodi et al., 2021; Glanz & Schönauer, 2021; Schmidt & Donsbach, 2016) and on the identification of influential actors and conflict areas for Denmark specifically (Andreasen & Sovacool, 2014a, 2014b).

This thesis section aims to complement the existing literature through presenting a snapshot of the actors involved in the emerging SHNs in the Dutch energy landscape. The analysis of primary and secondary data sources led to the identification of 37 stakeholders, distributed broadly over 6 distinct categories (Table 5).

Tabel 5 - Categories of stakeholders related to SHN formation

			Category	Description
Enablers of SHNs - Central SHN actors	Affected	1	Energy providers and hydrogen producers	Essential for the realisation of mainly the upstream part of the hydrogen value chain
		2	Infrastructure and distribution providers	Essential for the realisation of mainly the midstream part of the hydrogen value chain
		3	End-users / private vs business consumers	Essential for the realisation of mainly the downstream part of the hydrogen value chain
	Affecting	4	Public bodies	Essential during the formation phase and addressing social or spatial challenges
		5	Intermediaries	Essential in guiding complexity, knowledge sharing or addressing economic challenges
		6	Large stage setters	Essential in setting the context and shaping of the overall energy landscape

It's important to acknowledge that stakeholders in the hydrogen sector often exhibit dynamic roles, and they may belong to multiple categories or transition between them over time. Due to this inherent complexity and diversity, establishing rigid definitions for these categories is not always feasible (Schlund et al., 2022). Nonetheless, the proposed categorization offers a valuable framework for understanding the key actors shaping the development of SHNs in the Netherlands.

4.1.2.2 Identification and Categorisation

Each category brings its unique perspective, interests, and capabilities to the forefront of hydrogen integration. Energy providers and hydrogen producers (category 1) are at the heart of hydrogen generation, while infrastructure and distribution providers (category 2) ensure the seamless transport and storage of this crucial energy carrier. End-users (category 3), whether private individuals or businesses, represent the ultimate consumers, and their choices influence the adoption of hydrogen. Public bodies (category 4), on the other hand, set policies, regulations, and standards that govern the hydrogen ecosystem. Intermediaries (category 5) bridge gaps, facilitating collaborations and knowledge exchange, while large stage setters (category 6) are influential actors shaping the direction of hydrogen initiatives on all levels. The following Tables (6-11) define each actor, their interests / objectives and their agency / resources within each category.

*Table 6 – Category 1 - **Energy Providers and Hydrogen Producers***

Actor	Definition elaboration	Interests / objectives	Agency / resources
Energy supplier (and service) companies	Includes commercial companies (e.g. Eneco, Essent) integrating green hydrogen into their portfolio as an alternative energy carrier to other gasses or electricity	Economic growth and consumer satisfaction through ensuring a reliably supply of energy and/or hydrogen	Exploring opportunities to fulfil a societal energy provision role through investments, ownership of (hydrogen) energy supplies, and forming partnerships for (local) delivery solutions
Renewable energy suppliers (e.g. local energy corporations or private producers)	Includes onshore wind and solar (farms or smaller-scale), producing renewable energy and possibly green hydrogen through integrated or close by electrolysis facilities	Fulfilling local (community) energy and/or hydrogen demand	Initiators of local participation projects and managing part of the supply chain for own or external use
Hydrogen producers / production facilities	Includes alternative actors that produce hydrogen as a by-product or utilise renewable energy to produce green hydrogen	Generating hydrogen for different end-uses incentivised by financial and societal gains	Providing and operating the necessary installations and influence on the end-product state (purity levels, gas pressure) for further storage or transport

*Table 7 - Category 2 - **Infrastructure and Distribution Providers***

Actor	Definition elaboration	Interests / objectives	Agency / resources
Hydrogen technology providers	Includes the manufacturing and provision of the physical entities (e.g. fuel cells, electrolysers, storage tanks like tube trailers, (re-)compressors, hydrogen suitable pipelines etc.)	Securing reliable and affordable technologies	Exploring areas for technological improvement or alternative techniques and managing scaling up production for potential buyers
Regional electricity and gas operators (Distribution System Operators, DSOs)	Includes grid operators like Liander, Enexis and Stedin	Maintaining a stable and safe electricity and/or gas grid, changing or expanding it within their capacity, keep their distributing role and minimise stranded assets of infrastructure investments	Employing the technical/operational expertise of distributing energy, exploring the building and operations of alternative or additional networks, enabling the RESs, taking responsibility for maintenance needs and deciding on grid connection possibilities
(Regional) transport operators	Includes mainly above ground hydrogen transport but also e.g. private underground pipeline transport within a geographical area	Handling the logistics for reliable and cost-effective hydrogen transport	Employing technical expertise, ensuring safety measures are in place, engaging in contractual agreements with suppliers and consumers, involvement in logistics management and overseeing the integrity of the network
(Local) storage operators	Includes mainly small-scale hydrogen (buffer) storage in tanks or pipelines during local production, distribution or close to its end-use	Ensuring a secure, efficient, and safe storage environment for hydrogen while meeting customer demands	Maintaining the operationality of the hydrogen network through optimising the inventory management of hydrogen, responding to changing market dynamics and thus balancing supply and demand fluctuations
Fuel station operators	Includes the management of mainly stationary refuelling infrastructures (e.g. Greenpoint, Total Energies, Shell) or of mobile refuelling units	Providing reliable and safe public access to hydrogen for a range of vehicles or other applications	Managing and maintaining the entities required such as dispensers, hoses and safety systems to ensure a user-friendly experience in addition to influencing pricing strategies for revenue generation
Other hydrogen technology operators	Includes the management of any other hydrogen integrated installations or appliances	Mostly providing demonstrations on the feasibility of designs or business proposals via proof-of-concept principles	The testing and monitoring of hydrogen integrated installations or appliances, subsequent adjustments or improvements and overseeing implementations elsewhere

*Table 8 - Category 3 - **End-users / Private vs Business Consumers***

Actor	Definition elaboration	Interests / objectives	Agency / resources
6th cluster industry	Includes the "smaller" industrial companies scattered across the Netherlands (e.g. the food industry, paper and cardboard industry, ceramic industry, waste processors and data centres) utilising hydrogen as energy source or feedstock	Complying with (future) sustainability regulations whilst still operating in a cost-effective way	Executing ambitious sustainability plans through technological alterations or infrastructure investments or leaving the Netherlands when this turns out to be a too large financial (long-term) risk
Heavy transport and mobility on road or water	Includes buses, trucks, boats, taxis or other speciality vehicles either heavy or light duty	Enhancing overall hydrogen-powered vehicle performance and complying with (future) emission regulations	Advocating for financially supportive policies to encourage adoption, decreasing emissions, reducing noise pollution and increasing transport efficiency through lower weights, refuelling times and higher ranges
Agricultural sector	Includes e.g. farmers that can contribute to decentral energy generation and consumption	Decreasing the pressure put on them by the nitrogen crisis through engaging in more sustainable practices	Utilising their available space and/or organic waste for green hydrogen production and/or decarbonising their operations through embracing cleaner hydrogen-powered technologies
Construction sector	Includes e.g. construction companies, builders, project developers	Decarbonising its operations mostly on or around construction sites and complying with emission regulations	Decision power on replacing polluting diesel power equipment (e.g. generators, cranes) with hydrogen-powered ones and reducing noise or fume pollution in cities
Built environment	Includes residential (homeowners, renters or housing/owner associations), commercial buildings or local entrepreneurs that are seeking alternative energy solutions	Securing affordable and reliable energy provision especially in remote locations or for hard to insulate buildings (e.g. historical city centres)	Initiating action, influencing social acceptance, (collectively) deciding on alternative sustainable solutions for heating, cooling and/or (back-up) power and reducing grid congestion issues

*Table 9 - Category 4 - **Public Bodies***

Actor	Definition elaboration	Interests / objectives	Agency / resources
Regional governments	Includes the 12 provinces of the Netherlands	Carrying economic and spatial responsibility for the region while reaching emission reduction objectives and implementing sustainability measures across sectors	Influence the course of an integrated approach (through the pMIEK), allocate (financial) resources, oversees initiatives and can decide to interfere or redirect
Water boards	Includes the 21 waterboards of the Netherlands "*waterschappen*"	Taking responsibility for water management practices	Oversee the availability of water for green hydrogen production, research the potential of producing and using hydrogen in sewage treatment plants
Local governments	Includes the 342 municipalities of the Netherlands	Dealing with matters of direct concern to its own citizens, e.g. developing local transitions plans for a liveable environment	Compose the local environmental vision "*omgevingsvisie*", grants permits and subsidies, implements national law
Safety regions	Includes the 25 safety regions of the Netherlands "*veiligheidsregio's*"	Overseeing, maintaining or improving the safety of citizens in the specific regions	Influence what is or what is not allowed concerning hydrogen integration closer to society, ensure knowledge development to close gaps in legislations and address risk aversion measures to eliminate possible incidents

*Table 10 - Category 5 - **Intermediaries***

Actor	Definition elaboration	Interests / objectives	Agency / resources
Program managers	Includes publicly or privately appointed professionals whose job is to help oversee and coordinate various projects	Making sure all involved parties are connected, timely informed of developments and cohesion is guaranteed	Influence the building, implementation and staffing of projects, develop strategic planning, engage with various stakeholders and monitors performance
Project developers	Includes an entity (e.g. Hygro) or individual responsible for conceiving, planning and overseeing projects	Developing economically viable projects or hydrogen value chains through identifying bottlenecks and optimising processes	Can employ an integral approach, find synergies, develop case-by-case solutions, and define and execute additional investments or secure funding
Legal experts	Includes an entity or individual that can interpret and apply laws, regulations and contracts	Ensuring legal compliance, protecting the rights and interests of clients, and providing effective legal solutions to challenges	Providing clarity, minimizing legal risks and supporting clients in making informed decisions within the bounds of applicable laws and regulations
(Green) hydrogen certificate market facilitators	Includes developers (e.g. CertifHy) or traders (e.g. STX group) of hydrogen certification schemes	Supporting hydrogen's market growth by providing reliable tools for consumers to track hydrogen's origin and environmental attributes	Expertise in renewable energy markets, regulatory frameworks, and trading systems thus promoting safe and transparent hydrogen integration
Electricity traders and energy aggregators	Includes the entities that operate in the power market by buying and selling electricity (often in bulk or on behalf of multiple actors) as well as hub operators	Optimizing demand and supply practices, enhancing trading strategies, managing of risks, and profit maximisation through e.g. participating in emerging hydrogen markets to capture new revenue streams	Expertise in renewable energy markets, energy pricing and predictive analytics which can be leveraged to optimize the integration of hydrogen-related activities or extend their portfolios to adapt to evolving energy landscapes
Consultants or advisors	Includes external service companies (e.g. Witteveen en Bos, Berenschot) or individuals that are appointed by a client	Providing expertise / specialised knowledge (e.g. technical, market, economic) / guidance in solving or navigating issues in the form of advice or design proposals	Helping clients make informed decisions, solve complex challenges, seize opportunities and drive the successful implementation of hydrogen integration

Actor	Definition elaboration	Interests / objectives	Agency / resources
Research institutes / centres	Includes publicly oriented or privately oriented organisations or research programs (e.g. TNO, Hydelta, TKI)	Primarily contributing to R&D and advancing scientific knowledge and technological innovations related to (hydrogen) developments	Have access to specialised research facilities, laboratories, and expert researchers, and can collaborate with industry partners or government agencies to carry out research and publish findings
Universities	Includes higher education institutions (e.g. TU Delft, Leiden University)	Providing education, training, and research into various fields to foster a skilled workforce and generate knowledge through these academic programs	Can steer education and research into relevant or unknown areas, offer specialised courses, engage in research activities, contribute to knowledge dissemination and can collaborate with a large array of (external) partners
NGOs	Includes independent non-profit associations (WaterstofNet, NWBA) that operate for a specific goal	Advocating for responsible developments in terms of e.g. social, policy and environmental changes	Can leverage advocacy, communication and outreach to raise awareness in influencing decision-making processes related to (hydrogen) developments
Financiers / investors	Includes non-governmental organisations (e.g. banks, companies) or individuals with money	Providing funding or financial resources to support various projects, initiatives or businesses, potentially in exchange for (partial) ownership and balancing of risk versus expected rewards	Enabling activities and developments that might otherwise lack the necessary capital, can range from start-up capital to operational infrastructure funding
Landowners	Includes entities or individuals that own land	Seeking economic benefits from selling or leasing their property or ensuring sustainable land utilisation practices	Possess the physical resources that might be needed for hydrogen developments, can negotiate terms and agreements, can block or align with land-use plans in favour of a specific community or party
Trade associations	Include industry or business organisations that represent certain businesses within a specific sector or industry	Advocating for the interests of members and working to promote the growth, success and sustainability of their respective industries	Can advocate for policies, regulations, and legislation that benefit their industry and member businesses through providing a unified voice, making sure their perspective is considered

Actor	Definition elaboration	Interests / objectives	Agency / resources
Society	Includes the broader community of individuals, residents, citizens or communities that are directly or indirectly affected by hydrogen developments	Seeking environmental sustainability, transitioning to clean energy, ensure safety and affordability, most importantly community well-being	Have the ability to protest or vote, organise themselves for a specific goal (e.g. energy cooperation or environmental advocacy group) and influence hydrogen supply chains through what they demand
Steering groups	Includes initiatives or groups of actors that see themselves as frontrunners (e.g. GROWH or other consortiums of companies, public bodies and research institutes)	Aiming to accelerate the transition through the bundling of resources, knowledge gathering, experimenting, and leading the way for others to follow	Have the ability to coordinate projects, advocate for local autonomy, showcase what is feasible, raise awareness of bottlenecks and share their expertise to comparable areas or cases

*Table 11 - Category 6 - **Large Stage Setters***

Actor	Definition elaboration	Interests / objectives	Agency / resources
The EU Commission	Includes the executive body of the European Union	Ensuring the proper functioning of the EU and therefore e.g. promoting and advancing hydrogen integration to support its climate and energy objectives	Can allocate funding, develop policies, influence legislative processes, support R&D initiatives and foster international collaboration and agreements to create enabling environments
The national government	Includes the 12 ministries of the Netherlands, specifically the Ministry of Economic Affairs and Climate Policy (Energie Beheer Nederland) and the Ministry of Infrastructure and Watermanagement (Rijkswaterstaat)	Aiming to achieve climate targets, energy transition goals, and economic growth objectives while aligning with global trends and standards securing a reliable and affordable energy provision	Highly influences the execution of Dutch (energy) vision plans for 2050, can foster stimulating environments (e.g. investments, subsidies, R&D, policy formulation) or discouraging ones (prohibitions, complexities)
National gas operator (Transmission System Operator, TSO)	Includes the gas grid infrastructure company Gasunie	Ensuring a central role for gas in the future sustainable energy system, focusing on security of supply and adapting the existing gas infrastructure for hydrogen and other gas integration	Can utilize their existing infrastructure, technical expertise, and investments to enable the transportation, distribution, and storage of hydrogen, making adaptions where necessary
National electricity operator (Transmission System Operator, TSO)	Includes the electricity transmission grid infrastructure company Tennet	Aiming for a reliable and secure transmission of electricity across the national grid through infrastructure planning, integrating renewables, and focusing on accommodating flexibility	Can leverage their grid management expertise, ensure synergies between gas and electricity systems, and advocate for regulatory frameworks facilitating different integration activities into the grid to balance supply and demand
International energy agencies	Includes international organisations (e.g. the IEA, the IRENA)	Providing research, analysis, policy recommendations, and collaboration on various energy topics, including hydrogen	Providing a platform for exchanging knowledge, technical expertise, and best practices to accelerate the energy transition worldwide

4.1.2.3 Analysis of Roles and Interrelations

Understanding the roles and interrelations within these categories provides valuable insights into the dynamics of SHNs in the Netherlands. Figure 20 illustrates the simplified relationship between them.

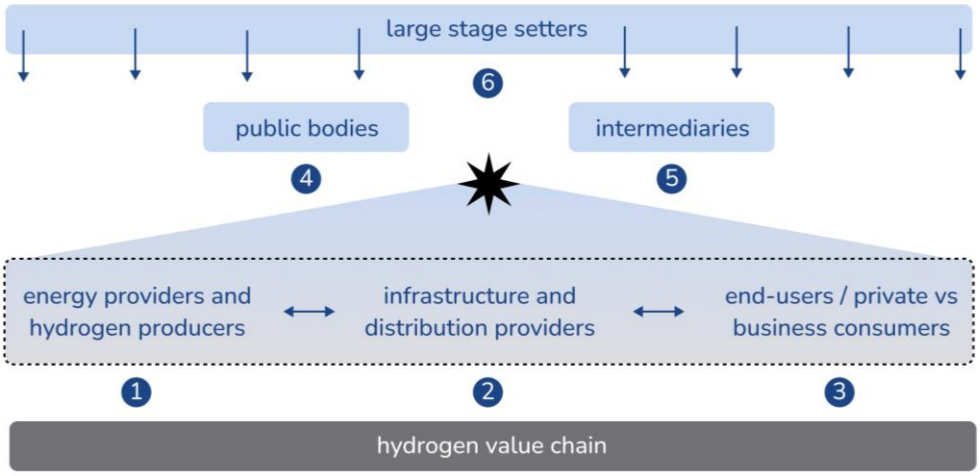

Figure 20 - Simplified relational overview of the involved actor categories within SHNs

Central actors along the hydrogen value chain (categories 1, 2 & 3) need to connect. Several interviewees mention them as the most active actors as these make up the operational part of SHNs. However, their problems are mainly based on tackling financial uncertainties and the division of responsibilities. As noted by interviewee #11 "*Yes, you have to find end-users, you have to find producers, you have to find operators, you have to find a lot of actors to get it right. That in itself is not the problem. Parties do find each other, certainly in a certain region. The problem is, who goes, who stays with the biggest risks and is there enough compensation for that risk?*". Interviewee #9 furthermore emphasises: "*everyone, especially locally, wants to fill in the gaps, take the initiative, until they hear how complicated it is, no, how complicated it is being made.*"

This is where the notion comes in that closely associated public bodies (category 4) should take a more active directing role, especially on a small-scale. As mentioned by interviewee #1, they play a part as "*authorised supervision*" besides being supportive financially, regulatory or guiding participation. Additionally, as noted by interviewee #3, "*local conditions, strongly determined by the government, make sure someone steps in and fills in what is necessary in that area*". However the general consensus is that this highly varies between certain regions, depending on their capacities and openness for innovation (#7).

This is reflected in another strong component between different actors: time. Although categories 4, 5 and 6 (public bodies, intermediaries, and large stage setters), can take on enabling roles, they can also restrict. For example, if there is no clear legal guidance available, if a municipality does not take any responsibility for the energy transition, if financers refrain from funding because of too significant risks, if security regions are uncertain about defining new norms and standards or if citizens protest against specific projects: the pace and complexity of hydrogen integration is influenced, delaying SHN formation and functioning.

Especially in these early stages, innovation requires essential supportive resources before, at some point, SHNs become self-sustaining. For small-scale projects, it is challenging to get all these resources together, to tackle the "*unprofitable top*" (#5, #7, #9). Moreover, after (demonstration or pilot) projects are forming and slowly setting-up, often a connection to infrastructure is needed, but priorities are elsewhere (#6).

As these quotes highlight: *"In the great violence of Gasunie, the backbone, large national transmission networks, and ultimately again distribution to the regions. That's where those smaller players actually don't play a role, so the stakeholders are the big guys, they define that whole playing field." (#1)* and *"In particular, the energy transition is a lobby of a lot of big companies and there are only few companies that are really consumer companies that are in that lobby. They are mostly industrial parties talking about solutions for the industry."(#12)*

This does not mean that e.g. a Gasunie is only affecting, and not affected by, smaller players, but in general they have more power, which can create problem areas for these actors. Moreover, communication plays a central role. Often "*big guys*" are used to working B2B or within their scope (#6) and not used to working with smaller parties or directly with consumers and vis versa leading to conflicts because of wrong-assumptions (#12). As mentioned by interviewee #4, their energy cooperation "*became a partner for the project team and the municipality to support the relations, so all kinds of new connections need to be created to facilitate the transition*".

All in all, the integration of hydrogen and the formation of SHNs becomes a complex undertaking due to the involvement of a large array of stakeholders with varied roles, motivations, and relationships that complicate decision-making processes. Analysing these roles highlights mediating and/or organisational activities. It illustrates different levels of difficulties during the collaboration process and during the subsequent steps needed to progress the operationality of SHNs.

In line with Bryson (2004), "*figuring out what the problem is and what solutions might work are actually part of the problem, and taking stakeholders into account is a crucial aspect of problem solving* [...] *we are moving into an era when networks of stakeholders are becoming at least as important, if not more important, than markets and hierarchies*" (p.24). In other words, no single entity exercises full authority, and no organisation completely encompasses the issues to be tackled.

4.1.3 Institutional Exploration

This section explores what institutional playing field the actors from the previous section operate in. First, the differing rules to be comprehended to understand the system and the importance of analysing these changing environments is discussed. Then, the institutional context that determines the (in)formal power configuration between actors is discussed according to Williamson's four-layer model, as explained in section 3.3.3. Sub-question three is addressed: *What is the current institutional landscape that may shape or hinder the emergence and subsequent functioning of an SHN?*

4.1.3.1 Background

Ostrom (2005) defines institutions as the set of rules that "*humans use to organise all forms of repetitive and structured interactions*" (p. 3). Similarly, Hodgson (2006) describes institutions as "*systems of established and prevalent social rules that structure social interactions*" (p. 2). They shape the individual and collective decision-making processes by acting as constraints or opportunities (Cole, 2013). A distinction can be made between formal rules and informal rules. While the first includes laws, regulations, and protocols that are consciously established, the latter encompasses administrative practices, norms, professional codes, traditions, and customs that are less explicit but also impact SHN formation (Mesdaghi et al., 2022).

In light of the energy transition, these rules have evolved according to specific technologies but are in need of replacement (Fuenfschilling & Truffer, 2016). Formerly dominant regimes need to be de-institutionalised to make room for more sustainable emerging technologies and practices. In this case, institutional re-design is necessary to support an upcoming hydrogen market. At the moment, many actions for this transition are undertaken on quicksand, based only on loosely institutionalised alternative socio-technical configurations.

Consequently, it is essential to bring stability back, as many of the challenges faced in forming hydrogen networks are caused by the absence of an institutional framework (Langeraar, 2021). Moreover, several interviewees argued that technology is not the problem. Instead, there is a vacuum of support in the stage after a high Technology Readiness Level (TLR) is achieved. The ARENA (2014), therefore, introduced the Commercial Readiness Index (CRI), which extends beyond the TRL (see Figure 21). It can be used as a benchmark to assess the non-technical challenges in new technologies' demonstration and deployment stages.

Two of its indicators[4] include the *regulatory environment* and *stakeholder acceptance*, highlighting the importance of diving into the institutional factors and conditions that stimulate the formation and subsequent functioning of SHNs. Given the context-dependent nature of the institutional environment, the following passages provide an overall discussion regarding the essential institutional rules that play a role in the Netherlands. These rules are categorised using Williamson's four-layer model, described in section 3.3.3.

[4] The other indicators are: technical performance, financial proposition – costs, financial proposition – revenue, industry supply chain and skills, market opportunities and company maturity

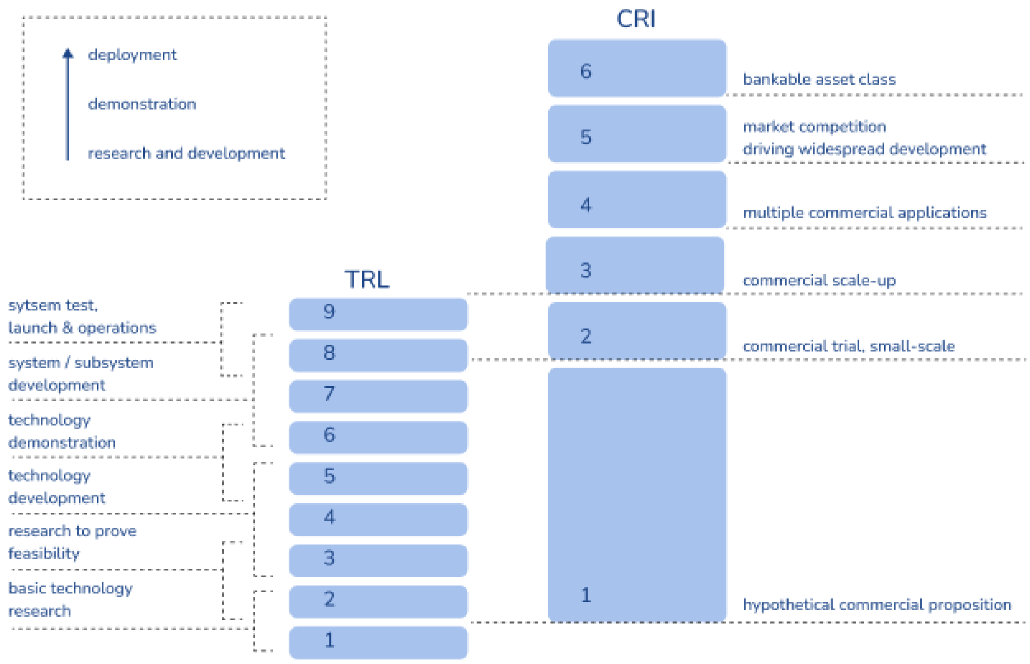

Figure 21 - The Commercial Readiness Index as compared to the Technology Readiness Level, adapted from ARENA (2014)

4.1.3.2 Analysis

Layer 1: Embeddedness

Includes the informal rules such as norms, traditions and shared values.

In the Netherlands, we have been "*spoiled*" with a steady natural gas supply for a long time (#6). However, in the late 1990s and early 2000s, the liberalisation of the gas and electricity market started as a part of broader European Union efforts to create a single energy market across member states (Ciucci, 2023). This process resulted in a more competitive and efficient energy market, allowing multiple companies to participate in each segment along the value chain. Consumers gained the freedom to choose their energy suppliers, fostering competition and potentially lower energy prices (ACM, 2007). Still, energy has mostly been seen as a public responsibility, but in recent years it has increasingly become a private endeavour.

We live in an age where the boundaries between the public and private sector are blurring, and there is a growing overlap between private and public life (Council of Europe, 2018). This evolving landscape reflects the dynamic interplay between government, businesses, and individuals, with significant implications for how society is organised, governed, and how individuals engage with both their professional and personal spheres. Additionally, current societal trends toward greater individualization, digitalization, internationalization, and intensification continue to evolve (Veldhuisen & Snel, 2014). Individuals are embracing increasingly conflicting roles, identities, and diverse loyalties (Auby et al., 2014). This dynamic reflects the complexity of modern life, where people often juggle multiple roles and affiliations that may at times appear to be in conflict or flux. As such, public awareness, individual interests and public responsibility are often intermingled.

From empirical literature and survey data, it becomes evident that there is broad support among the Dutch population for '*democracy*,' '*freedom*,' and '*equality*' as general values (Dekker & den Ridder, 2016). Simultaneously, we can see a shift towards integrating more sustainable practices, taking care of our environment, and tackling the climate crisis. A significant event in the Netherlands and globally was the Urgenda case: a lawsuit filed in 2013 against the Dutch government and ruled in favour of it in 2015 (De Rechtspraak, 2015). It argued that current climate policies where insufficient and threatened human rights by failing to address climate change adequately. Another breakthrough was reflected in the signing of the Energy Agreement for Sustainable Growth in 2013 by representatives from the Dutch government, environmentalists, and the energy sector (EZK, 2013).

As the Netherlands transitions away from fossil fuels, the shared value of embracing renewable alternatives influences attitudes toward hydrogen. Dutch people have a tradition of embracing innovation and technological advancement and value collaborative decision-making. These inclinations are reflected in the "*hype*" for integrating hydrogen into the energy mix. Hydrogen technologies align with the Dutch spirit of innovation and the desire to remain at the forefront of sustainable energy solutions.

Layer 2: Institutional Environment

Includes the "rules of the game" in terms of the political, legal and governmental formal arrangements

Hydrogen integration is severely influenced by government policy (EZK, 2020). The government is, therefore, mainly responsible for steering and guiding this process. However, legislation and regulations are still in a relatively early stage of development (van Zoelen et al., 2023). The government strategy on hydrogen outlined five key aspects that serve as a general roadmap for this journey:

- Use of existing gas grid: to define new responsibilities as the evolution of hydrogen supply chains is expected to mirror that of network sectors like electricity and natural gas
- Market regulation and temporary tasks for network operators: to give the market room to manoeuvre and enable experimentation, statutory and regulatory flexibility is to be created
- Guarantees of origin and certification: to facilitate a transparent and reliable market for hydrogen
- Safety: to determine the necessities for effectively managing risks and addressing safety issues combined with additional monitoring practices
- Main Energy Infrastructure Programme: to coordinate with the current electricity and gas infrastructure, mostly related to the spatial impact of hydrogen integration.

These legal frameworks are under construction and are to be streamlined with the EU (hydrogen) policy context. Therefore, the existing Electricity Act 1998 and the Gas Act are to be replaced by a New Energy Act (EZK, 2022). The bill encompasses various crucial provisions. It addresses consumer protection, broadens the array of strategies available to network operators for managing the entire electricity grid, enhances opportunities for households and businesses to actively engage in the energy market, and establishes secure and regulated data exchange among network operators, market participants, and energy consumers. The new law aims to streamline and simplify regulations while eliminating unnecessary distinctions between gas and electricity rules. This harmonization is pivotal for advancing the ongoing energy transition and essential for hydrogen gas as it currently does not fall within the definition of gas covered by the Gas Act (*Gaswet*, 2000).

Moreover, several EU policy incentives influencing Dutch national policies are the EU green deal, the Fit for 55 packages (including the *Hydrogen and decarbonised gas market* package) and the REPowerEU plan as introduced in section 1.1. These include targets set by 2030 to increase renewables capacities to 1236GW, increase electrolysers capacities to 17.7GW annually, and propose 10 million tonnes of domestic renewable hydrogen production (van Zoelen et al., 2023). The EU primarily employs binding targets, particularly for various categories of end users, as the primary stimulus to promote the adoption of hydrogen within its member states. However, again, many policies are still under discussion or being adjusted, e.g., the Renewable Energy Directive (RED II), one of the critical stimulants of facilitating the emerging market (EZK, 2020). It includes the definition of what renewable hydrogen is, contains targets for hydrogen in mobility and industry, and regulates a European certification scheme of which hydrogen is also a part (NWP), 2022). Additionally, it allows room for a "*blending obligation*" for hydrogen in the current natural gas grid to support the scaling up of green hydrogen. This is an ongoing (European) discussion (Collins, 2023). Furthermore, the EU taxonomy is a relevant classification system. It decides what a private sustainable investment is, including hydrogen investments, and is therefore relevant to get loans from banks (European Commission, 2023). Moreover, the Energy Taxation Directive determines minimum tariffs of energy tax, including the tariffs to be determined for hydrogen (European Commission, 2021b). Finally, the recently adopted EU Alternative Fuel Infrastructure Regulation (AFIR) is important for the roll-out of refuelling stations and the encouragement of alternative fuel use, such as hydrogen (European Council, 2023c).

Nationally, market regulation holds paramount importance. It entails the structuring of markets, delineating the eligibility criteria and conditions for participation by both public and private entities. This encompasses the formulation of rules and regulations governing market operations. Additionally, it defines the rights and responsibilities of end customers. This framework profoundly impacts the intricate interplay between production, transportation, storage, infrastructure construction and management processes. The question "*who is allowed what*'" is already partly determined but still has some areas that require decisions (Gasunie, 2022; NWP, 2022).

Besides this, Dutch targets set out in the National Climate Agreement are to be supported by policy changes. These are, for instance:

- The heightening of the target for electrolyser capacity to 6-8 GW in 2030
- Proposals for (renewable) fuel targets and zero-emission transport (50 refuelling stations, 15,000 fuel cell vehicles and 3,000 heavy-duty vehicles by 2025; 300,000 fuel cell vehicles by 2030)
- "Tolerance policies" or in Dutch "*gedoogbeleid*" introduced as temporary frameworks for hydrogen use within, e.g. the built environment (Autoriteit Consument en Markt, 2022). An important aspect here is the security of delivery regulation.
- Allowing adjustments to certain machines/technologies or tests for easier integration of, e.g. grid congestion services

However, to reach all these targets, significant investments are required. Support schemes focus on funding demonstration and research projects, scaling-up processes, and subsequent roll-out requirements (EZK, 2020). The most important ones that could be relevant on a small-scale as well include:

- SDE++: "*Stimulering Duurzame Energieproductie en Klimaattransitie*", a grant instrument for the large-scale production of sustainable (renewable) energy and techniques that reduce CO_2 (NWP, 2022). From 2020 onwards, the production of hydrogen through electrolysis is included (EZK, 2020). However, investments remained limited as projects need to compete with more mature carbon reduction technologies. Since 2022, a new addition involves the capture of excess CO_2 generated during the production of hydrogen from industrial residual gases, as well as the hydrogen production from electrolysis directly linked to a wind or solar park (Elzenga et al., 2021).
- DEI+: "*Demonstratie Energie- en Klimaatinnovatie*", a grant instrument for stimulating pilot- and demonstration projects or test and experiment infrastructure, that contribute to accelerating hydrogen integration, and thus involve e.g., cost price reduction of electrolyses, hydrogen production from biomass, electrochemistry, transportation (transmission lines or distribution grids, storage, and end-uses of hydrogen (NWP, 2022; RVO, 2023c).
- EIA: "*Energie-investeringsaftrek*", a tax arrangement for entrepreneurs that mainly focuses on implementing hydrogen as fuel, its storage or distribution. They are allowed to deduct 45.5% of the investment costs from the profit which lowers their taxable profit (RVO, 2023a).
- OWE: "*Opschaling volledig hernieuwbare waterstofproductie via elektrolyse*", a recently introduced subsidy for producing renewable (sustainable) hydrogen through electrolysis for capacities in between 0.5 and 50MW. The grant is a tender meaning companies compete for the available money (RVO, 2023d).
- PAW: "*Programma Aardgasvrije Wijken*", municipalities and regions can request a contribution for making neighbourhoods natural gas-free or natural gas-free ready. This mainly includes district heating or all-electric but also transitioning to renewable gasses, including hydrogen (RVO, 2023b).

- IPCEI: "*Important Project of Common European Interest*", grants subsidies to projects that are connected to each other in order to help boost the formation of hydrogen chains (across borders) (NWP, 2022; RVO, 2022).

The IPCEI is complementary to e.g. SDE++ or DEI+, however most other subsidies cannot be combined, e.g. OWE with EIA is not allowed (RVO, 2022, 2023d) . Two other instruments influencing the institutional environment worth mentioning are the EU ETS (European Emission Trading System) and the Dutch Energy Tax Act "*Energiebelasting*". The ETS is the world's largest cap-and-trade program, i.e. carbon market. Under the EU ETS, a cap is set on the total amount of greenhouse gases that can be emitted by around 10 000 installations in the energy sector and manufacturing industry, and allowances are distributed accordingly. Installations can buy or sell allowances, creating a market-driven incentive for emissions reduction, e.g. utilising low-carbon or green hydrogen. Alternatively, the Dutch energy tax is a fiscal policy implemented to promote the adoption of cleaner technologies. Specifically, it entails lowering taxes on electricity while slowly raising them for natural gas (FIN, 2023).

Layer 3: Governance

Includes the "play of the game" in terms of decision making, the coordination of transactions and allocation of responsibilities.

Since the energy landscape is changing immensely and responsibilities are relocated, this layer can be expected to become much more complex and important to streamline (Hafner et al., 2020). The "*play*" within SHNs is transformed into negotiation scenarios, necessitating involvement from local interest and additional public authorities. There must be room for advice and commitment from various groups of stakeholders (CSWW, 2021). The traditional decision-making process, primarily involving government entities, may not fully align with the approach of e.g. the new "*omgevingsvisie*"[5] (environmental code). For the formation of SHNs, recognizing the need for a more inclusive approach, private actors are now integral not only in implementation but also in decision-making (Bureau Energieprojecten, 2023).

This is reflected in the shift towards the concept of "*network governance*" (Hoppe & Miedema, 2020). Network governance represents "*more or less sustainable patterns of social patterns between reciprocally dependent actors, which cluster around certain policy or other social problems.*" (Klijn, 1996). In several SHN cases there will not be a decisive authority, so agreements and trade-offs will need to be discussed together. In certain instances, similar to what occurs in competitive industries, these circumstances can lead to the emergence of divergent and conflicting public and private interests. Defining the governance will provide a lot of clarity. As mentioned by interviewee #2 on getting all the actors together:

[5] 26 separate laws become one overarching law and 120 separate regulations become four as of January 1st 2024 (Rijksoverheid, 2023)

"*In what legal form should it take place? What do those trade contracts look like? What do you do if someone wants to quit their company or another party wants to join or.... well, all those kinds of complicated issues. It involves pushing and pulling, but not everyone likes challenges and every change is threatening. Quite a bit of water has to go through the IJssel before you get there.*"

The precise connection between institutional restructuring and the reliability of networks is often overlooked or not thoroughly explored (Broekhans & Correljé, 2008). Therefore a new set of rules has to be developed to engage local and regional authorities in the initial formation of the value chain. These will necessitate the integration of fresh definitions, interpretations, and arrangements pertaining to insurances, liabilities, and the delineation of responsibilities for both public and private actors.

Specifically for the value chain two important questions arise: could the fragmented infrastructure still be safe and reliable? And could the parties involved be kept responsible? To lower these risks, what we often observe is the signing of a declaration of intent leading up to concrete proposals of the specifics of a collaboration. These can then take the form of bilateral agreements, multilateral agreements, partnership agreements, consortia agreements or joint ventures with running times up to 25+ years.

Layer 4: Resource Allocation & Employment

Includes the individual analysis of the operations and management of the system.

This layer is most closely related to the actual formation of SHNs. Although very function, project or sector-specific, it mainly contains micro-level decision-making. This includes, e.g., having meetings, formulating business plans, or executing feasibility studies. It affects how actors get aligned or what actions are initiated. This can include pricing decisions, production choices or infrastructure investment considerations. It encompasses the daily routines and objects of interest of all actors involved that influence allocating efforts or resources.

4.2 Recap SHN Definition

Section 4.1 outlined the principal dimensions of an SHN: technological innovation along the value chain, actors involved in the system, and the institutional landscape. This section first summarises these findings in a short overview, after which the interrelations of these three dimensions are discussed, answering sub-question 4: *What are the interrelations of these three dimensions – technologies, actors, institutions – within SHN formation?*

A small-scale hydrogen network refers to a localized system or infrastructure designed to cater to a particular region or community instead of a more extensive, national, or global network. For instance, this might entail a project for producing hydrogen on a local level, with a focus on regional approaches to storage, distribution, and utilisation. Important is that at least two connections differ in spatial location. For example, a company producing, storing and using hydrogen on-site is not a network, only if it is connected to, e.g. an external renewable energy provider or part of its hydrogen production is transported to another hydrogen end-user. The scale of available resources, relationships, and expertise in the specific area dictates the implementation of such a network. See Table 12 for the overview and Figure 22 for a visual representation of the dimensions.

Tabel 12 – Summary of SHN definition as outlined in the previous sections

<table>
<tr><th colspan="2">Technology</th><th colspan="2">Actors</th><th>Institutions</th></tr>
<tr><td rowspan="2">Upstream
Sources &
production</td><td>Local renewable energy generation (e.g. solar, wind) and a potential connection to the electricity grid as a back-up, purchasing only certified renewable energy</td><td rowspan="2">Energy providers and hydrogen producers</td><td rowspan="5">Public bodies

Intermediaries

Large stage setters</td><td rowspan="5">Embeddedness

Institutional environment

Governance

Resource allocation & employment</td></tr>
<tr><td>Electrolyser with a capacity between 0.5-50 MW, type depending on local conditions</td></tr>
<tr><td rowspan="2">Midstream
Transport &
storage</td><td>Road transport via tube trailers (or similar alternatives like gas cylinder bundles) and/or short-distance (<30 km) pipeline transport</td><td rowspan="2">Infrastructure and distribution providers</td></tr>
<tr><td>Physical storage predominantly as compressed hydrogen at different pressures, with optional use of rest heat and oxygen</td></tr>
<tr><td>Downstream
Usage or
application</td><td>6th cluster industry
(Heavy) transport and mobility on the road or water
Agricultural sector
Construction sector
Built environment</td><td>End-users / private vs business consumers</td></tr>
</table>

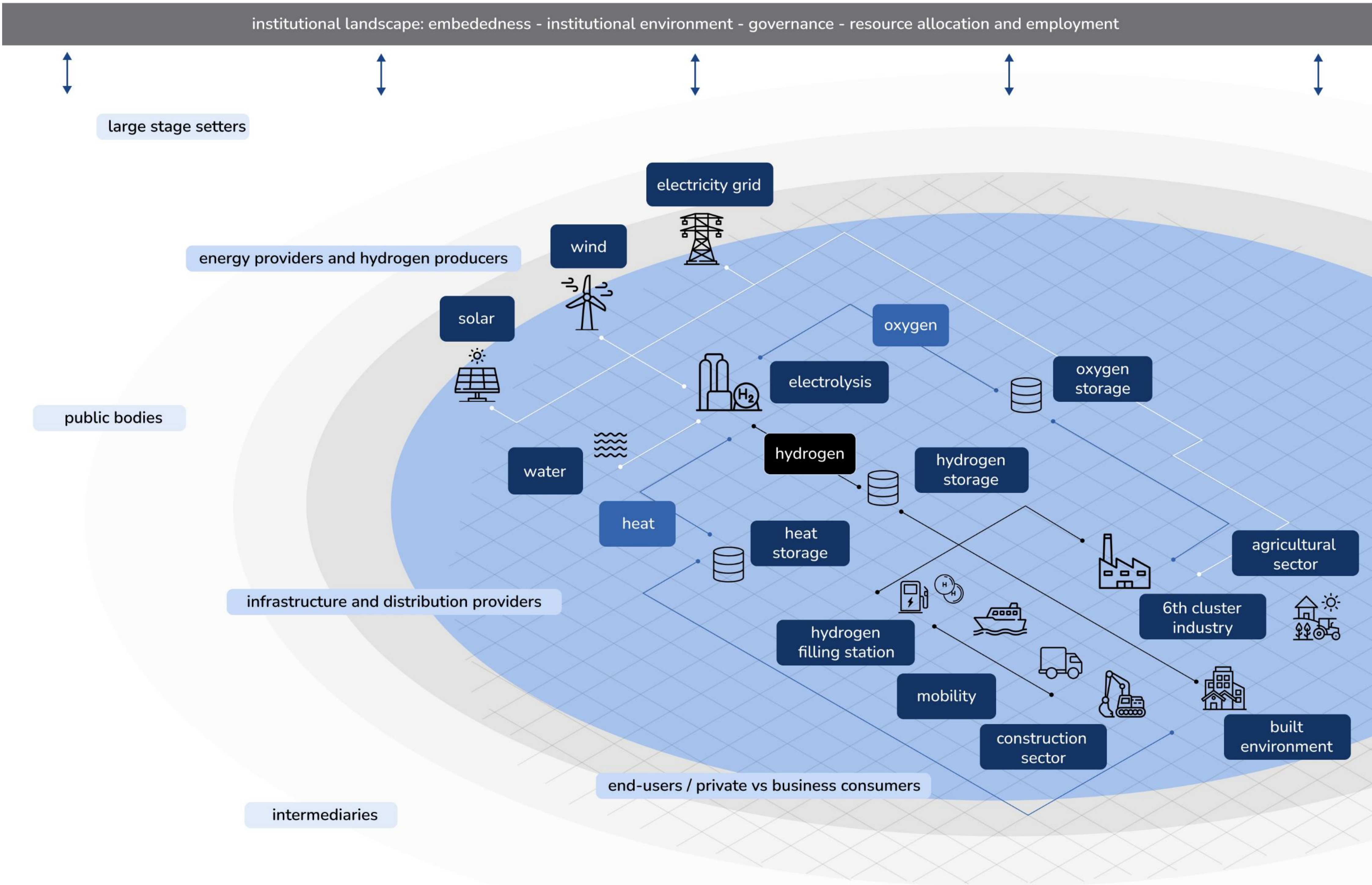

Figure 22 - Visual representation of SHN possibilities as defined in 4.1, figure adapted and adjusted from (Schöffer et al., 2022)

The interrelations between these dimensions are dynamic and complex. For instance, the availability and efficiency of technologies can shape the participation of actors. For example, if a new, cost-efficient electrolysis technology emerges, it may attract more producers to join the network. At the same time, actors drive technological development. Demands from actors can stimulate innovation in hydrogen production and utilization technologies. For example, if a transportation company requires hydrogen for its vehicles, it may push for more efficient and cost-effective production methods. The components of the hydrogen value chain also influence the institutional landscape. Technological advancements can e.g. prompt regulatory bodies to update or create new policies and regulations. For example, if a breakthrough in hydrogen storage technology improves safety standards, it may lead to revised regulations.

Moreover, institutions provide the regulatory framework; they create the rules and standards that govern how technologies are deployed and used within the SHN. They also shape actor behaviour: regulations, incentives, and standards set by institutions influence actors' decisions. For example, subsidies for renewable hydrogen production may encourage more producers to adopt green technologies. Conversely, the actions and demands of actors can influence the development of policies and regulations. For instance, a coalition of hydrogen users might advocate for more supportive policies related to SHN developments, pushing for re-evaluating existing rules.

Overall, these interrelations are crucial for successfully forming and operating a small-scale hydrogen network. A well-balanced and coordinated approach between technologies, actors, and institutions is essential for the network's viability, scalability, and effectiveness.

- Chapter 5 -
Case: Goeree Overflakkee

This chapter provides a focused examination of a potential small-scale hydrogen network forming within this specific region. Beginning with an overview of the area (section 5.1), it sets the stage for a detailed analysis of SHN factors, considering technical, actor and institutional dimensions (section 5.2). The chapter concludes by synthesizing the outcomes, offering valuable insights into scattered SHN developments in the Netherlands (sections 5.3 and 5.4).

"We are the empirical decision makers who hold that uncertainty is our discipline, and that understanding how to act under conditions of incomplete information is the highest and most urgent human pursuit."

— Nassim Nicholas Taleb, 2007

5.1 Overview of the Region

This section explores the recent history of Goeree-Overflakkee, after which the focus is shifted towards a potential SHN-Goeree-Overflakkee (SHN-GO) in this region. It breaks down the SHN-GO from the three key perspectives: technology, actors, and institutional landscape. This multifaceted analysis provides a comprehensive understanding of the case and sets the stage for further exploration.

5.1.1 Background

Goeree-Overflakkee, an island and municipality located in the southwest of the Dutch province of South Holland, anticipated an excess of renewable energy production in 2020 (Jaspers, 2017). To address this, the region explored avenues to utilise this energy efficiently, including its conversion into green hydrogen (#4). Consequently, in 2017, a hydrogen covenant was endorsed by over 25 private, public, and semi-public entities, designating this locale as a pioneering "*energy island*" for green hydrogen initiatives (Waterstofconvenant, 2017). This laid the foundation for the inception of the H2GO program (*Programma - H2GO*, n.d.).

The program encompasses scalable sub-projects that work on the production, distribution, and demand for green hydrogen across diverse societal domains. It aims to establish an open system where hydrogen becomes a viable choice across all sectors. This vision seeks to foster a local marketplace on the island, facilitating the exchange of green hydrogen between suppliers and users. This interconnected approach underscores the exploration of synergies between the various projects within the program (*Programma - H2GO*, n.d.).

The goals of H2GO are contributing to a reliable energy supply with hydrogen, replacing fossil fuels with hydrogen, reusing existing natural gas infrastructure for hydrogen and sharing their knowledge and experiences so that it is possible to duplicate. One of the principal objectives is the decentral, flexible production of green hydrogen, connecting projects close by via suitable hydrogen infrastructure and thereafter exploring connections to more extensive networks to increase flexibility and security of supply. In this case, infrastructure connecting to the "Haven Industrieel Complex" (HIC, Port Industrial Complex) in Rotterdam and/or the national hydrogen backbone of Gasunie (Hellinga, 2019).

Figure 23 provides an overview of the projects connected to the program, including developments for, e.g. mobility, heating of homes, generation and application in agriculture, and balance, buffer and storage applications. A distinction can be made between smaller "stand-alone" projects and bigger interconnected ones that will eventually be linked to a hydrogen infrastructure (#5). We will focus on the later as these can potentially form a network.

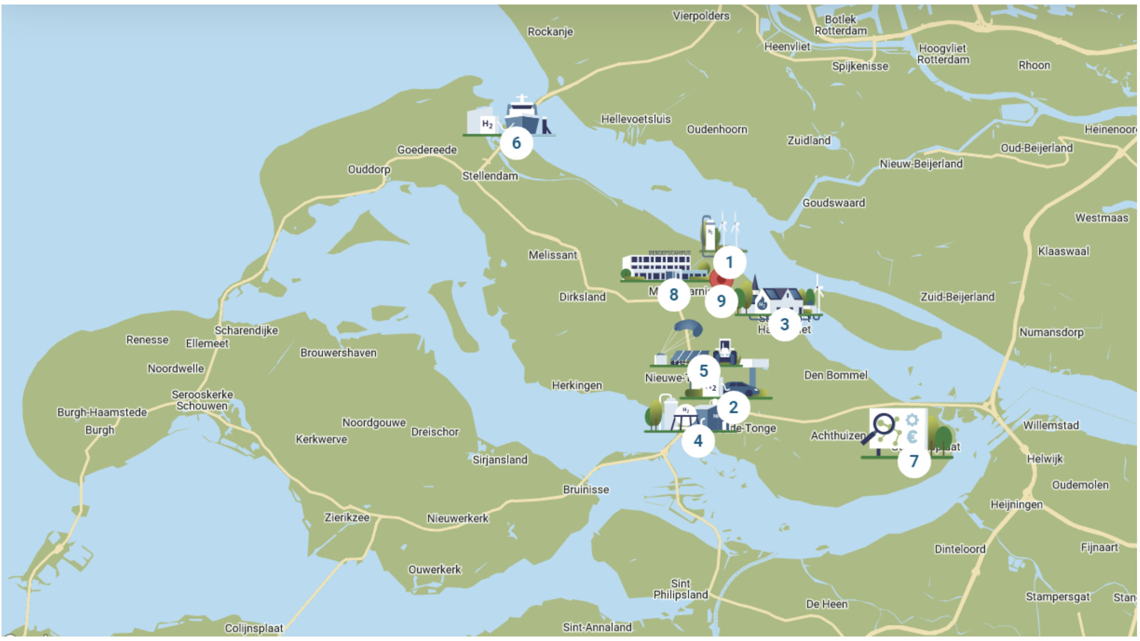

Figure 23 - Overview of the H2GO program projects, (1) Hydrogen Windfarm Van Pallandt, (2) Mobility, (3) Stad Aardgasvrij - Hydrogen City, (4) Energy park Oude-Tonge, (5) Agriculture, (6) Shipping, (7) Production, Transport, Storage, (8) Education, (9) InnovaHub (Programma - H2GO, n.d.).

5.1.2 SHN-Goeree-Overflakkee

Goeree-Oveflakkee is an example of an *aspiring* SHN. It aims to become a localised system or infrastructure that first serves a specific region or community rather than only focusing on a large-scale national or international network. It contains local hydrogen production projects with a regional attitude regarding storage, distribution and end-uses.

To clearly define the SHN-GO, one needs to analyse the technology, the actors and the institutional landscape. Using the concept definition of the socio-technical system of SHNs described in Chapter 4, we can briefly describe the to-be-established SHN-GO from these three perspectives.

Technology

As outlined in section 4.1.1, the technological part of an SHN can be broadly divided into upstream, midstream and downstream (Ma et al., 2023). This division has proven useful in describing an SHN and is therefore employed to illustrate the case characteristics accordingly. See table 13 for a broad overview on the available information on the components of the value chain in the SHN-GO. Figure 24 gives a spatial impression of SHN they are working towards on Goeree-Overflakkee.

Table 13 - Overview of technology related components of the SHN-GO

Upstream Sources & production	Midstream Transport & storage	Downstream Usage or application
The van Pallandt project aims to use the windfarm to produce hydrogen directly on site. The electrolyser capacity has yet to be determined but will be below 50MW.	A new pipeline needs to be built and connected to the Gasunie and Stedin network to transport the compressed hydrogen. The pipeline will be below 20 km.	(6th cluster) industry for processes or energy Built environment (Stad aan 't Haringvliet), heating of homes using hydrogen(boilers)
The Greenpoint fuelling station uses wind and solar energy from the island to produce hydrogen on-site. At the moment, the electrolyser is 2MW but will be scalable in the future as demand increases.	A new pipeline (<10km) from Gasunie (30 bar) will go to a transformer station, after which the existing natural gas infrastructure of Stedin will be used (8 bar) to transport the compressed hydrogen into Stad aan 't Haringvliet. Additionally, on-site pipelines will connect the hydrogen to the filling stations. Lastly, a surplus of green hydrogen can be transported via tube trailers to other consumers.	Filling station for (heavy) transport and mobility on road or water The agricultural sector's diverse uses The construction sector's diverse uses Built environment (Stad aan 't Haringvliet), heating of homes using hydrogen(boilers)
Oostflakkee Industrial Park will be transformed into an energy park. The aim is to realise a 26MW plant for green energy carriers, including hydrogen (and green ammonia).	The produced green energy carriers can be transported via road to consumers or via a pipeline to the Greenpoint fuelling station next to the facility.	Diverse uses, supplying the Greenpoint fuelling station and Stad aan 't Haringvliet, possibilities for close-by greenhouse horticulture businesses

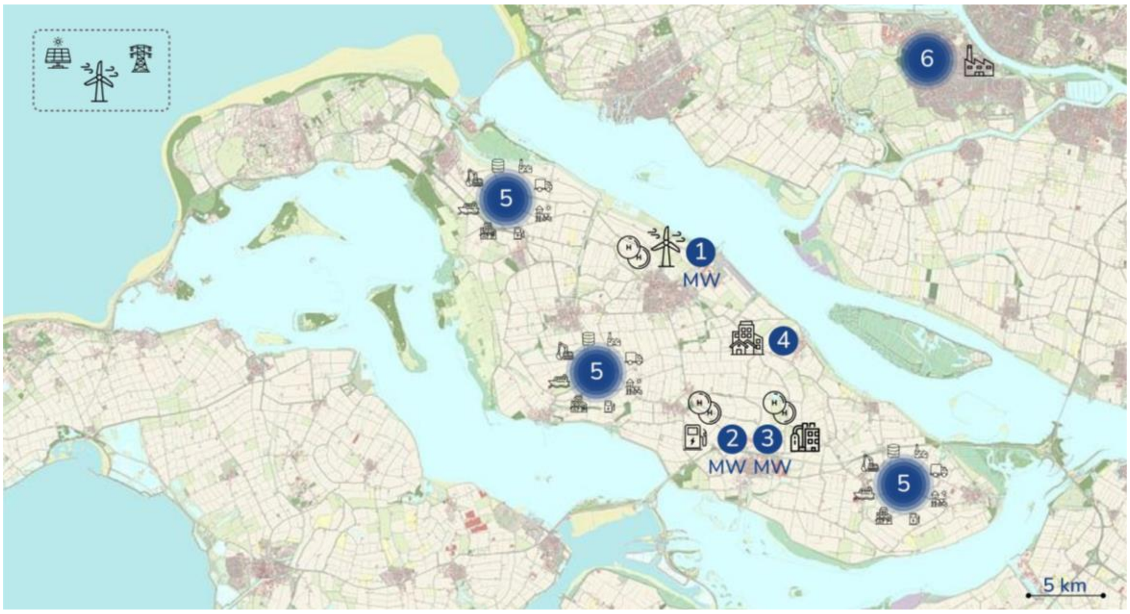

Figure 24 - Draft of the SHN they are working towards on Goeree-Overflakkee, (1) hydrogen production via the van Pallandt wind farm, (2) hydrogen production at the Greenpoint fuelling station, (3) hydrogen production at the Oostflakkee energy park, (4) Stad aan 't Haringvliet as hydrogen consumer, (5) other spread out regional utilisation in e.g. agriculture, mobility or the construction sector, (6) representation of the possible national backbone connection or pipeline to the Rotterdam industry

Actors

As previously highlighted, various public, private and community partnerships are emerging. The projects within the H2GO program all have different initiators and partners engaged in their experimentation and deployment. The following paragraph discusses these actors according to the categorisation established in section 4.1.2, the actor system analysis.

For example, the van Pallandt project consists of the energy supplier and service company Eneco, the cooperation Deltawind as renewable energy supplier and the company Hygro mainly as the state-of-the-art technology provider in addition to service and expert advice for the direct production of hydrogen from wind energy. The main initiators for the Greenpoint refuelling station are the van Kessel Olie, a supplier of (green) fuels, and the local agricultural company van Peperstraten Group. The local government, however, also plays a role here in allowing the hydrogen addition to the fuelling station to go through. Alternatively, the Oostflakkee Industrial Park is a venture of research institutes (TNO), universities (TU Delft), private technology companies (Proton Ventures, Wetec, Siemens Energy) and energy companies (Eneco). For the project making Stad aan 't Haringvliet natural gas-free, the partners include the large stage setter Gasunie, the regional grid operator Stedin, the cooperation Deltawind as an energy supplier and intermediary, the energy service company Essent and the private companies Greenpoint and Hygro. The most important actors are the eventual consumers in the built environment, including the residents and the housing association Oost West Wonen. The local government, Goeree-Overflakkee and the regional government, Zuid-Holland, are also essential parties in facilitating the participation of this experimental set up.

The actors from these specific nodes will need to work together to form links that create the supply and demand network. It is a broad collaboration between the municipality, local entrepreneurs, respected knowledge institutions, education, national players and residents. It is important to note that these partnerships and the definition of roles are still an ongoing and dynamic process. They include many more intermediaries that have not been specifically discussed as they were hard to pinpoint in a short time snapshot and are constantly subject to change to meet the developing project requirements and goals.

Institutions

The four-layer model of Williamson, as discussed in section 4.1.3, is used to define the boundaries of the institutional analyses of the case. Concerning the first layer, embeddedness, it can be argued that Goeree-Overflakkee is a representation of the average Dutch culture relating to values, norms and traditions with a slightly higher inclination towards forward-thinking hydrogen integration-wise because of its more extended history discussing the gas and it's potential to bring value to the region.

However, it becomes evident that when trying to detail layer 2, the institutional environment of the SHN-GO cannot be appropriately outlined here as many laws, rules, regulations and governmental formal arrangements are still to be determined and not at all well-established. Moreover, this environment will differ significantly per sector. For example, hydrogen applied in the built environment will probably have more rules associated with the in-house gas connection, its safety pressure-wise and the security of supply.

In comparison, hydrogen generation will be more closely related to getting the proper certifications and attaining installation subsidies. Fuelling stations might have to deal more with getting the correct permits for building the infrastructure and on-site storage of fuels. The details and complexities of these rules are beyond the scope of this thesis and deserve extensive attention in follow-up research.

The same applies for an analysis of layer 3, the governance. The SHN-GO case is a great example of changing governance structures, specifically towards the concept of "*network governance*" as previously discussed. Projects are individual in character but need each other in order to operate, demanding commitments from several actors. There is a focus on the modularity of the supply chain, characterised by relatively adaptable and interchangeable relationships among actors, allowing for greater agility in responding to changes in future demand, technology, or market conditions. However these set-ups are rather pre-mature, although they serve well for rapidly changing environments and uncertainty, they also evoke a need for closer collaboration and streamlining, which might prove difficult in reality. For the case, a program manager was appointed after the program got to a standstill. Their main role is to accelerate the transition through exploiting the collaborative opportunities and keeping all parties in the loop. As such, insurances, liabilities, and the delineation of responsibilities for both public and private actors are constantly under discussion.

This brings the analysis to layer 4, the allocation of resources and employment. Actors within the to-be-established SHN-GO also work on an array of other projects, and therefore need to allocate there limited time and resources. The complexities of formation are evident, highlighting that a lot of factors need to be taken into consideration which increases the efforts needed in comparison to more established practices. However, from the case study it can be noticed that the intention and enthusiasm is there. Actors *want* to make the quick decisions, and allocate their efforts, but at the same time the complexities of the layers above severely hinder alignment and action taking.

5.2 Case Analysis

In a sustainable energy system, the ability to connect supply and demand in terms of time, capacity and distance, even on a small scale, is essential. The following section touches upon the key enablers and barriers related to the formation of the SHN-GO mentioned by the interview respondents related to the case. The main factors are more specific to a potential SHN on Goeree-Overflakkee but also relevant for other SHN formations, see section 5.3 and 5.4.

The key barriers mentioned were related to the negative business cases, the regulatory void and limited capacities. The key enablers for successful formation included the organisational culture, an innovator mindset, and synergy creation. Figure 25 illustrates how these factors relate to the three dimensions of technology, actors and institutions as described in section 5.1.

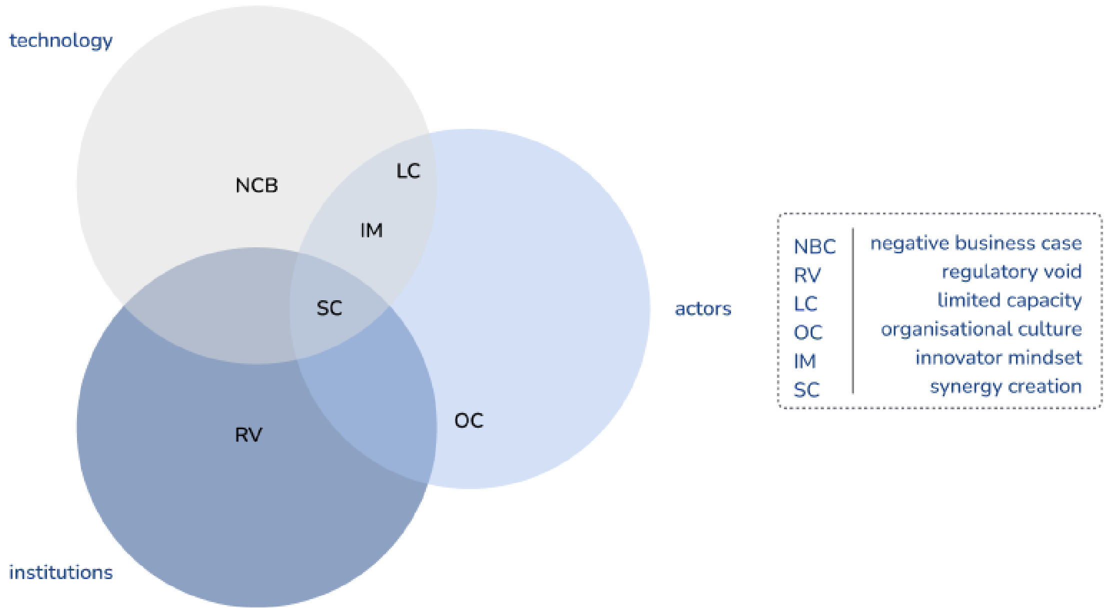

Figure 25 - Interrelation of factors and the three dimensions

Negative business case

This barrier emerged from the in-depth analysis of the case study on Goeree-Overflakkee. It could be considered primarily technology-related as it involves issues with technology adoption, cost-effectiveness, or other return of investment related factors. It mostly encompasses issues rooted in the supply chain, all of which have technological components.

Forming a small-scale hydrogen network presents a challenging business case primarily due to its experimental nature. Sustainable business models for such networks are yet to be established, making it difficult to guarantee long-term profitability. The cost price of hydrogen associated with its production, storage, and distribution remains high or uncertain, further impacting the venture's viability. Additionally, the absence of a liquid market and present-day limited market opportunities could lead to inflated prices, deterring potential consumers.

"We see this in Stad aan 't Haringvliet, which is very costly and has such a negative business case that if it were a normal project, it would actually not take off." (#6)

Moreover, the legal separations of the current Dutch energy system hinder the spreading of investment risks, potentially leaving stakeholders vulnerable to market fluctuations and uncertainties. Therefore, a crucial aspect of success lies in meticulously delineating costs and revenues, ensuring a balanced financial framework for the small-scale hydrogen network to thrive. Despite *potential* governmental subsidies, these challenges underscore the need for a comprehensive and meticulously planned approach before embarking on such a venture.

Regulatory void

The regulatory void barrier was identified through an examination of the challenges faced in implementing steps towards SHN formation. The case study highlighted the need for clear regulations and laws governing various aspects, from safety norms of operational aspects to technology certification and infrastructure permits. This was underlined by statements of the interview respondents who emphasized the need for clarity and endorsements. It is a clear example of an institutional barrier, pertaining to the absence or inadequacy of regulations and laws necessary for the formation of small-scale hydrogen networks.

"... everything must be reinvented..." (#4)

For Goeree-Overflakkee, one crucial aspect is the regulation that ensures that the inhabitants of Stad aan 't Haringvliet receive a continuous supply of hydrogen, even during extreme cold weather conditions (e.g. -17 degrees for three weeks straight). This, unfortunately, necessitates the transport capacity, the spare capacity and the production capacity of hydrogen to be much higher than otherwise required, which raises efficiency concerns when the used electrolysis installations are largely underutilised. Moreover, current regulations do not support hydrogen value chain formation, e.g., previous gas laws are unsuitable for the intermittent supply of green hydrogen production. Combining subsidies or other financial (incentive) instruments also lacks clear guidelines, further contributing to regulatory uncertainty.

Another layer of complexity is added through the legal right to a natural gas connection. The project would go through for Stad aan 't Haringvliet if >70% of inhabitants said yes. However, it is not yet legally established that that is sufficient; the number is based on the percentage required from residents of a housing corporation that wants to implement sustainability improvements. This, combined with all actors being constantly restricted in their operating fields, highlights the intricate web of regulatory challenges.

Limited capacity

The barrier of limited capacities was discerned from an exploration of the significant human and technological resources needed for the formation of the SHN-GO. It straddles both technological and actor-related aspects because it encompasses challenges related to both the physical infrastructures and the capabilities of actors in the context of forming and operating an SHN.

"Capacities must be scaled up, and at the same time, the capacity must be found for that" (#5)

This demands a dual approach. On the one hand, capacities across various aspects, such as human resources for construction, transportation, and application development, must be escalated. This includes ensuring a sufficient workforce in industry supply chains, installers, and other skilled personnel. At the same time, it is difficult for smaller actors, particularly public bodies, to get the resources, people, and teams together to run the required experimentation projects. Interview respondents have emphasised several times that projects are short of the hands of civil servants and business actors who can (and have to) shape these kinds of transitions.

On the other hand, it is imperative to efficiently utilise the capacities of the technological components of an SHN. What can be done to limit loses? How can we optimize renewable energy use during different peak periods? How can we tackle the capacity problems of the electricity grid? This is all related to the capacities of the cables, pipelines or storage units. In the realm of hydrogen, transport, storage, and capacity are intricately interlinked. The higher the pressure, the quicker it is to transport and the easier it is to fill up, e.g. a hydrogen-fuelled vehicle at the right pressure (>350 bar). However, the safety norm for the regional grid operators pipelines is 16 bar. In other words, this requires a strategic allocation of resources and a comprehensive approach to maximise all the available capacities to increase the speed of getting hydrogen to storage units, applications or end-users. This again requires skilled individuals and teams available to manage the project effectively.

Organisational culture

The enabler of a conducive organisational culture was identified as a critical factor contributing to the success of SHN formation. The case study revealed this plays a pivotal role in creating a unified and collaborative environment. It is an important aspect related to the actor dimension, but also pertains to the governance layer of the institutional landscape. It influences how actors collaborate, communicate, and work towards common goals.

"You have this saying "you go further together, you go faster on your own" and you have to find a balance... actors have their own interest in such projects, you have to be able to communicate about them" (#12)

Visibility, characterised by unified voices within the sectors, creates a solid collective presence that garners attention and support. Initiatives with pre-work completed tend to stand out, as they offer a clearer path forward, making it easier for actors to join in. Crucially, top-down support reinforces the importance and commitment to the venture, while bottom-up backing from stakeholders fosters a sense of ownership and dedication to achieving the goals.

Collaboration and forming strategic partnerships are essential elements, pooling resources and expertise for mutual benefit. A culture prioritising transparency and trust further solidifies the foundation for successful collaboration. Clearly defined scopes of projects, supported by robust letters of intent and well-structured business cases, provide a tangible roadmap, instilling confidence and attracting key players to participate in the development of small-scale hydrogen networks.

Innovator mindset

Several interview respondents highlighted the importance of stepping outside the current norms of the energy landscape. As such, an innovator mindset is a powerful catalyst for establishing small-scale hydrogen networks. It directly impacts the technological aspects of a project as individuals are more likely to engage with, develop, and adopt new technologies or trajectories. Concurrently, this mindset is related to the actor domain. It encourages a proactive approach to problem-solving, a willingness to take risks, and a drive to explore creative new avenues, driving technological advancements.

"We need to start practising with these kinds of localised networks" (#3)

For example, it was observed that energy cooperatives that recognize the limitations within their regions demonstrate a forward-thinking approach. They acknowledge the need for novel solutions, as is demonstrated with the Goeree-Overflakkee case. Moreover, risk-taking individuals play a crucial role, willing to venture into uncharted territories and confront challenges head-on. A continuous learning and experimentation culture is essential, fostering a community of actors eager to test and refine new ideas. This spirit extends to consumers, who are early adopters, demonstrating a willingness to embrace innovative energy solutions, e.g. driving a hydrogen-powered vehicle or being open to hydrogen for heating their homes. Supportive investors willing to take calculated risks and believe in the future of hydrogen technology are indispensable in providing the financial backing necessary for these ventures. Moreover, social acceptance and enthusiasm for sustainable energy initiatives play a pivotal role in propelling the development of small-scale hydrogen networks, creating a conducive environment for progress and sustainability.

Synergy creation

While synergy creation involves collaboration among actors, it also has an institutional-technological aspect. It can be linked to external partnerships that involve leveraging existing infrastructures or systems, which are part of the broader institutional and spatial context. It was identified as a fundamental enabler for establishing the SHN-GO. This concept spans across actors, technology, and institutions because it involves collaborative efforts among individuals, the optimization of technological components, and the establishment of supportive frameworks and networks. The case study demonstrated the need for exploring these various elements for mutual benefit.

> *"It is a condition for us that a project has multiple synergy benefits." (#8)*

Leveraging synergies is thus integral to success on all levels. Various elements with substantial potential can be harnessed to drive progress, and a balance between supply and demand becomes more attainable, ensuring a stable network. This can take the form of using surplus heat and oxygen from electrolysis to be repurposed for low-heat applications or in sewage treatment installations. While the financial gains from utilising these "rest products" may be modest, it makes the ongoing efficiency debate more positive when comparing the use of hydrogen to full electrification. Similarly, in certain areas, hydrogen integration can alleviate electricity grid congestion issues, or excess hydrogen production can find alternative valuable applications or end-users, enhancing the cost-benefit trade-off and increasing the installation's efficiency. Synergy creation is also essential in supporting a shared vision and common goals that unite stakeholders across the value chain, aligning efforts towards a collective aim. Heightening efficiency and optimizing returns on investment become achievable through these synergistic endeavours. For instance, hydrogen producers can collaborate with equipment manufacturers to develop efficient and tailored electrolysis systems. This illustrates the multifaceted benefits of collaborative efforts.

In conclusion, the formation of the SHN-GO hinges less on technological feasibility, which has proven both attainable and safe, and more on the chaos of institutional rules and financial viability. This environment and the need for skilled individuals and new governance structures emerge as the primary hindrances to a successful transition. These factors, if not appropriately addressed, render the integration of hydrogen into our energy system particularly unfeasible. It becomes evident that fostering new configurations of actors and promoting collaborative efforts is a shared challenge that must be undertaken collectively. The discussed enablers highlight that by dismantling institutional barriers and embracing innovative collaborative partnerships, the path towards scattered SHN developments can be paved.

5.3 Scattered SHN Developments

The phenomenon of the SHN-GO is not an isolated development. Across the Netherlands, a constellation of initiatives is slowly beginning to take form, aligning with the concept definition of SHNs as proposed in Chapter 4. These emerging projects, driven by a shared commitment to sustainable energy solutions, are making strides in integrating hydrogen on a smaller scale. Examples include for instance:

A feasibility study done in 2022 on the formation of a local hydrogen value chain in and around the municipality of Terneuzen in the province of Zeeland. One of the interviewees provided this confidential report delineating the decision-making steps and factors to be taken into account. In short, the focus was on providing alternative opportunities for the close by industry and the heavy mobility in the region. The research was based on local generation of renewable energy, processing this energy into hydrogen, distribution via tube trailers with the possibility of a future pipeline, and procuring small-scale demand. The conclusion was that in theory the realisation of such a network is technically, organisationally and legally possible if hydrogen demand is high enough.

Another example, discussed with one of the interviewees, is the formation of a network in the municipality and surroundings of Zutphen. The local energy cooperation is in discussion with a gas company willing to invest in an electrolyser. The cooperation will provide the renewable energy for the production of hydrogen; then to be used by several companies in the region via a small-scale distribution network via road. The electrolyser will be placed on-site of a hydrogen utilising company on the business park de Mars, also known for other developments regarding electricity sharing. The timeline is that this year a declaration of intent is to be signed by all involved actors on follow-up steps technically, financially and legally.

The project GROHW, was also mentioned as an example of a collaboration for the formation of a small-scale hydrogen network or "*a local green hydrogen hub*". Their aim is to optimize the hydrogen value chain on a small-scale. At the moment they are busy experimenting in the city of Deventer as a pilot case, after which the lessons learned can serve as a blueprint for other Dutch cities. They pay special attention to the system design, the electrolyser choice, the aspect of system integration, a discussion of a trading platform, and business case and financeability analysis (Schöffer et al., 2022). Figure 26 shows a spatial impression of the SHN they are working towards.

Figure 26 - GROHW geographical overview of the actor and infrastructure network (Schöffer et al., 2022)

5.4 The Integrated Value Chain

This section leverages additional insights gathered from the interviews specifically for small-scale developments, besides the ones mentioned in section 5.2. It aims to synthesize existing literature on barriers of hydrogen integration, providing a comprehensive understanding of the challenges that can impede progress in this domain. By combining these sources of knowledge, the aim is to give an impression of the barriers and enablers (Figure 27 & 28) that pertain specifically to the Dutch context. Based on the previously identified factors for the SHN-GO, the identified barriers and enablers are categorised withing these six categories. The following paragraphs delve into an elaboration of each identified factor, shedding light on their respective impacts and implications for small-scale hydrogen network formation.

It's important to acknowledge that enablers can sometimes turn into barriers, and vice versa. For instance, obtaining the right subsidy, intended as an enabler, can become a significant barrier if it leads to future financial dependency. Similarly, advanced technologies, while enabling, may require costly upgrades or specialized expertise, potentially hindering widespread adoption and creating future barriers. Striking a balance is crucial for building a sustainable and resilient small-scale hydrogen network.

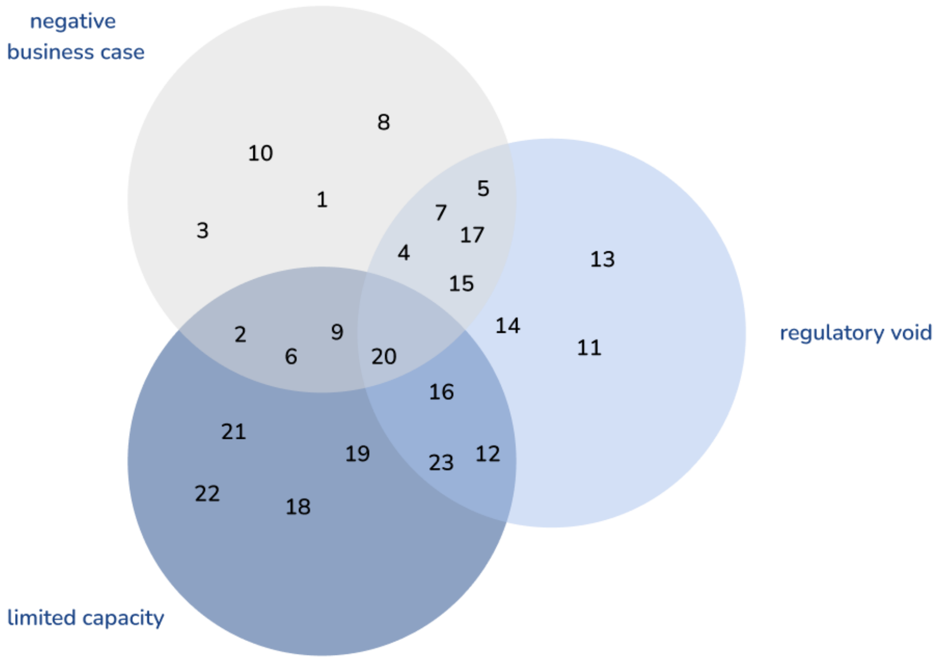

Figure 27 - Overview of barriers and their interrelations: (1) Quality Assurance for Hydrogen Viability, (2) Uncertainty about Backbone Connections, (3) Uncertainty in Consumer Base, (4) Cost of Hydrogen Production, (5) Challenges in Acquiring Suitable Subsidies, (6) Renewable Energy Source Adequacy, (7) Strategic Placement of Electrolysers, (8) Local Opposition or Public Perception, (9) Lack of Economics of Scale, (10) Technology Maturity and Capital Intensity, (11) Absence of Clear Safety Regulations, (12) Impact of License and Permit Providers, (13) Role of Temporary Rules and Tolerance Policies, (14) Hydrogen Blending into the Natural Gas, (15) Lack of Standardization for Small-Scale Infrastructure, (16) Ensuring Security of Hydrogen Supply, (17) Market Price Incentives, (18) Limited Transportation Modes for Hydrogen Distribution, (19) Municipalities' Responsibility and Commitment, (20) Avoiding Procrastination and Delays in Implementation, (21) Shortage of Skilled Personnel, (22) Limited Availability of Infrastructure Components, (23) Regional Grid Operator and Hydrogen Quality.

Negative business case

1. Quality Assurance for Hydrogen Viability
   Maintaining the proper purity levels of hydrogen is crucial for its acceptance and success in the market. This involves employing distribution options that ensure the quality of hydrogen for its intended end-uses. However, this requirement introduces additional costs, particularly in sectors like mobility, where a dedicated infrastructure or end-use purification may be necessary. This cost increment impacts the overall business case, making it important to balance quality requirements with cost considerations, especially within small-scale integration (#8, #9, #12).
2. Uncertainty about Backbone Connections
   Uncertainty regarding the availability and accessibility of connecting small-scale projects to a future backbone can introduce financial uncertainties that negatively affect the business case. Having a clear vision or at least a conceptual idea of where possible connections to a national or regional backbone can be made in the future is essential. This forward-thinking approach allows for the strategic placement of assets and prepares for potential future users, thereby strengthening the business case (#3, #6, #8, #11).
3. Uncertainty in Consumer Base
   Ambiguity surrounding the number of potential consumers poses a challenge in establishing a clear supply and demand delineation for hydrogen. This necessitates simultaneous efforts in demand-side management and encouragement for hydrogen production. Having a well-defined and committed consumer base is crucial for building a solid business case. For instance, a city with a larger population might be more economically viable to start with than targeting individual farmers (#5, #7, #12).
4. Cost of Hydrogen Production
   The economic viability and profitability of small-scale hydrogen integration hinge on the stable and affordable cost of hydrogen production. This is particularly pertinent in localized settings. Factors such as increased taxes on fossil fuels, decreasing renewable energy costs, and the commercialization of hydrogen-related technologies can positively influence its cost-price (#4, #7, #8, #9, #10, #11, #12).
5. Challenges in Acquiring Suitable Subsidies
   The inability to secure appropriate subsidies for projects, even after obtaining permits, severely weakens the business case. Sufficient coverage of both initial investment costs and operational expenses is imperative for making a favourable financial investment decision. The availability of subsidies is crucial for offsetting some of the associated costs and ensuring the project's economic viability (#1, #7, #9).
6. Renewable Energy Source Adequacy
   Inadequate availability of renewable energy sources can necessitate the purchase of renewable electricity from the grid for hydrogen production. This inherently increases production costs, negatively impacting the business case. The intermittent nature of renewables further compounds this challenge. It is imperative to secure a reliable and sufficient supply of renewable energy for green hydrogen production in the specific region to ensure economic viability (#2, #3, #4, #7, #12).

7. Strategic Placement of Electrolysers

   Optimal placement of electrolysers is critical for a successful business case. For instance, siting electrolysers at fuelling stations and in proximity to regional grid access allows for efficient utilization and minimizes unnecessary transportation losses. This strategic placement enhances the economic viability of the venture and contributes to a more robust business case (#2, #5, #6, #10, #12).

8. Local Opposition or Public Perception

   Public perception and community acceptance of hydrogen-related projects can influence the business case. Negative attitudes, concerns over safety, or opposition from local stakeholders may lead to delays, increased permitting costs, or even project cancellations. Engaging with communities and addressing concerns is essential for building trust and ensuring project success (#1, #2, #3).

9. Lack of Economics of Scale

   Small-scale hydrogen production and distribution may suffer from a lack of economies of scale, resulting in higher production costs per unit of hydrogen. Larger-scale operations often benefit from lower unit costs due to higher production volumes. Overcoming this barrier may involve innovative strategies such as cooperative ventures, aggregation of demand, or shared infrastructure to achieve economies of scale (#1, #2, #5, #6, #12).

10. Technology Maturity and Capital Intensity

    Developing and implementing advanced hydrogen technologies can be capital-intensive, especially for small-scale projects. Additionally, the maturity of some technologies may still be evolving, potentially leading to higher costs, technical challenges, and uncertainties. Striking a balance between investing in cutting-edge technologies and achieving economic viability is crucial for a positive business case (#7, #9, #11, #12).

Regulatory void

11. Absence of Clear Safety Regulations

    In small-scale hydrogen integration, the absence of clearly defined safety regulations can lead to delays and uncertainties. This is particularly critical as emerging hydrogen technologies are implemented in new use areas. Establishing reasonable safety demands, specific to the unique characteristics of small-scale projects, is crucial for dispelling myths surrounding potential hazards and risks associated with hydrogen operations (#1, #3, #4, #8, #9, #11).

12. Impact of License and Permit Providers

    License and permit providers, including e.g. municipalities and safety regions, play a pivotal role in the regulatory process. Their decision-making timelines and adherence to existing industrial standards versus adapting to hydrogen implementations closer to the built environment, can significantly impact the pace of integration. It is essential for these providers to actively engage in the process to facilitate innovative solutions, considering not only prevention and control measures (#1, #2, #3, #6, #7, #8, #10, #11)

13. Role of Temporary Rules and Tolerance Policies

Temporary rules and tolerance policies serve as essential mechanisms for enabling experimentation in small-scale hydrogen integration. However, it is equally important to strike a balance. While these policies provide a necessary stepping stone, there is a need for more certainty regarding the future regulatory framework. Lengthy processes for policy creation and uncertainty about their continuity can add regulatory complexities, potentially impeding progress in small-scale projects (#8, #10).

14. Hydrogen Blending into the Natural Gas

Regulatory impediments preventing the blending of hydrogen into the natural gas grid can hinder the development of a sustainable energy system, especially on a small scale. Incrementally increasing the allowable percentage of hydrogen in the natural gas grid is critical. This approach not only enhances the security of hydrogen production across the Netherlands but also facilitates a smoother transition to full hydrogen grids, particularly in localized settings (#8, #12).

15. Lack of Standardization for Small-Scale Infrastructure

The absence of standardized guidelines and specifications for small-scale hydrogen infrastructure can lead to inconsistencies and uncertainties in design, construction, and operation. Standardization efforts specific to small-scale applications are necessary to ensure safety, quality, and interoperability across projects (#5, #9).

16. Ensuring Security of Hydrogen Supply

Small-scale hydrogen projects can face the challenge of guaranteeing a reliable supply of hydrogen due to being obligated to follow natural gas laws that do not fit the intermittency of hydrogen production. It is therefore imperative to integrate connections that provide flexibility in managing supply and demand discrepancies. This may involve the incorporation of buffer units, allowing for adjustments in pipeline pressures, and expanding supply pathways. These measures are essential to establish a robust and secure hydrogen supply chain (#2, #4, #8, #12).

17. Market Price Incentives

Failing to provide the right price incentives through e.g. only tax measures can create uncertainty for hydrogen projects, as they are subject to annual adjustments, not offering long-term security. In contrast, the SDE++ provides a more stable legal framework, which is not easily altered. This offers greater predictability, reinforcing the importance of a well-defined and stable regulatory framework (#3, #9, #11).

Limited capacity

18. Limited Transportation Modes for Hydrogen Distribution

In certain areas in the Netherlands, the availability of transportation modes suitable for hydrogen distribution may be constrained. This limitation can hinder the efficient delivery and utilization of hydrogen. For instance, in some cases, pipeline transport may be the desired mode, but it might not yet be feasible. It is crucial to explore and implement distribution options that align with the specific demands and purity requirements of hydrogen. This ensures that hydrogen can be effectively transported and utilized within the region aiming to establish a network (#1, #4, #7).

19. Municipalities' Responsibility and Commitment

    The successful transition towards small-scale hydrogen integration in the Netherlands depends on the active involvement and commitment of various stakeholders, including municipalities. However, there may be instances of inadequate responsibility and commitment, possibly due to political considerations or a desire for re-election. Overcoming institutional complexities is essential. Civil servants play a pivotal role in driving the transition, and it is imperative that they prioritize and fulfil their responsibilities, even in resource-constrained environments (#3, #4, #5, #7, #11, #12).

20. Avoiding Procrastination and Delays in Implementation

    The limited capacity inherent to small-scale hydrogen projects can lead to a scenario where stakeholders, such as public bodies and investors, may hesitate or delay their involvement. This can create a bottleneck effect, where progress is stalled as each party waits for the others to take the lead. For instance, initiators may await the establishment of governance frameworks, while public bodies may await concrete initiatives from initiators. Investors may hold off until the viability of hydrogen as an alternative energy source is assured. Overcoming this barrier necessitates proactive and synchronized efforts from all stakeholders, ensuring a coordinated and timely progression of projects (#5, #7, #11).

21. Shortage of Skilled Personnel

    A shortage of skilled personnel, including technical and legal experts and entities knowledgeable in the intricacies of small-scale hydrogen projects, can limit the capacity to effectively manage the technical and institutional complexities involved. In the Dutch context, having individuals and entities with the requisite expertise is crucial for navigating technical, regulatory, legal, and administrative challenges. Addressing this barrier requires targeted efforts to enhance expertise and ensure that there are ample resources available to manage and oversee the implementation of these hydrogen projects (#2, #3, #5, #6, #10).

22. Limited Availability of Infrastructure Components

    The availability of essential infrastructure components, such as hydrogen storage tanks, fuel cells, and refuelling stations components, may still be limited. This scarcity can impede the scalability and deployment of small-scale hydrogen projects. Efforts should be made to develop a robust supply chain for these components to ensure a steady and reliable source for projects to develop (#7, #9).

23. Regional Grid Operator and Hydrogen Quality

    The national grid operator's exclusive responsibility for hydrogen quality management places a significant constraint on regional grid operators. They are left with the role of overseeing processes without direct influence, revealing a limitation in their capacity. Managing hydrogen quality necessitates specific skills and equipment, and if regulations don't explicitly task regional operators with this responsibility, it can pose challenges for end-use applications that require precise purity levels. This underscores the importance of clear regulatory frameworks to optimize the potential of hydrogen integration at a regional level (#10, #12)

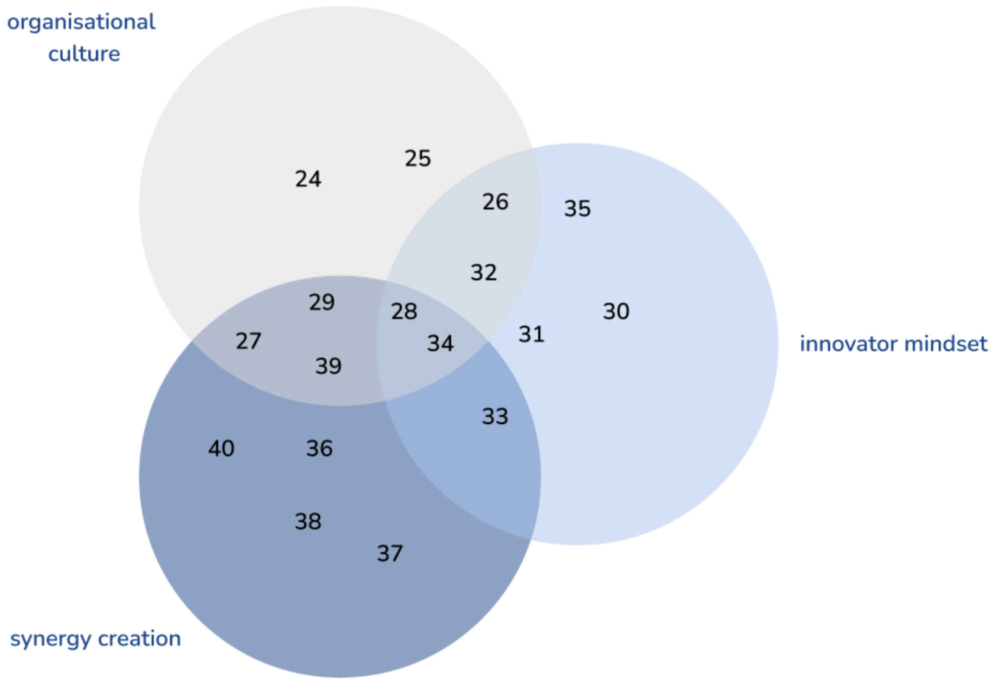

Figure 28 - Overview of enablers and interrelations: (24) Well-Defined Actor Roles, (25) Dedicated Energy Teams, (26) "Hydrogen First" Standpoint, (27) Partial Socialization of Costs, (28) Knowledge Sharing and Collaboration Platforms, (29) Inclusive Stakeholder Engagement, (30) Innovative Local Visions and RES Implications, (31) Gradual Process Conversion in Companies, (32) Continuous Learning and Adaptability in Spatial Developments, (33) Courageous Actors in the Transition, (34) Public-Private Partnerships for Pilot Projects, (35) Regulatory Sandboxes for Innovation, (36) Cross Sectoral Alignment and Financial Support, (37) Scalability of Electrolyser Installations, (38) Optimal Number of Actors for Smooth Operations, (39) Coordinating Entity, (40) Stimulating a Free Market.

Organisational culture

24. Well-Defined Actor Roles

Clearly defined roles within an organisation or project provides individuals and entities with a clear understanding of their responsibilities and possible contributions. This clarity fosters an environment of efficiency, where each participant can focus on executing tasks that align with their expertise and role. This, in turn, prevents misunderstandings, enhances coordination, and encourages an atmosphere of innovation and progress. In the rapidly changing energy landscape, where actors may face institutional restrictions, well-defined roles become crucial for effective collaboration and successful project implementation (#1, #4, #8, #9, #12).

25. Dedicated Energy Teams

Organisations or municipalities that establish dedicated energy teams or employ personnel specifically focused on increasing energy sustainability practices can significantly accelerate the integration of hydrogen. These teams serve as focal points for knowledge, expertise, and action in the pursuit of sustainable energy solutions. When such dedicated resources are in place, the process of planning, developing, and executing hydrogen initiatives becomes more streamlined. Conversely, in cases where knowledge and resources are lacking, additional time and efforts are required to educate and mobilise stakeholders (#3, #4, #10, #12).

26. "Hydrogen First" Standpoint

An organisational culture that prioritizes hydrogen as a primary solution in the pursuit of sustainable energy signifies a strong commitment to innovation. This approach encourages a proactive stance towards integrating hydrogen technologies across various aspects of operations and projects. While hydrogen is sometimes viewed as a secondary solution, especially in comparison to electricity, it holds the potential for greater capacity efficiency. It's important to note that considerations, such as the cost-effectiveness of pipelines compared to cables, should be taken into account (#6, #9).

27. Partial Socialization of Costs

Cultivating a culture that encourages the sharing or spreading of costs among actors is instrumental in fostering collaboration and synergy creation. For example, in the case of grid operators, the practice of receiving a portion of their investments back through grid management tariffs is a model of cost-sharing. Extending similar principles to hydrogen-related integration initiatives can provide financial incentives for actors to participate and invest in projects. This approach promotes a collective effort towards achieving common goals in the transition to sustainable energy solutions (#2, #5, #10).

28. Knowledge Sharing and Collaboration Platforms

Establishing platforms and forums for knowledge sharing and collaboration, both within organisation and with external partners, encourages the exchange of ideas, best practices, and lessons learned. This culture of open communication and collaboration accelerates the development and implementation of effective hydrogen integration strategies on a small-scale (#1, #4, #5).

29. Inclusive Stakeholder Engagement

Actively involving a diverse range of stakeholders, including community members, industry experts, and government representatives, fosters a culture of inclusivity and shared ownership. This approach ensures that various perspectives and expertise contribute to decision-making, leading to more well-rounded and sustainable hydrogen integration projects (#2, #5, #12).

Innovator mindset:

30. Innovative Local Visions and RES Implications

    Regions that embrace innovative visions and are open to exploring new solutions play a crucial role in enabling hydrogen integration. The Regional Energy Strategies (RES) further amplifies this impact, shaping the energy landscape. Municipalities with forward-thinking transition strategies, especially regarding heat and energy solutions, create opportunities for suitable regions to integrate hydrogen seamlessly (#4, #5, #7, #10).

31. Gradual Process Conversion in Companies

    Incremental adoption of hydrogen in industrial processes demonstrates an innovator mindset. Rather than an all-or-nothing approach, companies that phase in hydrogen integration, such as using hydrogen in a fraction of their machinery, reduce financial risks. This step-by-step conversion allows for experimentation and learning, ultimately smoothing the transition (#10, #12).

32. Continuous Learning and Adaptability in Spatial Developments:

    Embracing continuous learning and adaptability in spatial planning and development is crucial for fostering an innovator mindset. This approach recognizes that the energy landscape is dynamic and requires ongoing adjustments to accommodate emerging technologies like hydrogen. Staying open to spatial innovations ensures that regions remain at the forefront of sustainable energy solutions (#4, #6, #10).

33. Courageous Actors in the Transition

    Actors who demonstrate courage in the transition towards hydrogen integration are pivotal enablers. This courage encompasses a willingness to challenge conventions, take calculated risks, and pioneer new approaches. Such individuals and organizations play a critical role in driving innovation and pushing boundaries in the pursuit of sustainable energy solutions (#1, #3, #7, #9)

34. Public-Private Partnerships for Pilot Projects

    Establishing partnerships between public entities, private companies, and research institutions for pilot projects can drive innovation. These collaborations allow for real-world testing of new technologies, providing valuable insights and paving the way for broader adoption of hydrogen solutions. New forms of communication might need to be employed to keep these relations healthy and overcoming challenges of working B2B or B2C (#6, #10).

35. Regulatory Sandboxes for Innovation

    Creating regulatory sandboxes provides a controlled environment where innovators can test and validate new hydrogen technologies without immediate regulatory constraints. This encourages experimentation, learning, and the development of breakthrough solutions (#8, #10)

Synergy creation

36. Cross Sectoral Alignment and Financial Support

    Achieving alignment across different sectors and securing consistent financial support is crucial for synergy creation. When projects from various sectors work together towards a common goal, it streamlines efforts, maximizes resource utilization, and strengthens the overall network. Moreover, having a unified source of funding eliminates potential delays or complications that can arise from diverse funding streams (#4, #7, #9).

37. Scalability of Electrolyser Installations

    The ability to scale electrolyser installations is a key enabler for synergy creation. It allows for flexibility in adjusting the size of the hydrogen production infrastructure based on anticipated demand. While determining the initial size may be challenging, having a scalable system ensures that production can be adjusted to meet evolving requirements (#5, #7, #12).

38. Optimal Number of Actors for Smooth Operations

    Striking the right balance in terms of the number of actors involved is essential for smooth operations and effective resource utilization. Too few actors may lead to inefficiencies, while an excessive number can overcomplicate processes. Finding the optimal mix ensures that expertise is effectively leveraged without unnecessary complexity (#3, #8, #9, #12).

39. Coordinating Entity

    A coordinating entity plays a pivotal role in synergy creation by connecting essential management functions. This entity is responsible for planning, communication, and direction, ensuring that efforts across different projects and sectors are aligned. It helps maintain focus, resolve conflicts, and facilitate efficient progress towards shared objectives (#3, #5, #10)

40. Stimulating a Free Market

    While not yet possible due to the lack of an established market, stimulating a free market for actors is an important future enabler. This would grant actors greater flexibility in making choices related to hydrogen integration. A free market environment encourages competition, innovation, and the efficient allocation of resources, ultimately enhancing synergy creation (#6, #8, #9).

In conclusion, this chapter provides a detailed analysis of the barriers and enablers specific to the formation of small-scale hydrogen networks in the Dutch context. By synthesizing insights from the case study, the interviews and existing literature, a comprehensive understanding of the challenges impeding progress in this domain is presented. The nuanced understanding of these factors underscores the dynamic nature of enablers and barriers, illustrating their interrelations and interdependence. The identified factors serve as a valuable guidepost for actors involved in the transition towards a more sustainable energy future.

- Chapter 6 -
Discussion & Conclusion

This chapter discussed the main findings by answering the sub-questions and the main research question (section 6.1). The concept of SHNs is reflected upon (section 6.2), after which the generalisability of the findings is discussed (section 6.3). Practical recommendations are given (section 6.4), and the limitations of the study are outlined (section 6.5). Lastly, the chapter ends with suggestions for further research (section 6.6).

"The best way to predict the future is to invent it."

— Alan Kay, 2008

6.1 Main Findings

This research aimed to explore the formation of small-scale hydrogen networks by answering the research question: *What are the barriers and enablers of small-scale hydrogen networks in the Netherlands?* This was made possible by describing the *concept* of SHNs according to their required technical specifications, the involved actors and interrelations, and the institutional landscape affecting its emergence.

The first sub-research question served to contextualise the operational part of an SHN. The answer to this question *"What would be the technical specifications, the limitations, and potential applications of an SHN?"* is given by describing the small-scale value chain divided into upstream, midstream and downstream. A small-scale hydrogen network encompasses key technical specifications that will differ greatly depending on the specific needs and resources essential for its operation within a region. However, this network typically features electrolysis units with capacities below 50 megawatts, with a primary focus on green hydrogen production from local renewables such as wind and solar with a possible connection to the main electricity grid. The electrolysis process, facilitated by these units, involves the conversion of water into hydrogen and oxygen using electrical current. The resulting hydrogen, usually in compressed form, becomes the commodity of the SHN. Transportation modes predominantly involve road-based distribution via specialized vessels like tube trailers, designed for shorter distances, or pipelines for more continuous supply over longer distances.

The hydrogen produced finds diverse end-uses across various sectors, including industrial applications, transportation, energy storage, and even integration into the built environment. These technologies include e.g. hydrogen-powered vehicles, combined heat and power systems or fuel cells for stationary power generation. Moreover, the SHN may integrate advanced purification and compression technologies to meet specific quality standards for different end-users or for aiding the utilisation of released heat and oxygen during production.

The second sub-research questions "Who would be the actors involved and what are their objectives, potential roles and interrelations in an SHN?" more specifically focused on the identification of actors and their roles within the contemporary system. In a small-scale hydrogen network, a diverse array of actors would play crucial roles, divided into six key categories ranging from core SHN actors to a shell of enablers. Category 1 encompasses energy providers and hydrogen producers, including energy supplier companies, renewable energy suppliers, and hydrogen producers or production facilities. They form the bedrock of hydrogen generation and renewable energy supply. Category 2 focuses on infrastructure and distribution providers, such as hydrogen technology providers, regional electricity and gas operators, transport operators, storage operators, fuel station operators, and other hydrogen technology operators. They ensure seamless transport, storage, and distribution of hydrogen. Category 3 involves end-users, both private individuals and businesses, spanning industries like the 6th cluster companies, (heavy) transport and mobility, agriculture, construction, and the built environment, driving demand for hydrogen.

Public bodies, in Category 4, including regional governments, water boards, local governments, and safety regions, guide and regulate the hydrogen ecosystem. Intermediaries, from Category 5, play vital roles—program managers, project developers, legal experts, (green) hydrogen certificate market facilitators, electricity traders, aggregators, consultants, research institutes, universities, NGOs, financiers, investors, landowners, trade associations, society, and steering groups. They facilitate collaboration and knowledge exchange among stakeholders. Finally, Category 6's large stage setters – the EU Commission, national governments, national gas and electricity operators, and international energy agencies – shape policies and provide overarching direction to hydrogen initiatives. The interrelations between these categories form a complex web of cooperation, regulation, and support essential for the successful establishment and operation of an SHN. Actor configurations will differ greatly per project as the ultimate goals of SHNs depend on the needs and resources in a specific area.

The third sub-research question *"What is the current institutional landscape that may shape or hinder the emergence and subsequent functioning of an SHN?"* aimed to enhance the understanding of factors that influence SHN formation. The current institutional landscape in the Netherlands regarding small-scale hydrogen networks is characterized by a complex web of regulations and policies across different sectors. This multi-faceted framework poses significant challenges for the formation and functioning of an SHN. Each sector has its own set of regulations, making it difficult to create a cohesive network that complies with all necessary rules. Moreover, the Netherlands is heavily reliant on EU regulations as a basis for its own policies and laws. However, the pace at which EU regulations are progressing may not align with the urgency of the transition towards green hydrogen integration. This misalignment adds an additional layer of complexity to the regulatory landscape.

A notable influence on policy formulation and law changes comes from powerful industrial entities, often leading to a skewed allocation of attention and resources. This lobbying effort can potentially divert focus from essential aspects of SHN formation. The introduction of the new energy law represents a step towards addressing some regulatory challenges. However, it is important to note that this law is just one component of the broader regulatory framework that requires adjustment to facilitate SHN development.

Subsidies play a crucial role in shaping the success of sustainable energy projects, including SHNs. Lessons should be learned from past experiences, particularly in the wind and solar sectors, to avoid repeating similar mistakes (e.g. putting electrolysers at random or in places they do not make sense). A thoughtful and strategic approach to subsidies is imperative for the long-term viability of SHNs. Public bodies, particularly municipalities, bear a significant responsibility in the formation of SHNs. However, they often face resource constraints in tackling the complexities of certifications and permits that can significantly slow down any (technical or spatial) request. Ensuring that these bodies have the necessary resources and support is vital for the success of SHNs.

Coordinating and aligning diverse interests while ensuring accountability, transparency, and effective decision-making can be a complex task. The evolving nature of the institutional landscape and the need for adaptability further compounds the challenge of finding suitable governance structures that can effectively navigate these dynamics over time Therefore, simplification and reduction of complexity should be a central focus of new regulations and collaborative ventures. Streamlining processes and providing a sense of security for involved actors will be instrumental in facilitating the emergence and functioning of SHNs.

Additionally, while large-scale projects may offer substantial reductions in CO_2 emissions on paper, it is important not to overlook the potential social benefits of smaller-scale projects when re-designing the regulatory frameworks. A balanced approach that considers both the environmental and societal impacts will lead to a more holistic and effective SHN formation strategy.

The fourth research question *What are the interrelations of these three dimensions – technologies, actors, institutions – within SHN formation?* focused on underscoring the connection between the three perspectives. These interrelations are integral to understanding the complex dynamics at play in this emerging field. Technologies serve as the foundational backbone, providing the means for hydrogen production, storage, and distribution. The choice of technologies not only impacts the efficiency and spatial implications of the network but also influences the actors involved. Actors, comprising various stakeholders such as government bodies, industry players, and local communities, are pivotal in shaping the trajectory of these networks. Their roles span from policy formulation and investment to project execution and community engagement. Simultaneously, the institutional landscape, encompassing regulatory frameworks, policy incentives, and governance structures, exerts a profound influence. It provides the necessary scaffolding for these networks to flourish and serves as a guiding force in navigating the complexities and challenges inherent in this emergent field.

For instance, the regulatory environment can facilitate seamless integration or present considerable hurdles to network development. Moreover, a responsive institutional landscape has the potential to spur innovation, encouraging the adoption of more sustainable and efficient technologies. Establishing these rules guides the interactions among actors and technologies. These interrelations form a dynamic and reciprocal ecosystem where technological advancements can trigger shifts in actor involvement, which prompts adaptations in institutional frameworks. For instance, breakthroughs in hydrogen production may incentivize greater private-sector participation, leading to the formulation of supportive policies or regulatory adjustments. Conversely, shifts in regulatory frameworks may spur technological innovation to meet evolving compliance standards. Recognizing and analysing these interrelations is pivotal in devising effective strategies for the sustainable development of small-scale hydrogen networks, ensuring alignment between technological capabilities, actor interests, and the evolving institutional landscape.

This leads to the main research question *"What are the barriers and enablers of small-scale hydrogen networks in the Netherlands?"*. After a comprehensive analysis of the challenges and drivers impacting the formation of SHNs within the Dutch energy landscape, several key insights have emerged. Notably, significant barriers have been identified, with negative business cases, regulatory gaps, and limited capacities standing out as pivotal hindrances. Overcoming the current lock-in of the infrastructure and institutional setting and navigating complex actor interactions emerge as key attention points in SHN development.

Regulatory barriers, exerting a pervasive influence across the entire supply chain, play a central role in impeding progress. The absence, ambiguity, or excessive stringency of regulatory instruments reverberates through various facets of the hydrogen sector, creating a cascading effect that impedes progress at each phase of the supply chain. Regulatory uncertainties also introduce instability for potential market participants and the general public, exacerbating the situation. Furthermore, financial impediments, such as inadequate or non-existent subsidy schemes, significantly decelerate the evolution of a competitive market economy. The "chicken or egg" conundrum, wherein actors across supply chain phases await each other's commitment to financial and developmental tasks, adds another layer of complexity. While producers await concrete demand articulation for scalability, consumers require assurance of receiving the required quantity and quality of hydrogen.

However, even under the most favourable regulatory and financial conditions, the shortage of knowledgeable actors such as researchers, physical workers and multidisciplinary experts poses a significant barrier. This scarcity of specialized expertise hinders the seamless transition towards fully functional hydrogen networks. It underscores the need for strategic investments in workforce development and training programs to address this critical gap in the advancement of sustainable energy solutions.

In addition to the barriers, it is crucial to acknowledge the enablers that have the potential to pave the way for successful SHN formation. The organizational culture, an innovative mindset, and the fostering of synergy emerge as key catalysts for progress. Notably, the creation of synergy, while enhancing the appeal of the project, simultaneously introduces complexity to the endeavour. Moreover, the steady support and guidance of local governments play a pivotal role in facilitating the establishment of small-scale hydrogen networks. It is underscored that governmental leadership is of paramount importance, ensuring that all stakeholders have a clear understanding of roles, responsibilities, and accountability from the outset. This is particularly crucial given the public interest nature of these projects. While the possibility of fully outsourcing stakeholder management to the developing party (e.g. an energy production service company) can be considered, it can be met with resistance, emphasizing the indispensable role of local government in overseeing sustainable management. Ultimately, the local government, vested with jurisdiction over the area's real estate under Dutch law, becomes the primary source of information for inhabitants, highlighting the significance of considering the broader societal benefits and implications in the planning and execution of SHNs.

6.2 The Concept of SHNs

This study explored the formation of small-scale hydrogen networks in the Netherlands in an effort to gain critical insights into how these networks can be effectively established and integrated into the broader energy landscape. SHNs were defined as localised systems or infrastructures that serve a specific region or community rather than a large-scale national or international network. The focus was on local hydrogen production initiatives emphasizing a regional outlook in terms of storage, distribution, and utilisation.

Examining these new socio-technical configurations through the lenses of technology, actors, and the institutional landscape has proven to be conducive to understanding and identifying SHNs enablers and barriers within the Dutch context. By dissecting the technological aspects, a granular understanding of the infrastructural requisites for efficient hydrogen production, storage, and distribution within localized networks is achieved. This understanding is pivotal in designing networks that are tailored to the specific resources and expertise available in a given region. Furthermore, delving into the actors involved and their interrelations elucidates the social dynamics that underpin the functioning of these networks. It allows for the identification of key stakeholders, their objectives and their agency. Moreover, it helps pinpoint their potential contributions and sheds light on required collaboration opportunities, all of which are pivotal in steering the networks towards successful fruition. Additionally, analysing the institutional landscape provides crucial context on the regulatory frameworks, policies, and governance structures that may either facilitate or impede network formation. Recognizing the institutional factors at play is imperative for navigating legal and administrative challenges and ensuring the long-term viability of these networks. In sum, this multidimensional approach offers the necessary tools to identify the enablers and barriers for the formation of small-scale hydrogen networks, thereby providing the knowledge to address challenges or leverage opportunities.

6.3 Beyond the Case of Goeree-Overflakkee

Even though this research zoomed in on the case of Goeree-Overflakkee, it is essential to acknowledge that the concept description outlined in Chapter 4, and the conclusions drawn and discussed in the following Chapters, also holds for other cases in the Netherlands. Moreover several countries in Europe, specifically in the North-West, given their similar developmental hydrogen ambitions, institutional environments and spatial contexts could benefit from these insights.

For example, Smith et al. (2022) explored the challenges of a demonstration project for 100% hydrogen distribution in a gas grid at the neighbourhood level in the United Kingdom. Similarly to the case in the Netherlands, they concluded that while some technical challenges remain, financial support (questions on who should fund what), developing sustainable business models and redundant regulatory frameworks are the main hurdles. Furthermore, they recognize the value of collaboration between public and private actors and highlight that without government support and market intervention, the long-term operationality of the projects becomes significantly more difficult. In the case of Norway, Espegren et al. (2021)

investigated the role of hydrogen in the transition to a low-carbon society. The study highlights current infrastructural and institutional lock-ins because of the power sector and big industry. Most importantly, in line with the findings in this thesis, it emphasises synergy creation and municipalities as active facilitators of regional hydrogen developments.

The North-western region, mainly encompassing Belgium, Denmark, France, Germany, the Netherlands, Norway, and the United Kingdom, stands at the forefront of hydrogen development, spearheading initiatives to advance the hydrogen economy. These countries are pivotal players in the development of a Europe-wide hydrogen backbone, offering significant opportunities for the formation of SHNs in proximity to this extensive infrastructure. The International Energy Agency underscores the collaborative efforts within the North-West, emphasizing the benefits of shared hydrogen developments among neighbouring countries to expedite national deployment and stimulate a robust hydrogen market (IEA, 2021). Electrolysis, the key technology, holds substantial promise for small-scale hydrogen production, enabling the creation of hydrogen through relatively compact electrolysis systems (Ulseth, 2023).

The Clean Hydrogen Partnership, a notable public-private collaboration under the Horizon Europe Programme, plays a pivotal role in advancing research and innovation in hydrogen technologies across Europe. Its primary objective is to accelerate the progress and implementation of cutting-edge clean hydrogen applications, bolstering the competitiveness of the clean hydrogen value chain within the European Union. This partnership has also catalysed the establishment of the Mission Innovation Hydrogen Valleys platform (Clean Hydrogen Joint Undertaking, 2023).

A Hydrogen Valley, an encompassing geographical area where hydrogen serves multiple end-users and applications in mobility, industry, and energy, emerges as a cornerstone of regional hydrogen economies (Horizon Europe, 2022). These projects necessitate significant financial investments and encompass crucial steps in the hydrogen value chain, from production to storage, transport, and distribution to various off-takers. Although larger in scale than the SHNs proposed in this thesis, Hydrogen Valleys share similar barriers and enablers.

While there is limited academic literature on these projects, the platform provides up-to-date information, aligning with the conclusions drawn in this thesis (Clean Hydrogen Partnerships, 2023). Notably, small-scale projects, defined as those with an investment volume below 50 million euros or a hydrogen production volume lower than 1 ton per day, face comparable challenges. Funding, permitting, and authorization procedures are identified as primary hurdles, particularly the lack of experience in hydrogen permitting or the absence of established procedures. Additional factors include the viability of project business cases, regulatory provisions, and stakeholder collaboration. Local public acceptance, experienced personnel, political support, project governance models, and risk-sharing mechanisms among project partners also feature prominently.

Notably, smaller-scale projects face heightened barriers in constructing a financial model compared to larger-scale endeavours (>10 ton/ day). Key success factors lie in the development of a robust business case and securing public financial support through subsidies or grants, in addition to securing consumer commitments to de-risk the financial model and attracting private investors. These observations highlight the shared challenges and opportunities between the Netherlands and other European nations, emphasizing the collective efforts required to advance the hydrogen agenda across the continent.

6.4 Practical Recommendations

In light of our increasingly intricate, decentralized, and sometimes unstable energy landscape, the imperative for alternative solutions and emerging technologies becomes apparent, especially in the pursuit of seamless renewable energy integration. However, it is crucial to acknowledge that the prominence of large industrial players in energy discussions should not overshadow the critical role of small-scale initiatives. These smaller endeavours hold equal weight in fostering innovation and sustainability. The often-fixated gaze on a distant end-state for our energy system, set for the year 2050, can be a misleading premise. Realistically, such a transformation cannot transpire overnight. Therefore, there is a pressing need to allow for transitional steps, particularly in the context of small-scale network formations.

This may encompass strategies like hydrogen blending into the existing grid, the adaptation of gas boilers for both natural gas and hydrogen, or the quick approval of viable transport alternatives for hydrogen. Adaptive management, diversified investments, and flexibility in testing new ideas are also paramount in navigating this transition. Furthermore, a nuanced examination of cost socialization could mitigate investment risks and avert the prospect of sunk cost. The establishment of stable legal frameworks that cannot be abruptly changed every year is paramount to provide the private sector with the security necessary to expedite decision-making processes. Additionally, the cultivation of a specialized talent pool proficient in managing small-scale hydrogen network projects could be pivotal in driving progress across different regions. Customizing small-scale hydrogen network components to suit the distinctive needs of specific regions is of utmost importance, delineating the functionalities that may thrive in comparison to other technologies in those areas.

Encouraging a rapid increase of projects, particularly on a smaller scale, not only ensures broader participation but also fosters acceptance of emerging hydrogen technologies. Shifting focus from technology-centric approaches towards prioritizing commercialisation, as indicated by the Commercial Readiness Index, will be instrumental in propelling these initiatives forward. Moreover, a heightened emphasis on local developments and the inclusive role of all energy users highlights the potential of small-scale hydrogen networks as a robust foundation for communal energy sharing and storage.

6.5 Limitations

Although the research sheds light on understanding the contexts involved in forming small-scale hydrogen networks, particularly what conditions could enhance or hinder their emergence, several limitations have to be acknowledged when looking at the thesis research design approach. In general, the definition of the concept itself, the selection of the theoretical background and the case study have constrained the scope of the research.

Moreover, alternative methods and frameworks for conducting institutional analysis, such as the multiple streams or IAD framework, were not explored in depth. Incorporating these different analytical approaches could offer valuable perspectives and potentially lead to alternative data interpretations. Additionally, this research heavily relied on interviews for data collection, aiming to capture diverse viewpoints on project-related issues in a balanced manner. However, sample bias can influence the insights gained, as the perspectives gathered are contingent on the individuals selected. Additionally, social desirability bias may lead participants to provide responses they believe are socially acceptable, potentially skewing the authenticity of the data. Moreover, the potential for response bias and memory recall errors introduces a level of uncertainty in the accuracy of the information collected. Finally, the time constraints inherent in a Master's thesis can limit the depth and breadth of viewpoints gathered, potentially impacting the comprehensiveness of the final analysis.

For example, the consensus among interviewees regarding the high level of lobby and social acceptance for hydrogen technologies may be influenced by their specific professional contexts. In practice, greater resistance to hydrogen technologies might be encountered. Lastly, it is important to note that SHNs are still in the early stages of development, and challenges specific to their full-scale operationalization may not have been comprehensively accounted for in this study. Overall, these limitations provide avenues for future research to delve deeper into the complexities of SHN formation and operation.

6.6 Further Research

In light of the findings presented in this thesis, several avenues for further research can significantly contribute to the advancement of small-scale hydrogen networks. Firstly, a comprehensive case-by-case comparison of operational SHNs, analysing their successes and failures, as well as their ability to sustain themselves when financial support diminishes, would provide invaluable insights into their long-term viability. Additionally, research should focus on identifying and addressing missing institutional rules, particularly those that intersect various sectors, and explore how they may influence synergies and de-risking strategies.

Moreover, investigating the legislative procedures concurrent with SHN implementation and their impact on investment timelines can be enhanced through agent-based modelling, considering spatial, technical, and market uncertainties along with actor flexibility. Conducting a Commercial Readiness Index analysis for projects while tracking their progress and addressing any emerging challenges can offer a valuable tool for project evaluation and improvement. Furthermore, delving into the intricacies of financial agreements among SHN actors and understanding their implications for project success is a crucial area that warrants further attention.

Moreover, examining the efficiency of subsidy systems and uncovering the barriers that projects face when applying for financial assistance can shed light on the efficacy of subsidies as enablers for SHN development. Additionally, conducting more extensive research into the perspectives of key actors, along with employing social network analysis to study complex organizational processes within SHN projects, can provide a deeper understanding of stakeholder dynamics and collaboration. Exploring the ownership and management structures of SHNs is also paramount for achieving widespread success. Finally, in-depth analysis and mapping of high-potential areas, such as industrial sites, fuel stations, or suitable neighbourhoods for hydrogen heating, can serve as catalysts for secure demand and supply of hydrogen, creating opportunities for even smaller initiatives and hydrogen users in their vicinity, contributing to a more diversified and sustainable energy landscape.

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Appendix I – Interview Guide Round One English

Before starting

- Thanking them for their time.
- Introducing myself and thesis topic.
- Point out again the interview sections taken into the thesis will be anonymised, and any non-anonymised data will be deleted after the finalisation of the thesis project.
- Ask verbal confirmation they understand this and give permission to record.
- Ask if everything is clear or if they have any questions.

Introductory question

- Could you shortly explain what your occupation entails?
    - Is there something you or your company is currently working/focusing on?

Topic 1: Current transition

- In general, how do you think the energy transition has gone so far in the Netherlands?
    - Since hydrogen has been included in the Dutch Climate Agreement, there has been a lot of discussion about its potential role. Are you convinced that hydrogen will play a major role in the future of our energy mix?
    - Why/why not?

Topic 2: Hindrances

- In your opinion, what would be the main barriers towards incorporating hydrogen into local/regional energy systems in the Netherlands?
    - What are the specific risks or pitfalls of… (anything they mention)?
    - How does this relate to… (anything they mention)?

Topic 3: Chances

- If these barriers would not exist, how would you imagine the ideal regional/local energy landscape?
    - What are the biggest opportunities and strongest drivers for including hydrogen in this scenario? What would be the steps to get there?
    - Which elements do you see as most promising, and which ones are lagging behind in their development in the current energy system?

- When considering the future of regional planning, how do current and ongoing policies influence the process of application for hydrogen-related technologies?
    - Future scenarios for hydrogen are being developed by different parties, can you share any policy documents or published plans of companies or other involved actors you know of?

- GasUnie is building a hydrogen backbone to connect big industries. Do you see potential in this to connect more scattered energy communities as well?
    - Why, why not?

- When considering market formation, would you consider the supply-push or the demand-pull as more defining, and why?

Topic 4: Stakeholders

- In your opinion, which stakeholders are most important in facilitating the emergence of more bottom-up hydrogen-integrated energy systems?
    - Can you think of anyone with potential and/or influence?
    - What would be the main interest or concerns of the actors involved?

- Can you imagine new collaborations or partnerships between stakeholders?
    - If so, can you give (an) example(s)?

- What would be possible conflicts of interest among different stakeholders, especially during the market ramp-up?

- What is your view on the best way to exchange, e.g. knowledge and information within a future hydrogen network?
    - Where do you spot room for improvement?
    - Do you see possible roles within a regional/local hydrogen network not currently populated by any stakeholders?

Topic 5: Acceptance

- How do you see the current and future level of public acceptance for hydrogen-related technologies and services?
    - In your opinion, what would be the main differences compared to the solar and wind market ramp-up?

- From your perspective, how do you see the role of the government in accepting hydrogen for big industries and smaller players?

- There is an art in guiding the process of organising change. What is your experience in supervising or taking part in such processes?

Ending

- To come back, what do you identify as the 2-3 main actions that need to be taken for the hydrogen transition to be successful?
- Are there any other comments you would like to share?
- Can you think of anyone that would be interesting for me to connect to as well?
- Again thanking them for their time and stopping the recording.

Appendix II – Interview Guide Round Two English

Before starting

- Thanking them for their time.
- Introducing myself and thesis topic.
- Point out again the interview sections taken into the thesis will be anonymised, and any non-anonymised data will be deleted after the finalisation of the thesis project.
- Ask verbal confirmation they understand this and give permission to record.
- Ask if everything is clear or if they have any questions.

Introductory question

- Could you shortly explain what your occupation entails?
    - Is there something you or your company is currently working/focusing on?
    - Can you tell me a little bit more about (any project example(s) they mention)?

Topic 2: Barriers/hindrances

- In your opinion, what are the main barriers towards hydrogen integration on a small scale in the Netherlands?
- Think of:
    - Technical/operational barriers
    - Social/cultural barriers
    - Market/institutional barriers
    - Economic/financial barriers
    - Policy/political barriers
    - Resource/physical barriers
- What are the potential risks and uncertainties in the mentioned project example(s) and Goeree-Overflakkee as a testing ground?
- Are there any barriers you have already encountered that you have overcome? If yes, how, if not, why not?

Topic 3: Drivers/chances

- Imagine you had a magic wand, what would you wish for to give your project(s) a boost?
- What else would you wish?
- If you get everything you want, when will a project be successful, in what time frame?
- From your perspective: what would need to happen to facilitate this?

- GasUnie is building a hydrogen backbone to connect big industries. Do you see potential in this to connect more scattered energy communities as well? Why/why not?

- When considering market formation, would you consider the supply-push or the demand-pull as more defining, and why?

Topic 4: Stakeholders

- Can you say anything about the configurations of actors you encounter in projects? What stands out?
- If you imagine an operational small-scale hydrogen network, who would be at the core of this configuration and which actors would be surrounding this core?
- What would be their interest and concerns?
- Do you experience any conflicts of interest among different stakeholders during the development of the hydrogen transition / its market ramp-up?

Topic 5: Opportunities

- Do you see possible roles within a small-scale hydrogen network not currently populated by any stakeholders?
- Do you have anything to say on the topic of synergies or lack thereof?
- To what extent do you collaborate with other institutions or actors in the Netherlands?

Ending:

- To come back, what do you identify as the 2-3 main actions that need to be taken for the hydrogen transition to be successful?
- Are there any other comments you would like to share?
- Again thanking them for their time and stopping the recording.

Appendix III – Background Understanding the Energy Landscape

Energy transition

When asking interviewees about their view on the energy transition in general, the main consensus was negative in the past and positive at the moment. "*We have been spoiled with gas in the last decades*" (#6)" but also "*a lot has happened in the past 20 years*" (#1). One interviewee mentioned that *"if you look at the application of sustainable energy in Europe, then we haven't been doing so well*" (#8). This is reinforced by the notion that "*if we thought things were going well, then we didn't exist as energy cooperatives [...] we picked up where nothing was happening locally*" (#2).

Several interviewees mentioned in one way or another it's not going fast enough for them (#3, #4, #6). Especially since "*we actually already knew all the preconditions at the time, and we are now more than 20 years further*" (#4). However, the overall consensus is that "*we are catching up, it has started to gain momentum in recent years.*" (#8). At the same time, it is emphasised that "*we have very big ambitions in the Netherlands, we want a lot, but we also run into a number of practical limitations*" (#6). And although, in general, it is going "*good in terms of intentions [and] in terms of national attention*" (#7), there are different views on the feasibility of the task at hand.

One interviewee states that "*things are finally picking up speed at the moment, only it is not going fast enough to achieve the objectives*" (#5). Whereas another is fully convinced, "*it's starting to pick up steam now [...] the objectives that we agreed on in the climate agreement, we are going to achieve*" (#2).

Others mention: "*the size of the task sometimes makes me a bit pessimistic about the feasibility [...] whether we will all make it*" (#6), "*we are only at the beginning*" (#3) and "*what you're noticing now is that we're really starting to hit stumbling blocks, big stumbling blocks*" (#5).

These concerns are reflected in opinions on the current tempo of the transition: "*I think we are now at the moment where we cannot go any faster than we are now within the current regulations, legislation, frameworks, consumer protection, protection of nature and landscape. We can't actually go much faster.*" (#2). Another interviewee states they find "*there is a bit of an atmosphere or a mantra around [writing policies] that we do what is considered possible, not what is deemed necessary, that disappoints me in the energy transition.*" (#7)

So even though "*on sunny days or windy days you have more than half of the electricity, at least, generated with sustainable sources*" (#1), "*there are many opportunities that we can link to in the transition that are not really being done yet.*" (#2)

Ideal landscape

Based on the question of what ideal energy landscape interviewees envision, the following paragraph synthesises the answers into a coherent vision.

The ideal energy landscape already starts before energy production. Citizens reduce their energy consumption, use energy-efficient appliances, and isolate their buildings (#2 & #6). Energy production from renewables is maximised and locally sourced as much as possible (#1, #2, #3, #4, #5, #8). In addition, flexibility measures or behaviour changes are introduced to bring supply and demand closer together (#1, #6). An emphasis is laid on maximum electric (#7, #2), the optimal use of residual heat (#1), and energy storage (#3, #4). Batteries are mentioned but only for the short term (#6). "*A revolution is necessary*" to use them for the long term (#7). Energy sharing (between communities) and increasing synergy benefits are mentioned as well (#2, #8).

There is an overall bias towards decentral solutions, acknowledging that they are often overlooked: "*when everyone focuses on very big things, they forget that a lot of small things can also be big sometimes*" (#1). This can be explained by the majority of interviewees being involved in local innovation projects. However, even the interviewees representing bigger energy companies state system integration is necessary "*not only on a national level but also decentralised*" (#6). Additional comments are made on reducing the power of fossil parties and increasing independence and autonomy from bigger energy companies especially within the current energy climate (#2, #5, #7).

Nonetheless, all interviewees agree it is going to be a mix of a lot of different things as an ideal landscape is difficult to imagine: "*it is very location specific as well*" (#8). This is where in some cases, the production, distribution and use of hydrogen as an energy carrier can fill gaps or enhance existing systems.

All eight interviewees are convinced hydrogen is going to play a role in the current transition.