HYDROGEN IN THE DUTCH BUILT ENVIRONMENT

Exploring the transition from natural gas to hydrogen-based heating in the Dutch built environment through Socio-Technical Scenarios

MSc. Management of technology

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Executive Summary

Due to the Paris Agreement of 2015, the Dutch government published a Climate Accord in 2019 which stated that all houses in the Netherlands should be heated without natural gas by 2050. The Dutch built environment is currently being heated with natural gas. This forces the actors within the heating system of the Dutch built environment to look for new technologies. At the same time, the increase in electrical vehicles and the use of electrical heat pumps leads to higher energy demand resulting in electricity grid congestion. The Dutch government has identified electric, green gas, district heating (high and low temperature sources) and hydrogen as viable alternatives for natural gas.

This thesis investigates the use of hydrogen for heating homes in the Netherlands and explores different future scenarios. The research question that is being answered in this thesis is "*What is the development status of the hydrogen niche for heating homes in the Dutch-built environment and which socio-technical scenarios can be expected?".* The aim is to gain insight into the development status of hydrogen technologies for heating the Dutch built environment and which scenarios could be expected. The theoretical frameworks, Multi-level Perspective, Strategic Niche Management, and Socio-technical scenarios were complementary used to analyse the context. With these theories, the interaction between technology and social elements have been analysed. Additionally, a qualitative study is executed by conducting 14 semi-structured interviews with experts from the field.

There are various hydrogen technologies developed for built environments. Some technologies are focussed on space heating like the hydrogen boilers in combination with a heat pump. While there are also technologies being developed which are primarily aimed at addressing the electrical net congestion challenge like fuel cells. These fuel cells also enable decentralized hydrogen production and storage. However, the feasibility is doubted among the interviewers due to limited scalability and safety concerns.

Currently, the top-of-mind barriers regarding the adoption of hydrogen in the Dutch built environment are mainly the uncertainty about the availability of green hydrogen, future prices, labour shortage, and user acceptance. The dominant barrier is the uncertainty about hydrogen availability. Due to still lacking availability of hydrogen companies are hesitant to invest resources in the development of hydrogen applications. The barrier labour shortage has not been found in previous literature, which makes this finding a novel contributions to academic research.

In this study 2 socio-technical scenarios regarding hydrogen in the Dutch built environment are formulated. In scenario 1 a reconfiguration transition occurs, whereas in scenario 2 a transformational transition occurs. These scenarios differ on the extent the electricity grid congestion is resolved. In both scenarios an extensive international hydrogen market established. Scenario 1 deals with a large amount of hydrogen and poor electricity grid capacity. In this scenario, hydrogen will be used as an alternative energy carrier to the built environment by utilizing fuel cells. Scenario 1's demonstration that fuel cells can be part of the solution for the electricity grid congestion. In scenario 2, the hydrogen economy is established and there is a resolved grid issue, which will lead to hydrogen being used for direct space heating.

This study shows how the niche could react to the development of hydrogen availability and the ability of the network operator's electricity grid capacity in determining the role of hydrogen in the Dutch built environment. Additionally, it underscores the significance of government commitment and proactive policies for sustainable energy transitions. A generalization of this study to other countries may be challenging, mainly due to the existing natural gas infrastructure in the Netherlands.

The research's theoretical implications lie in its complementary utilization of the Multi-Level Perspective (MLP), Social Network Analysis (SNM), and Scenario Technique (STSc), offering a novel approach to analysing complex energy transitions. By utilizing SNM in combination with STSc enabled the writer to formulate a richer scenario due to a broader understanding about the niche. Moreover, the study's unique focus on the Dutch hydrogen niche and demonstrated how these frameworks enhances our understanding of niche and regime dynamics, contributing to academic knowledge. With utilizing the SNM in this context a missing actor was identified. This research serves as a valuable resource for shaping the future of hydrogen-based heating technologies in the Netherlands and potentially other European countries, offering practical insights and theoretical innovations for addressing contemporary energy challenges.

From the study resulted multiple recommendations. The Dutch government should leverage the potential of hydrogen as a cost-effective heating solution by actively promoting its adoption. To reduce uncertainty among niche actors, the government should commit to making a specific amount of hydrogen available for the built environment. Both government and municipalities should take an active role in creating social acceptance for hydrogen heating technologies. Furthermore, infrastructure actors and the Dutch government should recognize the potential benefits of fuel cell technologies, as a strategy for resolving electricity grid congestion.

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1. Introduction

The Paris Agreement, signed in 2015, aims to limit global warming to well below 2 degrees Celsius and to pursue efforts to limit the temperature increase to 1,5 degrees Celsius. To ensure that global warming is maintained at 1,5 degrees, emissions must be reduced by 45% by 2030 and reach net zero emissions by 2050. One of the key areas of focus in achieving these goals is the reduction of CO_2 emissions. In the Netherlands, the residential heating sector is a significant contributor to these emissions, with most houses being heated by natural gas (Van Alphen, 2021).

Due to the Paris Agreement of 2015, the Dutch government published a Climate Accord in 2019 which stated that all houses in the Netherlands should be heated without natural gas by 2050 (Ministerie van Economische Zaken en Klimaat, 2019). This is quite a challenge because in 2015 99% of the residences in the Netherlands use natural gas for heating. This means that the new policy of the Dutch government of switching to fossil-free heating will affect almost all houses in the Netherlands (Tigchelaar et al., 2019). Currently, it is still unclear which technology is the most suitable for heating houses in the Dutch built environment. The Dutch government presented an initial analysis which stated that they are exploring multiple concepts for achieving this goal, like district heating, electric solutions, bio-based gas, and hydrogen (van Polen et al., 2022).

Hydrogen is expected to play a key role in the transition to a sustainable energy system. It enables us to transport green energy from places where the yield from renewable energy sources is higher to places where yield of green energy of renewable energy sources is lower. It is also suitable for long-term storage of energy (Luscuere & van Wijk, 2021a). The European Union believes that hydrogen is essential for the decarbonisation of certain sectors that can replace fossil fuels. Their vision is to become a global leader in the hydrogen economy (Zabanova, 2022). The Dutch government also believes in the importance of hydrogen and aims to become the hydrogen hub of Europa by being a large importer of hydrogen through the port of Rotterdam (Jetten et al., 2022).

Due to the large potential and key role hydrogen is expected to play in the energy system, it is useful to understand if hydrogen could also play a role in space heating in the Dutch built environment. Multiple pilots have been started to get a better understanding of the potential for using hydrogen in the Dutch built environment. One of the projects is in Wagenborgen where multiple houses from the 1970s will be connected to a hydrogen network. These houses are equipped with hybrid systems which use hydrogen boilers and heat pumps. Hydrogen will only be used when the heat pump cannot deliver the peak demand that is required in cold periods. Through pilot programs, valuable insights are being collected to determine the viability of using hydrogen boilers for heating houses in the Dutch built environment (Koel, 2023). There is also a pilot in Hoogeveen where 427 existing houses and 100 new houses were converted to a hydrogen heating system. In Stad aan 't Haringsvliet is a project starting which tries to switch 550 buildings from gas to hydrogen fields (RVO, 2022; Van der Molen, 2021). There are also plans for starting projects where excessed solar energy is being stored in hydrogen and converted back to electricity for heating when this is necessary (FODEO, 2023). While there is a clear goal set by the government, there is still an unclarity on how homes in the Dutch-built environment will be heated the future and how this transition will be realized.

1.1 Problem statement

In the climate Accord of 2019, the Dutch Government announced that new construction buildings will be no longer connected to the natural gas infrastructure and should be heated without creating CO_2 emissions. Over time the existing built environment should also be heated without fossil fuels. Currently, it is unclear which technology solution will be used on a large scale as a substitute for natural gas in the Dutch built environment (Ministerie van Economische Zaken en Klimaat, 2019). It is also uncertain to what degree hydrogen could play a role in heating the Dutch built environment.

There have been multiple academic studies conducted to understand the potential, challenges of new technologies for space heating. There have also been studies conducted on what the potential challenges could be in the adoption of these new technologies for users (Alverà, 2020; Chapman et al., 2019; Gordon et al., 2022; Tigchelaar et al., 2019). Additionally there have also been studies conducted on the role hydrogen can play in the transition to a carbon-free energy system (Luscuere and van Wijk, 2021a).

Addressing the uncertainty surrounding various heating technologies is crucial for advancing our understanding of their potential. A comprehensive understanding of the challenges and benefits associated with the further development and transition of these technologies will yield valuable insights into achieving the goals outlined in the Dutch Government's 2019 Climate Accord. While existing literature focuses on exploring the potential and barriers, it fails to provide a clear picture of the progress made in developing hydrogen technologies for heating the Dutch built environment. Additionally, the current academic research lacks clarity on the most probable scenarios of hydrogen technology adoption in this context. Resolving these gaps will be pivotal in formulating appropriate strategies for sustainable heating solutions in the Netherlands.

1.2 Knowledge gap and research objectives

Since the start of these pilots in the Netherlands a lot of new insights and a broader understanding of the potential opportunities and challenges for hydrogen heating technologies in the Dutch built environment have been gathered.

Instead of a shortage of potential technical solutions for solving an environmental problem, it seems that there are many potential technologies of which each has its barriers and advocates (Elzen & Hofman, 2010). While existing academic studies explore the potential and barriers of hydrogen heating within the built environment (Alverà, 2020; Chapman et al., 2019; Gordon et al., 2022; Tigchelaar et al., 2019), there is a notable knowledge gap in understanding the specific development status of hydrogen technologies for heating the Dutch built environment. Another knowledge gap that is being addressed is to provide a better understanding of what hydrogen scenarios could occur in the Dutch built environment and what this transition will look like.

The research objective of this study is to bridge the existing knowledge gaps and provide a comprehensive understanding of the development status of hydrogen heating technologies within the Dutch built environment since the initiation of various pilots in the Netherlands. The research aims to identify and analyse if new opportunities and challenges are identified due to these pilots in the Dutch built environment.

Furthermore, the research seeks to address the knowledge gap related to the scenarios for the adoption of hydrogen technologies in the Dutch built environment. By examining the potential pathways for transitioning to hydrogen-based heating solutions, the study aims to gain insights into how key stakeholders are involved in shaping the future of hydrogen heating technologies.

1.3 Research questions

To answer the formulated knowledge gaps and research objective in Chapter 1.2 the following research question is formulated:

"*What is the development status of the hydrogen niche for heating homes in the Dutch-built environment and which socio-technical scenarios can be expected?".*

To answer this main research question, the following sub-questions need to be answered:

1. What are the landscape and regime developments of heating homes in the Dutch-built environment?

This sub-research question delves into understanding significant events that have a notable impact on the existing heating system. These events create openings for hydrogen to address these challenges, as referred to as landscape developments. Additionally, it examines the origins of the current heating system in the Dutch built environment and explores its susceptibility to influence from these novel significant events, referred to as regime developments.

2. How is the hydrogen niche for heating homes in the Dutch-built environment developing?

The purpose of this sub-research question is to investigate the development of hydrogen technologies for heating the Dutch-built environment, which is referred to as niches. This involves assessing the trajectory of the learning process and understanding the diverse expectations held by various stakeholders involved in this niche development.

3. Which barriers of the landscape and regime should the niche overcome?

This sub-research question focuses on identifying the challenges and obstacles faced by hydrogen heating technologies in their integration into the Dutch-built environment. Understanding these barriers is crucial for facilitating the transition to a hydrogen-based heating system within the Dutch-built environment.

4. What socio-technical scenarios can be developed regarding the hydrogen niche and how could the transition from niche to regime take place?

This research question aims to explore various scenarios that could emerge if hydrogen were to replace the current heating regime in the Dutch built environment. Understanding these scenarios can shed light on the potential pathways and implications of adopting hydrogen-based heating solutions.

1.4 Research relevance

1.4.1 Societal relevance

This research holds significant societal relevance as it delves into the potential of hydrogen as a replacement for natural gas in the Dutch built environment for heating. By gaining insights into stakeholders' perspectives and expert opinions, the study will inform on the formulation of effective strategies to achieve climate objectives and drive a sustainable future for the Dutch population. Understanding the progress that has been made in developing hydrogen technologies and thereby exploring various adoption scenarios in the Dutch-built environment will empower policymakers, researchers, and stakeholders to make informed decisions.

1.4.2 Academic relevance

This research is filling the knowledge gaps in the existing academic literature. While previous studies have explored the potential and barriers of hydrogen heating technologies within the built environment, there is a lack of analysis of the specific development status of hydrogen technologies in the Netherlands.

By examining large development which forces companies within the heating system of the Dutch built environment and their internal challenges, new insights are gained into what the different technologies are trying to resolve. Also, the development of hydrogen heating technologies is being analysed by looking at the ongoing pilot projects. This study aims to contribute new insights into the field of sustainable hydrogen heating technologies and their potential application for the Dutch built environment. This study also contributes by presenting how the theoretical approaches MLP, SNM, and STSc can be complementary utilized. The expectation is that this gives more comprehensive scenarios. In chapter 3 the theoretical frameworks and the conceptualization will be discussed.

1.4.3 Relevance to the MOT Program

With a study background in the Management of Technology, the necessary skills and knowledge is gained to analyse the technological and organizational aspects of the transition to fossil-free heating of houses, with a strong emphasis on innovation and transition. Through the specialisation Emerging Technology-Based Innovation & Entrepreneurship a range of theoretical frameworks and analytical tools were introduced that are relevant to this thesis, such as Strategic Niche Management, Multi-Level Perspective. These tools will enable me to identify the barriers to the transition to fossil-free heating and formulate a pathway to overcome them while considering the broader system context. As a student in this field, I have gained a deep understanding of the innovation process, including technology development, commercialization, and diffusion. I have also learned about the management of complex systems, including the interaction between technology, organizations, and society.

Undertaking this thesis research can significantly increase my knowledge as a student in analysing technology transition. Through the research, I will gain insights into the technical, economic, and social aspects of this transition, and how they interact with each other. The thesis will also provide an opportunity to apply the theoretical frameworks and analytical tools of the study to a real-world problem. This will enable me to deepen my knowledge and expertise in these areas and enhance my problem-solving and analytical skills. Furthermore, through this research, I will get in contact with stakeholders of the energy transition, including policymakers, industry stakeholders, and households. This will help me to further understand their perspectives and learn how to engage with them effectively to stimulate the heating transition. It also will improve my management skills by setting up interviews with important stakeholders. Also, by looking from the perspective of a policymaker on a complex social issue a better understanding is gained of the complexity of administrative decisions.

Overall, my study background in the management of technology equips me with the necessary skills and knowledge to undertake this research and provide valuable insights into the challenges and opportunities of the transition to a sustainable energy system. At the same time, this thesis process will further increase my understanding of these frameworks and improve my knowledge about stimulating technology transitions.

1.5 Structure

The research report is structured into 10 chapters, starting with the Acknowledgement and Abstract. The report begins with an Introduction (Chapter 1) that sets the foundation for the study. In this chapter, the problem statement is outlined, along with identifying the knowledge gaps that the research seeks to address. The research objective and research question are also clearly defined. Moreover, the scope and the relevance of the research are highlighted to underscore its importance.

In Chapter 2, the Literature Review section dives into the existing knowledge and research on the potential role of hydrogen within the new energy system. It thoroughly explores the application of hydrogen within the built environment and examines the associated barriers. Additionally, this chapter investigates various alternative technologies being developed for heating the built environment.

Chapter 3 presents the Theoretical Framework, where several frameworks are discussed which are being used to analyse the context to answer the research questions. These include SNM, MLP, and STSc. Additionally, complementary frameworks are explored to provide a comprehensive understanding of the topic.

Chapter 4 explains the Methodology of the research. It outlines the research design, case selection process, data collection, and data analysis methods. The chapter also addresses aspects of validity, reliability, generalizability, and limitations to ensure the credibility of the research.

Chapters 5 to 8 present the comprehensive findings from the analysis conducted in this study. In Chapter 5, the hydrogen niche is extensively described, addressing the first sub-research question. Moving on to Chapter 6, a thorough Regime and Landscape analysis is conducted to answer the second sub-research question. Chapter 7 is dedicated to examining the interactions between different levels and the barriers that the niche must overcome, crucial in answering the third sub-research question. Finally, Chapter 8 delves into Socio-technical Scenarios, offering valuable perspectives on potential future developments in the research area, effectively addressing the fourth sub-research question.

Chapter 9 contains the Discussion section, where the findings from the research and their limitations are thoroughly discussed. Lastly, chapter 10 presents the Conclusion, answers all the sub-research questions and answers the main research question.

2. Literature review

This chapter presents a comprehensive literature review. Initially, it delves into the establishment of the current Dutch heating system, elucidating the involved actors and its operational mechanisms. Subchapter 2.2 highlights the significance of hydrogen in the upcoming energy transition. Subchapter 2.3 examines various hydrogen applications, specifically in the context of the built environment, drawing on insights from existing literature. Moving forward, subchapters 2.4 and 2.5 thoroughly analyse the barriers associated with hydrogen implementation, followed by an exploration of the policies devised to surmount these challenges. Finally, subchapter 2.6 focuses on the actual implementation of hydrogen within the Dutch built environment.

For this literature review the methodical approach of Wee & Banister (2016) is followed. The key steps in the literature review process included:

1. Defining the Topic: The initial broad topic focused on hydrogen heating in the Dutch built environment and policy implications.
2. Search Engine: The primary search engine used was Scopus. Grey literature was sought through Google Scholar, with an emphasis on the reliability of sources based on the author's affiliations.
3. Keywords: Keywords like "heating houses," "hydrogen," "policy," and "transition" were employed to refine the search.
4. Keyword Refinement: Various combinations of keywords were tried to improve search results.
5. Selection Strategy: Articles were filtered based on relevance to the study's focus, excluding those primarily focussing on the engineering of hydrogen applications or global supply chain optimization, or unrelated fields.
6. Further Analysis: Selected articles were subjected to in-depth analysis, including reading abstracts, introductions, conclusions, and relevant subsections.
7. Exploration of Keywords: Alternative keywords like "adoption" were explored to broaden the search, resulting in additional selected articles.
8. Reference Scanning: References in selected articles were scanned for additional relevant sources.

In total, 11 papers from Scopus were included in the literature review which formed the basis of this literature review.

2.1 Role hydrogen within the new energy system

Since the Paris Agreement of 2015, it has been recognized that the increased CO_2 in the atmosphere is a contributing factor to climate change and that humanity partially is responsible. This requires a transition from fossil fuels to renewable energy. The most obvious solutions would be solar energy and wind energy which could be extracted anywhere in the world. However, there are areas in the world that can achieve 3 times more yield than in for example the Dutch area in the northwest of Europe, meaning the costs per kWh can also be a lot lower (Luscuere & van Wijk, 2021b).

According to Luscuere and van Wijk (2021), global energy demand is about 18.3 TW per year. The sun provides 10 thousand times that need for energy per year. If 10% of Australia was covered with solar panels, the entire energy demand could be met. In areas like Saudi Arabia, Spain and Australia the yield per solar panel is higher than if installed in the Netherlands. Therefore, it makes sense to extract renewable energy in the areas where yields are highest and transport it to areas where there is a need (Coenen, 2021).

However, there are two challenges when renewable energy is to be extracted in these areas. The energy must be stored and transported over long distances. Storing and transporting electricity-power is very expensive. Converting electricity-power into hydrogen for storage and transport is cheaper. Direct storage of electricity is costly and requires intensive resources of scarce materials (Luscuere et al., 2021). In addition, this affordable large storage option of hydrogen also offers flexibility in the energy system to bridge the difference in generation and demand needs (Abbing, 2021; Hellinga & van Wijk, 2021).

Van Alphen (2021) expect hydrogen storage to be 100 times cheaper than using batteries for seasonal electricity storage in large quantities. In the Netherlands, the availability of salt caverns could allow large quantities of hydrogen to be stored. This is already a proven technique because in both United States and United Kingdom hydrogen is stored in salt caverns. In addition, caverns in the Netherlands have been used for the storage of natural gas for more than 10 years and it is expected that the first caverns will be ready for large-scale storage of hydrogen in 2025 (Abbing, 2021).

In addition, it is argued that energy in gaseous or liquid form can be transported more cheaply all over the world compared to using an electricity network (Luscuere & van Wijk, 2021b; Van Alphen, 2021). According to van Dorp (2021) and Abbing (2021), we should therefore not see hydrogen as an energy source such as a fossil fuel, but as an energy carrier. A gas network can be used according to Van Alphen (2021) to transport 10 times more energy than an electricity network at the same price. In addition, a gas network can easier absorb a high a peak demand compared to an electricity network.

By using hydrogen as an energy carrier, it becomes possible to reuse existing gas infrastructures. At the moment, about 95 % of homes in the Netherlands have a gas connection, which is one of the arguments why natural gas is a cost-effective solution (Bijkerk, 2021). Hydrogen, like the option of 'green gas', differs from 'all-electric' solutions and heat networks in that it can be a direct replacement for natural gas as a gaseous energy carrier. It allows to use the existing gas infrastructure with only limited modifications, unlike heat networks that require a completely new infrastructure (Weeda & Niessink, 2020). By reusing the gas network, the existing gas network gets a second life (Van Alphen, 2021). Several academics and the Dutch government believe in the potential of hydrogen and think it is likely that hydrogen will have an important role in the future energy system of the Netherlands.

The Minister of Economic Affairs and Climate Policy Wiebes (2020) stated that CO_2-free gases (which also include hydrogen) are the most cost-efficient ways to make parts of the built environment more sustainable and it is seen as necessary to absorb the peak load for energy. According to Abbing (2021) the small users in the built environment are creating a large variations in energy use. This energy demand from these small users can vary per season and between weekends and working days.

There are also experts who argue that the necessary renewable energy could be produced locally from solar panels and wind turbines. A downside of renewable energy is that the electricity yield will fluctuate from day to day and even from season to season. There are even periods when there is no sunlight or wind at the same time, which are called 'Dunkelflautes'. This means that even with large amount of local renewable energy large amount of energy storage is required due the difference in energy demand and supply in certain periods, for which hydrogen is very suitable (Abbing, 2021; Hellinga & van Wijk, 2021).

2.2 Heating solutions for the built environment

To achieve zero-emissions heating in the Dutch built environment new technologies have to be developed. Rather than facing a scarcity of potential technical solutions for addressing environmental challenges, the situation appears to be characterized by an abundance of potential technologies, each with its own set of obstacles and proponents (Elzen & Hofman, 2010). According to Hellinga and van Wijk, (2021); Schutte (2021) and van Cleef, (2021) the Climate Accord of 2019 forces the Netherlands to look for an alternative heating technology which does not produce any CO_2 emissions for the built environment. The Dutch government assigned the Planbureau voor de Leefomgeving (PBL) government institute the task of conducting a first initial analysis in 2020 to create an overview of potential technology clusters that might be used in the Dutch built environment for space heating (van Polen et al., 2022). This resulted in 5 main strategies:

1. Individual electric through heat pumps
2. District heating with medium and high-temperature sources
3. District heating with low-temperature sources
4. Green gas (biogas)
5. Hydrogen

The initial analysis utilizes five main strategies, indicating the insulation level for each technique. Through the initial analysis, insight was gained into national costs, energy consumption, and CO_2 reduction per strategy. However, the system only incorporates a national average and includes regional costs such as insulation, purchasing new equipment, and network conversion (Heat Expertise Center, 2021).

The initial analysis shows that the technical solution of hydrogen is not currently applicable due to limited availability. However, considering its significant technical potential and system advantages such as seasonal storage, it was still valuable to include this technique in the analysis. It is assumed that hydrogen can be applied in the built environment from 2030 onwards, depending on the development of the hydrogen market. There is also considerable uncertainty regarding green gas, as the availability is uncertain. Therefore, the advice is to primarily focus on Strategies 1 to 3 (Heat Expertise Center, 2021).

2.3 Hydrogen technologies

There are multiple ways how hydrogen can be used to heat houses. The main hydrogen applications for heating discussed in the literature are hydrogen boilers, hybrid solutions and micro-CHP. The fuel cell is the most popular micro-CHP technology. A third solution is a hybrid solution which combines the 2 main solutions. In this section, a short introduction is given to these technologies.

2.3.1 Hydrogen boiler

In the Netherlands, most households are currently being heated with natural gas boilers. This established technology could prove difficult to displace with alternatives because consumers perceived these technologies as safe, cheap, effective, and easy to control (Dodds et al., 2015). To most similar technology would be hydrogen boilers of which there are multiple variants in development. The main boiler technologies for hydrogen are according to Dodds et al. (2015) direct flame combustion boilers and catalytic boilers. The benefit of hydrogen boilers is that they can be connected to the existing central heating system without the need of expensive insulation (Hellinga & van Wijk, 2021; Lammers & den Ouden, 2020).

The direct flame combustion boiler is identical to gas boilers in Europa, but instead of burning natural gas, it burns hydrogen. A catalytic boiler heats space and water by passing hydrogen gas over a highly reactive metal catalyst. This causes an exothermic chemical reaction that produces heat without a flame. The process results in a more controlled heat output compared to a naked flame burner. These hydrogen boilers operate and perform similarly to gas boilers from the perspective of the consumer (Dodds et al., 2015).

Hydrogen boilers can also be integrated into collective heat systems. This can be a local heating system which are used in for example apartment complexes, and central district heating networks. In these systems hydrogen boilers can be used as a primary heating technology or as a assistance heating during peak demand or as a backup at other times (Hellinga & van Wijk, 2021). Multiple manufacturers have announced to bring a hydrogen boiler to the market in the future but currently these boilers are only used in research pilots.

2.3.2 Hybrid solution

A hybrid solution consists of a hydrogen boiler with a heat pump. Compared to using only a central heating boiler, hybrid systems also use electricity as energy sources. A heat pump is more efficient than a hydrogen boiler, but it can produce less heat. A standalone heat pump would require heavy insulation of houses and large electricity grid reinforcements (Lammers & den Ouden, 2020). When using both a hybrid solution of a hydrogen boiler and heat pump, the heat pump would heat the house. Only when it cold outside the hydrogen boiler would used to produce extra needed heat. By utilizing both technologies a higher efficiency can be achieved, which results in lower annual energy cost, without the need for heavy insulation and electricity grid reinforcement (Hellinga & van Wijk, 2021).

An argument against this could result in higher costs due to both the needed electricity and hydrogen connections (OECD, 2021). At this point, there is not a lot of research done on hydrogen boilers in combination with a heat pump (Speirs et al., 2017). Currently, there is experience being acquired with heat pumps paired with natural gas boilers. The Dutch government has introduced a new regulation that mandates homeowners who wish to replace their natural gas boilers to also install a heat pump alongside it (Jetten, 2022). Due to this regulation Dutch boiler manufactures are already heavily investing in this new technology which shows there is already experienced gained with combining a heat pump and a boiler (Wagenaar, 2023).

2.3.3 Micro-CHP (Fuel cell)

CHP stands for Combined Heat and Power which are systems that convert hydrogen to electricity and heat. The captured heat can be used for heating houses and the electricity could be used for electric heating systems like heat pumps (Sun et al., 2021). This CHP is also known as cogeneration. According to Dodds et al. (2015), fuel cells is the most known micro-CHP technology and can produce the highest amount of energy of the current available CHP technologies. This makes it the most promising micro-CHP technology for houses. Some fuel cell systems are developed just for converting hydrogen back into electricity. There are multiple types of fuel cells in development. Adoption of the micro-CHP system is taken place in South Korea and Japan due to government programs. This shows that the technology is market ready but still requires government fundings to compete with the existing technology (Dodds et al., 2015). According to Dodds et al. (2015), PEMFC (proton exchange membrane fuel cells) and SOFC (solid oxide fuel cells) are fuel cell technologies which are commercially ready for residential uses.

2.4 Barriers of hydrogen technologies

This sub-chapter focuses on the obstacles to the widespread adoption of hydrogen applications regarding space heating in the Dutch built environment.

2.4.1 Willingness public

There are multiple barriers to the adoption of hydrogen. The paper “Homes of the future: Unpacking public perceptions to power the domestic hydrogen transition” written by Gordon et al., (2022) tries to identify these barriers. From the analysis was concluded that the public has limited knowledge and awareness about hydrogen due to the absence of relevant information. Gordon et al., (2022) recommend that there should be more public trust created and consumers should be encouraged to engage as a stakeholder to stimulate the transition. The largest barrier determined in the research was the affordability of the new inhouse installation. And even when households can pay for the new installation, there is doubt that households are even willing to pay for it and accept the installation time.

2.4.2 Supply of hydrogen

Hydrogen is not an automatic solution for reducing CO_2 emissions and is not necessarily sustainable. Like electricity, this depends on the sources used for its production, since there are different methods of producing hydrogen. There are more than 40 different technologies for producing hydrogen. However, there are mainly three categories being discussed on how hydrogen is produced, which are grey, blue and green hydrogen (Alverà, 2020).

Grey hydrogen is characterized by its use of fossil fuels like natural gas to produce hydrogens. This process leads to CO_2 emissions and does not result in a reduction in the total CO_2 emissions (Hellinga & van Wijk, 2021; Weeda & Niessink, 2020). 10 % of Dutch natural gas is used to produce grey hydrogen (Wiebes, 2020). The Netherlands therefore already has the necessary experience and the use of hydrogen. Blue hydrogen, on the other hand, is produced from fossil fuels, whereby the released CO_2 is captured and permanently stored in, e.g., empty gas fields. This is also called low-carbon or blue hydrogen, and it results in a reduction in CO_2 emissions. The degree of CO_2 capture can vary between 55% and 90% (Hellinga & van Wijk, 2021; Weeda & Niessink, 2020). Green hydrogen is the promising approach which will use renewable sources to produce hydrogen. Green hydrogen is produced by splitting water into hydrogen and oxygen using renewable electricity sources. For this water-electrolysis, an energy efficiency of 70% can probably be achieved (Hellinga & van Wijk, 2021; Weeda & Niessink, 2020).

Companies are hesitant to invest and use hydrogen technologies due to the lack of available green hydrogen. There is some green hydrogen production project announced in the Netherlands. Shell for example is building a hydrogen plant in at the Second Maasvlakte in Rotterdam. Also international are some green hydrogen production plans announced, which shows the supply of green hydrogen will increase over time due to the growing hydrogen production (van Dijk, 2022). Luscuere and van Wijk, (2021) mentioned that this reluctance makes it even harder for production companies to invest in producing green hydrogen, thus hindering the hydrogen production development. Also, the required infrastructure is still missing to bring the hydrogen from the producer to the user. Haket and De Vos, and van Cleef (2021) argued that the development of a hydrogen infrastructure should not wait until there is sufficient green hydrogen available. It will take years to build the infrastructure for hydrogen and the system that supports it.

To overcome barrier of hydrogen shortage which results in companies holding back in investing in technology, it is argued that grey and blue hydrogen production is necessary to bridge the gap until there is sufficient green electricity to begin building the hydrogen economy (Haket & De Vos, 2021; Luscuere et al., 2021; van Cleef, 2021). Some people are against this proposal due to the belief that investments in blue hydrogen could lead to a delay in the competitiveness of green hydrogen, which in turn would prolong our dependence on fossil energy. This group states that it is essential to focus directly on green hydrogen to enable a faster and complete transition to a sustainable energy (Weeda & Niessink, 2020). Lammers and den Ouden (2020) mention that grey hydrogen can also be phased out gradually by a CO_2-implement levy that can gradually make grey hydrogen more expensive while green hydrogen becomes cheaper over time. In addition, it creates money to stimulate green hydrogen more.

2.4.3 Hydrogen price

With the current price of hydrogen, hydrogen heating application is unable to compete with alternative space heating solutions (OECD, 2021). The International Energy Agency (IEA) conducted research on the global development of hydrogen in 2021 where they also focused on the price development of hydrogen in coming years. The price for hydrogen produced from renewable energy is a variance between 3 and 8 US dollars per kg. Hydrogen produced from natural gas costs between 0,5 and 1.7 US dollars per kg. IEA expects that the price of hydrogen produced by renewable energy will drop to the range of 1,3 to 1,5 US dollars per kg by 2030 (OECD, 2021). Chapman (et al., 2019) and Alverà (2020) both propose that nuclear energy is a suitable technology to achieve large-scale production of hydrogen without emissions at a lower price.

In areas such as Mexico and Saudi Arabia, green electricity costs around 1.7 cents per kWh. The expectation is that it will drop to 1 dollar cent per kWh (van Wijk & Wouter, 2019). The cheapest electricity from fossil fuels (coal-fired power plants) currently costs between 3 to 4euro cents per kWh. Converting green electricity to hydrogen will create the necessary costs through efficiency loss and transport costs. However even though green hydrogen now is even more expensive LUSCUERE et al. (2021) expects that in time this will be cheaper than fossil fuels and in price it will compete away.

The still high-cost price of hydrogen is seen as a large barrier to the adoption of hydrogen. The price of hydrogen depends on the production, storage and transportation. Chapman (et al., 2019) also states that the cost of changing the infrastructure for hydrogen should be taken into account. Hellinga and van Wijk (2021) assume that with a price around 3.6 euros per kg hydrogen will be the most cost-effective solution for 66 – 75 % of the Dutch built environment for heating (Hellinga and van Wijk, 2021).

2.4.4 Infrastructure

Even though Luscuere and van Wijk, (2021) and Van Alphen (2021)) stated that it will be much cheaper to reuse the gas infrastructure with hydrogen multiple actors stated this will lead to a logistical challenge regarding the infrastructure (Alverà, 2020; Chapman et al., 2019; Speirs et al., 2017).

The challenge with converting the gas infrastructure to hydrogen is that it is very difficult to switch just one house from gas to hydrogen. If only one house wants a hydrogen supply through the existing gas network, all the houses that are connected to that network need to be converted simultaneously which will create a logistical challenge. At the same time, it creates a switchover period where households will be without a heating system. For the transition of a large group of consumers, there is a need for a high level of consumer acceptance required.

2.4.5 In-house installation barrier

If the local gas network is changed to carry hydrogen, it will be essential to adapt or replace current in-house applications due to the differences in characteristics between hydrogen and natural gas. This will require that households need to purchase a new installation that is compatible with hydrogen and the existing gas service pipes probably need to be replaced. It is possible to use the same services pipes, but this requires the pipes to be checked to make sure there are not any leakages of hydrogen which is plausible because hydrogen is a smaller molecule than natural gas. These installation costs are a barrier for most households because they cannot pay for these installation costs by themself (Speirs et al., 2017).

Consumers have this barrier also if they change their heating system to an electric heat pump. According to Speirs (et al., 2017), a full-electric solution like a heat pump has even higher cost than hydrogen solutions like a hydrogen boiler. Quarton and Samsatli (2021) concluded in their research that full-electric solution with a heat pump will require more insulation which will result in higher installation cost.

2.5 Policies for overcoming barriers

This part discusses different findings regarding policies and which policies researchers propose to implement, to stimulate the adoption of hydrogen in the Dutch built environment.

2.5.1 Willingness households

According to a 2016 SCP study, only 15% of Dutch citizens believe the national government should enforce strict policies and legislation for the energy transition. However, qualitative results indicate that they do believe changes in behaviour will be necessary for the large-scale adoption of hydrogen (Dekker et al., 2016). Excessive enforcement may result in resistance from Dutch homeowners but relying solely on the voluntary choices of individuals is unlikely to result in the large-scale change that is needed (Tigchelaar et al., 2019). López-Bernabé (et al., 2022) explain in their paper that including stakeholders during the process of formulating a policy helps with designing an effective policy and creating more acceptance.

Tigchelaar et al., (2019) explained that one of the reasons for a lack of adoption is that most people are not willing to invest their own money in making their houses more sustainable. There is also not an immediate trigger for people to invest and renovate their houses. This lowers the adoption of new technologies. Tigchelaar et al., (2019) suggested that the government should develop a policy that creates more urgency for people to invest in the sustainability of their house.

2.5.2 Usages and installation cost

Tigchelaar (et al., 2019) and Alverà (2020) both focus in their papers on which policy instruments could be used to reduce the costs on hydrogen usages for the built environment. Cost reduction is very important for making gas alternatives more affordable for households. Tigchelaar (et al., 2019) suggested that policies should focus on stimulating not just the transition of individual homes but on a larger project like a neighbourhood, because this leads to economies of scale. With this policy, the installation cost for each house is reduced. As early explained, according to Speirs (et al., 2017) is this inevitable for hydrogen because consumers are not able to choose by themselves to switch, as they are connected to a larger network. Speirs (et al., 2017) article suggested that government policies should focus on solving this logistical challenge for hydrogen.

Currently, the Dutch government has multiple policies for stimulating citizens to insulate their houses. The benefit of insulation is that it reduces the amount of energy required for heating houses, which reduces CO_2emission immediately. It will also reduce the peak demands for energy and avoid or reduce the investments in increasing the capacity of the infrastructure (Tigchelaar et al., 2019).

According to Quarton and Samsatli (2021), the government should create policies that both disincentivise existing technologies and support emerging technologies. This can be achieved through increasing taxes on older technologies which can help close the price gap with newer technology. The government may also enact new regulations that gradually phase out harmful technologies.

2.5.3 In-house installation cost

As explained in Chapter 2.4.5, one of the barriers is investment costs which are currently too high for most households to make a transition to hydrogen or electric heating. Policies should focus on how to make these alternatives more affordable for households by creating policies that created financial support (Tigchelaar et al., 2019).

Examples of a supporting emerging technologies policies are that the government invests in research of new technology or a grant policy which helps reduce the cost of switching to new technology. These policies are focused on creating a competitive advantage or even a playfield for the new technology (Quarton & Samsatli, 2021).

These different kinds of policies are evaluated in the analysis of Quarton & Samsatli, (2021), which resulted in the conclusion that the CO_2 budget and CO_2 taxation can stimulate the transition to net-zero emissions heating of households. Madurai Elavarasan (et al., 2022) concluded from qualitative research about decarbonisation households in Europa that taxation of fossil fuels is expected to be the most effective tool to stimulated carbon free heating technologies for houses. It was also concluded that combining multiple policy instruments into one package increases the effectiveness of a policy. The Dutch government has established an ISDE subsidy that enables homeowners to improve the insulation of their homes, purchase a solar water heater or a heat pump, and, if feasible, connect their homes to a district heating network (Rijksoverheid, 2022b).

2.5.4 Safety

There are potential safety risks with hydrogen which should be considered when implementing the technology on a large scale. Multiple research projects are conducted to identify potential risks of implementing hydrogen and this risk should be minimized through policies.

One of the risks that Speirs (et al., 2017) highlighted was that hydrogen does not smell. Gas also has not any smell but due to the added smell additive leakage can be noticed. An odorant must be added to hydrogen which makes it possible for people to smell if there is a hydrogen leakage. Also, by changing from gas to hydrogen new safety standards and training for operators of the gas network need to be developed (Speirs et al., 2017).

Both Speirs (et al., 2017) and Scott and Powells (2020) suggested that government should create programs or policies for developing these standards for hydrogen which minimize the risk. There is also the need for further research which can give more robust evidence on the safety issues before large transitions are possible. Due to this uncertainty about safety, the Dutch government published in 2022 3 factsheets about hydrogen safety. The main risk to hydrogen compared to natural gas is that hydrogen has an invisible flame and can lead to a rapid shockwave in case of an explosion. Natural gas has a visible flame and the combustion process is slowly compared to the hydrogen (Rijksoverheid, 2022a).

Hydrogen could also be used for cooking. This will create a safety risk because the flame is not visible. Scott and Powells (2020) propose that if hydrogen would be used for cooking, a colourant should be developed. This enables people to see the flame when they are cooking. But they also explain that using hydrogen for domestic heating will challenge public acceptance and suggest only the use of hydrogen for heating and to replace gas hobs and ovens with electric and induction alternatives.

2.6 Existing scenarios and pathways

There has been research conducted on potential scenarios for heating the Dutch built environment. For example, Yang et al., (2022) performed a case study about the residential energy transition to 100% electric heating in the Netherlands by using a bottom-up dynamic building stock model. With this, a pathway to a climate-neutral energy supply was formulated by giving clarity about how much electricity is required in the future and how the types of houses in the Netherlands will change over time.

There was only one report found that described a hydrogen-based scenario for the Dutch built environment. In this report the Netbeheer Nederland (2023) has formulated four scenarios. These scenarios differ on two key factors: degree of involvement by the Dutch government's and whether there is a more national or international energy-oriented market. In the two scenarios with a national oriented energy market, the majority of energy production is expected to come from solar panels within the Netherlands and offshore wind turbines in the North Sea. Whereas the scenarios with an internationally oriented energy market, renewable energy will be generated in places such as Spain and North Africa and then imported into the Netherlands.

A low degree of government involvement with the emerging of a national oriented energy market would result in local initiatives by citizens. In this scenario houses will be heated with a wide variety of solutions like district heating, biogas, heat pumps and hydrogen. Whereas a high degree of government involvement with a national energy market will result in mainly district heating. In the scenarios where there establishes an internationally energy market, most of the houses will be heated with hydrogen. Some of the houses will be heated with electric heating and district heating. Netbeheer Nederland also discussed their expectations for hydrogen's role in energy storage in this report. However, in each of the four scenarios, batteries will hold the largest amount of the flexible energy and hydrogen will hold only a small amount of it (Netbeheer Nederland, 2023).

2.7 Conclusion

In conclusion, the comprehensive literature review presented in this chapter provides first an exploration of the role of hydrogen could play in the new energy system. For this literature review the methodical approach of Wee & Banister (2016) as used. To tackle climate change a transition from fossil fuels to renewable energy is required. Hydrogen could play a key role in the new energy system as an efficient carrier for renewable energy. It enables the capture of renewable energy from high-yield regions like Australia or Spain to be transported to areas where energy demand is high. It also creates the possibility of affordable long-term energy storage, especially in salt caverns. The Dutch government recognizes hydrogen's role in achieving a CO_2 free energy system.

To achieve zero-emissions heating in the Dutch built environment new technologies must be developed. The Dutch government analysis highlights multiple technology strategies for space heating: individual electric heat pumps, district heating with various sources, green gas, and hydrogen. Different technologies are being developed which utilize hydrogen for heating, like hydrogen boilers, hybrid solutions, and micro-CHP. Hydrogen boilers provide a familiar transition from natural gas. Hybrid systems combine hydrogen boilers and heat pumps, offering cost-effective flexibility. Micro-CHP, primarily fuelled by fuel cells, presents a promising path toward efficient energy generation for the built environment. Further research is needed to optimize these technologies.

In the literature review, concluded that the main barriers that constrain the adoption of hydrogen technologies in the Dutch built environment are willingness to the public, supply of hydrogen, hydrogen price, non-existent infrastructure, and in-house installation cost. Multiple authors stated that the significance of government involvement and policies are required to overcome these barriers.

Furthermore, the literature review concluded that the existing scenarios formulated by Netbeheer Nederland expects that if an international energy market emerges, hydrogen boilers will become the primary heating technologies for houses in the Netherlands. A drawback of the Netbeheer Nederland (2023) report is that the scenarios only addresses the use case for hydrogen boilers, but leaves out fuel cell technology and local hydrogen production and storage.

3. Theoretical framework and conceptualisation

In this chapter the theoretical frameworks are discussed which will be used to analyse the development of a new technology and identify potential scenarios regarding new technological innovations. In this section, the multi-level perspective (MLP), Strategic Niche Management (SNM) and Socio-technical Scenarios (STSc) are discussed. Also, a conceptual framework is formulated which explains how the three frameworks are used complementary to analyse the context of hydrogen in the Dutch built environment.

3.1 Multi-level perspective (MLP)

Large technological transitions require not only a new technology innovation but are also influenced by user practices, legislation, infrastructure, and a network of stakeholders. This means a technical transition does not only have technical aspects but also social aspects. With the socio-technical transition, the interaction between technology and society is being analysed (Elzen et al., 2004). In this case not only the technical developer, but also other parties e.g., policymakers, and consumers can have input on the technology development. In a socio-technical transition the technologies interact with larger societal systems comprising both technological and social elements. These social elements e.g., organizations and regulation established by the governments and user behaviour. Transition research using socio-technical approaches focusses on the technological innovation within a transition (Geels, 2002, 2004).

However, these approaches underscore that technology is only effective within a societal context when integrated into a socio-technical system. This system is formed by a network of actors such as users, producers, suppliers, public authorities, financiers, and the respective infrastructures, patterns of behaviour, cultural values, and policies (Geels, 2004). This means that a socio-technical transition goes further than just acknowledging the adoption of new technology but includes the new infrastructure and social acceptance of users (Geels et al., 2017). The MLP can be used to explain the socio-technical transition by making the distinction between landscape, regime, and niche innovation levels and how these levels are interacting with each other (Geels, 2002).

The landscape level represents major changes in society and/or politics how challenge the current socio-technical regime. The landscape factors mainly develop slowly and are difficult to change because they are deeply rooted in our society. There is also the possibility of unexpected events which can influence society very heavily in a very short time due for example a natural disaster, economic crisis or a war (Geels, 2004, 2005).

The regime level reflects the current system in which various actors operate. To make sure that these actors can function together there are normative and cognitive, and regulative rules. Regulative rules are implemented by the government. The industry should follow these laws and standards. Normative rules are about shared values and the code of conduct within the regime. This explains more about the different roles of actors and what their responsibilities are. Cognitive rules are shared beliefs and routines between the actors. These rules are established in a regime, but in the niche, the rules still need to be developed. If these rules are presented between the actors than there is a regime (Geels, 2004, 2005). Also, these rules influence the behaviour of the actors. At the same time actors empower these regulations by the usages of them. According to Geels (2004) there is a interaction between technology, human actions and social structures in the regime.

The niche level represents the area where radical new innovations are developed. According to Schot et al. (1994), a niche has the protective space where the technology can be developed without the need of competing with the established technology. Smith and Raven (2012) have described the characteristic of a protective space in more dept by identifying the three processes of a protective space which are shielding, nurturing and empowerment. This is necessary because the niche cannot sustain within the regime where there is an established technology. During the shielding process, the niche innovations are not challenged by the same selection criteria as regime innovations. This shielding process can be active or passive. Passive shielding could be established through geographical spaces which means that the current technology is not usable in specific locations. An example is that a house is heated with electricity because the house is in such a remote place located that they are unable to connect the house to the gas infrastructure. In this example, the established technology of gas boilers cannot compete due to the geographical space. Active shielding is established through policies of the government. Empowerment can be understood in two forms: one where niche innovations become competitive within the existing selection environments, and the other where the selection environments are influenced by the niche, resulting in changes that favour the niche innovation. Nurturing refers to the process in which the niche is develop until a point that it can compete with the existing regime or gets embedded in the existing regime. When the niche enters the broader market, the protected space will disappear over time. Most events like a new policy from the government create shielding, nurturing and empowerment simultaneously but the process still is very different (Smith & Raven, 2012). According to Geels and Schot (2007), the niche and regime have a similar structure but they differ in size and stability. The regime a large quantity of actors is participating and there are established rules between the actors which creates stability. In contrast the niche has small number of actors participating and still undeveloped rules which creates instability.

The purpose of MLP is to show how these three levels are interacting with each other and process of how the transition of how an established technology is being replaced by a new technology. Figure 1 shows the MLP. The MLP works in the following steps, the landscape developments put pressure on the regime which can lead destabilizes the regime. For the regime to stabilize again it looks for new technologies in the niche level. The regime wants to include new innovations to adapt to the new pressure from the landscape. This creates a window of opportunity for new innovations to be adopted into the regime because they solve a problem for the dominant regime (Geels & Schot, 2007). These innovations come from the niche innovation layer and within the analysis is looked at how the regime is affected by upscaling of the niche from the niche level (Kamp & Vanheule, 2015). The complex socio-technical transitions can be simplified and made more transparent with this framework. It also makes it easier to answer the question of what destabilizes the current regime, which players are active in this regime and what is needed to stabilize the regime (Geels, 2005). There is always some landscape pressure but the regime uses established technologies which are locked in by for example regulations to created barriers for new technologies to enter the regime (Kamp & Vanheule, 2015). Niches and regimes are similar in kind, but niches are not stable and are still in the making in contrast to regimes (Geels & Schot, 2007).

According to Geels and Ayoub (2023), the transition from niche to the regime happens in four phases. The first phase is experimentation where radical innovation emerges in the niches. The second phase is stabilization, which means the innovation finds stability in small niche markets. In the third phase the niche transitions and diffuses to the regime by entering the mass market. In this phase, the innovation is competing with the current technology. In the last phase is called institutionalisation which means the new technology is embedded in the new regime. This means for example that people see technology as normal, people have the habit of using it and is implemented in our regulatory programs.

Between phases two and three is the tipping point. In that moment the technology is not seen as a fragile innovation which is still in development and is not ready to challenge the existing technology. But transitions to a robust and competitive technology which aligns with our socio-technical element and diffusions to the mass market. This could be the case if the cost reduces due to the implementation of subsidies (Geels & Ayoub, 2023). The multilevel perspective process is visualised in Figure 1, the circled area represents the tipping point.

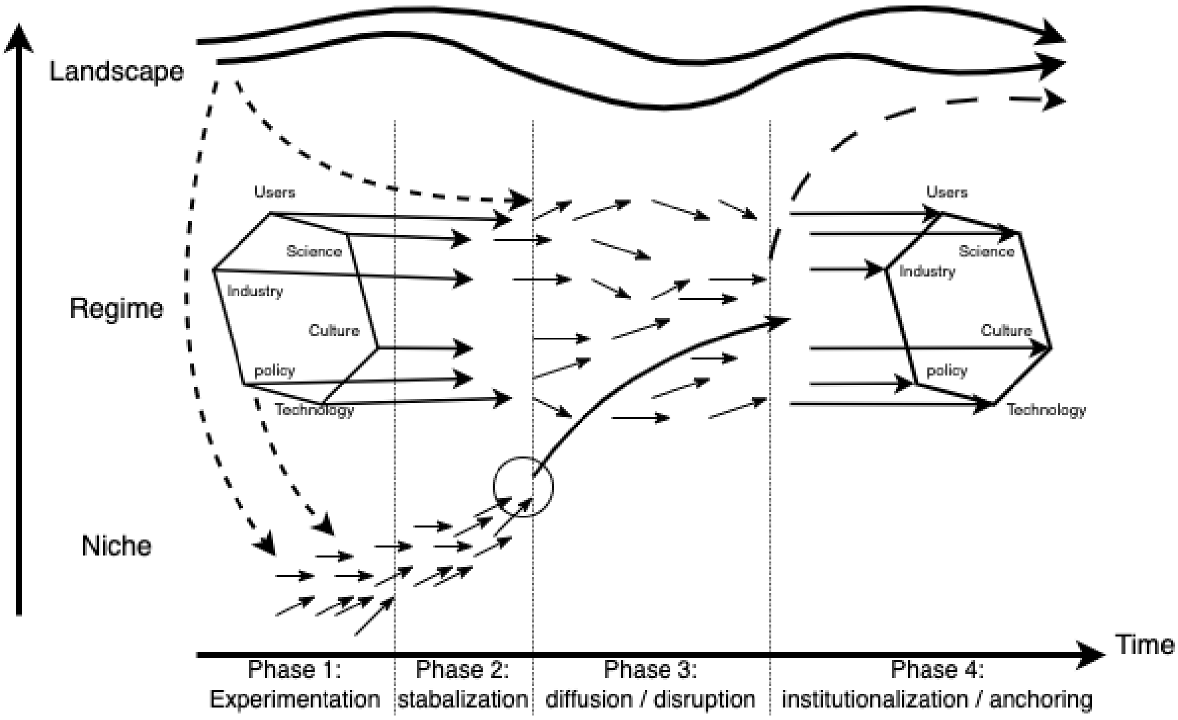

Figure 1, multi-level perspective with the defined phase and tipping point, Adopted from (Geels, 2002; Geels & Ayoub, 2023)

3.2 Strategic Niche Management (SNM)

SNM is an analytical tool that can be used to review and analyse the development of innovative technologies in niches. These niches can be seen as incubation rooms or protective systems surrounding the new technology. In the niche, the innovation can grow and develop to become viable through gradual experimentation and learning by networks of actors (Kemp et al., 1998). A technological niche can evolve into a market niche, a space where users start to recognize the values of the innovation and where it can compete over the established technologies (Kamp & Vanheule, 2015).

With the SNM the development of technology can be analysed. This is done by analysing three processes:

- Shaping expectations: Focusses on expectations actors of the technology and if their expectations are aligned. If this is the case, it can attract new resources and actors who want to contribute to the new technology. These expectations can change over time (Raven, 2005).
- Network formation: To develop a technology a network of relevant actors needs to be established. This in return will attract new actors and improves the learning process. The network should consist of actors with different interests and roles but should also have an aligned vision (Raven, 2005).
- Learning process: Explains the process of learning which influences the expectation over time and aligns them with the different actors. It also focuses on improving innovation and developing the norms and values with are related to innovation (Raven, 2005).

By using this SNM a better understanding of how the technology needs to mature and how policymakers can contribute to that process. At the same time, it is useful to perform this analysis in combination with the MLP because it is more comprehensive by including external processes (Schot & Geels, 2008). Kamp and Vanheule (2015) improved the understanding of these process by formulating indicators on how to identify these processes. These indicators give together an insight into which direction the niche is developing.

The shaping and voicing of expectations of actors are important for niche development because it creates a shared belief on how this technology should work in the Netherlands and what its role is within the larger transition. Kamp and Vanheule (2015) introduce exogenous and endogenous indicators for expectations. Exogenous indicators focus on developments outside the niche which influences the expectation of the niche. This could be due to changing landscape pressure. Endogenous indicators focus on expectation forming due to developments within the niche. This could be for example changing production costs which could influence the expectation of adoption of the technology. Kamp and Vanheule (2015) also introduces internal expectations relate to actors' aspirations and goals, while external expectations are from actors outside the niche.

Network formation is about the different actors within the niche. The goal is to identify the network composition and the role and goals of these actors. Also, the alignment of the network on vision and expectation is analysed (Kamp & Vanheule, 2015). The actors analysed in this section will be part of the niche, whereas the actors analysed in the MLP are part of the regime.

The learning process is not about the learning process of one actor but about the learning process of the niche of which multiple actors are part of (Kamp & Vanheule, 2015). Hoogma (2002) distinguished the learning process within the niche between first-order learning and second-order learning. First-order learning focuses on innovation development, whereas second-order learning is about the shared norms and values of the technology. These learning orders can be analysed on five aspects which are technical development and infrastructure, social and environmental impact, industrial development, user context and legislation. Kamp & Vanheule (2015) have adopted these distinctions of Hoogma (2002) into five indicators which are technical development, infrastructure development, social development, user usage, and government policy and regulation. Analysing the learning of technology provides insights into the niche's progress in harnessing hydrogen-based heating technologies effectively. Assessing infrastructure development focuses on the niche's understanding of the required infrastructure for hydrogen implementation. Learning about safety is vital to ensure the niche's ability to address safety concerns associated with hydrogen applications. Understanding user acceptance and usability is crucial to gauge the potential for widespread adoption of hydrogen heating solutions. Lastly, learning about legislation and policies aids in comprehending the niche's responsiveness to regulatory frameworks and its alignment with government priorities. The indicators are presented in Table 1.

Niche process	**Indicators**	**Analysis on**
Expectation	Internal	Expectations of actors in the niche
	External	Expectations of actors outside the niche
	Exogenous	Expectations due to changing landscape, regime or development of other niches
	Endogenous	Expectations from learning experiences and network composition
Network formation	Network composition	Desired composition and completeness of the network
	Network interaction	How actors are interacting with each other
	Network alignment	The alignment on the vision about the niche

Learning process	Technical development	Learning of technology
	Infrastructure development	Learning about the required infrastructure
	Social development	Learning about safety
	User acceptance and usages	Learning about user acceptance and useability
	Government policy and regulation	Learning about legislation and policies

Table 1, indicators of niche development, adopted from (Kamp & Vanheule, 2015)

3.3 Socio-technical scenarios (STSc)

As stated in sub-chapter 3.1 a transition does not only require new technology but requires also changes in user practice, legislation, infrastructure, and a network of stakeholders (Geels, 2004). When dealing with system innovations for tackling climate change one of the challenges is that there is not just one but multiple suitable technology solutions. At the same, a variety of combinations is probably required to deal with large system changes (Elzen & Hofman, 2010).

Most scenario methods aim at finding clues on what will happen in the future if certain trends will continue (Elzen & Hofman, 2010). Traditional technology forecasting methods do not consider the interaction between society and technology. This is why Elzen et al. (2004) developed the tool socio-technical scenarios. According to Elzen et al. (2004), traditional forecasting methods for assessing future scenarios assumed that the future will look similar to the past and that focus on a specific topic without looking at the broader system. At the same time, multiple technologies emerge simultaneously and affect each other during the process. Traditional forecasting scenarios do not take this process into consideration. Another methodology for analysing future development is through backcasting in which a desirable future is described. Backcasting takes the interaction between technology and social considerations, but it lacks clarity on how transition may occur due to the unclarity about the learning process (Elzen & Hofman, 2010, 2007).

STSc have a more qualitative approach to exploring potential futures. This enables the ability to take a broader approach in which the interaction of actor strategies, social networks, rules and learning processes are taken into consideration. Whereas to the traditional approach which mostly focuses on performance and price. The goal with STSc is to write plausible stories about how the transition could occur (Elzen et al., 2004; Elzen & Hofman, 2010). STSc utilizes the MLP to explain how different multi-level patterns could lead to a certain transition. By using these patterns in STSc a better understanding is gained of why certain linkage and developments occur (Elzen et al., 2004; Elzen & Hofman, 2007; Hofman & Elzen, 2010). Elzen et al. (2004) formulated some example patterns which could occur and should be implemented in the scenario:

1. The regime is under landscape pressure which results in space for niches.
2. The regime tries to deal with the landscape pressure through various improvements.
3. Niches can merge which is called hybridisation or split up which is called forking during the process.
4. The new technological developments create also societal development.

STSc are only intended to explore the potential future, but they are not a prediction of the future. During the process, potential routes of transitioning are explored by focusing on the interaction between technological and social changes (Elzen et al., 2004; Elzen & Hofman, 2010). What socio-technical scenarios also differentiated from other scenarios methods is that it takes the development of the expectations of actors within the niche and regime into consideration (van Bree et al., 2010). The stories are written as the history of the future, which means they are written in the past tense which helps the reader to be more critical of how likely the potential future is. These scenarios contain the following characteristics:

- The socio-technical developments, by describing the co-evolution of the social and technical developments. With co-evolution means how the expectations change of actors over time due to other developments (Elzen & Hofman, 2007).
- The interaction between the niche, regime and landscape level (Elzen & Hofman, 2010).
- Multiple patterns that lead to a scenario instead of just one driving force (Elzen & Hofman, 2007).
- Learning process and niche dynamics described as is explained in sub-chapter 3.2 (Elzen & Hofman, 2010).
- Technology changes, combines with other technologies, splits into different lines of development. The scenario should describe the interaction between different technologies developments (Elzen & Hofman, 2010).
- The niche accumulation is described, which means that the technology is over time entering larger markets (Elzen & Hofman, 2010; Geels & Schot, 2007).

In a STSc the transition from the niche to regime is described. According to Geels and Schot (2007), there are four typologies of pathways on how a niche can transition to the regime. According to Hofman and Elzen (2010) these transition pathways are used as building blocks for formulating the scenarios. The four formulated typology pathways are Transformation, De-alignment and Re-alignment, Substitution and Reconfiguration (Geels and Schot, 2007). Geels et al. (2016) add later categories which explains how these pathways differ from each other. These categories are actors, technologies and rules and institutions. Geels et al. (2016) explains that the transition could outside-in or an inside-out approach regarding actors. Outside-in means that the new companies are in competition with incumbent firms in the regime. Inside-out means the incumbent firms are developing an innovation which can be incremental or radical. In the categories technologies a differentiation is made between radical or incremental innovation. The focusses on the emerging of new rules and institutional change that occurs in the transition. In Table 2 are the transition pathways formulated with the difference in actors, technology and rules and institutions change. Geels and Schot (2007) also acknowledge that during the process a transition could shift between pathways. The stories contain also short-term patterns of how the transition occurs.

Transition pathways	**Actors**	**Technologies**	**Rules and institutions**
Substitution	New firms struggle with incumbent firms, resulting in new firms overthrowing incumbent firms	Radical innovation which substituted the existing technology	Limited institutional changes
	New kind of entrants like citizens, social movement, or firm who incumbent in another sector.	Radical innovation which substituted the existing technology	New rules and institutions are created which are suited for the niche innovation

Transformation	Incumbent actors maintain control by adjusting routines and procedures	1) Incremental improvement in existing technologies	Limited institutional changes
		2) Incorporation of symbiotic niche-innovations and add-ons	Limited institutional changes
	Incumbent firms maintain control by developing radical new technologies and even new believes and business model	Incumbent firm focus on new and existing technology	New rules and institutions are created which are suited for the niche innovation
		New technology replaces the existing technology	New rules and institutions are created which are suited for the niche innovation
Reconfiguration	Alliance forming between incumbent and new firms	Combination of new and existing technology	Limited institutional changes
De-alignment and re-alignment	Incumbent firms disappear and new entrant take regime over	Old technology disappears and new technology take over	New rules and institutions are created which are suited for the niche innovation

Table 2, transition pathways, adopted from (Geels et al., 2016)

According to Elzen and Hofman (2010, 2007) the scenarios consists out of 4 episodes. These episodes will be used as a layout for writing the scenarios. The scenario consists out of the following episodes:

1. Disconnection: in this part the regime experiences pressure from the landscape which destabilizes the regime. The motivated niche actors to develop new technologies.
2. Linking: Niche links up with events in regime and technology changes, combines with other technologies, splits into different lines of development to adopted to the need of the regime.
3. Transformational: The new technology gradually takes over the regime.
4. Evolution: The new technology is established in the regime.

To construct a STSc, 7 methodological steps needed to be taken, which are presented in Table 3. The steps should not be strictly followed in a linear sequence, as there can be some flexibility to move back and forth, particularly during the process of crafting the scenario architecture(s).

	Methodology step	**Description**
1	Specification scenario objective	Describe the objective of the scenario and which regime and niche is being researched.
2	Analysis of current dynamics between levels	Describe the regime, niche and landscape dynamics
3	Inventory of potential linkage/patterns	Identify potential linkage between landscape and niche. Also, how user behaviour changes from actors. But also, between technical and political developments.
4	Design choices	Requirements of the scenarios are specified: • Timeframe • Number of scenarios

		• Which transition pathways to include? • Describe which niches to include in scenario. • Which variables are used in the scenarios? • Level of detail for each scenario described. • Specific focus of scenario
5	Develop scenario architectures	Write the scenario based on the patterns as identified in step 3 and formulated a layout for the scenarios
6	Elaborated all scenarios	Check if the scenario is according to the characteristics of STSc
7	Reflection and recommendation	Evaluated scenarios and develop recommendations

Table 3, methodological steps STSc, adopted from: (Elzen & Hofman, 2010, 2007).

3.4 Conceptual model

So far it is discussed how MLP, SNM and STSc all can contribute to further understanding of how socio-technical transitions occur. This sub-chapter describes how these theories are complementary and how they are conceptualised in this thesis.

The MLP framework provides a useful theoretical framework for understanding the broader dynamics of transitions, but it may not provide as much guidance for specific actions that can be taken in the present to improve the transition. The MLP focuses on the interplay between niches, regimes, and landscapes. While understanding these dynamics is important for promoting sustainability transitions, it may not always provide clear guidance for immediate action. Geels and Schot (2007) explain that a possible downside of MLP is that it focuses more on a macro level which creates less attention for stakeholders. A limitation of only using SNM is that it only focuses on how the niche is developing and that it could transition by further nurturing the niche. But it leaves out how ongoing processes within the regime and landscape are developing (Geels & Schot, 2007).

With STSc not only future exploration can be conducted on the niche level but also on the interaction between all three levels. STSc uses the MLP framework to explore linkages between the levels which will create transition pathways (Hofman & Elzen, 2010). Also, the expectations of actors can be explored within STSc (van Bree et al., 2010). A limitation of STSc is that the formalized scenarios are subjective which results from the nature and complexity of the transition (Hofman & Elzen, 2010). By using all three frameworks these limitations are minimized and create the benefit of a large understanding of the transition.

The MLP will be used to analyse the landscape, regime, and interaction dynamics between the levels. To identify landscape developments external factors will be analysed, such as changing regulations, evolving societal expectations which could pressure the regime. The regime developments will be analysed by looking at the cognitive, and regulative rules that exist in the heating regime for the Dutch built environment.

In this thesis SNM will be used to creates a detailed understanding of the niche. This is done by utilizing the indicators proposed by Kamp & Vanheule (2015) which are presented in Table 1. To analyse the expectations of the actors the indicators internal, external exogenous and endogenous expectations are used. These indicators are used to identify how actors, within and outside the niche, expect on how the niche will further develop and which challenges in the regime they expect to resolve. To analyse the network formation of the niche the indicators network composition, alignment, and interaction are used. The 4 indicators technical, infrastructure, social and user development are used to identify how the learning process of each technology is taken place. Also, the indicator government policy and regulation are used to describe which policies and regulation are still in development which are required for the niche to transition to the regime. With the insight gained from both SNM on the niche and MLP on regime and landscape the MLP is further used to on how the niche interacts with the regime and what is holding back the adoption of the technology by identifying the barriers.

In this thesis the methodological steps formulated by Elzen and Hofman from 2007 and 2010 as presented in Table 3, are used for formulating socio-technical scenarios. The objective of the scenarios is to illustrate multi-level patterns that may occur which leads to an active role of hydrogen in the Dutch built environment. STSc utilizes inputs from both SNM and MLP analyses to formulate the design choices for the scenarios. The design choices contain the timeline and layout of the scenarios. Also, the influencing factors and potential patterns are formulated. The episodes formulated by Elzen and Hofman (2010, 2007) are used as a layout for formulating the scenarios. Instead of using all four episodes proposed by Elzen and Hofman (2010, 2007) the disconnection episode is left out. In the disconnection episode is discussed how the regime experiences pressure from the landscape and how niche actors are motivated to develop new technologies. In this thesis this process is described in the MLP and SNM analysis which will be conducted before the STSc formulation. The scenarios will contain the linking, transformational and evolution episode in which the learning processes, current dynamics between the levels and potential linkage and patterns are described. From the scenarios the transition pathways are determined based on the actors, the type of technology, and the degree of changing regulations and institutions as proposed by Geels et al. (2016). Figure 2 shows how these three theoretical frameworks are used to formulate a conceptual framework.

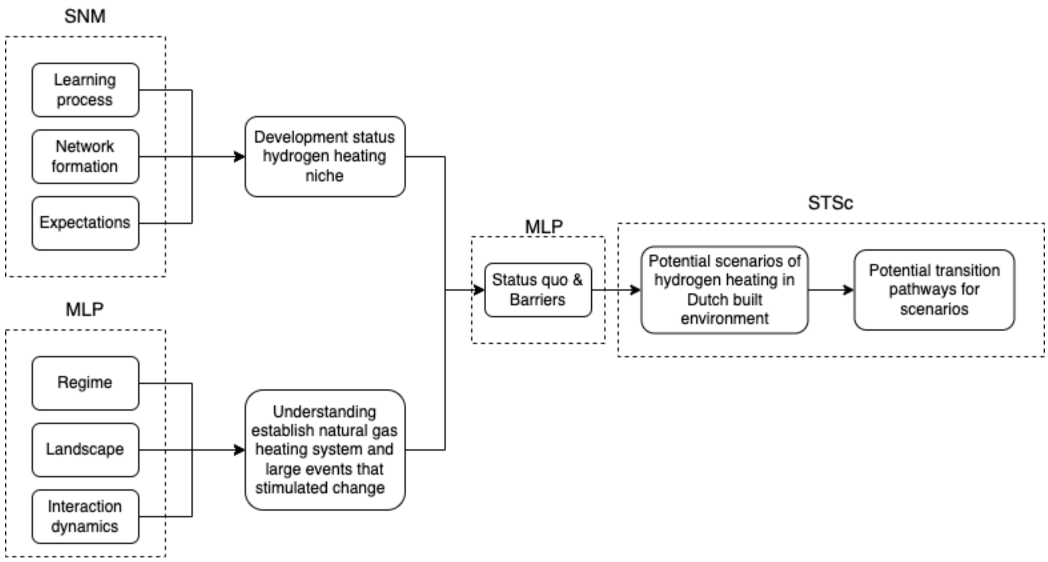

Figure 2, conceptual model, own creation

The complementary usages of the frameworks in this thesis are also visualised in Figure 3 which represents the MLP and the role SNM and STSc have in understanding the dynamics between the levels. The blue circled elements are the niche in Figure 3 and are analysed with SNM. The green elements in Figure 3 are being analysed using the MLP by examining landscape and regime developments and the dynamics between niches, regimes, and landscapes. The red elements represent the transition pathway in Figure 3 and is analysed using the STSc which starts from the stabilization phase. This point is selected because as stated in the literature review, chapter 2.3, hydrogen applications for heating have not find a niche market which means it has not yet in the stabilization phase. In the socio-technical scenarios can be explored how these niche markets can establish. By visually differentiating the elements based on colour, it becomes clear which framework is analysing each aspect of the transition. The blue circled elements correspond to SNM's analysis of the niche, the green elements are examined through MLP, and the red elements are studied using STSc. This complementary usage of the frameworks offers a more comprehensive understanding of the transition process.

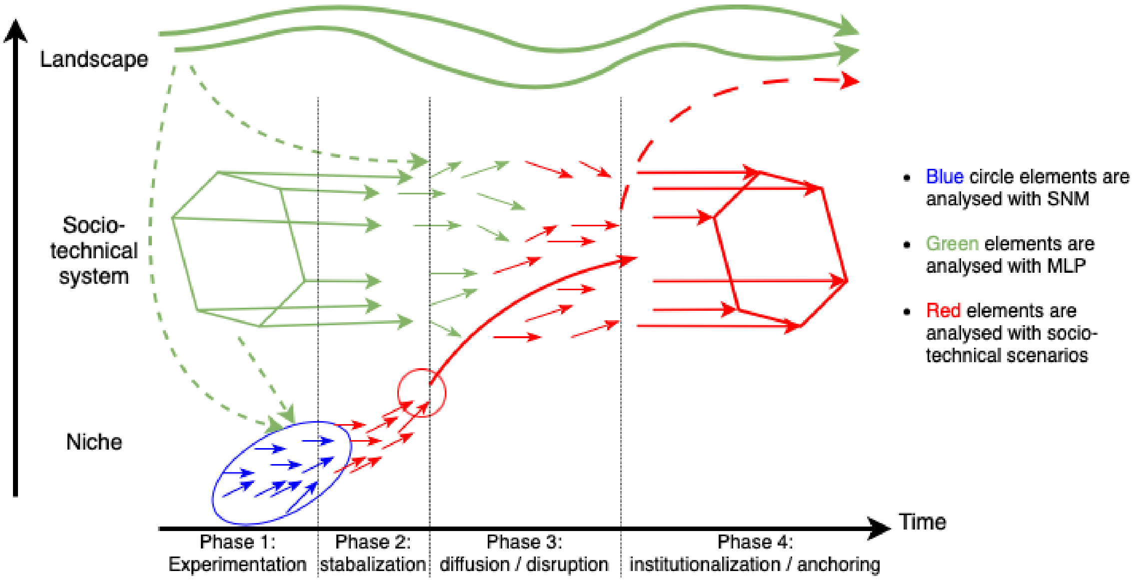

Figure 3, multi-level perspective with indicated areas of SNM and STCs, MLP adopted from (Geels & Ayoub, 2023)

3.5 Conclusion

This chapter MLP, SNM and STSc are explored, which are useful for analysing socio-technical transitions. It highlighted the importance of recognizing that transitions are more than just a technological change. It also involves shifts in user practices, policies, infrastructure, and stakeholder networks. Socio-technical transitions involve the interaction between technology and society, encompassing both technological and social elements. In the conceptual framework is explained how MLP, SNM, and STSc are used complementary to analyse the current transition and formulated multiple socio-technical scenarios.

The MLP framework divides the socio-technical system into three layers: landscape, regime, and niche. It helps explain how landscape factors exert pressure on the regime, destabilizing it and creating opportunities for niche innovations to be adopted into the regime. The MLP also identifies four phases of transition from niche to regime: experimentation, stabilization, diffusion, and institutionalization. MLP will be used for analysing the landscape and regime. And for analysing the dynamics between the landscape, regime, and niche. The regime will be analysed by looking at the cognitive, and regulative rules that exist in the heating regime for the Dutch built environment.

SNM provides a way to analyse the development of innovative technologies within niches, offering insights into how these niches can transition to the regime. SNM focuses on shaping expectations, network formation, and learning processes within the niche to understand how the technology can mature and be integrated into the broader system. In this study the indicators proposed by Kamp & Vanheule (2015) are used to analyse the expectations, network formation, and learning processes of the hydrogen heating niche.

STSc are used to explore potential futures of transitions, considering the interaction between technology and society. STSc offer a qualitative approach to scenario development, considering actor strategies, social networks, policies, and learning processes. These scenarios provide a comprehensive understanding of the transition process, helping policymakers make informed decisions. In this study the STSc utilizes inputs from both SNM and MLP to develop potential future scenarios and transition pathways.

4. Methodology

The purpose of this chapter is to describe the methodology of this research. First, the research design presents the research approach and what exactly is researched. Additionally, a clear case description is given and explained how the data is collected and analysed. Furthermore, the Validity, reliability, generalizability, and limitations are discussed.

4.1 Research design

In this study a case study is conducted about the hydrogen heating applications in the Dutch built environment. As explained in Chapter 1 the following main research question has been formulated: "*What is the development status of the hydrogen niche for heating homes in the Dutch-built environment and which socio-technical scenarios can be expected?".*

To answer this main research question, qualitative research will be conducted. Semi-structured interviews will be conducted with experts from this field. Also, a literature study will be conducted into the relevant aspect of this study about hydrogen usage for heating the Dutch built environment. The rationale behind selecting a qualitative research method is to gain a comprehensive understanding of the development of the hydrogen niche for heating Dutch built environment. Through in-depth interviews with experts and a thorough literature review, the aim is to identify likely scenarios for hydrogen heating in the Dutch built environment. By employing qualitative research, rich and nuanced insights can be gathered that will contribute to a well-rounded exploration of the subject. The research is structured in 6 as visualized in Figure 4.

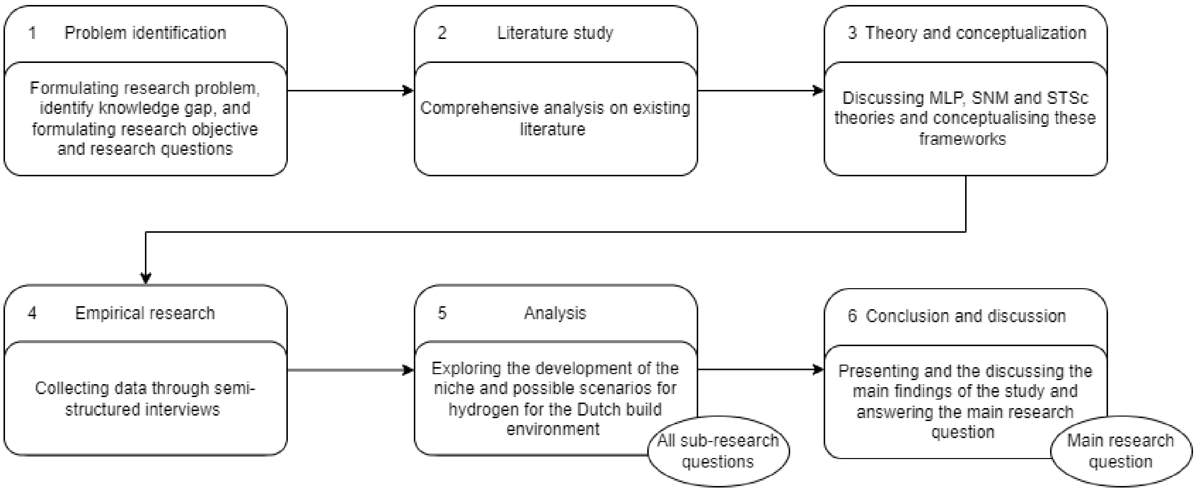

Figure 4, research design, own creation

4.1.1. Research scope

This study aims to investigate the development status of the hydrogen niche for heating homes and explore potential scenarios in the Dutch-built environment. The primary focus is on understanding the development of hydrogen heating technologies in the Netherlands, with a special emphasis on the insights gained from ongoing pilot projects. By delving into these new insights, the research aims to provide a comprehensive understanding of the socio-technical possibilities of hydrogen utilization in the Dutch built environment and the transitional pathways that may unfold. This includes gaining insights into the different roles envisioned for hydrogen in the context of space heating. The scenarios also illustrated the multi-level patterns that may occur, which leads to an active role of hydrogen in the Dutch built environment.

The scope of this academic research centres on the potential role of hydrogen in the built environment, specifically in the domain of space heating. This choice is driven by the prevalent use of natural gas for heating purposes in the current technology landscape of the built environment. The built environment encompasses not only residential buildings but also various other types of structures such as offices, shopping centres, and industrial facilities. The decision to focus on the built environment is motivated by the Dutch government's interest in exploring hydrogen not only for residential buildings but also for commercial and industrial settings where natural gas is currently the primary energy source for space heating (Ministerie van Economische Zaken en Klimaat, 2019).

Hydrogen's potential role in space heating within the built environment is diverse. Firstly, it can be directly used by burning hydrogen to produce heat. Secondly, an indirect approach involves converting hydrogen into electricity through fuel cells and subsequently utilizing this electricity for heating purposes. The inclusion of the indirect use of hydrogen in heating scenarios is driven by its promising potential, as evidenced in the relevant literature (Dodds et al., 2015b; Hellinga & van Wijk, 2021; Sun et al., 2021). Fuel cells represent a viable technology that can efficiently harness hydrogen for heating applications.

4.2 Case selection

The demographical focus of this study is the Netherlands. This is chosen due to various reasons. One of the reasons is that there are multiple ongoing pilots in the Netherlands with hydrogen in the built environment e.g., in Wagenborgen, Hoogeveen and Stad aan 't Haringsvliet. This makes it a relevant and timely topic to research the development of this niche due to the potential new knowledge resulting from these hydrogen pilots in the Dutch built environment. This study aims to identify and analyse if new opportunities and challenges are identified due to these pilots in the Dutch built environment. It also aims at exploring possible scenarios on hydrogen usage for the Dutch built environment.

Also, the Dutch government has announced that they want to become the hydrogen hub of Europa with the port of Rotterdam. This will result in a large increase of hydrogen in the Netherlands in the coming years (Jetten et al., 2022). Also, the European Union is focussed on establishing a hydrogen economy hydrogen strategies and agreements are made with other European countries to establish an integrated hydrogen infrastructure across countries (Luscuere & van Wijk, 2021b; Rijksoverheid, 2023b). Moreover, in the wake of the 2019 Climate Accord, the Dutch government forces the existing energy system to search for a new heating technology. These unfolding events signal an imminent shift in the established regime and underscore the potential for hydrogen heating application in the Netherlands, which makes it a compelling subject to further investigated.

This study will not cover other potential uses of hydrogen, such as transport or industrial applications. It will also not focus on the further development of the production of hydrogen. The study will focus on the Netherlands as a case study and will not examine the usage of hydrogen for heating houses in other countries. Despite the physical boundary of the Netherlands, it is important to note that the production of hydrogen for heating houses does not necessarily have to occur within the country's borders. The focus of this case study is to explore the current situation and how Dutch organizations are operating in terms of using hydrogen for heating houses, as well as the opinions of experts on how the transition to hydrogen heating should be implemented specifically within the Netherlands.

4.3 Data collection method

To effectively address these research questions, qualitative research methods will be employed. A combination of a comprehensive literature review and in-depth semi-structured interviews will be conducted.

The literature review will serve as the foundation for understanding the historical context and existing knowledge about the Dutch-built environment's heating system. Desk research is conducted by reviewing existing literature, articles, and reports relevant to the research topic. This will help to build a solid foundation of knowledge on the subject matter. By getting a broader understanding of the current energy system and its stakeholders, identify any barriers to hydrogen heating and what current policy solutions that being investigated. Also, further literature research is conducted into the legislation surrounding space heating in the Dutch built environment and how this has changed in recent years due to climate awareness. Furthermore, the development of the hydrogen niche will be researched as to what the expectation is for further development.

The decision to use semi-structured interviews was based on the providing the needed flexibility to delve into specific topics and themes in greater depth while maintaining a level of structure and consistency across all interviews. This approach allows for a comprehensive understanding of the development status of hydrogen heating technologies in the Dutch built environment and sheds light on the likely scenarios for their adoption. This approach ensures that the study can address the knowledge gaps effectively and offer valuable insights into the opportunities, challenges, and pathways for the future of hydrogen heating technologies in the Netherlands.

There have been a large variety of experts interviewed, which range from government employees to researchers and employees at infrastructure companies. The chosen interviewees were for example involved in the development of energy policies, regulations and hydrogen pilots. In total, there have been 14 interviews conducted with experts from the industry. The interviews were conducted during the months of May and June 2023. The interview question can be found in Appendix A. Two of these interviews have been conducted face to face. The other 12 interviews have been conducted online with MS Teams. These interviews took between 30 till 60 minutes and participants were contacted through LinkedIn to participate in the study.

Before the interviews had been conducted a Data Management Plan (DMP) was created which was reviewed and approved by a Human Research Ethics Committee (HREC) of the TU Delft. DPM can be found in the appendix. Also, the participants have been asked to sign a consent form which explicitly explains that the findings from the interviews will be used to answer the research question, see Appendix B. The signed consent forms are stored on Surfdrive cloud from the TU Delft. The interviews have been transcribed using the Word Transcribe tool and have been manually checked and improved when necessary. These interviews are anonymous and only a clarification will be given to which type of stakeholder group they belong. In Table 4 an overview is given of the interviewees by defining the type of stakeholder group they associated with and give a job description. Also, an assigned code is given to each interviewee, to which will be referred in the report. The table is arranged in alphabetical order based on the codes given to each interviewee.

Code	Stakeholder	Description
EA1	External advisor	Representative for companies in the heat and energy market in the Dutch market. Mainly focussing on advocating the interests of heat companies towards the government concerning new policies and legislation.

EA2	External advisor	Advises municipalities on the energy transition by identifying heating alternatives for neighbourhoods and conducting cost-benefit analysis different heating solutions.
EA3	External advisor	Advisor at a bank. Conduct research on the energy transition in the Netherlands and gives advice on investment opportunities in companies and technologies related to the energy transition.
EA4	External advisor	Advisor for government institutions on energy transition in the Dutch built environment. Also advises on the role of hydrogen within the energy transition and advises on market trends in the energy market.
HAP1	Hydrogen application producer	Business developer at company how develop hydrogen boilers. Develops new business models for new markets and participates in lobby activities for policies regarding heating in the Dutch built environment
HAP2	Hydrogen application producer	Founder of company how develops a fuel cell for in the built environment. Mainly focussing on developing technology and forming an adequate business model
LG1	Local government instituted	Policy advisor on climate and energy for municipalities. Also involved with a hydrogen pilot in which citizens participated.
LG2	Local government instituted	Climate advisor at a municipality and involved with a hydrogen pilot in which citizens participated.
NG1	National government institution	Advisor energy transition at a Dutch government institution with the focus on the Dutch built environment. Responsible for developing tools and policies for ministries.
NI1	national gas network operator	Involved in the development of hydrogen in the Dutch built environment. Has been part of various initiatives and pilots related to hydrogen and sustainable solutions, including the implementation of hybrid heat pumps to reduce natural gas consumption.
RE1	Researcher	Professor from a Dutch university who is conducting research on hydrogen and potential usages in the Dutch built environment
RE2	Researcher	Researcher who is involved with hydrogen pilots and mainly focussed on the infrastructure
RI1	Regional gas network operator	Strategy director how is responsible for the development of hydrogen usages and responsible for lobbying activities in relation to regulation
RI2	Regional gas network operator	Focusses on policy development concerning the electricity market and focus on addressing issues related to security of supply and CO_2 free controllable power.

Table 4, interviewers overview with stakeholder type and description, own table

4.4 Data analysis method

After the necessary data is gathered, the data is analysed using thematic analysis and an abductive coding approach. Abductive coding balances between inductive and deductive coding in which the existing theories and concepts are used for creating the first set of codes, but their room for inductive coding. Abductive coding is done by undertaking the following steps, which are adopted from the proposed methodology steps from Caulfield (2019) and Vila-Henninger et al., (2022):

1. Familiarize with data: To familiarize with the data the transcript of the interviews is reviewed multiple times by the researcher to get a deeper understanding of the data.
2. Formulated a codebook: Informed by the theoretical foundation, an initial set of codes is established. After familiarizing with the data, also inductively codes where formulated.
3. Collate codes within data: Identify elements in the data and give an appropriated code to each element.
4. Group code into themes: The next step is to identify overarching themes within the codes. This gives a broader understanding of the findings within the data.
5. Reviewing themes: Themes will be examined for coherence to make sure they adequately represent the data and respond to the research questions.
6. Defining and naming themes: A closer look is taken at how to define and name each theme so that it is clear where the theme is about. Also is validated if there are enough sources for each theme and if they are distinctive from each other, otherwise merging themes can be a solution.
7. Writing analysis: In this step, the findings of the themes will be presented in a coherent story and discussed in relation to the research questions.

For coding the transcripts, the software tool Atlas.ti will be used. Furthermore, an explanation will be given into how each sub-research question will be answered with which theory.

Approach sub-research question 1:
What are the regime and landscape developments of heating homes in the Dutch-built environment?

Sub-research question 1 gives an answer on the regime and landscape and how they are interacting, which are visualised in Figure 5 with the green elements. To answer this question the MLP proposed by Verbong and Geels (2007) is utilized. As stated in sub-chapter 3.5, the landscape developments are analysed by looking at external factors such as changing regulations, evolving societal expectations, and technological advancements will be conducted. This approach was chosen because understanding the landscape pressures is essential to comprehend the broader contextual forces that influence the development and transformation of heating regimes, thereby ensuring a comprehensive assessment of the Dutch built environment heating systems. Also as stated in sub-chapter 3.5, the regime developments are being analysed by looking at the cognitive, and regulative rules that exist in the heating regime for the Dutch built environment. By incorporating these rules into the research design, a valuable insight is gained into the establishment and dynamics of the current heating regime of the Dutch-built environment.

Approach sub-research question 2:
How has the hydrogen niche for heating of the Dutch-built environment developed?

The second sub-question of this research thesis is focused on investigating the internal activities of the niche and their efforts towards developing a mature technology. To accomplish this, the research design incorporates the SNM, which centres on the learning process, actor formation, and expectations within the niche. As stated in the sub-chapter 3.5 the indicators proposed by Kamp & Vanheule (2015) are used to identify the learning process, network formation and expectations, see Table 1. These indicators will help to identify the internal activities of the niche and shed light on the ways in which it has developed in the past. Insight about the regime and landscape will help with describing these SNM elements. Also is described how actors see hydrogen technologies in the niche are interacting and compete with other heating technologies like electric heating and district heating. Sub-research question 2 contributed by giving an understanding about the niche, which is visualized with the blue circled in the Figure 5.

Approach sub-research question 3:
Which barriers of the landscape and regime should the niche overcome?

In this sub-question, the barriers are discussed for the hydrogen heating niche for the Dutch built environment. As explained in the chapter 3, the niche experiences barriers which holds back the adoption to the regime. These barriers are identified through the semi-structured interviews and explained by utilizing the MLP to explain the interactions and interdependencies between the niche level and the regime level. This approach enables us to identify the key challenges that the niche must overcome to achieve successful integration and adoption into the regime. Sub-research question 3 gives an understanding of the interaction and barriers, which is visualized with the orange elements in Figure 5.

Approach sub-research question 4:
What socio-technical scenarios can be developed regarding the hydrogen niche and how could the transition from niche to regime take place?

In this sub-research question, socio-technical scenarios are formulated using an adopted version of the methodological steps by Elzen en Boelsen (2007; 2010). The objective of these socio-technical scenarios is to illustrate the multi-level patterns that may occur which leads to an active role of hydrogen in the Dutch built environment. According to the methodological steps by Elzen en Boelsen (2007; 2010) first an analysis of the current dynamics of the levels should be conducted based on the MLP. In this study the insights from the sub-research 1, 2, and 3 are used, in which MLP and SNM are utilized, to get an understanding about the current dynamics between the levels. By also using SNM a deeper understanding of the niche current expectations, network formation and learning process which could result in richer socio-technical scenarios.

In line with the methodological steps of Elzen en Boelsen (2007; 2010), the design choices are made before writing the scenarios, which include the timeframe and layout, factors, and patterns. Also is decided which transition pathways are used for writing the scenarios. This gives a clear overview on how the scenarios are constructed and how these scenarios will differ. To make these design choices insights gained from the MLP and SNM, which are utilized for sub-research 1, 2, and 3, are used.

After making the design choices the socio-technical scenarios are written. This done using the formulated patterns and factors. There are also insights gained from the semi-structured interviews on how interviewees expect that certain events will play out on how actors may react to certain events. Lastly an evaluation is made on the scenarios in which the key aspects between the scenarios are compared. By evaluating these scenarios, a better understanding is gained on how different development could lead to different outcomes. To make sure the stories are deemed plausible an expert validated the scenarios which increases the reliability of the scenarios. In sub-research question 4 a potential transition pathways of the niche to the regime is described, which is visualised with the red elements in Figure 5. Table 5 gives an overview on how all the mythological steps conducted in this study to answer the main research question.

	Methodology steps	Description	Sub research question
1	Analysing landscape and regime development	Utilizing MLP and SNM to analyse the current development and dynamics of the different levels.	1
2	Analysing niche development	Identify linkage between landscape and niche. Also, how user behaviour changes from actors. But also, between technical and political developments.	2

3	Identify barriers	Describe the landscape and regime barriers which the niche should overcome, to be adopted to the regime	3
4	Design choices	Formulated design choices for the scenarios are: • timeframe and layout of the scenarios. • factors to include. • patterns to include. • transition pathways to use.	4
5	Develop scenario architectures	Write the scenario based on the factors, patterns and insights from interview questions. Describe how the levels are interacting whith each other and how the barriers are overcome	4
6	Elaborated on scenarios	Check if the scenario is according to the characteristics of STSc	4
7	Evaluation of scenarios	Evaluated scenarios and develop recommendations	4

Table 5, methodological steps formulating STSc, adopted form: (Elzen & Hofman, 2010, 2007)

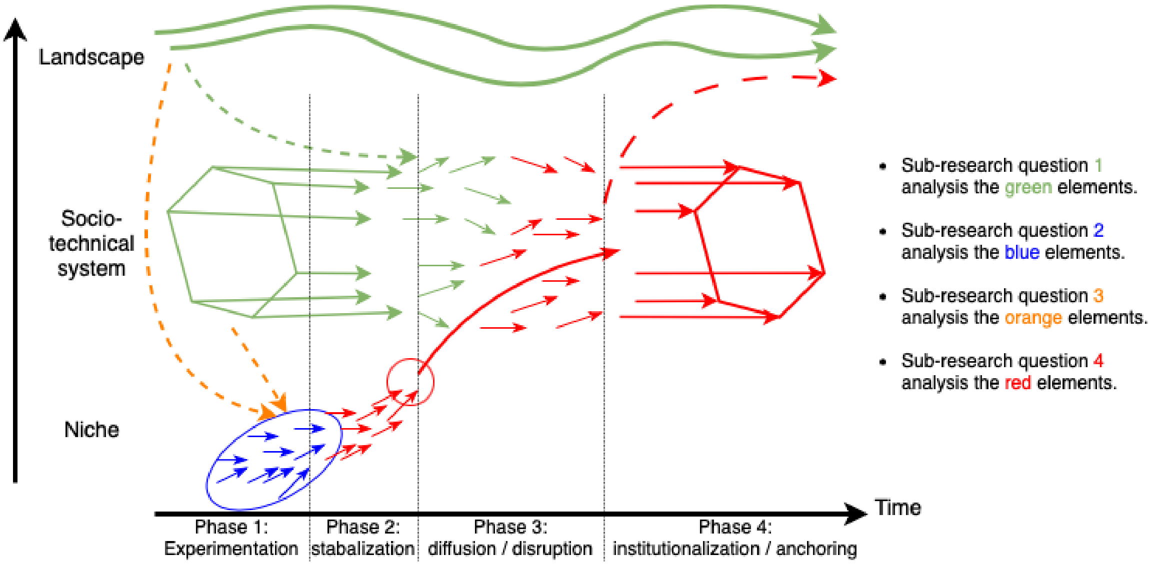

Figure 5, visualisation contribution sub research questions to analysing transition in MLP, adopted from: (Geels, 2002; Geels & Ayoub, 2023)

4.5 Validity, reliability, generalizability, and limitations

This section provides an overview of the validity, reliability, generalizability, and limitations of the research methodology employed in this study.

4.5.1 Validity

The validity of this research is ensured through a rigorous methodology and data collection process. The use of qualitative research methods, such as semi-structured interviews and thematic analysis, helps to gain in-depth insights into the research questions. By using multiple data sources and triangulating the findings, the research aims to increase the validity of the results. Also, to improve the validity of this study the supervisors were asked to validate the interview questions. Furthermore, the integration of the SNM, MLP and STSc enriched the theoretical basis and validity of the research outcomes.

4.5.2 Reliability

To enhance the reliability of this research, a systematic and transparent approach is employed during data analysis. The use of Atlas.ti software for coding the interview transcripts ensures consistency in the coding process. Additionally, peer debriefing is conducted, where an expert in the field validates the research findings. By adhering to a structured methodology and clearly documenting the research process, the study aims to improve the reliability of the outcomes.

4.5.3 Generalizability

It is essential to acknowledge that the findings of this research may not be readily generalizable to other countries or contexts. The study's focus on the Netherlands and its specific energy transition landscape, including established gas infrastructure and cultural/legal factors, limits the generalizability of the results to other countries (Geels et al., 2016; OECD, 2021). Each country has unique socio-economic, political, and technological factors that influence its energy transition processes differently. Therefore, caution should be exercised when applying the research findings to other regions or countries. Also, with conducting semi-structured interviews the results and findings change overtime, due to changing perspectives and opinions from the interviewees.

4.5.4 Limitations

Despite the robust methodology and data collection approach, there are inherent limitations to this research. Firstly, the study focuses solely on the Netherlands, which restricts the scope and applicability of the findings to other countries. Secondly, the use of qualitative methods, while providing valuable insights, may not capture a comprehensive view of the entire energy transition landscape. Additionally, the reliance on semi-structured interviews could introduce biases based on the perspectives and experiences of the interviewees. Moreover, as with any research, there may be limitations concerning the representativeness of the interview sample. While efforts were made to include a diverse range of stakeholders, the sample may not fully represent the entire spectrum of actors involved in the Dutch energy transition. Furthermore, the study's reliance on publicly available literature may lead to information gaps or outdated data.

4.6 Conclusion

This chapter presented the methodology employed for this thesis. Qualitative research is conducted, which involved a combination of a literature review and 14 in-depth semi-structured interviews with various stakeholders. The study focused on the Netherlands due to the ongoing hydrogen pilots and the ambitious climate targets set by the Dutch government. By focusing on space heating and considering both direct and indirect hydrogen utilization, the study seeks to contribute valuable insights into the possibilities and challenges of integrating hydrogen into the built environment for sustainable heating solutions.

The collected data is examined using a method called thematic analysis. This study uses the MLP, SNM and STSc framework to explore the regime and landscape developments of heating homes in the Dutch-built environment, the development of the hydrogen niche, barriers the niche should overcome, and potential socio-technical scenarios for the future.

To address sub-research question 1, the three dimensions proposed by Verbong and Geels (2007) are used to explain the establishment of the regime and which landscape pressures are destabilizing the regime. Sub-research question 2 delved into the development of the hydrogen niche, employing the Strategic Niche Management (SNM) framework to analyse learning processes, actor formation, and expectations within the niche. Sub-research question 3 explored the barriers that the niche must overcome, utilizing the Multi-Level Perspective (MLP) framework to examine interactions and interdependencies between the niche, regime, and landscape levels. Lastly, sub-research question 4 aimed at developing socio-technical scenarios for the potential transition of the hydrogen niche replacing the current heating regime in the Dutch-built environment. Possible transition typologies are determined as proposed by Geels et al., (2016) and plausible stories are constructed about the future transition. From there, plausible stories were constructed to envision potential future outcomes of the transition.

However, it is important to acknowledge the limitations of this research, including the focus on the Netherlands, potential biases in the interview sample, and the use of qualitative methods, which may not capture a comprehensive view of the entire energy transition landscape. Also, because the study's focusses on the Netherlands and its specific energy transition landscape, including established gas infrastructure and cultural/legal factors, the generalizability of the results to other countries is limited.

5. Landscape and heating regime analysis

This chapter discusses the landscape changes that destabilizes the regime. Also, the establishment and the developments of the natural gas heating regime for the Dutch built environment.

5.1 Landscape

As stated before, climate change has become a pressing global concern, necessitating the reduction of greenhouse gas emissions and the transition towards clean and sustainable energy sources. In response to the Paris Agreement of 2015 the Dutch government introduced the Climate Accord in 2019, and a subsequent version in 2022, laying out a wide-ranging set of measures and objectives aimed at diminishing greenhouse gas emissions and facilitating the shift towards a sustainable energy system. The Climate Accord sets ambitious goals for sectors such as industry, transportation, agriculture, and buildings, including the residential sector. In this accord was stated that the Dutch government aims at achieving 50% less greenhouse gas emission in 2030 compared to 1990 and in 2050 zero (Rijksoverheid, 2022). The Climate Accord of 2019 states that by 2050 the Dutch built environment needs be heated t without creating greenhouse gas emissions which means fossil fuels are not allowed. As a first step, the first 1.5 million existing homes will be made more sustainable by 2030. To this end, a district-oriented approach has been devised in which each municipality determines what kind of strategy can be applied per district. This asks the municipalities to publish a heat transition vision by 2021 at the latest, in which they indicate when they want to remove gas from which district and what possible alternatives are. Various tools have been offered by the government to residents, municipalities and organizations that must develop these new techniques. Climate change and the following Climate Accord are the main drivers and starting point for a transition to a new technology in this regime (EA1, EA3, RI2, RE1, GOV3, RI1).

The gas fields, located in the province of Groningen, have been a primary source of natural gas for the Netherlands for decades. However, extensive gas extraction from these fields has caused seismic activity and resulted in damage to buildings and infrastructure in the region. As a result, the Dutch government implemented measures to reduce gas production from the Groningse Gas fields and eventually phase it out completely. The sentiment to move away from Groningen natural gas also created pressure for actors to search for a new technology to heat the Dutch built environment according to an interviewee (RI1).

The recent Russian invasion of Ukraine has put the security of energy supply to the test and highlights the urgent need for accelerated sustainability. The REPowerEU plan, presented in May 2022, advocates reducing dependence on Russian fossil fuels. In addition, the plan includes ambitious targets for large-scale production and import of renewable hydrogen, which could be an important step towards a more sustainable and stable energy future (National Hydrogen Program, 2022). The war between Russia and Ukraine has led to supply uncertainty and a significant increase in gas prices, prompting a greater focus on insulation and encouraging people to explore solutions for reducing their gas bills. This conflict between Ukraine and Russia creates pressure on the current regime according to an interviewee (EA3).

5.2 Regime

5.2.1 The development of the natural gas heating system

In 1959, a substantial gas field was found in Slochteren, Groningen, which turned out to be one of the world's largest known reserves at that time. This marked the beginning of a transformative journey for the Dutch built environment, as natural gas emerged as a new system for heating households. The importance of the Groningen field was acknowledged by the Dutch government due to its potential to provide the country with a dependable, cost-effective, and environmentally friendly energy source, thereby offering substantial economic opportunities (Correlje et al., 2003).

At that time governments and the industry thought that value of the natural gas had an expiration date due to the expected arrival of nuclear energy which would become the new standard. This meant that the goal was to create a high demand for natural gas (Correlje et al., 2003). To create the necessary infrastructure the Dutch government took a leading role in introducing natural gas, forging public-private cooperation among the state, Shell, and Exxon. This led to the creation of the company Gasunie as a new actor (Geels, 2007). From here a network of actors was created which consisted of the NAM which focused on gas production, Gasunie how handled transportation and distribution companies established the infrastructure in neighbourhoods and sold gas to households (Correlje et al., 2003). The introduction strategy centred around the market for space heating in households and buildings, which allowed for high prices and profits, benefiting the Dutch state (Geels, 2007).

Gasunie embarked on a well-planned transition to natural gas, winning people over through carefully designed campaigns. Starting in 1965, comprehensive campaigns using brochures, booklets, films, and informational visits of women addressed concerns such as the need for new pots for gas stoves. The conversion from town gas and coal to natural gas followed a neighbourhood-based approach, ensuring efficient implementation and minimizing complaints (Eskes, 2021).

By the end of 1963, natural gas from the Groningen field was supplied to consumers, and by 1969, approximately 80% of all Dutch houses were connected to the gas grid, and 60% of them were heated with gas. This widespread adoption of natural gas brought numerous benefits to both the Dutch industry and households. Industries could capitalize on the availability of natural gas, while households enjoyed the convenience of gas-fired central heating, cooking, and hot water supply (Correlje et al., 2003).

The reason that the transition from city gas to natural gas went so quickly was, according to van Dorp (2021) that natural gas was cheaper than the existing city gas. In addition, the transition was also rapid because many cities already had a gas network, which accelerated the transition. Because it was considerably cheaper than the existing system, there was a demand from the market to switch (van Dorp, 2021). The gas brought to the residential buildings was mainly used in the kitchen for cooking and creating hot water (Gales, 2013).

In the past, the Netherlands primarily relied on coal stoves for space heating, limited to warming up just one room. However, with a rising demand for more efficient heating solutions, the concept of central heating emerged. This innovative system involved the transfer of heat through a network of pipes to radiators and other heating surfaces, using hot water as the medium. Initially, central heating was prevalent in public buildings like offices, hospitals, and hotels. A few affluent individuals could also afford to adopt this technology. However, it was not until around 1965 when the country's prosperity increased significantly, enabling a larger portion of the Dutch population to afford central heating. The key advantages of central heating are twofold. Firstly, it ensures an even distribution of heat throughout various rooms, providing a consistent and comfortable temperature throughout the space. Secondly, central heating contributes to better air quality in the heated rooms, making it a preferred choice for residential and commercial spaces alike (Couwenbergh, 2023). Although some resistance existed, with people expressing nostalgia for the cosy atmosphere around a crackling coal stove, central heating offered advantages such as cost-effectiveness, convenience, and cleanliness. For cooking was mainly done with city gas which consisted 62% of hydrogen. The town gas was mainly extracted from coal in the local gasworks (Eskes, 2021).

5.2.2 Policy revision and energy conservation

In 1973, a significant shift occurred in the Dutch government's perception of natural gas due to the oil crisis. Natural gas, once seen as a cheap fuel, was now regarded as a resource that needed to be used prudently. Additionally, the anticipation of nuclear energy as a potential replacement for natural gas began to fade due to increased discussions regarding nuclear waste and safety concerns (van der Steen, 2018).

This change in perspective prompted the Dutch government to undertake the first major policy revision. The new policy aimed to stimulate gas exploration in the North Sea while also reducing the consumption of natural gas. The focus shifted to smaller fields with higher extraction costs. To incentivize oil companies to engage in exploration, the Gasunie ensured a minimum price for the gas produced (Correlje et al., 2003)

The Groningen gas field, once the primary source, began to be utilized as a marginal field during this phase, as the focus shifted to other reserves. This meant that it could be used strategically for season storage (van Geuns et al., 2017). At the same time, Gasunie started in 1977 to import gas from Germany and gas fields in Norway to Groningen, from where it was further transported to Belgium and France (Correlje et al., 2003).

In this same period central heating become a more established technology in the Dutch built environment. In 1975 around 35% of the built environment used natural gas for space heating using central heating (Gales, 2013).

5.2.3 Market liberalization

In the late 1980s, the energy market in the Netherlands embarked on a path of liberalization, driven by developments at the European level. The European Union had long been advocating for the liberalization of energy markets to foster competition and improve market efficiency. This movement gained further momentum with the introduction of the EU Gas Directive (98/30/EC) by the European Union Commission which required the Member States to restructure and regulate their national gas sectors, granting consumers the right to choose their gas suppliers. This had a profound impact on the structure of the Dutch gas market, affecting production, distribution, and consumer choice (Correlje et al., 2003).

To comply with the EU Gas Directive, the Netherlands enacted the Wet Onafhankelijk Netbeheer (OWN). This law, passed in November 2006, outlined three main provisions. Firstly, it mandated the separation of energy companies into separate entities for production and supply, and network management. Secondly, it required network operators to manage their networks independently. Lastly, it strengthened the authority of the Dutch Authority for Consumers and Markets (ACM) in overseeing compliance with the law. This law resulted in changing formal rules but also cognitive rules due to the changing roles actors had in the system. As a result of the liberalization efforts, the transport and trading activities of Gasunie, a major gas company in the Netherlands, were separated. The ownership of the trading activities was proposed to be unbundled, reducing the state's influence in gas field exploitation. However, the state retained ownership of the transmission system through Gasunie (Correlje et al., 2003).

In 2005, Gasunie underwent further restructuring, leading to the creation of GasTerra, which became responsible for the sales of natural gas. Gasunie, on the other hand, focused solely on the transportation of natural gas and became a state-owned company (Gasunie, n.d).

5.2.4 From export to import

To this day, the Netherlands has been self-sufficient in terms of energy supply due to the availability of the Groningen gas fields. However, in August 2012, significant earthquakes with a magnitude of 3,6 on the Richter scale occurred in Huizinge, Groningen, which had a major impact on the gas production policy in the Netherlands. This led to production ceiling reductions in 2014 (van Geuns et al., 2017).

The change in political policy altered the dynamics of the regime, shifting from primarily exporting to importing gas. In the past, the Netherlands already imported natural gas from Norway and Russia, and this policy change is expected to increase importation (van Geuns et al., 2017).

By 2018, the tipping point was reached, with the Netherlands importing more natural gas than it exported (Geijp, 2019). In the meantime, gas production within the Netherlands has been further reduced, and as of mid-2022, the government expects that the Groningen field will only be necessary as a reserve measure to ensure supply security (Blok, 2021).

5.2.5 Regime change

The landscape pressure, Climate Accord of 2019, is already resulting in regime changes. One of the new policies is that new buildings are not connected to the natural gas network and should be heated with green gas emissions (RI1, Weeda & Niessink, 2020).

Also, the existing built environment needs to change. A new policy of the Dutch government is that when the central heating boiler is replaced from 2026 should be combined with a heat pump or another sustainable alternative, such as a heat network. In the short term this will lead to a reduction in green gas emissions and help to achieve the 2030 climate target (Jetten, 2022). In the longer term, this can also offer the possibility of a full CO_2 neutral solution by combining it with hydrogen (RE1, HAP1). These new policies are showing that the Dutch government is moving away from an only natural gas heated regime (EA2, EA4, HAP1, RE1, RI1, NG1). Choosing the hybrid route of natural gas boilers and a heat pump creates the benefit for network operators, because they do not suddenly have to write off half of their infrastructure. They can simply leave the gas network intact and continue to supply gas, albeit in combination with the hybrid heat pump (EA4).

The Dutch government made the decision to transition away from natural gas to address climate change concerns, even though the current natural gas system is highly functional due to its affordability, well-established infrastructure, and high level of supply security (RE1, EA1, EA3, RI1, NI1). The climate accord describes how actors work together to achieve these goals. Furthermore, is explained the neighbourhood-orientated approach. This means that the transition to a new technology for heating buildings will take place for each neighbourhood separately.

Also resulting from the Climate Accord, solar panels are stimulated in the built environment, resulting in local electricity production. The solar energy is expanding faster than the capacity of the electricity grid which creates grid congestion (RI2, EA2, RE1, LG2, NG1). Traditionally, the power in the network flows in one direction, from large power plants to consumers.

However, due to this development of solar energy, electricity now flows in both directions, which can lead to further congestion of the electricity network (Bijkerk, 2021; van der Blij & Zeman, 2021). The Dutch built environment will experience a significant surge in electricity demand, driven by the increasing use of electric vehicles, electric cooking, and heat pumps. A report by Netbeheer Nederland (2023) indicates that electricity demand is projected to rise by 180-250% by 2050 compared to 2019. The present approach to addressing net congestion involves increasing the network capacity through the replacement of current cables with thicker ones and upgrading to larger transformers. However, this solution is both costly and time-intensive (RE1, Bijkerk, 2021; van der Blij & Zeman, 2021). Due to the Paris agreement of 2015 the nitrogen emissions should also be limited. One of the interviewees mentioned that increasing the grid capacity is currently challenging due the nitrogen limitations (RI2).

The war between Ukraine and Russia had a significant impact on gas prices, leading to a shift in the regime dynamics. Before the conflict, the Netherlands relied heavily on Russia for its gas imports, around 25% of the total import. However, the geopolitical tensions and disruptions in gas supplies caused by the war prompted the Netherlands to diversify its sources. According to a report of the Dutch Government (2023), the Netherlands reduced its dependence on Russian gas and started importing more Liquefied Natural Gas (LNG) from other countries such as Belgium and the United Kingdom. The high gas prices resulting from the conflict between Russia and Ukraine are also causing companies to significantly accelerate their electrification plans. To transition from fossil fuels to electricity, companies have submitted plans over the past few months in which they request additional electricity capacity. This capacity is currently missing which result, in at least 6700 companies and institutions waiting for a connection (Kleinnijenhuis & van Hest, 2022). Figure 6 give an overview of the actors involved in the regime.

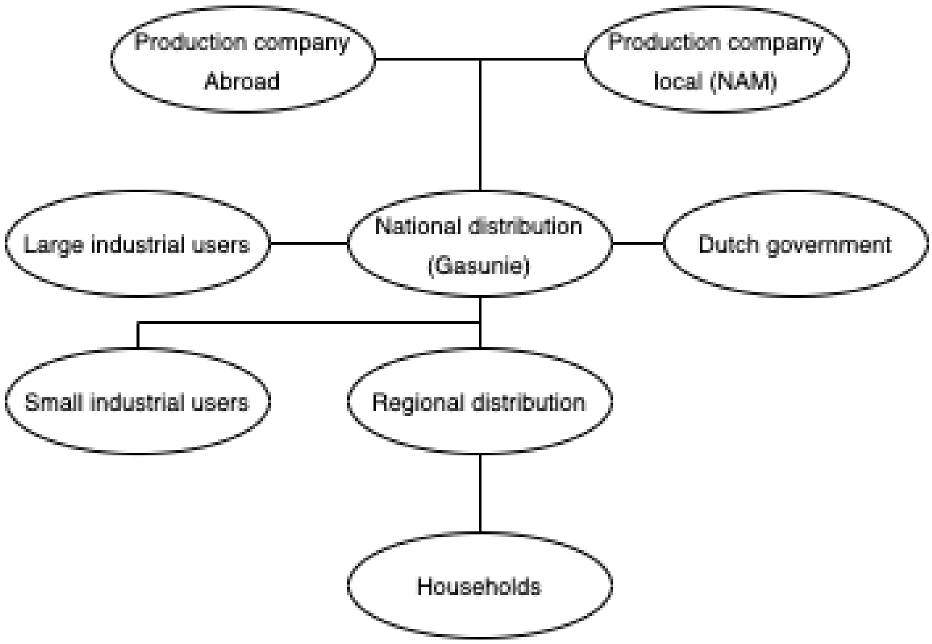

Figure 6, actor overview regime, adopted from: Correlje et al., (2003)

5.3 Conclusion

In this chapter, the landscape and regime development have been discussed. The establishment of the natural gas heating system in the Dutch built environment started with the findings of the natural gas field in Groningen in 1959. The government recognized the potential of natural gas as a clean and low-cost energy source, so it created the company Gasunie, together with Exxon and Shell. Gasunie developed the infrastructure to export the gas to the built environment. In 1969 approximately 80% of all Dutch houses were connected to the gas grid, and 60% of them were heated with gas. Nowadays around 95% of the Dutch built environment is heated with natural gas. Most of the natural gas is now being imported. Residential buildings use a central heating system which consist out of radiators and natural gas boiler for space heating. The Dutch government had an important role in the establishment of the current regime.

The landscape analysis highlights the pressing global concern of climate change. This has led to the main landscape pressure, the Climate Accord that the Dutch government's introduction in 2019. The accord aims to decrease greenhouse gas emissions and shift towards clean and sustainable energy sources. Due to the Climate Accord the regime is forced to stop with the use of fossil fuel for heating the Dutch built environment in 2050. The Climate Accord of 2019 marks, according to many interviewees, as the starting point for large-scale changes in the heating regime, moving away from natural gas to more sustainable alternatives. This accord led to the introduction of several policies that push for changes in the existing system. One of these policies mandates that new buildings must not rely on the natural gas infrastructure. Additionally, the Dutch government has put forth another policy stating that starting from 2026, any replacement of a natural gas boiler must include the integration of a heat pump. These new policies resulting from the Climate Accord forces the regime to look for new technologies for heating the Dutch built environment according to the interviewees.

Because natural gas is not an option in the future, a new system is required with a different energy type for heating the Dutch built environment. For the new construction buildings, the main technology used is electric heating due to its high efficiency. For the existing built environment, it is less clear what the best new technology will be due to low insulation and the large transition that it requires. Simultaneously, the growth in renewable energy generated by solar panels has led to a challenge in the electricity infrastructure due to net congestion. The expectation that the electricity demand in the built environment will only increase. The current strategy on tackling this issue is by installing thicker cables.

The Climate Accord states that the Dutch government has chosen for a district-oriented approach. This means that municipalities will determine for each neighbourhood what type of technology will be used and when implementation will take place.

6. Niche analysis

In this chapter, the development of the hydrogen niche for the Dutch built environment is discussed. The development is explained by describing the expectations, network formation and learning process.

6.1 Expectations

As stated in chapter 5, the regime is faced with the pressure to create emission-free heating. At the same time, the regime is confronted with alleviated stress on the electricity grid. The hydrogen niche is developing technical solutions to address critical challenges faced by the regime.

As already stated in the literature review, the expectation is that hydrogen will play a key role in enabling the storage and transportation of renewable energy. Well, there is disagreement among the interviewees. The actors participating in the niche expect that hydrogen will be available in large quantities due to its ability to enable the import of renewable energy from countries around the world and its ability to store renewable energy for a long period (EA1, EA4, GOV3, RE1, NI1). Also, the Dutch government believes in the role of hydrogen and focuses on creating the required supply lines for the import (Jetten, 2023). Green hydrogen will be accessible in the short term; however, the availability will be limited and is allocated for heavy industrial use (EA2, EA3, EA4, RI2). There are also interviewees who stated they believe renewable energy remains a scares resource in the future. This means the converting of renewable energy to hydrogen will lead into too much energy lost and we should therefor strive for as much efficiency which means is more achievable with full electrification (EA2, EA3, EA4).

Gasunie is in the process of creating a hydrogen infrastructure to link major industrial zones in the Netherlands which is achieved through repurposing obsolete natural gas pipelines. Around the year 2026, the main industrial cluster will be connected and around 2030 the hydrogen infrastructure will be connected to Germany and Belgium (Tezel, 2021). The expectation is that also the local natural gas infrastructure of the built environment could be connected to the infrastructure (RE1, RE2, HAP1, HAP2, LG2, NG1; Hellinga & van Wijk, 2021).

6.1.1 Emission-free heating

Hydrogen boilers are seen as a suitable technology for space heating. Interviewees claim that the hydrogen boilers are from a technical perspective ready for commercial use (HAP1, EA3, RE1, Hellinga and van Wijk (2021), however the regulation, the required infrastructure and the availability of sufficient hydrogen are currently holding back the adoption. The expectation is that when hydrogen becomes available in residential houses citizens could adopt the hydrogen boiler (HAP1, RE1).

Hydrogen boilers offer several advantages, making them a valuable alternative to natural gas heating in the Netherlands. One of the main challenges faced by the Netherlands is the historically high reliance on natural gas heating due to the Groningen field, resulting in poorly insulated homes (NI1). Compared to other sustainable heating technologies hydrogen boilers can deliver high temperatures, which reduced the demand for extreme insulation. While optimal insulation is encouraged for improved efficiency, the transition to hydrogen allows homeowners to insulate at their own pace based on cost-benefit analyses (HAP1, RE1, NI1, NG1, LG2).

The seamless integration of hydrogen boilers into existing central heating systems allows for a smooth transition without requiring major adjustments to buildings or the behaviour of users (RE1, HAP1, RE2 ;(Bijkerk, 2021)). By using this approach hydrogen behaves almost identically to natural gas, but with the added benefit of being a sustainable energy carrier (Bijkerk, 2021).

The hydrogen boiler can also be effectively combined with a heat pump. The Dutch government's forthcoming policy, set to take effect in 2026, mandates that users replacing their natural gas boilers must also acquire a complementary heat pump (RI1, NI1, RE1, LG2, NG1). This approach offers several distinct advantages compared to using a standalone boiler. By integrating a heat pump, the hybrid system achieves high efficiency. At the same time, it relieves grid stress by using a hydrogen boiler during times of high electricity demand, showcasing its flexible dual-system capability (HAP1, RE1, NI1). This also means that the pressure to reinforce the electricity grids is much lower than in an all-electric option which solely relies on a heat pump. Additionally, when needed, heat can be supplied at a high temperature, eliminating the need for underfloor heating and extensive insulation measures. A benefit of this system compared to an all-electric solution is that it does not require an increase in insulation (RE1, RI2, HAP1 Hellinga & van Wijk, 2021).

Moreover, the inclusion of hydrogen within the hybrid solution not only facilitates its seamless integration into the built environment but also safeguards the future viability of the hybrid heat pump system (HAP1, RE1). Notably, one interviewee anticipates that the hydrogen boiler will likely only be operational for approximately two weeks per year (RI1). This means there is a limited business case for hydrogen due to the limited use of the infrastructure (EA3, RI2, NI1).

Multiple interviewees believe in multiple heating solutions will coexist (HAP1, EA1, EA3, NG1, RE1, RE2). Some expect that hydrogen will only play a role in cases where electric heating or district heating is not feasible, like with monumental buildings or buildings in remote areas. (EA1, EA4, RI1, RI2). In a report by Netbeheer Nederland (2023), the role of hydrogen in the Dutch built environment depends on the development of the international hydrogen production market. With a large international hydrogen market and a large amount of hydrogen import, the Dutch grid operators expect that 60% of the homes will be heated with a hybrid hydrogen system or a standalone hydrogen boiler (Netbeheer Nederland, 2023).

Hydrogen boilers could also be used in district heating. Now, many district heating are being heated with natural gas. This will have to change in the future. Heat companies are busy greening their sources, including geothermal energy, aqua thermal energy, or heat from, for example, datacentres or industrial companies. Hydrogen boilers could also be used for heating, but it expected that this will mainly be for peak and backup installations which means it would have a small contribution to the heating of the Dutch built environment (EA1, EA3, RI2).

Another expectation is that when hydrogen is produced, this is accompanied by the release of a lot of heat. This heat could be a valuable source of sustainable heat supply. Suppose a large electrolysis plant of several hundred megawatts is installed, this could be a suitable source for tapping heat and transporting it to a city or district via a heat network. Since electrolysers are often placed near urban areas, this can potentially be interesting as a sustainable heat source (EA3).

6.1.2 Net congestion electricity

To address the potential grid congestion risk arising from the substantial increase in energy demand, hydrogen in combination with a fuel cell emerges as a viable solution for ensuring grid stability and flexibility. Interviewees emphasized the use of fuel cells to mitigate net congestion (RE1, HAP2).

Implementing fuel cells on a street or neighbourhood level allows the conversion of hydrogen to electricity, reducing the need for an extensive electricity grid. The local produced electricity can be used by heat pumps for space heating (HAP2, RE1, RE2, Weeda and Niessink 2020). With this setup of a fuel cell with a heat pump, the efficiency is as with direct electricity from the grid in combination with a heat pump, without the challenge of electricity grid congestion (HAP2, RE1).

New large energy consumers cannot currently be connected to the electricity grid, and people are asked to only use electricity during the evening hours to spread out electricity consumption (Kleinnijenhuis & van Hest, 2022). As stated in the landscape chapter the expectation is that electricity demand will double or even triple over the coming years (EA2, Netbeheer Nederland, 2023). This large increase in energy demand could jeopardise electricity grid stability even further. Hydrogen is seen as a solution for ensuring stability in supplying energy to the built environment (LG2, NG1, RE1, HAP2, RE2).

With both electricity and hydrogen being supplied to homes, one can flexibly utilize both forms of energy. If residents install a fuel cell or hybrid solution in combination with a heat pump it allows them to switch between hydrogen and electricity based on availability and demand (RE1). By incorporating hydrogen as a complementary energy source, the vulnerability of relying solely on electricity transportation is reduced, as fuel cells can generate energy when needed, helping alleviate peak demands on the electricity grid (Hellinga & van Wijk, 2021). This way, there's no need to reinforce the electricity network, and the gas network can be repurposed, which is expected to be more cost-effective. According to van Dorp (2021) strengthening the electricity infrastructure will cost society 40 billion euros over the next 10 years. It also avoids breaking streets open for increasing the electricity grid capacity (NI1, RE1, HAP1, HAP2, RE2).

Additionally, there's a problem when a portion of the generated green energy from solar panels cannot be transmitted due to issues with the electricity network. This can be resolved with a fuel cell which uses the surplus of electricity to produce hydrogen. This may be the case, for example, if the residential buildings have solar panels and converts the surplus electricity into hydrogen and store until electricity is required (LG2, RE1, Hellinga & van Wijk, 2021). The benefit of this is that are not depended on the electricity capacity because currently the surplus which cannot be discharged over the electricity grid is lost energy (LG2, RE1). There are five pilots announced who wanted to investigate this technology in combination will local hydrogen storage. But all the interviewees from this study do not see potential for this for decentralized hydrogen storage. This mainly due to safety risk of storing hydrogen locally and the expectation of much higher cost compared to a large storage system of salt caverns (RE1, RE2, EA2, RI1, NI1).

Delivering hydrogen from decentralized areas like residential buildings back to the infrastructure can present challenges, comparable to the congestion problems we now experience on electricity grid with solar panels. While the capacity of gas networks is generally sufficient, they are designed to provide customers with gas from high pressure to low pressure, not the other way around. So, from a large gas field to a residential area. If hydrogen needs come from residential areas, the pressure should be increased at certain points to higher network levels, which is technically complex (RE1, RE2, LG2, NG1, NI1). New technologies are being developed to make this possible, but technological readiness has not yet been reached. The expectation is that this will only be economical when a sufficient scale of hydrogen could be produced, by for example a solar park. For each residential house, this seems unlikely due to technical complexity and high investment cost (RE1, NI1).

At the same time, a lot of interviewees do not believe in fuel cells are not a suitable technology for solving the unstable electricity grid. They see it as a temporary challenge which grid operators expected to resolve in 15 years which would reduce the demand for it (EA3, EA4, RI2, NI1). The cost of expanding the heat pump's electricity capacity is considered a small additional expense because the electricity grid needs to be upgraded due to the rising demand of solar energy which still needs to be transported from the built environment to a central point where it is stored (EA1, EA3, RI2, NI1).

While interviewees agree that hydrogen is suitable for storing renewable energy, others argue that direct transport of electricity should be as much stimulated. Converting electricity to hydrogen and then back to usable energy results in about 30% energy loss (RI2, NI1, EA1, EA3, EA4). By using hydrogen as an energy carrier there should be more renewable energy produced which slows the transition speed (EA4). In combination with the argument that the electricity grid will be upgraded some interviewees suggest that hydrogen only should be used for seasonal energy storage to balance the electricity grid but not as an energy carrier to the built environment (EA1, EA3, EA4, RI1, RI2). The outcome of the interviews is that there is a lack of a shared vision regarding the potential role of fuel cells in the built environment (HAP2).

6.2 Network formation

6.2.1 Network composition

The development of hydrogen technologies in the built environment involves multiple actors, each playing a crucial role. According to the interviews, the technical components gradually developed. It started with testing hydrogen in laboratory conditions, but now the technology is being tested in residential buildings. Over time the number of actors involved in the development process is increasing. In pilot projects, hydrogen boilers are now used in pilots by ordinary users and installed by regular installers (HAP1).

In the Climate Accord of 2019, the Dutch government stated that they want to stimulate the development of the Zero emissions built environment (Ministerie van Economische Zaken en Klimaat, 2019). To promote technological advancement, the government has implemented twelve regulations and allocated 400 million euros for pilot projects. These pilots are funded through the programme Aardgasvrije Wijken of which 66 pilots are underway in the Netherlands, of which 3 involve hydrogen. There are also hydrogen pilots underway who are outside the Aardgasvrije Wijken program. Also, knowledge platforms like Heat Expertise Center have been established to foster collaboration and knowledge sharing among stakeholders (Progress of pilot projects, n.d.).

Municipalities are instructed by the government to stimulate and support the implementation of the pilots. They will also provide information to citizens. Network operators share their knowledge in the field of safe, reliable and customer-friendly management of gas networks so that the parties involved can explore the preconditions for the distribution of hydrogen via both new and existing (gas) infrastructure in the pilots (Rijksoverheid, 2021). One pilot engaged 22 parties, including municipalities, as the project required collaboration across various regions (LG1). Interviews revealed varying perspectives on the composition and degree of involvement of these actors in technology development. Some interviewees expressed that all necessary actors, ranging from housing corporations to the fire brigade and regulatory bodies like ACM, actively participate in advancing the technology (EA1, EA3, HAP1, NI1, RE1, RE2).

The current limited availability of hydrogen creates a risk for actors to invest in the development of hydrogen technologies (RE2, HAP2). Large market players have proven that their technology works but deem it too risky to further innovate due to a lack of sufficient hydrogen. This same argument is also the case for small players to participate in further developing technology (RE1, RE2). Even municipalities and the Dutch government hesitated to focus on hydrogen due to still lacking supply of hydrogen (NG1).

6.2.2 Network alignment

However, challenges exist, as some interviewees pointed out their dependence on network operators for fuel cell pilot projects and there are some reluctant to work together. Without the operators' support, the testing of new technologies can be hindered (HAP2). While some believe that only a limited number of parties are presently involved in hydrogen development in the built environment, it is anticipated that this involvement will grow as hydrogen becomes more available (NG1).

Notably, the current focus of pilot projects in the Dutch built environment is on hydrogen boilers. Yet, network operators' primary focus lies on meeting the growing demand for electricity and strengthening the grid, which can sometimes overshadow hydrogen-related initiatives (NG1). These network operators are inherently risk-averse, and careful consideration of investment is essential (RI2). However, there is optimism that if the Dutch government promotes hydrogen use in the built environment, network operators may transition their gas infrastructure to support hydrogen (RE1). Another interviewee, functioning as an infrastructure operator, expresses moderate expectations regarding hydrogen technology. However, they still engage in its development, reasoning that in the event of a surplus of hydrogen, the necessary expertise for its implementation would already be in place (RI1).

The consensus among interviewees is that municipalities play an important role in the energy transition. This significance stems from the Climate Accord, which promotes a district-oriented approach, allowing municipalities to determine which technology and when to implement it in their districts. Despite their interest in solutions and willingness to contribute, several interviewees note that municipalities often struggle with the complexities of the energy transition. They are faced with the challenge of navigating legal resources, ensuring the security of supply, and coping with a shortage of skilled employees (NG1, HAP1, EA1, RE2). Despite these difficulties, municipalities remain crucial partners in driving the transition to sustainable energy solutions.

6.2.3 Missing actors

At this moment there are still no actors who are producing green hydrogen on a large scale and supplying this to the Dutch market (RE2, RE1, EA3, RI2, NI1). As stated in the literature review Germany and the Netherlands are the largest producers of hydrogen in Europe, but this mainly concerns grey hydrogen. Although green hydrogen producers are on the rise in the Netherland and abroad, the scale is not yet sufficient to be able to use them in the built environment. Furthermore, interviewees stated that the green hydrogen generated from the electrolysers currently under construction in the Netherlands are allocated for to the heavy industry sector (EA2, EA3, EA4, RI2). Due to the still lacking hydrogen, companies are reluctant to further develop hydrogen applications for the built environment (RE2). Multiple interviewees mention that due to the absence of green hydrogen producers that green hydrogen will remain a scare resource and the built environment will probably be heated through other technologies (EA2, EA3, EA4, RI2). This uncertainty about supply creates also reluctancy from government institutions to participated in the development (NG1).

6.3 Learning process

To gain experience and stimulate development, various actors are participating in ongoing pilots, with a focus on hydrogen boilers and hybrid solutions. These pilots aim to explore the safe and efficient application of hydrogen in the built environment, as there is currently limited relevant experience (Weeda & Niessink, 2020). In Table 6 gives an overview of the hydrogen pilots in the Dutch built environment. In the sub-chapters of 6.3 is discussed what the participating parties what they are trying to learn in these pilots.

There is not an alignment between the interviewees on how the learning process is going. Two interviewees stated that the development of hydrogen has only recently started and in recent 5 years there is still just as much uncertainty about the feasibility of hydrogen in the built environment (EA1, EA2). Compared to other interviewees who claim that the hydrogen boilers are technical developed and ready for commercial use (HAP1, EA3, RE1, Hellinga and van Wijk (2021)). They acknowledge that steps need to be taken in legislation and regulations but that the technical and logistical knowledge are available. In this sub-chapter the different hydrogen pilots are discussed and analysed how they evolved.

	Name	Involved parties	Description	Duration period
1	Hydrogen pilot P2G, Rozenburg, Rotterdam	Stedin Remeha GasTerra	With electricity from the electricity grid, hydrogen is made. This is used in hydrogen boilers to heat 25 apartments. Boilers are in separated boiler house (Stedin, 2019).	2019 - 2023
2	Watstofpilot The Green village, Delft	Stedin, Allianders, Enexis group	Converting natural gas network to hydrogen network	2019 - 2025
3	Temporarily rebuilding Uithoorn	Stedin	14 demolition homes were temporarily converted from the existing natural gas network to a hydrogen network (Stedin, z.d.-a).	2020
4	Hydrogen Experience Centre Apeldoorn	Network operator Alliander, Rehema	Practising hydrogen within a building	2021 – 2026
5	Waterstofwijk Wagenborgen	Enexis group Group Essent	Around 40 rental houses are converted to a hybrid solution, which uses a heat pump and hydrogen boiler	2022 - 2032
6	Waterstofpilot H_2 Lochem	Alliander Remeha, municipality	Provide 12 monumental homes with hydrogen through the existing natural gas network	2022-2025
7	Waterstofpilot Hogeveen	Rendo, Essent, Gasunie, Remeha, municipality Installation	From May 2023 the hydrogen infrastructure will be installed by the network operator Rendo and should be operational in September 2023. The goal was to convert 427 houses but due to increasing prices the target is reduced to 18 houses.	From 2023
8	Stad Aardgasvrij, Stad aan 't Haringsvliet	Gasunie Stedin Remeha	The hydrogen must be used to heat the 600 houses in the village. The existing gas network can be used for this, so there is no need to install a new network. A referendum will be held in June 2023, in which >70% of the inhabitants must respond positively to continue.	From 2025
9	InnovaHub, Goeree Overflakkee	Hylife Innovations	Converting surplus of renewable energy in hydrogen for seasonal storage. Hydrogen converted back to electricity and district heating	Concept phase
10	FODEO, Oosterwold	Nedstack fuel cell (8 partners total)	Testing a system of a self-sustaining neighbourhood of 10 buildings which produce hydrogen with unused electricity form solar panels. When power is needed for heat a fuel cell is used to convert the hydrogen into electricity (FODEO, 2023)	Concept phase
11	De Groene Walvis, Graft-De Rijp	Eneco	Goal is to produce hydrogen locally with solar power and store it. When houses need	Concept phase

			hydrogen, it's transported to the houses which usages hydrogen boilers (Clevers, 2021)	
12	Energiehub Eeserwold	RENDO, Steenenergie municipalties Hydronex	Local production of hydrogen from solar energy from the neighbourhood. Hydrogen used for energy storage and for car hydrogen station	Concept phase
13	H2H.nu, Wageningen	Local initiative of 5 people	Local hydrogen production and storage from local solar energy. The hydrogen is transported to residential buildings	Concept phase

Table 6, Dutch hydrogen pilot overview-built environment, own creation

6.3.1 Laboratory setting

The technical development of hydrogen elements progressed gradually through testing and evaluation in laboratory testing location to inhabited buildings (HAP1, RE1, RE2). These laboratory testing where for example conducted in the Green Village, Hydrogen Experience Centre Apeldoorn and Uithoorn where 14 demolition homes were converted from a natural gas to hydrogen network (MissieH2, z.d.). In the last 5 years the conversion from gas to hydrogen network has been practiced in The Green Village. The aim is to develop the right practices and standards for hydrogen networks, as this is an essential step in the transition to hydrogen. This involves collaboration with scientists, companies, start-ups, and network operators who use facilities such as those of the Green Village to conduct research and contribute to the development of the hydrogen sector (RE2). Learning from laboratory settings has proven valuable, providing insights into the challenges of connecting homes to hydrogen and the performance of the technologies (HAP1, RE1, RE2, LG1). The laboratory testing areas are currently used for testing new equipment and training operators on how to convert a natural gas network to hydrogen (RE2, LG2).

6.3.2 Hydrogen boiler pilots built environment.

There are currently 4 hydrogen pilots ongoing in which users are involved. There are also 3 pilot areas (sometimes called living labs) where actors can test new technologies or train operators to work with hydrogen (MissieH2, z.d.). These living labs are very valuable learning experiences and provide insights into the possibilities and obstacles in connecting homes to hydrogen (LG1, RE2).

The 4 pilots are ongoing in the Netherlands in which users are actively involved. The project in Rozenburg started in 2019 and was the first pilot where hydrogen was used for heating residential users. In this project, the hydrogen is produced on-site and used in hydrogen boilers for the heating of 25 apartments. The boilers are not located in the building but in a separate boiler house. This pilot made it possible for actors to gain there first practical experience with hydrogen boilers (Stedin, n.d.).

In the period of 2022–2023, three pilots started in the Netherlands which involved users in Wagenborg, Lochem and Hoogeveen. The organizations involved in the hydrogen pilots in Wagenborg are trying to prove that hydrogen is a safe and sustainable alternative to natural gas in combination with home insulation and a hybrid heat pump. The project is unique because it is the first residential area from the 1970s to switch to hydrogen (SodM, 2023). An interviewee added that also the purpose of this pilot was to learn whether hydrogen is financially feasible for these types of houses (LG1).

Another ongoing pilot is in Lochem, which involves 13 monumental buildings. Organizations are trying to learn whether hydrogen is a safe and sustainable way to heat homes via the existing gas network. The project is a world primeur because it is the first time that inhabited homes are connected to just a hydrogen boiler (Remeha, z.d.). They also want to gain experience storage and distribution of green hydrogen by getting a better understanding of the hydrogen demand in cold winters. This pilot uses monumental buildings (Alliander, z.d.).

Further into 2023, a hydrogen project unfolds in Hoogeveen, designed to demonstrate the feasibility of transitioning a neighbourhood from natural gas to hydrogen. The project comprises two phases: initially, an 80-home new neighbourhood will receive hydrogen through a dedicated pipeline, followed by the conversion of a pre-existing neighbourhood of 400 homes to hydrogen via the established gas network (Hoogeveen, 2020). The pilot's extensive scale introduces a heightened level of complexity learned actors about new challenges pertaining to technology, safety, and regulation (HAP1).

The interviews show that there are various challenges regarding the current hydrogen pilots in the built environment. First, there is the issue of price barriers. To get the pilots off the ground, the participating parties decided that residents would pay the same rates for hydrogen as they would have paid for natural gas, regardless of the rates for hydrogen. This provides certainty and prevents direct confrontation with any higher costs for hydrogen for residents (LG1). These price guarantees and costs are a challenging issue for these pilots. In a specific project, a party that wanted to supply the hydrogen could not give a price guarantee for 15 years, this was considered too great a risk (NI1). In addition to the price guarantee, there is also the challenge of supply security. It is important to ensure that sufficient hydrogen is available, even in extreme weather conditions. This sometimes leads to large stocks of hydrogen that must be ready at locations for extreme cases (NG1). Currently, tube trailers are used to deliver hydrogen by truck. This poses challenges, as there is not yet a network from which the hydrogen can be purchased. This makes the logistics of hydrogen for these pilots very expensive (HAP2, RE2, NI1, NG1). These challenges illustrate the complexity of further development of hydrogen in the built environment. Also, technical challenges emerged, such as the need for increased volume flow through boilers due to hydrogen's lower energy value, leading to more noise (LG2).

6.3.3 User acceptance pilot

The importance of social acceptance in the transition to new energy sources cannot be overstated. The pilot project in Stad aan 't Haringvliet serves as a crucial test not only for the technological aspects but also for the social aspects of the transition. In this pilot the actors were trying to learn about the acceptance by user. The residents of Stad aan 't Haringvliet were given the opportunity to vote on participating in the pilot, which involved replacing the existing natural gas infrastructure to hydrogen. At least 70% of the residents needed to be in favour of the project which was seen as a challenge (RE2).

On June the 30 the provisional outcome was announced in which was stated that 77.6% of residents voted in favour of the pilot project, with an impressive turnout of 84.8%. The successful voting outcome highlighting the willingness of the community to embrace new heating system like hydrogen. The estimation is that the pilot is realised in 2025 (RE2; Stad Aardgasvrij, 2023).

6.3.4 Future pilots fuel cell

Although there have been experiments conducted with hydrogen boilers fuel cells, they have not been tested on a large scale (RE2, HAP2). There are 5 pilot initiatives that focus on experimenting with local hydrogen production of the surplus of renewable energy. These pilots are currently in the conceptualization phase. The aim is to prove that net congestion resulting from locally produced renewable energy could be resolved by decentralized hydrogen production and storage until the energy is required again. Of these pilot initiates four pilots focus on converting the hydrogen back to electricity on a central point. One pilot aims at transporting the hydrogen to households where it could be used for boilers or fuel cell (FODEO, 2023; Scheurleer, n.d.; Clevers, 2021).

6.3.5 Missing regulation

Interviews highlight the absence of regulation for hydrogen in the built environment. Hydrogen lacks gas recognition in the Gas Act, hindering its transport and distribution within regular network operations. While the Gas Act allows network companies to manage hydrogen infrastructure, there's a need for experimental space beyond the standard framework (Weeda & Niessink, 2020). The Dutch Government aims to adjust laws for experiments, enabling regional and national grid operators to experience hydrogen transport and distribution. Because hydrogen is not recognized as a gas under the Gas Act, exemptions for experiments involving pure hydrogen are currently unavailable (Ministry of Economic Affairs and Climate, 2019).

In the early stages of the learning process, the complexity of hydrogen was underestimated. As the project progressed there was a greater understanding of the complexity and the new way of looking at safety for the infrastructure. Several working groups and extensive safety documents have now been set up to ensure that working with hydrogen is well thought out (LG1, RE2, NI1). But still there is a lot of technical learning to be done about converting existing natural gas pipelines to hydrogen pipelines to ensure safety and minimize any risks. For example, there is still no official procedure on how to flush old pipes before they can be used for hydrogen (HAP1, EA1, RE2, RI2). Many of the measures that are now being used in pilots are based on regulation for natural gas. Work is underway to develop rules and standards specifically aimed at hydrogen (RE2).

The lack of regulations on hydrogen is already a bottleneck for the installation of hydrogen pipes at farms and the generation of hydrogen at wind turbines (LG1). Developing appropriate legislation and regulations is essential to promote the energy transition and to stimulate the transition to natural gas-free solutions. Temporary solutions are currently being found, such as tolerance decisions, but structural adjustments are needed in the long term (NG1, NI1).

6.4 Conclusion

In this chapter, the exploration of niche analysis for the development of the hydrogen niche in the Dutch built environment conducted. The preceding sections have delved into expectations, network formation, and the learning process that surround this emerging field. There are two main challenges of the regime which potentially can be solved with hydrogen which are heating without emissions and reducing the pressure on the electricity grid.

Actors within the niche have high expectations for hydrogen's role in the built environment. They expect that in the future hydrogen will be in large quantities available, but also multiple interviewees stated that they renewable energy remains scares in the future which means the converting of renewable energy to hydrogen will lead into too much energy lost. They believe we should therefor strive for as much efficiency which means is more achievable with full electrification. The green hydrogen which will be produced in the Netherlands is allocated for the heavy industry. Some belief this will remain the case due continuing limited availability of green hydrogen. This uncertainty regarding the availability of hydrogen, makes companies and government institutions reluctant to further develop hydrogen applications for the built environment.

Hydrogen is seen as a solution to accommodate the increasing energy demand without overloading the electricity grid. It's anticipated to play a pivotal role in storing renewable energy, providing flexibility, and ensuring stability in energy supply. Despite some disagreements about specific applications, there is a consensus that hydrogen can complement electricity in various ways, particularly through hydrogen boilers, fuel cells, and hybrid systems. Some interviewees see fuel cells in combination with a hydrogen infrastructure as a facilitator of electricity to the built environment. Whereas the hydrogen boiler is merely seen as a technology which prevents an increase in electricity capacity demand for heating. On the other hand, there are actors who believe that the electricity issue will be resolved by upgrading the electricity grid capacity and hydrogen is unnecessary.

The development of hydrogen technologies involves multiple actors, including government bodies, municipalities, network operators, researchers, and private companies. The Dutch government's initiatives and funding have driven pilot projects to test the feasibility of using hydrogen in residential areas. These projects are pivotal for knowledge-sharing and practical learning, as they encompass diverse elements from laboratory testing to inhabited buildings.

The learning process has been marked by a gradual transition from laboratory testing to real-world applications. Hydrogen pilot projects have provided valuable insights into technological challenges, user acceptance, and supply security. While technical readiness and integration have been achieved to some extent, challenges remain regarding regulatory adaptation, pipeline conversion, and logistics. The ongoing pilots involve hydrogen boilers whereas fuel cell pilots are expected to occur in 2030. This is in combination with decentralized hydrogen production and storage.

The development of the hydrogen niche in the Dutch built environment holds promise, yet it also faces complex challenges. There is still a misalignment among actors regarding what regime issues there are trying to resolve. The network is forming as different stakeholders collaborate, and the learning process is ongoing through pilot projects and technological trials. The lack of hydrogen regulation is an existing bottleneck that needs to be addressed, but the commitment of various actors, including the government, municipalities, network operators, and researchers, highlights the dedication toward a sustainable transition.

Because the niche technologies are only being used within pilots for experimentation and the technologies have not stabilized in small niche markets, the niche is still in the experimentation phase of the MLP.

7. Barrier analysis

In this chapter, the barriers to the niche that emerged from the interviews to be adopted by the regime are discussed. First is given an overview of the status quo of the transition, second an overview of the barriers identified in the literature and third the barriers are discussed which resulted from the semi-structured interviews.

In the literature review are the following barriers identified, shortage and price of hydrogen, user acceptance, missing required infrastructure and new installation cost. From the semi-structured interviews barriers emerged that are top of mind by the different actors. These are discussed and explained how the different actors are tackling this issue. The chapter ends with a conclusion which will also explain how the barriers are reflected in the theoretical model.

7.1 Supply shortage of green hydrogen

Currently, there is no green hydrogen, and it is still unclear when green hydrogen will become available (EA2, EA3, EA4, RI2). Import is seen as a solution for tackling the hydrogen supply shortage (RE1, RE2, HAP2). The Dutch Government is actively stimulating the import of hydrogen to tackle the uncertainty around hydrogen availability. The Government of the Netherlands and Spain made an agreement to develop and supply line from Spain to the Netherlands. The expectation is that from 2027 hydrogen would arrive at the harbour of Rotterdam from Spain (Rijksoverheid, 2023). Shortly after a pipeline from Portugal and Spain to France and Germany is under construction and will be operational in the 2030s (Hogenkamp, 2023). Gasunie is connecting the Dutch high-pressure hydrogen pipe network to the European hydrogen infrastructure, which will connect the Netherlands directly with the hydrogen production in Spain and Portugal (NI1, RE1).

There are also industry initiatives for local hydrogen production. At the same time, local hydrogen production is stimulated by the Dutch government. For example, the ambition is to have 8 GW of electrolysis capacity for the production of hydrogen by 2032 (Jetten, 2023). In addition, the government is making 250 million euros available for the development of large-scale hydrogen storage. It is expected that the upscaling of electrolysis will reduce costs but will remain mainly dependent on the costs of renewable electricity (Wiebes, 2020). Shell is building Electrolyse installations of 200 MW on the “Maasvlakte 2” which should be able to produce 60.000 kg of hydrogen every day (Shell, 2022). Interviewees argue that hydrogen could best be used in heavy industry where CO_2 reduction would have the most effect (EA2, EA3, EA4, RI2, INF4).

While certain interviewees highlight that the hydrogen generated by these electrolysers is intended for industrial purposes (EA2, EA3), an opposing perspective suggests that this effort will contribute to establishing the required supply, consequently jumpstarting the green hydrogen market in the Netherlands. This increase in hydrogen availability enhances the likelihood of widespread technology adoption within the built environment. Additionally, some interviewees stated that there is already a lot of demand so we should be cautious with developing more demand (EA3, INF4). For the large implementation of hydrogen solution, this needs to be resolved because multiple interviewees stated that manipulates only feel confident enough to make a transition to hydrogen if is there enough supply available (EA3, NI1).

7.2 Uncertainty hydrogen price

There is still a lot of uncertainty on the future green hydrogen prices which creates uncertainty it is an affordable solution (EA3, EA4, RI2, RE1, RE2). Currently the price of hydrogen for heating is high much higher compared to natural gas or electric (EA2, RE1, RE2, NI1, RI2).

The niche however expects low prices. Solar energy in countries with much sunshine like e.g., Saudi Arabia and Spain can produce hydrogen (HAP2, RE1). The hydrogen produced in Spain and Portugal is expected to be around 2 euro per kg, compared to 4 euro per kg in the north of Europa (Hogenkamp, 2023). When considering the total supply chain costs (including all costs for infrastructure and within the buildings), hydrogen at a price of 3,6 euro per kg is likely the most cost-effective solution for 66-75% of the Dutch built environment compared to the other emissions free heating solution due to the much lower infrastructure cost (Hellinga and van Wijk, 2021). According to one interviewee, the price prediction of hydrogen is different in each report. In some reports, the calculations are based on small hydrogen production compared to other reports who predict their prices based on large production (RE1).

Opponents of hydrogen in the built environment argue that even if the price of hydrogen means the price of renewable energy is also decreasing because hydrogen is made from electricity (EA2, EA3, EA4). Another argument is that they believe imports will be still more expensive than the electricity produced locally. Also considering the energy loss of the hydrogen production and converting it back to hydrogen and the transportation compared to producing electricity in the Netherlands. There is no legislation for green hydrogen yet. there is no one who knows what green hydrogen will cost in the future (EA3).

The recent rise in natural gas prices has moved consumers, accelerating the transition to alternative energy sources which indicated that price is an important driver for users. This uncertainty of price is less an issue with electricity due to the already established electricity market, which makes it easier to predict what the future prices will be compared to the cost of green hydrogen (EA3). It's worth noting, however, that even the electricity market would necessitate transformation, considering its current reliance on coal and natural gas for production, both of which require a transition to renewable energy sources (Hellinga and van Wijk, 2021). The user will ultimately choose a solution which would be the cheapest solution for him (EA3, EA4).

7.3 Labour shortage

A challenge faced by infrastructure companies and municipalities revolves around the shortage of available and qualitative employees. Interviewees stated that infrastructure companies have already too much work due to the fast-growing demand of electricity. However, the scarcity of personnel poses a significant hurdle, making it difficult for them able to implement the required infrastructure (RI2, NI1, RE1, LG2). There is also a consensus among interviewees is that municipalities play an important role in the energy transition. This significance stems from the Climate Accord, which promotes a district-oriented approach, allowing municipalities to determine which technology and when to implement it in their districts. Despite their interest in solutions and willingness to contribute, several interviewees note that municipalities often struggle with the complexities of the energy transition. They are faced with the challenge of navigating legal resources, ensuring security of supply, and coping with a shortage of skilled employees (NG1, HAP1, EA1, RE2).

7.4 User acceptance

User acceptance of hydrogen is seen as a big challenge by some interviewees. The expectation is that people are reluctant when it comes to the energy transition and accepting the associated costs and changes in their daily lives (EA4, RI2, NI1). Gordon et al., (2022) concluded that this mainly results from the limited public knowledge and awareness about hydrogen.

The positive result from the recent pilot at Stads aan ‘t Haringsvliet is seen as a good indicator about the willingness of citizens to adopted to hydrogen heating. In this pilot an information campaign was setup including a show house in which focussed on informing the residents of Stads aan ‘t Haringsvliet about the use and implementation of hydrogen (RE2; Stad Aardgasvrij, 2023). The result from this pilot was after published the interviews had been conducted, so their view on these results have not been discussed.

Tigchelaar et al., (2019) explained that excessive enforcement from the government to adopt a heating technology may result in resistance from Dutch homeowners. But relying solely on the voluntary choices of individuals is unlikely to result in the large-scale change that is needed (Tigchelaar et al., 2019). The current strategy to overcome this hurdle is by empowering municipalities with the authority to disconnect neighbourhoods from natural gas. This is a powerful instrument that allows the municipality to accelerate the transition to sustainable heating. It provides clarity and a concrete end date for people in that neighbourhood. A municipality could e.g., inform citizens that in 8 years, natural gas will no longer be available, and they will be connected to the hydrogen infrastructure (EA1, EA3, NG1). An interviewee states that to increase the willingness among users the price of natural gas should be increased further through a CO_2 tax (EA3). According to Spek (2022), the average household paid in 2021 around 200 euros in CO_2 tax in the Netherlands for natural gas and electricity.

7.5 Conclusion

This sub-research question focuses on identifying the challenges and obstacles faced by hydrogen heating technologies in their integration into the Dutch-built environment. Understanding these barriers is crucial for facilitating the transition to a hydrogen-based heating system within the Dutch-built environment. From the interviews resulted multiple top of mind barriers currently faced by the regime which were the availability and cost of green hydrogen, labour shortages, and user acceptance challenges.

Uncertainty about hydrogen availability is seen by many as the largest barrier. If there is no hydrogen available there is no business case. At the same time, it is holding back organisations and companies to invest in the technology due to this uncertainty. To address the shortage of hydrogen, the import of hydrogen from abroad, notably from Spain and Portugal, is being actively promoted by the Dutch Government. Simultaneously, local hydrogen production is gaining traction, supported by electrolysis processes. However, the produced hydrogen from this project is allocated for the industry which makes companies uncertain if there will be hydrogen available for the built environment.

Uncertainty surrounds future green hydrogen prices, making it an uncertain solution for heating. Currently, hydrogen prices are higher than natural gas or electric, but the growing production market is expected to decrease hydrogen prices over time. Some research stated that for 66-75% of Dutch built environment hydrogen boilers would be the most cost-effective solution with a price of 3.6 euro per kg. Opponents argue that the price of hydrogen may also decrease renewable energy prices, as it is made from electricity.

An additional challenge lies in the shortage of qualified personnel, hampering infrastructure implementation efforts by key players. Municipalities, vital in driving the energy transition, struggle with complexities stemming from the Climate Accord district-oriented approach. This encompasses navigating legal considerations, guaranteeing supply security, and managing workforce constraints.

User acceptance poses yet another obstacle, with public apprehension towards the energy transition and its potential financial and lifestyle impacts. Addressing this, successful pilot projects, such as the one at Stads aan 't Haringsvliet, demonstrate that informed campaigns and tangible showcases can foster willingness to embrace hydrogen heating solutions. However, the challenge remains to trigger immediate investments and renovations in homes, even as empowering municipalities with the authority to phase out natural gas emerges as a strategy to catalyse change.

The labour shortage, availability and cost of green hydrogen are barriers which are resulting from landscape development and outside the influence of the regime. Whereas the user acceptance is a barrier which results from the regime.

8. Socio-technical scenarios

In this chapter, potential scenarios of hydrogen usage in the heating of households in the Netherlands are explored. As stated before, these scenarios are only intended to explore potential futures, but they are not a prediction of the future. These scenarios are written in the past tense. As stated in the sub-chapter 4.4, first the design choice for the scenarios is formulated. This includes the timeframe, layout scenarios, factors, and potential patterns. Then the 2 scenarios are presented, and a comparison is made between the scenarios.

8.1 Design choices scenarios

From the niche analysis in chapter 6 emerged that niche actors expect a role for hydrogen in the Dutch built environment as soon as a hydrogen economy is established. This is in line with the scenario formulated by Netbeheer Nederland (2023) in which was concluded that if a large international hydrogen economy emerges this will likely lead to the import and storage of hydrogen. According to the scenario of Netbeheer Nederland (2023) this will lead to an adoption of more than 60% of hydrogen heating applications for houses. As stated in chapter 2, these scenarios do not consider the use of fuel cells.

As explained in sub-chapter 6.1, the niche actors also expect a continuing of the electricity grid congestion which could have a large impact on adoption the hydrogen application in the Dutch built environment. This is why the decision is made to write two scenarios in which both scenarios are based on the establishment of a large international hydrogen economy. The rise of an international hydrogen economy will likely result in an increasing amount of hydrogen being imported to the Netherlands. The first scenario will contain an unresolved electricity grid. The current electricity grid is at maximum capacity. Today this congestion already delays the needed expansion of the grid connection of new solar parks and industrial areas. In the scenario this issue will only increase, also due to the growing energy demand in the built environment. This scenario will follow a reconfiguration transition pathway where alliance is formed between new and incumbent actors and will coexist in the regime due to the emerging of hydrogen boilers and fuels cells. Also, existing, and new technologies will emerge and coexist in the regime and limited institutional change occur.

In the second scenario, the net operators can resolve electricity grid congestion issue. The focus of the scenarios is to illustrate which multi-level patterns may occur, which leads to an active role of hydrogen applications in the Dutch built environment. This scenario will follow a transformational transition pathway where incumbent firms will remain control by developing radical new technology of hydrogen boiler with heat pumps.

Timeline & layout scenarios

The scenarios will follow a certain layout. As explained in sub-chapter 3.4, these scenarios will consist out of 3 episodes, namely linking, transformational and evolution. The selected timeframe for the scenarios is from 2023 until 2050. This timeframe is selected due the government goal for CO_2 free heating in the built environment from 2050. This creates the assumption that by that time the transition should have taken place. Based on the insight gained from chapter 5, 6 and 7 the decision is made to formulate the following timeframe:

- Linking episode 1: 2023 - 2030
- Transformational episode 2: 2031 – 2038
- Evolution episode 3: 2039 – 2050

Factors
In Table 7 the following landscape, regime factors of the scenarios are included.

Factors	Scenario 1	Scenario 2
Landscape factor: Hydrogen availability	Through active involvement of the Dutch government hydrogen gets imported on a al large scale.	Through active involvement of the Dutch government hydrogen gets imported on a al large scale.
Regime factor: Infrastructure electricity	Network operators are unable to increase electricity grid capacity;	Network operators can increase electricity grid capacity;

Table 7, factor overview scenarios, own creation

Potential patterns
In chapter 5, 6 and 7 are the current dynamics between the levels analysed. From this analysis emerged multiple patterns between the different levels. These patterns are used as input for formulating the scenarios. The following patterns have been identified:

Patterns between the landscape and regime:
- Increasing pressure of climate change (Landscape factor) leads to new regulation for the regime to reduce CO_2 emissions.
- Increasing energy prices lead to more openness to new heating technologies and isolation activities by users in the regime.
- With a clear technical choice with a strong campaign from the government could lead to a broad acceptance by users.

Patterns between regime and niche:
- When there is more experience and trust in a technology gained in the niche, regime actors are willing to participated in larger pilots.
- The continuing of the electricity grid congestion leads to more initiatives for local hydrogen storage pilots. The expectations for fuel cells increase among the niche actors.

Patterns between landscape and niche:
- Uncertainty about availability and price of green hydrogen leads to lower expectations of niche actors. They limited their investments and time into the development of hydrogen applications. This leads to more focus into other technologies like district heating or electric heating.
- Labour shortage creates hesitance and wait and see attitude by regime actors which holdback the transition.

8.2 Scenario 1: Hydrogen role in reshaping the energy infrastructure

This scenario is based on the conditions of high availability of hydrogen in combination with unresolved electricity grid congestion.

Linking episode: 2023 – 2030
In this episode is described how the niche actor's links up with events in regime and technology changes, combines with other technologies, splits into different lines of development to adopted to the need of the regime.

In the period 2023 until 2030, at landscape level**,** this government policy enabled the emerging of a hydrogen economy in the Netherlands by setting up international supply chains. The shift in government policy showed that the Dutch government believes that hydrogen will become a central player in the global energy landscape. The Dutch government made multiple announcements, about new import contracts of green hydrogen and stated that there will be hydrogen available for the built environment. In the Netherlands some industrial companies start their own green hydrogen production from wind-mill parks, this leads to some availability of green hydrogen for the Dutch industry. Internationally, hydrogen production has also gained traction, with the port of Rotterdam becoming a key hub for importing hydrogen. Also, a large hydrogen storage become available. This declaration sparked considerable excitement among niche actors who saw vast potential in hydrogen technologies, primarily driven by the high availability of hydrogen.

Simultaneously, incumbent firms recognized that hydrogen was set to become more likely available, leading to increased investments in the development of hydrogen boilers. Infrastructure actors began participating more actively in pilot projects aimed at understanding how to transition the existing natural gas infrastructure to hydrogen infrastructure. This development was a response made by the regime-level to the changing landscape, where established players adapted their strategies to align with the evolving hydrogen narrative.

The years from 2023 to 2030 witnessed a steady development of hydrogen applications for the Dutch built environment. Numerous pilot projects were launched to gain more experiences with various hydrogen applications in the built environment. At the niche level, these pilot projects were efforts to demonstrate the feasibility and benefits of hydrogen technologies. This also contributed to a growing sense of trust and understanding about the hydrogen's potential by citizens. As these projects gained momentum in the built environment, the connection of industrial clusters to the high-pressure hydrogen infrastructure took shape. This fostered collaboration among these clusters and laid the foundation for a broader hydrogen network.

The learning process for hydrogen heating technologies continued to progress, with increased investments into various hydrogen applications. However, this diverted resources from alternative technologies such as district heating and biogas. To foster greater adoption, research focused on enhancing the safe use of hydrogen, leading to new regulations. These regulations mandated the addition of a colorant to make the flame visible and an odorant to detect hydrogen leaks. At the regime level, this regulatory intervention aimed to ensure the safe integration of hydrogen into the existing energy system.

However, network operators faced ongoing challenges in upgrading the electricity grid, as permits were often delayed or denied. This uncertainty created anxiety among regime actors regarding the future electricity supply in the built environment. Consequently, niche actors began investing more resources in fuel cells technologies, with multiple actors announcing pilot projects. Due to the anticipated growth in the hydrogen sector, niche actors saw reduced potential for biogas due to hydrogen's scalability.

The ongoing struggle with upgrading the electricity grid and rising demand, made it difficult for companies to meet their sustainability goals. As a response, a few companies started to experiment with integrating with the new established high pressure hydrogen infrastructure, allowing them to generate electricity from the hydrogen using fuel cells. This integration initiated a wave of decarbonization across various industries. Niche actors also seized the opportunity, supplying fuel cells to the Dutch market and contributing to the growth of the hydrogen ecosystem. In the regime was highlighted that some established actors are looking for alternative technologies to achieve their sustainability objectives.

Meanwhile, the installation of solar panels in the built environment continued to rise. However, the surplus energy generated could not be absorbed due to grid capacity limitations. Niche actors identified a growing potential in local hydrogen storage and production, prompting increased investment in this technology. At the niche level, this response to grid limitations was an attempt to create a localized solution to the surplus energy problem, emphasizing the interplay between renewable energy sources and hydrogen technologies.

To facilitate the transition, the government implemented new regulations that empowered municipalities to disconnect gas supplies in neighbourhoods, effectively compelling citizens to transition to alternative heating technologies. At the regime level, this regulatory shift exerted top-down pressure on the incumbent heating technology and catalysed the adoption of hydrogen and other alternatives at the niche level.

Transformation episode: 2031 – 2038
In this episode the hydrogen applications are being adopted and further development takes place. At the *landscape* level, the period from 2031 to 2038 marked significant advancements in the use of hydrogen as an energy source. The Dutch hydrogen infrastructure expanded its reach, connecting with neighbouring countries and, ultimately, the rest of Europe. This integration fostered direct imports of hydrogen from Spain, Portugal, and even the Middle East and North Africa. At the *landscape* level, this expansion represented the internationalization of hydrogen markets and supply chains, reducing uncertainty about hydrogen availability.

As green hydrogen production scaled up, hydrogen prices decreased and stabilized. These developments helped overcome barriers related to hydrogen availability and cost. Large green hydrogen producers entered the market. This increased availability and reduced cost of hydrogen fostered collaboration among incumbents (*regime*) and *niche* actors, further driving the transition.

Simultaneously, at the *regime* level, the Dutch government-initiated programs to promote hydrogen use across various sectors and continues its investments in national hydrogen storage. This strategic move aimed to boost the regime's confidence in adopting hydrogen technologies. These efforts provided municipalities with a sense of availability security. During this period, natural gas boilers remained the standard for space heating, but the first neighbourhoods began connecting to the hydrogen infrastructure. This shift was made possible through regulations that empowered municipalities to transition neighbourhoods from gas to hydrogen. Hydrogen boilers and fuel cells began to enter the large market, benefiting from increased scale, which improved performance and lowered prices. These landscape development empowered regime actors to adopt technologies from the niche.

Municipalities and network operators encountered a labour shortage that hindered the transition. Recognizing the societal importance of the transition, the Dutch government provided subsidies to manufacturers, enabling them to increase wages for employees. This strategy attracted more talent to work for these manufacturers. This collaboration between the government and industry at the regime level to address labour shortages, enabled smoother transition in the energy transition. These subsidies result in higher transition cost.

Actors within the regime remained unable to upgrade the capacity of the electricity grid. This forced users to look at alternative solution that facilitated their electricity demand to meet their sustainability goals. Some companies adopted fuel cells to be able to generate electricity, where the electrical grid could not meet demand. The growing demand for fuel cells in various sectors also created opportunities for new companies to enter the market. New software companies emerged who enabled users to flexibly switch between hydrogen and grid electricity. This showed that already new firms are entering the regime.

Due to the continue limited electricity grid, the surplus of solar energy could not be fully supplied to the grid. This led to a renewed focus on local hydrogen storage and production as an alternative to harness surplus renewable energy. At the niche level, this response highlighted the interplay between renewable energy sources and hydrogen technologies in addressing grid limitations.

The popularity of fuel cells in the industry paved the way for their adoption in households. This merger of fuel cell technology with heat pumps became a viable option. Notably, hydrogen boilers did not fully merge with heat pumps due to insufficient grid capacity.

The Dutch government launched a campaign to raise awareness of hydrogen's benefits in the built environment, aiming to reduce uncertainty among citizens. At the same time subsidies are introduced by the Dutch government for citizens to reduce their investment cost of purchasing a hydrogen boiler or a fuel cell with a heat pump. This heightened awareness led to increased social acceptance and support for hydrogen initiatives, contributing to overcoming user acceptance barriers. The government-led awareness campaigns lead to societal acceptance of regime actors to adopted niche technologies.

Evolution episode: 2039 and 2050
In this episode the large-scale transition is taking place. At the landscape level, the international hydrogen economy strongly developed. The Dutch government started campaigns to improve the adoption of hydrogen in many sectors. Due to clear vision of the Dutch government regime actors gained more trust in embracing hydrogen technologies. By 2039, hydrogen boilers replace natural gas boilers and enforced a rapid transition of the natural gas infrastructure. The hydrogen economy has gained significant trust and momentum, thanks to the well-established high-pressure infrastructure and expanding international market. In this phase the existing natural gas infrastructure within neighbourhoods are being converted to transport hydrogen.

The built environment's energy demand continued to grow. Hydrogen was required to fill the gap as the electricity grid was not capable to fill all demands during the cold periods. The need for the availability of affordable fuel cells, in combination with heat pumps and hydrogen boilers grew. Hydrogen boilers became the dominant heating technology for houses. Initially, neighbourhoods centred around industrial clusters were connected to the hydrogen infrastructure, gradually connecting more neighbourhoods.

With the international established hydrogen economy, energy imports became more affordable. As a result, the need for local renewable energy production dwindled which led to a fade out of solar panels in the Netherlands. Also, the surplus of renewable energy remained unmanageable due to the limited capacity of the electricity grid. This change in the energy landscape influenced decisions at the regime level to reduce support for local renewable energy production. At the niche level actors were researching the potential of local hydrogen production and storage, but due to the low energy prices this technology became not affordable.

To address the societal shift brought by the introduction of hydrogen in the built environment, users had to adapt their behaviours. The hydrogen boiler fitted more seamlessly into user preferences. With the disappearance of natural gas in the built environment the user behaviour changes, for example the technology used for cooking.

Transition pathway:
In this socio-technical scenario, a reconfiguration transition has taken place. As stated in Table 2, the reconfiguration transition is recognized based on an alliance forming between new and incumbent actors and will coexist in the regime. Also, existing, and new technologies will coexist in the regime and limited institutional change occurs. Due to the successfully integrates hydrogen into its energy landscape with the lacking capacity of the electricity grid in this scenario, new firms enter the regime with fuel cells to resolve a local problem for some users, namely electricity shortage. Will incumbent firms develop hydrogen boilers for other users. There are some changes with regulation required due to the use of hydrogen in the built environment but due to maintaining of incumbent actors there is limited institutional change.

8.3 Scenario 2: Hydrogen and Heat Pumps Transform the Built Environment

This scenario is based on the conditions of high availability of hydrogen in combination with a resolved electricity grid congestion.

Linking episode: 2023 – 2030
This episode describes how the niche actors link up with events from the landscape and regime level. Also, the learning process in the niche level are described.

In the period from 2023 to 2030, the Dutch government and the European Union made a pivotal announcement, signalling further importation of hydrogen on a large scale. The Dutch government announces that the hydrogen will not solely by available for the industry but also for other sectors like the built environment. Meanwhile the establishment of a robust high-pressure hydrogen infrastructure, connecting industrial clusters across the country emerged. Internationally, hydrogen production experienced substantial growth, with the port of Rotterdam emerging as a pivotal hub for hydrogen imports. The Dutch government announced that they see that hydrogen will become an important energy source for multiple sectors in the Netherlands. This declaration increased expectations among niche actors, who discerned a promising future for hydrogen technologies. At the landscape level, the Dutch government also unveiled a comprehensive program aimed at bolstering the capacity of the electricity grid. This initiative not only provided financial support but also expedited the permitting process for construction. Such proactive measures increased confidence within both niche and regime actors that electricity supply in the built environment would not be a limiting factor.

Concurrently, incumbent firms observed the increasing future availability of hydrogen resources and consequently ramped up their investments in hydrogen technology research and development. Infrastructure actors eagerly engaged in pilot projects to understand the conversion process from natural gas to hydrogen, sensing a shift in the energy landscape. This showed that the landscape developments were empowering the regime and niche actors to participated further in the development of hydrogen technologies. Consequently, niche and regime actors began to envision a more significant role for heat pumps in the future and started directing their investments accordingly. This led to actors experimenting with the merger of the heat pump and the hydrogen boiler technology.

The rising expectations surrounding hydrogen availability prompted niche and regime actors to allocate more resources to the advancement of hydrogen heating technologies. Collaborative pilot projects materialized, bringing together network operators, local governments, and manufacturers to experiment with this technology. From 2023 to 2030, these initiatives laid the foundation for a comprehensive learning process within the niche, marked by the emergence of multiple pilot projects. These endeavours played a pivotal role in fostering trust and understanding regarding hydrogen applications.

With the knowledge of increased hydrogen availability and a clear plan to alleviate grid congestion, the learning curve for hydrogen boilers and heat pumps experienced a notable upswing. As more resources flowed into these developments, other technologies such as district heating and biogas received comparatively fewer investments. Simultaneously, the transparent strategy for enhancing electricity grid capacity curbed expectations for local hydrogen production and storage.

In pursuit of broader adoption, research endeavours focused on enhancing the safety of hydrogen usage. This resulted in regulatory measures requiring the addition of a visible flame colorant and an odorant to detect hydrogen leaks. To facilitate the transition, the government implemented new regulations empowering municipalities to cease gas supply in neighbourhoods, thereby compelling citizens to switch to alternative heating technologies.

Transformational episode: 2031 - 2038
In this episode the hydrogen applications have been adopted and further development has taken place. At the *landscape* level, the global landscape of the hydrogen economy strongly influenced developments within the Dutch regime. The increased prevalence of hydrogen importation from neighbouring countries, particularly Belgium and Germany, and the extension of hydrogen supply lines from the Middle East and North Africa to Europe signalled a growing international commitment to hydrogen as an energy source. Also, due the increasing scale in which green hydrogen is being produced results in lower prices. This global landscape development bolstered the confidence of regime actors in the Netherlands to focus on the adoption of hydrogen technologies. The electricity grid was gradually upgraded across the Netherlands. The waiting list from companies to increase a higher electricity connection was gradually reduced.

To tackle the uncertainty of hydrogen availability and security of hydrogen by the regime actors, the Dutch government invested in a national hydrogen storage to address a critical barrier. This initiative from the Dutch government of creating a national hydrogen storage empowered municipalities to consider transitioning their infrastructure from natural gas to hydrogen. Natural gas boilers remained the standard for space heating in the Dutch built environment. At the same time heat pumps were complementary installed to their existing natural gas boiler. This enabled users to reduce their CO_2 emission in the short run and it saved money as well due to the lower energy cost.

Government-led campaigns continued to foster public awareness and acceptance about hydrogen's safety and use in the built environment. At the *regime* level, the new regulation empowered municipalities to convert neighbourhoods gas infrastructure to a hydrogen infrastructure, resulted in the first neighbourhoods being converted. It resulted in the first step of gradual replacement of natural gas boilers with hydrogen boilers, marking a crucial step in the adoption of hydrogen heating technologies. Hydrogen boilers started to enter niche market which led to a growing scale and experience which resulted in a higher performance and lower prices.

The regime's ongoing struggles with labour shortages prompted another interaction with the landscape level. In response to this challenge, the Dutch government offered subsidies to municipalities and infrastructure companies, which enabled them to increase the wages which made it possible to hire more personal.

Evolution episode: 2039 and 2050
In this episode the large-scale transition took place. The international hydrogen economy strongly developed. At the landscape level the Dutch government started campaigns to improve the adoption of hydrogen many sectors. Due to clear vision of the Dutch government regime actors gained more trust in embracing hydrogen technologies which created an alignment between the landscape developments and the regime. From 2039 onwards, a pivotal transformation occurred as the hybrid hydrogen boilers replaced the natural gas boilers. The widespread adoption of hybrid solutions, featuring electrical heat pumps and hydrogen boilers, became the norm in the built environment. Standalone hydrogen boilers and single heat pumps also found their place in this evolving landscape which means the niche has accumulated to the large market.

As the capacity of the electricity grid expanded, which enabled the transport of locally generated solar energy and the conversion of surplus energy on a central level into hydrogen. As renewable energy started to be cheaply imported from abroad the need for local renewable energy production reduced. This led to the fade out of subsidies for solar panels which resulted in a stagnation of new solar panels being placed in the Dutch built environment.

A competition between the two solutions developed as the infrastructure for electricity and hydrogen were both being addressed. However, most municipalities selected hydrogen as the method to heat neighbourhoods due to the lower cost and less inconvenience for residents. Hydrogen-Integrated neighbourhoods emerged, starting with those in proximity to industrial clusters and gradually expanded to include a greater number of neighbourhoods. This was made possible by the earlier regulatory intervention allowing municipalities to transition neighbourhoods from gas to hydrogen infrastructure.

At the niche level, niche actors had now accumulated significant expertise and experience, enabling them to scale up their operations. Hydrogen boilers and heat pumps, once niche technologies, had now become mainstream in the Dutch built environment. Most users adopted a hydrogen boiler in combination with a heat pump due to the high efficiency and prevented the higher isolation cost which made it the most adopted heating technology in the Dutch built environment over time. Houseowners who use a natural gas boiler in combination with a heat pump replaced their natural gas boiler with a hydrogen boiler. The hydrogen boiler with heat pumps had transitioned from the niche to the regime. The transition also influenced the user behaviour, due to the replacement of cooking on natural gas to electric.

Hydrogen also took a central role in power generation and grid balancing. Excess renewable energy was stored as hydrogen during periods of high production and released to stabilize the grid during peak demand. Power plants equipped with hydrogen fuel cells contribute to grid stability, enhancing the reliability of renewable energy sources.

Transition pathways
In this socio-technical scenario a transformational transition occurs. As stated in Table 2, the reconfiguration transition is recognized based on an that incumbent firms maintain control by developing radical new technologies. In this scenario the hydrogen economy establishes, coupled with increased public trust and sophisticated energy management, positions the Netherlands as a leader in the global drive towards cleaner energy systems. The incumbent firms create hydrogen boilers, and pair them with heat pumps. New firms are kept out of the regime. As a result of the use of hydrogen in the built environment, new regulations have also been put in place to support the use developments.

8.4 Evaluation of scenarios

In this chapter the scenarios are compared and evaluated against the scenario objective. This is to illustrate multi-level patterns which leads to an active role of hydrogen in the Dutch built environment. The comparison between the scenarios is presented in Table 8.

KEY ASPECT	CHARACTERISTIC SCENARIO 1	CHARACTERISTIC SCENARIO 2
KEY TECHNOLOGIES	Fuel cells in combination with heat pumps; hydrogen boilers; central hydrogen storage	Hydrogen boilers with heat pump; central hydrogen storage;
KEY CONCEPTS	The emerging of international hydrogen economy; zero-emission heating in the Dutch built environment; Electricity grid congestion maintains unresolved; Users with large energy demand start to adopt fuel cells. Most house owners adopt hydrogen boiler	The emerging of international hydrogen economy; zero-emission heating in the Dutch built environment; Grid congestion is resolved; users adopted hybrid solution of hydrogen boiler and heat pump.
KEY MULTI-LEVEL PATTERNS	At the landscape level a hydrogen economy develops; At the regime level the actors are unable to upgrade the electricity grid; niche	At the landscape level a hydrogen economy develops; At the regime level the actors can upgrade the electricity grid; niche actors start to

	actors start to develop technologies based on the developments at landscape and regime level; due to the landscape developments the regime actors gain more confident in hydrogen technologies	develop technologies which are in line the developments at landscape and regime level; due to the landscape developments the regime actors gain more confident in hydrogen technologies
KEY ACTORS AND ROLES	Incumbent and new firms will coexist in the regime; new actors will play key role in energy supply in the Dutch built environment; due to the adoption of fuel cell new user behaviour emerges changes	Incumbent firm maintain dominant; roles between the actors maintain the same; due to the adoption of hybrid solution the user become flexible in the type of energy they use, which means their behaviour changes
KEY LEARNING PROCESS	Due to the progressive increase of hydrogen availability actors start to invest more money and time in the development of hydrogen applications; government and companies invest more in hydrogen pilots; due to unresolved grid congestion heat pumps and fuel cell technologies merges to match the growing electricity demand in the built environment	Due to the progressive increase of hydrogen availability actors start to invest more money and time in the development of hydrogen applications; Due to resolved grid congestion heat pumps and hydrogen boilers technologies merges to increase efficiency;
KEY INFRASTRUCTURE ASPECTS	The Gasunie finishes the hydrogen backbone; Backbone is connected to the hydrogen infrastructure of Germany and Belgium which enables the import of hydrogen from abroad; overtime in more neighbourhoods the infrastructure is converted from the gas to the hydrogen; Large solar parks have their own fuel cell which are connected to the hydrogen infrastructure	The Gasunie finishes the hydrogen backbone; Backbone is connected to the hydrogen infrastructure of Germany and Belgium which enables the import of hydrogen from abroad; overtime in more neighbourhoods the infrastructure is converted from the gas to the hydrogen; Renewable energy is converted through the electricity grid where on a central point hydrogen is produced

Table 8, comparison key aspects scenarios, own creation

In both scenarios the niche and regime actors react positively to the landscape development, regarding the international hydrogen market. The difference between these two scenarios is the ability of the regime actors to scale up the electricity grid. This result in a different infrastructure landscape in the Dutch built environment in each scenario. Niche actors start to react to these regime events which results in different learning process and the emerging of different key technologies. In scenario 1 the heat pump technology merges with fuel cells, whereas in scenario 2 the heat pump technology merges with the hydrogen boiler. This results from the adoption of fuel cells with heat pumps and hydrogen boilers in scenario 1, whereas in scenario 2 the incumbent firms develop hydrogen boilers and hybrid hydrogen boilers with a heat pump. Another difference between these scenarios is that in scenario 2 the incumbent firms remain dominant whereas in scenario 1 incumbent and new firms will coexist in the regime.

8.5 Conclusion

In this chapter, the two socio-technical scenarios for hydrogen integration in the Dutch built environment are described, highlighting the dynamic interplay between hydrogen availability and electricity grid development.

Scenario 1: With the emergence of large-scale hydrogen production at the landscape level, a gradual development of a hydrogen network takes shape in the regime level. In this scenario, the expansion of the electricity network is stagnating which leads to more grid congestion. Niche actors increase their investments in developing hydrogen technologies and reduces their resources into other technologies. The hydrogen network aids in stabilizing the electricity network and supplying electricity to the built environment through locally converting hydrogen to electricity. Industries and homes alike embrace this approach, with companies facilitating flexible energy usage. Also, hydrogen boilers become technologies which are used in the built environment for heating. Challenges arise as solar-generated green electricity struggles to traverse the conventional grid, making high-pressure hydrogen networks the primary source for homes. This scenario utilizes the existing gas distribution network and avoids extensive expansion of the electricity grid. A Reconfiguration transition has occurred in this socio-technical scenario because new and incumbent firms will coexist in the regime. Due to the remaining incumbent the institutional change in the scenario is limited.

Scenario 2: On the landscape level an international hydrogen market is established, and the electricity network issues are resolved at the regime level. This enables the niche actors to focus on hydrogen boilers in combination with the heat pumps. This trajectory facilitates the ongoing adoption of a hybrid approach, orchestrating a gradual shift from conventional gas boilers to hydrogen-based alternatives for space heating. Amidst this transformation, the infusion of green electricity generated by solar panels assumes a pivotal role, actively contributing to the establishment of a robust and sustainable energy ecosystem. This scenario requires an extensive expansion of the electricity grid and utilizes the existing gas distribution network for the distribution of hydrogen. In this socio-technical scenario, a transformation transition has occurred because of the implementation of new regulations and the adoption of new technologies by the incumbent firms.

In conclusion, both scenarios demonstrate a positive response from niche and regime actors to the evolving international hydrogen market. However, a key distinction lies in the regime actors' capacity to expand the electricity grid, leading to a different infrastructure landscape in the Dutch built environment. These differences prompt niche actors to focus on different technologies, resulting in distinct learning processes and the emergence of unique key technologies. In scenario 1, heat pump technology converges with fuel cells, while in scenario 2, it merges with hydrogen boilers. This contrast arises from the adoption of fuel cells with heat pumps in scenario 1 and the development of hydrogen boilers and hybrid hydrogen boilers with heat pumps by incumbent firms in scenario 2. Another notable difference is that in scenario 2, incumbent firms maintain dominance, whereas in scenario 1, incumbent and new firms coexist within the regime.

9. Discussion

In this chapter the interpretation of the results is explained. Furthermore, the practical and theoretical implications are discussed. The chapter ends with discussing the limitations and future research.

9.1 Interpretation of results

Landscape level
The landscape analysis reveals several key findings that are driving changes within the regime. The prominent landscape pressure that significant influence the regime is the Climate Accord of Dutch government. This accord forces the regime to undergo a substantial transformation towards becoming CO_2 neutral in 2050. This landscape factor has been in previous research also identified by Hellinga and van Wijk, (2021); Schutte (2021) and van Cleef, (2021). Additionally, interviewees stated that also two other landscape developments pressured the regime. These where the ongoing conflict between Ukraine and Russia and the closing of the Groningen gas field, adds further complexity to the regime's dynamics. Although these landscape developments destabilize the regime, they do not force the regime to fundamental change. The Climate Accord of the Dutch government however forces the regime to fundamental change their heating technologies.

Regime level
Due to the Climate Accord at the landscape level, the regime implemented new regulations with the aim of reducing CO_2 emissions within the built environment. The regime analysis show that the landscape factor is already forcing the regime to change because there is already an adoption of other technologies. For new construction, electric heating has emerged as the primary technology of choice due to its high efficiency. However, for existing built environments, identifying the optimal technology remains a challenge due to issues like inadequate insulation and the substantial transformation required. The Dutch government has put forth a new policy stating that starting from 2026, any replacement of a natural gas boiler must include the integration of a heat pump. Simultaneously, the growth in renewable energy generated by solar panels has led to a challenge in the electricity infrastructure due to net congestion. This challenge is already limiting companies their ability to electrify their processes and to achieve their sustainability objectives. As expectations suggest a continued rise in energy demand, the strain on the electricity grid is expected to intensify, adding further pressure on the regime to adapt and innovate within the evolving energy landscape.

The analysis further reveals that the current strategy of regime actors for addressing this issue is installing thicker cables. Moreover, the Climate Accord emphasizes a district-oriented approach, granting municipalities the authority to determine the appropriate technology and implementation timelines for each neighbourhood. This underscores the pivotal role played by municipalities in shaping the future adoption of technology within the regime.

Niche level
The niche analysis uncovers that the niche is trying to solve 2 two different challenges that emerge for the regime due to the developments in the landscape level. These challenges are the heating of the Dutch built environment without CO_2 emissions and resolving the electricity net congestion. What this analysis shows is that hydrogen is not only seen by niche actors as fuel for heating the built environment but could also as an energy carrier to resolve the issue of net congestion.

Initially, the expectation was to focus on technologies that utilize hydrogen directly for heating. Previous literature by Dodds et al. (2015) and Sun et al. (2021) describe fuel cells as a technology for creating heat and electricity. It could reduce pressure on the electricity grid but is not described as a technology for solving the electricity grid congestion challenges. However, during the interviews and after analysing the data a pattern emerged that hydrogen applications were not solely to facilitate space heating. But that hydrogen also could be used for supplying the built environment with electricity as an alternative to the existing electricity. This would remove the need to upgrade the electricity grid which is more expensive than converting the natural gas infrastructure to hydrogen. Whereas some actors in the hydrogen niche aim at solving the electrical net congestion, the players in the regime believe that the current strategy of just upgrading the electricity grid in the coming years is the best solution for them. Multiple interviewees believe that the infrastructure operators have the capability of successfully modernizing the electricity grid. This is likely why the ongoing pilots involve mainly hydrogen boilers and there is a limited focus on fuel cells.

As stated in literature review the niche actors expect that an international energy market with hydrogen will establish. Which results in the belief that hydrogen technologies are viable option for heating the Dutch built environment in the future. This vision aligns with the broader goals of sustainability and innovation, highlighting the potential for hydrogen to play a transformative role in the energy landscape. There are also regime actors involved with this development. What this study shows is that many interviewees are sceptical about the emerging of an international hydrogen economy over the coming years. They belief renewable energy remains scares in the future which means the converting of renewable energy to hydrogen will lead into too much energy lost. We should strive for as much efficiency.

From analysing the interviews, it was concluded that uncertainty regarding the establishment of an international energy market with hydrogen, made the niche and regime actors became hesitant with investing their time and resources in developing hydrogen technology. This has also been identified by Luscuere and van Wijk, (2021). The lack of participation of these actors could slow down the development of niche hydrogen technologies to become market ready. This niche analysis reflects the need for niche actors for clear indicators of hydrogen availability of the built environment, in order to stimulate further innovation and investment in hydrogen heating technologies. Also is concluded from the niche analysis that the niche is still in the experimentation phase because the niche technologies have not stabilized in small niche markets.

Barriers

In this study the top-of-mind barriers identified were shortage of hydrogen availability, price uncertainty of hydrogen, user acceptance, and labour shortage. The barriers shortage of hydrogen availability, price uncertainty of hydrogen and user acceptance were already identified in previous literature. However, this study shows that these barriers still exist which gives regime actors too much uncertainty for the adoption of hydrogen technology in the built environment.

This study delivered however a new insight by identifying a new barrier. Unlike previous academic studies, this study has identified a significant barrier: the shortage of qualified employees for infrastructure companies and municipalities. Especially the municipalities are struggling with finding qualified personnel, the Dutch government is delegating the decision-making planning and execution of the energy transition to them. This is hindering the smooth progress of the heating transition within the Dutch built environment. This study identified that labour shortage, availability and cost of green hydrogen are barriers are barriers from the landscape level and outside the influence of the regime. Whereas the user acceptance is a barrier which results from the regime.

Socio-technical scenarios

In previous literature Netbeheer Nederland (2023) formulated scenarios which stated that with the emerging of an international hydrogen economy, this will likely result in large adoption of hydrogen heating technologies in the Dutch built environment. In this study 2 socio-technical scenarios have been formulated where an international hydrogen market emerges, which result in the adoption of hydrogen technologies in the Dutch built environment. However, a crucial difference between the scenarios is the ability of the regime actors to expand the electricity grid, which could consequently shape infrastructural landscapes within the Dutch built environment. This study gives a new insight over the previous literature by showing that the development of the electricity grid could have a large impact on the development and adoption of hydrogen technology by the regime. Niche actors should look closely to this development to know if the Dutch industry and built environment could become an interesting market for fuel cells.

In the first socio-technical scenario is shown that if there is a large amount of hydrogen available and the grid congestion remains unresolved, which means large energy users will look at alternatives for their energy supply. This could result in the adoption of fuel cells which will result in new actors within the regime. In the second socio-technical scenario there is a large amount of hydrogen available, and the grid congestion is resolved which results in the adoption of hydrogen boilers with heat pumps. Incumbent firms will remain dominant in the regime. Incumbent actors will remain close to the existing technology, by using the gas infrastructure as a transportation tool for fuel. Whereas in the first scenario, new actors will look at the gas supply more as an energy carrier, which could be an alternative for electricity transportation instead of the normal electricity grid. These new actors will force a large institutional change, whereas in the scenario with resolved grid congestion, actors remain closer to their existing role.

What the scenarios also show that if actors have more security in hydrogen supply and price, they become more willing to invest money and time into hydrogen technologies. In these scenarios the Dutch government helps to overcome this uncertainty of the regime actors by stimulating hydrogen production and ability for large scale import. Once this becomes more visible and the pipelines are built, niche and regime actors gain more trust in the technology.

9.2 Implications

In this sub-chapter the practical and theoretical implications of this study are discussed. The practical implications focus on explaining why these findings are relevant. The theoretical implications reflect on the conceptualization of the three theories in this study, and how this makes an academic contribution.

9.2.1 Practical implications

The practical implications of this study are multifaceted and hold significance for regime and niche. One of the key findings of this study is that hydrogen niche is trying to resolve two issues, namely the heating of the Dutch built environment without CO_2 emissions and resolving the electricity net congestion. This is an interesting finding because in previous research was merely stated that the use of fuel cells in the built environment could be used to produce heat and electricity for the built environment and would merely reduce pressure on the electricity grid. But in this study was concluded that niche actors are this technology as a way of solving the electricity grid congestion issue in the Netherlands. A hydrogen infrastructure with fuels cells could be used as an alternative for the existing electricity grid for supplying the built environment with electricity. The first socio-technical scenario demonstrates how the fuel cell can address energy demand issues and show has this transition could take place overtime. It also showed that due to the adoption of fuel cell technology in the Dutch built environment new firms will enter the regime which will also leads to new regulation. To the knowledge of the researcher this is not done before. These findings could serve as a blueprint for companies and governments aim at understanding what events could result in the adoption of this technology. But also, how they could do to enable the development and future adoption of hydrogen applications in the Dutch built environment.

What this study also found is that there is among actors still much uncertainty about the availability of green hydrogen. Multiple interviewees are sceptical about the emerging of an international hydrogen economy over the coming years and believe that renewable energy remains a scares resource. Because of that we should strive for as much efficiency which makes electric solutions more suitable. This makes actors hesitant with investing their time and resources in developing hydrogen technology. In the formulated socio-technical scenarios in this study the Dutch government guarantees that there is a minimal amount of green hydrogen available for the built environment the actors will have more confidence in the technology. What these socio-technical scenarios show is that guarantee of green hydrogen for the Dutch built environment could stimulated the innovation into hydrogen heating applications.

In this study four top-of-mind barriers among the interviewees were identified, which were shortage of hydrogen availability, price uncertainty of hydrogen, user acceptance and labour shortage. Labour shortage was not identified in previous research and interviewees stated that due to this shortage actors we are less able to adopt new technologies. By identify this barrier an academic contribution. This study identified that labour shortage, availability and cost of green hydrogen are barriers are barriers from the landscape level and outside the influence of the regime. Whereas the user acceptance is a barrier which results from the regime. What this means is that when barriers originate from the regime, the regime actors are resistant to change and pose obstacles to the adoption of a new technology. Whereas the barrier originates from the landscape, barrier is beyond the control of actors and hinders the transition.

The direct generalizability of these scenarios to other countries may be challenging, primarily due to the distinctive natural gas infrastructure existing in the Netherlands. The well-established natural gas framework in the Netherlands could facilitate the relatively straightforward integration of these hydrogen technologies if hydrogen is in large quantities available for a reasonable price compared to other technical solutions. However, it's worth noting that the insights gained from this study could bear relevance to other European countries. The potential emergence of an international hydrogen economy could pave the way for increased availability and adoption of these technologies elsewhere. Moreover, the imperative for countries to undertake electrification measures as part of their climate change mitigation strategies is universal. Given variations in network congestion and the distinct barriers and opportunities in different regions, the direct transferability of scenarios might be limited. Nevertheless, the two identified conditions could influence the adopted heating technologies in other countries.

Ultimately, this research provides a comprehensive understanding of the complex interplay between actors, infrastructure, and policy in the transition toward hydrogen-based heating technologies for the Dutch built environment. It not only informs decision-makers in the Netherlands how they could influence the development, but also which development the niche and regime actors should keep an eye on because it could influence the potential adoption of the technology. This insight offers clarity to regime actors, allowing them to make informed decisions regarding investment, infrastructure development, and market positioning. Furthermore, the study sheds light on how government commitment to hydrogen market development can influence niche actors and, consequently, the overall development trajectory. It underscores the importance of proactive policies and incentives to foster the growth of sustainable energy solutions.

9.2.2. Theoretical implications

This study carries several substantial theoretical implications that enhance our understanding of heating transitions of the Dutch built environment, and it offers novel contributions to academic research. Firstly, the research demonstrates how the MLP, SNM and STSc can be complementary utilized, which was previously unexplored. While previous studies have employed these frameworks independently, this research showcases their complementary use. Elzen and Hofman (2010, 2007) show in their papers how MLP is utilizes for writing the STSc. In this research also the SNM was used to analyse the existing dynamics between the levels which was to the knowledge of the researcher not done before. What this study shows is that with utilizing SNM a deeper understanding about the internal development of the niche is gained, which made it possible to write a richer socio-technical scenarios in which the development in the niche is described due to the development in the landscape and regime level. Also, by conducting the SNM the writer understands which actors are missing in the niche. In socio-technical scenarios could be described how the niche formation occurs due to richer insights gained from conducting a SNM analysis.

Additionally, the study visualizes the integrated use of MLP, SNM, and STSc within the MLP framework in Figure 3. This visual representation offers a comprehensive and clear perspective on the analysis, providing a valuable tool for both researchers and practitioners in the field. This visual approach contributes to the development of innovative research methodologies and enhances the accessibility and applicability of the study's findings. To the knowledge of the researcher this visualization had not previously been undertaken.

Lastly, the study's scientific novelty emerges from its unique focus on the hydrogen niche within the Dutch built environment, employing the MLP, SNM, and STSc frameworks complementary. To the best of the researcher's knowledge, no prior investigations have delved into this specific realm, further accentuating the originality of this research. By doing so, the study transcends the conventional examination of CO_2 free heating technologies and instead explores the broader landscape and regime-level dynamics. This approach enables the discovery of deeper insights into the complex interplay between actors, technologies, and policy contexts in regional energy transitions.

9.3 Limitations and future research

While this study has provided valuable insights, it is essential to acknowledge its limitations, as they pave the way for future research and further advancements in the field. Firstly, it's important to note that none of the interviewees in this study advocated for decentralized hydrogen production and storage. During the interviews, safety and feasibility concerns were frequently raised surrounding decentralized hydrogen production and storage. However, the existence of multiple pilot projects indicates that there is still interest in decentralized hydrogen solutions. The relative low belief in decentralized hydrogen production and storage from the interviewees resulted in a one-sided view on this technology in the study. Future research could include this group of promoters of decentralized production and storage to gain deeper insights into the barriers they face. This would contribute to the development of a more comprehensive socio-technical scenario that accounts for the emergence of decentralized hydrogen technologies.

Secondly, this study did not delve into the long-term evolution of the international hydrogen economy, primarily because it focused on the development within the Netherlands, whereas the expectation is that hydrogen production would occur abroad. Nevertheless, the analysis highlighted the significance of this landscape development due to the large influence on the development of the niche. Future research could delve deeper into the dynamics of hydrogen importation in the Netherlands and examine the factors shaping this process. This would provide a more nuanced understanding of how the availability of hydrogen within the country evolves over time.

Thirdly, some interviewees expressed their expectation that various radical heating technologies will coexist in the future, developed by both new and incumbent firms. In the transition pathways formulated by Geels and Schot (2007), only the reconfiguration transition pathway expects that incumbent and new firms coexist in the regime with new and existing technologies. Future research could explore the formulation of a new transition pathway that accommodates the coexistence of incumbent and new firms developing distinct radical heating technologies. This area remains speculative, but it could be an interesting case to study when the transition has been finalized.

It is important to acknowledge that this study relies on interviews, which capture the opinions of participants at a particular moment in time. These opinions may evolve as hydrogen technology matures and greater clarity emerges regarding its availability and feasibility. To complement the qualitative research findings, future studies could incorporate quantitative methods such as surveys or data analysis of participation patterns and outcomes. This mixed-methods approach would offer a more comprehensive and robust understanding of the scope and effectiveness of equitable participation in regional energy transitions, considering evolving perspectives and circumstances. In doing so, researchers can continue to refine our understanding of the complexities and nuances surrounding heating transitions in the Dutch built environment in a rapidly changing landscape.

To ensure the credibility of the scenarios, one expert was consulted for the validation of the scenarios. In future research endeavours, the scenarios can be enriched by actively involving more experts in the discussions and integrating their perspectives, thereby constructing more comprehensive and robust scenarios.

10. Conclusion and recommendations

10.1 Conclusion

This study investigated the development of hydrogen heating technologies within the Dutch built environment and aimed to identify what future socio-technical scenarios can be expected. In this research qualitative research was conducted, which consisted out of desk research and 14 semi-structured interviews. Additionally the theoretical approaches MLP, SNM and STSc where complementary utilized. In this thesis the following research questions are being answered: "*What is the development status of the hydrogen niche for heating homes in the Dutch-built environment and which socio-technical scenarios can be expected?".* To answer this research question 4 sub-research questions have been formulated.

The first sub-research question, *"What are the landscape and regime developments of heating homes in the Dutch-built environment?"* was addressed by examining both landscape and regime levels. The landscape analysis emphasized the global concern surrounding climate change, which has manifested as the primary landscape pressure. In response, the Dutch government introduced the Climate Accord in 2019, as the starting point for large-scale changes in the regime. The Climate Accord mandates a complete phase-out of fossil fuels for heating the Dutch built environment by 2050, resulting in a significant shift from natural gas toward a sustainable alternative.

This accord has resulted in the implementation of several policies aimed at reshaping the regime. One of these policies introduced by the Dutch government is that from 2026 any replacement of a natural gas boiler must incorporate a heat pump. These policies force the regime to explore new heating technologies, as indicated by the insights from the interviewees. Additionally, the expansion of renewable energy generation through solar panels in the built environment has presented challenges for the electricity infrastructure, leading to issues of net congestion. The expectations are that the electricity demand will only increase in the built environment. The Dutch government has delegated the decision-making to the municipalities, allowing them to determine the appropriate technology and implementation timeline for each neighbourhood.

The second sub-research question *"How is the hydrogen niche for heating homes in the Dutch-built environment developing?"*. The hydrogen niche is developing technical solutions to address critical challenges of emission-free heating and alleviate stress on the electricity grid faced by the regime. This effort has given rise to innovative technical solutions, notably hydrogen boilers and fuel cells. Where fuel cells are mainly focused on solving the net congestion, hydrogen boilers are merely preventing increasing pressure on the electricity grid. The niche is marked by collaborative efforts involving government bodies, municipalities, network operators, researchers, and private companies. Pilot projects with hydrogen boilers have paved the way for real-world applications, learning from technical hurdles and user feedback. The ongoing pilots regarding hydrogen involve hydrogen boilers. Fuel cell pilots are still in the conceptual phase and expect to be implemented in 2030. But the technologies are not able stabilize in a small niche market due to still lacking hydrogen, which means the niche is still in the experimentation phase.

Nevertheless, there persists a misalignment among actors regarding the specific regime issues they aim to address. A notable bottleneck in the niche's development is the absence of comprehensive hydrogen regulation, which still requires attention. Despite these challenges, various actors, including government bodies, municipalities, network operators, and researchers, are dedicated to advancing a sustainable transition in the built environment. Actors within the niche have the expectations that hydrogen will be in large quantities available which creates potential for hydrogen use in the built environment. However, this study shows that there is also a lot of uncertainty regarding the availability of hydrogen. This makes companies reluctant to further invest recourses in the development of hydrogen applications for the built environment.

The third sub-research question *"Which barriers of the landscape and regime should the niche overcome?"*. In this study the top-of-mind barriers currently faced by the niche are the availability and cost of green hydrogen, labour shortages, and user acceptance challenges. Uncertainty surrounding hydrogen availability is seen as the biggest barrier. The labour shortage, availability and cost of green hydrogen are barriers coming from the landscape. Whereas the user acceptance a barrier is from the regime. Currently, hydrogen prices are higher than natural gas or electric, but the growing production market is expected to decrease hydrogen prices over time. User acceptance poses yet another obstacle, with public apprehension towards the energy transition and its potential financial and lifestyle impacts. An additional challenge lies in the shortage of qualified personnel, hampering infrastructure implementation efforts by key players. Municipalities, vital in driving the energy transition, struggle with complexities stemming from the Climate Accord district-oriented approach. Identifying barriers confronting the niche-to-regime transition is crucial for steering the sustainable energy shift.

The fourth sub-research question *"What socio-technical scenarios can be developed regarding the hydrogen niche and how could the transition from niche to regime take place?"*. In this study 2 socio-technical scenarios are formulated. In both scenarios a large international hydrogen economy emerges. What mainly differs between the scenarios is ability of the regime actors to resolve the electricity grid congestion. Both scenarios demonstrate a positive response from niche and regime actors to the evolving international hydrogen market. However, a key distinction lies in the regime actors' capacity to expand the electricity grid, leading to a different infrastructure landscape in the Dutch built environment. In scenario 1 a configurational transition has occurred because new and incumbent firms will coexist in the regime. Also, the institutional change remains limited in the scenario. In scenario 2 a transformation transition has occurred due to implementation of new regulations and the adoption of new technologies by the incumbent firms. These differences prompt niche actors to focus on different technologies, resulting in distinct learning processes and the emergence of unique key technologies. In scenario 1, heat pump technology converges with fuel cells, while in scenario 2, it merges with hydrogen boilers. This contrast arises from the adoption of fuel cells with heat pumps in scenario 1 and the development of hydrogen boilers and hybrid hydrogen boilers with heat pumps by incumbent firms in scenario 2. Another notable difference is that in scenario 2, incumbent firms maintain dominance, whereas in scenario 1, incumbent and new firms coexist within the regime.

The main research question was answered by answering the 4 sub-research questions. With conducting this research, a contribution is made into the understanding of hydrogen-based heating transitions in the Dutch built environment. The practical implications underscore the importance of available hydrogen and electricity grid capacity in shaping the role of hydrogen, offering guidance to decision-makers in infrastructure development and policy formulation. The insights gained from this study have broader relevance to European countries considering similar energy transitions. Moreover, the study emphasizes the critical role of government commitment and proactive policies in fostering sustainable energy solutions and mitigating climate change. The scenarios generated in this research provide valuable blueprints for addressing energy demand issues and reducing emissions, serving as a guide for companies and governments facing similar challenges.

This study makes an academic contribution by demonstrating how the MLP, SNM and STSc can be complementary used. To the researcher's knowledge previous studies have been constructed STSc by merely utilizing the MLP. The complementary use of SNM gave a deeper understanding about the dynamics within the niche, which made is possible to write richer scenarios. One of the benefits of using SNM is that it gives the research a better understanding about how landscape and regime developments influence the expectations of niche actors. Additionally, the study visualizes the integrated use of MLP, SNM, and STSc within the MLP framework. This visual representation offers a comprehensive and clear perspective on the analysis, providing a valuable tool for both researchers and practitioners in the field.

While this study has provided valuable insights into the dynamics of hydrogen-based heating transitions, it is crucial to acknowledge its limitations, which point the way for future research and advancements in the field. Future investigations could begin by addressing the limited representation of advocates for decentralized hydrogen production and storage. Further research should delve into the perspectives of promoters in this area, offering deeper insights into the barriers they face and contributing to a more holistic understanding of decentralized hydrogen technologies.

Additionally, this study did not extensively explore the long-term evolution of the global hydrogen economy. Its primary focus was on developments within the Netherlands. The hydrogen which should supply the Dutch built environment is expected to take place mainly abroad. Future research could delve further into the dynamics of hydrogen importation in the Netherlands and investigate the factors influencing this process. Such an approach would offer a more detailed perspective on how the availability of hydrogen within the country evolves over time.

Furthermore, the interviewees in this study expect that various radical heating technologies will coexist in the regime and will be developed by both new and incumbent firms. The transition pathway currently formulated by Geels and Schot (2007) does not include such a transition. Future studies could examine the creation of a new transition pathway that allows for the coexistence of established and new firms, in which both introduce distinct radical technologies in the regime. Although this area is still hypothetical, it might be an interesting case study once the transition has been completed.

10.2 Recommendations

Dutch Government:
Multiple studies have demonstrated that hydrogen holds the potential for the lowest societal cost compared to other CO_2 free heating technologies for the Dutch built environment. This should serve as a strong motivation for the Dutch government to actively stimulate the adoption of hydrogen. In this study was concluded that the uncertainty regarding hydrogen availability created hesitancy among niche actors to invest in hydrogen applications. To address the hesitancy among niche actors, the government should publicly announce its commitment of making a certain amount of hydrogen available for the built environment. This proactive approach would reduce uncertainty for niche actors and incentivize them to further invest in hydrogen applications. This would not only reduce uncertainty among niche and regime actors but also emphasize the seriousness of hydrogen as an alternative heating solution.

Furthermore, given the scenarios' suggestion that net congestion issues could be resolved with a hydrogen infrastructure and fuel cells, the Dutch government could consider exploring this avenue in future research to potentially avoid unnecessary high investment costs.

Moreover, taking inspiration from the historical role of the government in establishing the current regime with natural gas boilers, the government can play an active role in the rapid adoption of hydrogen heating technologies. This could involve creating educational programs to inform citizens about the technology and its benefits, following a strategy like the one employed during the natural gas rollout.

Municipalities:
Municipalities, who are facing labour shortages, should proactively prepare for the transition by scaling up their workforce. Regardless of the dominant heating technology, citizens will require assistance during the transition period. Additionally, municipalities should play an active role in enhancing social acceptance within their communities, recognizing that this will entail significant work. In anticipation of increased workload due to the impending heating transition, municipalities should also assess the potential cost barriers for citizens, particularly regarding installation costs. They can explore ways to support their citizens in overcoming these barriers and transitioning to new technologies.

Infrastructure:
Infrastructure actors need to recognize the potential of fuel cell technologies more actively. This study highlights the role of fuel cells in alleviating electricity grid congestion issues, which can be a significant benefit. To harness this potential, infrastructure companies should actively participate in the development of fuel cell technologies, ensuring that they align with the evolving energy landscape.

Niche Actors:
The niche actors involved in fuel cell technology development should closely monitor developments in electricity grid congestion. They should also proactively communicate to regime actors, especially the Dutch government, that fuel cells are a suitable solution that can prevent large investment costs.

Heat pumps will likely become a crucial heating technology in the future. Niche actors should recognize their significance and explore ways to integrate heat pumps with other technologies to maximize their effectiveness. This collaborative approach can enhance the versatility and effectiveness of hydrogen-based heating technologies.

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Appendix A Interview Questions

Current system [RQ1]:

1. What is your professional background and what role do you currently play within your organization?

2. Are there any specific challenges or limitations associated with the current system of heating homes?

Niche development [RQ2]:

3. Can you describe your perspective on the development of hydrogen heating in the Dutch context? How did it start and how did it grow?

4. What are the key benefits and opportunities you see for your organization to transition to hydrogen heating and how do you address them?

5. How do you think hydrogen heating can affect the affordability, reliability, and sustainability of the built environment in the long term?

6. What role do you see for different actors (government, industry, consumers, etc.) in driving the transition to hydrogen heating?

7. How do you see the role of hydrogen in heating homes and other technical solutions such as electric heating and heat networks?

Barriers and opportunities for hydrogen niche [RQ3]

8. What do you see as the biggest challenges of transitioning to hydrogen heating in your sector?

9. How do you see the risks and uncertainties associated with the development of hydrogen for heating buildings?

10. What are the main barriers you see for your organization/community to switch to hydrogen heating and how do you address them?

11. What are the key factors for developing and upscaling the hydrogen heating market and how can they be promoted? What should be more enabled/stimulated to make the transition succeed faster?

12. What do you think are the most promising policy and regulatory measures to support the introduction of hydrogen heating, and why?

Market development hydrogen (RQ4)

13. When do you think it is a suitable time to start heating the Dutch built environment with hydrogen?

14. What do you see as a likely course of the implementation of hydrogen for heating buildings in the Netherlands?

15. What impact will the government's production goals have on the transition to hydrogen for heating homes?

16. The European Commission has indicated that it wants to focus more on hydrogen and thus stimulate a hydrogen economy. To what extent could this have an impact on the technology we will apply for heating buildings in the Netherlands?

Completion of interview:
Thank you for taking the time for the interview!
I will send you a summary of all findings.

Do you have any suggestions for me regarding people or documents that might be interesting to interview or consult for this research? Both inside and outside your network?

Appendix B Informed Consent

Participation consent interview
MSc thesis Leon Verberne

You are being invited to participate in a research study titled “Space heating transition from gas to hydrogen for the built environment in the Netherlands”. This study is being done by Leon Verberne, a student from the TU Delft for your MSc thesis.

The purpose of this research study is about identifying what potential barriers are to the large adoption of hydrogen for heating houses and to get an understanding of how the transition to hydrogen heating may occur. The interview will take you approximately *60* minutes to complete. The data will be used to identify barriers experienced by stakeholders and the solutions they see to overcome these barriers. I will be asking about my view on the current transition from heating houses with gas to hydrogen. Questions I can expect are: What role would hydrogen play in the heating of households? What do you think is holding back the transition to hydrogen heating of houses in the Netherlands? How could the transition to hydrogen heating be further stimulated?

I understand that participating in this study could lead to legal (confidentiality) risk, due to unintended sharing of business practices or intellectual property. There is also a strategic risk, due to unintended sharing of valuable strategic insights of the organization which could give away a competitive advantage. Lastly, there is a reputation risk, as participating in interviews and sharing opinions and perspectives on the transition may result in negative publicity or backlash from certain people who may disagree with the viewpoints shared. To minimize these risks the findings of the interview will result in an **anonymous** summary.

As with any online activity, the risk of a breach is always possible. To the best of our ability, your answers in this study will remain confidential. The interview data (audio or video recording, transcript, and this proof of consent) will be safely stored on a Microsoft Teams account from the TU Delft and is only accessible to the researcher and the researcher's supervisor Thomas Hoppe, a professor from the TU Delft and will be deleted at the latest 2 years after the end of the study (expected around Sept. 2025).

I understand that taking part in the study also involves collecting identifiable information like my first and last name and associated personally identifiable research data like the organization or company I am associated with. Following the interview, we will produce an anonymous summary of our discussion. That **anonymous** summary will be sent to you for review and will be made publicly accessible with the MSc thesis. The summary may include quotes. You will be invited to approve the usage of those quotes.

Your participation in this study is entirely voluntary and you can withdraw at any time. You are free to omit any questions. If you do not feel comfortable using this data in this study, you can contact the researcher to ask to withdraw your interview and delete the data from your interview.

Contact information researcher:

Leon Verberne

Signatures

Name of participant [printed] Signature Date

I, as researcher, have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

Researcher name [printed] Signature Date

Study contact details for further information: Leon Verberne,

Appendix C Interview coding

Group Name	Code	Occurrence
Landscape	Landscape pressure	8
Regime	government current strategy	4
	Government policy regime	8
Expecation exogenous	Expectation decentralized hydrogen storage	5
	Expectation electric heating and network	5
	heatnetwork challenges	6
	heatnetwork expectations	3
	heatnetwork network formation	1
	electricity infrastructure challenges	16
	uncertanty market development	20
	learning process expectations	8
Expectations external	Discussion depence other countries	3
	Expectation energy avialability	1
	Expectation energy efficiency	6
	Expectation hydrogen energy efficiency	2
	expectation new construction	1
	Expectation price import	2
	expectations competition green gas	2
	uncertanty infrastructure actors	5
	Hydrogen demand heat impact industry	1
	Increasing electric infrastructure	4
	Reason to research hydrogen due to right to exist	2
	role hydrogen balancing energy system	4
	Role hydrogen within warmtenetten	6
Expectations Internal	Expectation blue hydrogen	5
	expectation hybrid warmtepomp	6
	expectation hydrogen	3
	expectation local governments	3
	expectation scenario's	2
	Expectations fuel cell	6
	Motivation to research hydrogen potential	1
	Expected regulation	4
	Benefit hydrogen flexibilty	2
	insulation argument	5
Learning process	development started recent	4
	learning infrastructure	3
	learning process challenges	6
	Learning process regulation	16
	learning process safety	3
	learning technical development	8
	Social Learning	2
Network formation	Network formation alignment	16
	network formation completeness	9
	Network formation interaction	14
	Network formation learning process	4
Barriers	Barrier cost	13
	barrier resident acceptance	3
	Barrier supply	12

	Current hydrogen demand	1
	implementation challenges labourshortage	4
	Natural gas system: performs well	2
	overcoming barriers	11
Vision	Benefit fuelcell usages heat	3
	Benefit hydrogen, security of supply	2
	Role hydrogen in international energy market	4
	Solving solar piek with hydrogen scenario	1
Scenarios	expectations implementation	12

Figure 7, coding interviews, own creation

Appendix D Overview actors participating in niche

Actor	**Activities**
National government	Developing and implementing policy and legislation for hydrogen in the built environment
	Stimulating research and development of hydrogen technologies by providing financial support to pilot projects.
Municipalities	Must determine which alternative can be applied in which district and when the transition will take place
	Supporting hydrogen pilots
Hydrogen producers	Development of hydrogen production
Energy supplier	Supplying green hydrogen to buildings for heating and electricity generation
	Researching business models and revenue models for hydrogen in the built environment
National infrastructure	Creating a national network to which regional grid operators can connect
Regional infrastructure	Adapting the gas network to enable hydrogen transport
	Collaborating with energy companies for the integration of hydrogen into the energy network
Construction companies	Construction and renovation of buildings with hydrogen infrastructure
	Testing and implementation of hydrogen-related technologies in buildings
	Training of personnel for working with hydrogen installations
Technology companies	Research and development of hydrogen technologies for application in the built environment
	Production and supply of hydrogen related equipment and systems
	Innovation and optimization of hydrogen technologies for efficiency and cost-effectiveness
Knowledge institutions	Researching the technical and economic aspects of hydrogen in the built environment

	Developing knowledge and expertise in the field of hydrogen technologies
	Collaborating with other actors for knowledge sharing and support
Users (building owners, housing corporations)	Adapting buildings for the use of hydrogen infrastructure
	Purchase of green hydrogen for heating and energy supply
	Provide feedback to other actors on the performance and usability of hydrogen systems
Financial institutions	Providing financing and investments for hydrogen projects. For example, banks offer mortgages for making homes more sustainable.

Figure 8, overview actors participating in niche, own creation.