# GREEN HYDROGEN POTENTIAL FOR THE DUTCH BUILT ENVIRONMENT

MOT 2910

Master Thesis Project

In partial fulfilment of the requirements for the degree of

MSc. Management of Technology

By:

Prakhardeep Sinha

5037387

Chair: dr. GP (Bert) van Wee

Second Supervisor: dr. JA (Jan Anne) Annema

First Supervisor: dr. M (Ming) Yang

# SUMMARY

## Context

The term “Green Hydrogen Economy” has been prevalent in the global economies in recent years. It refers to the use of green hydrogen in the future energy scenario and across various applications. Interest in hydrogen as an energy carrier has increased due to the global increase in air pollution, greenhouse gas emissions and increased energy demand. Hydrogen is a clean and versatile energy carrier that may be utilized to generate electricity and heat in a wide variety of end-use sectors. The Netherlands aspires to be a European leader in hydrogen deployment, as hydrogen is widely seen as critical to achieving the 2050 climate targets. The Netherlands has committed to launching a hydrogen program as part of its National Energy and Climate Plans (NECP) and National Strategy to meet its 2030 greenhouse gas emission reduction objectives. While generating renewable power reduces carbon emissions, it is not ideal for every application due to its intermittency.

Globally, the buildings sector consumes 30% of total energy, with approximately three-quarters of that consumed for space heating, hot water generation, and cooking. Notably, space and water heating account for a sizable portion of overall energy consumption. Residential heating accounts for roughly 12% of total energy consumption in the Netherlands, with natural gas combustion accounting for 71% of this proportion. However, growing controversy about natural gas usage makes this resource less favourable due to the earthquakes caused by natural gas extraction in the Dutch gas fields. Additionally, an all-electric energy system cannot fulfil energy demand due to capacity constraints and a mismatch between supply and demand. This sequence of events might enable green hydrogen to become an essential part of decarbonizing the Dutch built environment. Additionally, the Netherlands has a robust gas infrastructure capable of transporting green hydrogen. Thus, green hydrogen might prove helpful in ensuring both flexibility and continuity in domestic energy demand.

## Research Problem

It is challenging to replace conventional heating with low-carbon options and reduce heat demand via building improvements. Energy consumption decisions in buildings are complicated and are influenced by various variables, including building form, location, ownership, client preferences, equipment costs, energy pricing, and general convenience. Hydrogen is not appropriate for all building uses. Various variables will affect future building hydrogen demand, including existing natural gas infrastructure, energy requirements, etc. There are financial and customer acceptability hurdles, also a lack of the right policy mix for introduction and adoption, so hydrogen usage in Dutch households is scarce and restricted to small-scale demonstration projects. After introducing the Climate Accord in 2019, stakeholders like the opposition parties, housing associations and even the independent government bodies like the Netherlands Bureau for Economic Policy Analysis (CPB) have demonstrated the problems about replacing natural gas with green hydrogen. The current research on green hydrogen in the built environment focuses on making

technological electrolyzer capacity, increasing process efficiency. Even the demonstration projects are focused on testing and improving the technologies deployed to run a green hydrogen-powered house. There is a shortage of literature that discusses the economic, technological, and most importantly, societal aspects of green hydrogen use in the built environment. There are many unknowns concerning the introduction of green hydrogen in households. This complicates policymaking and may delay reaching sustainability goals. From this problem statement, the main research questions formulated are:

***Q.1 "What are the barriers and enablers for the potential use of green hydrogen as a replacement for natural gas in the Dutch built environment?"***

***Q.2 "What actions could be taken by stakeholders to realize a green hydrogen-powered built environment in the Netherlands?"***

## Research Methodology

To answer the first research question, a combination of a bibliometric approach and semi-structured interviews was used. This combination proved helpful in getting stakeholders' opinions and practical experiences concerning a complex topic like the transition to green hydrogen use. First, the Scopus database was used to get detailed information on the potential uses of hydrogen in households. Next, the research papers related to hydrogen production (Power-to-Hydrogen), storage, transportation process and related infrastructure were studied. The database was then used to look for the use-cases and demonstration projects for green hydrogen use in the Dutch built environment. Then the literature search aimed to find the barriers and enablers concerning green hydrogen production, storage, and transport in the built environment. This covered the empirical aspects of the hydrogen value chain in the built environment. Secondly, stakeholders' semi-structured interviews were conducted to better understand the barriers and enablers for hydrogen in households. A total of 10 interviews were conducted. The respondents ranged from researchers focusing on the technical aspects of the Power-to-Hydrogen process, the company professionals working on integrating renewable energy sources with hydrogen production, and a citizen from society. Next, a comparison between the data from the interviews and theory was made to come up with a final set of barriers and enablers. The barriers and enablers identified were classified under three headings, i.e., economic, technological, and social.

To answer the second research question, a transition theory was used. It was evident from the results of the first research question that the change to hydrogen-powered homes is a socio-technical transition because it affects technology, consumer behaviours, regulations, cultural meanings, infrastructures, and business models. Socio-technical transitions to sustainable solutions cannot be studied using traditional innovation sciences because they are multi-actor, long-term, goal-oriented, disruptive, disputed, and nonlinear. Therefore, these kinds of problems cannot be solved by short-term and ready-made solutions. The Multi-Level Perspective (MLP) was used to study the transition to a green hydrogen-powered built environment.

While applying MLP, the barriers and enablers found before are separated at different levels: niche innovations, socio-technical regimes, and socio-technical landscape. This would prove beneficial in finding focused solutions and methods to overcome barriers to a circular economy that can be implemented in order to facilitate socio-technical transitions, hence altering the socio-technical regimes of the Dutch built environment.

The activities at the landscape level were not studied because the changes at this level take approximately 20-30 years to happen and are therefore very difficult to identify and analyze. This research focuses on formulating the conditions that could facilitate the introduction of green hydrogen in the Dutch built environment in the near short term. Once the barriers and enablers have been segregated at different levels on the MLP, the next step was to develop suggestions to overcome the obstacles at various levels. These suggestions were also mapped on the MLP to help us understand the approximate timeline and identify the actors who could work on the suggestions following the timeline. For example, the technical barrier of an inefficient electrolysis process was placed at the niche level because it can be controlled or directly impacted by the activities at individual research firms. The segregation of barriers and enablers at different levels also proved helpful in adding a critical piece of information with them. The data is an approximate time horizon for resolving them. In this example, the inefficient electrolysis process was mapped at the niche level; this indicated that a probable estimate of time in which the barrier could be overcome is a short one (0-5 years). The recommendation made by the interviewees was to improve the efficiency of the process by carrying out research. This suggestion could now be placed on the niche level. So, now the suggestion/action has two elements of information: a possible time horizon (from the related barrier mapping) and a set of probable actors who could take action on the niche level, i.e., individual research institutions.

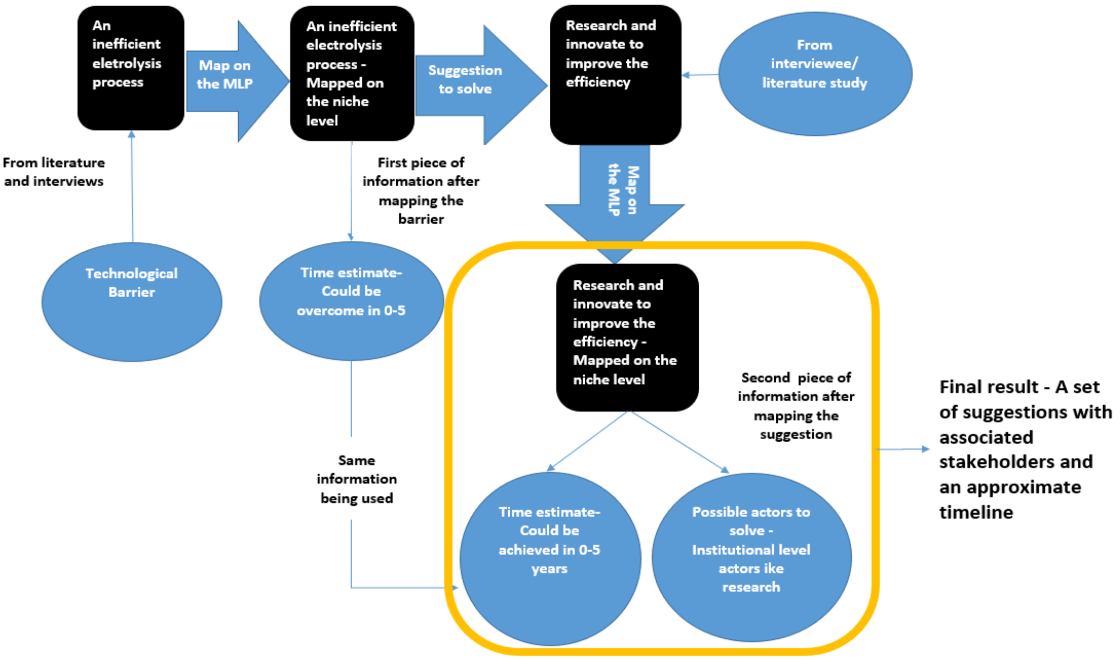


*Figure 1 Use of the Multi-Level Perspective*

## Results

A total of 20 barriers and 9 enablers were identified from literature studies and interviews. The interviewees ranked the economic barriers as needing immediate attention, followed by the social barriers and were neutral on the technological barriers. They felt that these would improve over time as the learning curves of the associated technologies improve. There was an overlap between theory and practice concerning the initial investments required (CAPEX) and operational expenses (OPEX) as the most critical economic barriers. Moving to the technological barriers, the interviewees and the researchers were concerned about the storage, transportation, distribution, and safety-related issues when using hydrogen in Dutch households. The interviewed experts and the theory considered persuading the society to use hydrogen in the households to be a challenge because of safety issues discussed in the technological barriers and the high upfront costs associated with the system installation.

The economic enablers like the government investment schemes and subsidies were mentioned by both the interviewees and in the literature study. The role of natural gas in promoting hydrogen usage in households was ambiguous as the literature considered eliminating/reducing the use of natural gas as an enabler for hydrogen penetration into society. In contrast, the interviewees regarded natural gas to be important in promoting hydrogen usage through blending. The literature study did not show any social enablers for promoting hydrogen usage in Dutch households. But the innovation and diffusion experts emphasized strengthening the knowledge networks and the motivation to have a green environment as forces that would prompt users to adopt hydrogen. In addition, the policy signals and statements from political leaders could also prove beneficial for promoting hydrogen usage in households.

In the MLP paradigm, the social barriers occurred mostly at the regime level since they would be outside the firm's immediate sphere of control. Additionally, impediments to system and process cost reduction were on the specialized niches since they may be investigated and overcome by institutions and individual actors. There were barriers and enablers which required combined efforts from actors at both regime and niche levels and were therefore placed at both levels. Barriers focused on standardization and regulations occurred at the broader regime level. The technical barriers were observed at both regime and niche levels.

## Conclusion

The goal of this study was to explore possibilities and problems associated with the transition of the Dutch built environment to green hydrogen-powered dwellings. The shift from a natural gas-powered environment to a green hydrogen-powered environment is envisioned as a transition. This transition could be possible when there is alignment between the different levels of the society (niche, regime and landscape). The barriers and enablers previously summarised and the corresponding suggestions from interviews were mapped on the three levels. This resulted in an approximate set of actions along with the required timeline and the actors who could work to overcome the barriers. The mapping of barriers and enablers according to the MLP shows a big divide between enablers and barriers. This divide has to be filled in for a smooth transition to green hydrogen. By mapping suggestions on the MLP, it was expected that we could get a clear picture on how to proceed with implementing them, i.e., taking a top-down approach or a bottom-up approach but surprisingly, the results were balanced. There is no clear indication about the suggestions that should be prioritized because of the third category of suggestions that were found during the research, which is the ones that need combined efforts from both niche and regime level players.

The uncertainties surrounding the energy transition in the built environment contributes to its complexity. Stakeholders are hesitant to support hydrogen energy applications in the built environment due to a lack of laws governing hydrogen usage in the built environment and significant gaps in the legislation impeding the transportation and manufacture of sufficient quantities of green hydrogen.

This study established is that a substantial number of stakeholders are not only at the landscape, regime, or niche level. They are active at both the landscape and regime levels, or at both the niche and regime levels, or occasionally at all levels. Both public and private actors appear to play distinct roles in growth.

## Recommendations

### For science

As a result of segregating barriers and enablers, we found that most of the barriers are present on the niche level, i.e., 70% of the total. As a next step, efforts to eradicate these barriers have also been discussed; now, investigation needs to be done to find out the processes through which niches could transition to the regime level. When the suggestion made to eradicate the barrier is implemented, the research done in the niches will result in new technologies and processes which should transition from niche to regime level to become the dominant practice, and the phenomena involved here needs to be analyzed carefully.

### For the European Union (EU)

The EU plays a significant role in facilitating the use of green hydrogen energy. The EU may provide (substantial) financial support for larger pilot projects in member states.

### For the Dutch government

37% of the suggestions made by the literature study and the interviewees are to be carried out by regime level actors, mainly the Dutch government, and 22% of the suggestions require a unified approach from the regime as well as niche level actors. This highlights the importance of the involvement of the Dutch government in making green hydrogen a part of Dutch society. The government should make amendments to the Gas Act to allow the transportation of green hydrogen gas inside the current natural gas system and establish use guidelines.

## For Local governments

Municipalities frequently place a greater emphasis on the development and implementation of energy transition programs in the built environment. It is critical to incorporate customized financial stimulation measures and to bring stakeholders together during the design process.

## For individual players

Finally, private actors (industries, consultancies, etc.) are critical in facilitating the use of green hydrogen in Dutch society. They are the primary developers of commercially viable products and are responsible for the introduction of new applications. They are identified as critical for the development of competitive new technologies in the EU's ambitious Energy 2020 strategy and the Dutch government's Energieagenda.

# TABLE OF CONTENTS

# CH.1 - INTRODUCTION

The context in which this thesis is written is explained in this chapter. The research questions have been mentioned, as well as the problem statement and research goal.

Giving everyone on the planet access to healthy and clean energy sources is undoubtedly one of humanity's most significant challenges in the twenty-first century. The use of energy has been vital to the functioning and growth of human societies throughout history. However, humankind learned to harness the highly concentrated forms of energy found within fossil fuels during the nineteenth and twentieth centuries. These provided the driving force behind the industrial revolution, resulting in an unprecedented rise in affluence and productivity for millions of people worldwide (Medved et al., 2021). As we approach the third millennium, there is an increasing recognition that the world's energy systems need to be drastically altered if they are to meet our long-term energy needs. The world's existing energy systems have been developed around the numerous benefits of fossil fuels, and we now depend on them almost entirely. The continued discovery of new reserves and the deployment of increasingly advanced exploration technologies have likely exaggerated concerns that supplies could run out in the short-to-medium term (FCHJHU, 2017).

Electricity and heat production accounts for the biggest part of industrial air pollution in the Netherlands. Most of our electricity comes from natural gas, nuclear, and other non-renewable power plants (Klimaat, 2020b). Energy production from non-renewable resources severely harms the environment, polluting our ecosystem’s elements. Using clean energy is the priority for the government, and renewable energy suits this purpose at best because of its ability to produce electricity with reduced emissions.

Variations in the climate affect the renewable energy supply; being dependent on specific weather conditions, these sources can jeopardize the consistency of an energy supply. For example, hydro generators need enough rain to fill dams to maintain the supply of flowing water. Wind turbines depend on the movement of the wind to produce energy. Clear skies and sunlight are needed for solar panels to obtain the heat required to produce electricity. Thus, it can be challenging to generate vast amounts of electricity the same way conventional fossil fuel generators do (Schnuelle et al., 2020). Wind energy is clean and green, has low running costs, and takes up little space, but a wind turbine’s capacity to produce electricity is weather dependent. As a result, predicting how much energy a wind turbine can make can be complex (FCHJHU, 2017). To solve this problem, some form of energy storage would be required, which is currently unavailable. This calls for an urgent switch to renewable energy sources linked to climate-neutral energy carriers.

Hydrogen best serves the purpose of not emitting carbon dioxide when it burns and is an excellent energy carrier. This differentiates hydrogen from conventional energy sources like petroleum and natural gas, which are at the core of most greenhouse gas emissions. The combustion of hydrogen also creates a large amount of heat that could be used for other applications. As an energy storage medium, renewable hydrogen has a lot of potential. It can ensure energy system security and meet demand when variable renewable energy, such as wind and solar power, is scarce. Appropriate energy storage approaches can assist in dealing with the intermittent nature of renewable energy sources and thus contribute to the decarbonization of a variety of verticals (IEA, 2019). One technique for producing hydrogen is through "Power-to-Hydrogen," which utilizes renewable energy sources to split water and generate hydrogen (also known as electrolysis). Electrolysis is the most ecologically benign way of generating hydrogen as a storage medium from renewable energy sources. On the other hand, Electrolysis generates just 4% of the total production; other, more cost-effective methods, such as steam reforming natural gas or refinery gas, are employed to make hydrogen (IEA, 2019). As a result, it is critical to conduct research and develop more practical and effective hydrogen usage to contribute to decarbonization.

## 1.1 Problem Statement

The Dutch government plans to reduce greenhouse gas emissions by 49% by 2030, compared to 1990 levels, and by 95% by 2050, to address climate change. The Climate Accord of 2019 established these objectives (Klimaat, 2020b). According to the Climate Accord, the target is to transition all buildings (7.7 million dwellings and one million other structures) from natural gas to a “sustainable energy source”, with “green hydrogen” playing a significant role. By 2030, 1.5 million dwellings will have been rendered ‘sustainable' in this manner as an intermediate goal.

Buildings utilize 30% of total energy globally, around three-quarters of that consumed for spatial temperature control, cooking etc. Notably, space and water heating consume a significant amount of total energy. In the Netherlands, residential heating accounts for around 12% of total energy consumption, with natural gas combustion accounting for 71% of this figure (Huang et al., 2017). However, rising disagreement over natural gas use has put this resource in a less favourable position due to the earthquakes generated by natural gas production in the Dutch gas fields. Additionally, an all-electric energy system cannot meet energy demand due to capacity limits and a supply-demand mismatch. This chain of events permits renewable hydrogen to become a critical component of the Dutch built environment's decarbonization (Momeni et al., 2021). Additionally, the Netherlands has a sophisticated hydrogen-transporting gas infrastructure. Thus, hydrogen can aid in the energy transition (through methane generation or blending) and long-term decarbonization plans for heat (via pure hydrogen production from renewables). As a result, hydrogen will contribute to the flexibility and continuity of domestic energy consumption.

With the Climate Accord, the Dutch government intended to get a clear strategy, backed by popular support, to achieve its climate goals and progressively transition the Netherlands off the gas in the following decades. However, reality will not be so straightforward. Since the draft Climate Accord was released in December 2018, the political landscape around climate policy has altered dramatically. In the same month, the natural gas costs increased. This price spike sparked a heated political discussion over the perceived high costs of climate action and how those expenses should be shared. The Central Bureau of Statistics announced in

February 2019 that average energy prices are anticipated to rise by about 20% in 2019, with half of the increase due to a tax increase connected with climate initiatives, particularly renewable energy subsidies. The Netherlands Bureau for Economic Policy Analysis (CPB), an official government agency, published an evaluation of the Climate Accord on March 13, 2019, which found that lower-income groups (particularly lower-middle-income groups) bear a higher burden of climate policy costs than higher-income groups. Welfare recipients and retirees, according to CPB, are the worst impacted. The then incumbent government promised a "fairer distribution of the burden of climate costs" in response to the findings of the CPB report and political pressure, particularly from the other political parties. In the past years, the objective of "getting rid of gas" became a hot subject in the Netherlands, with numerous enterprises, public housing corporations, and municipal governments participating. Several studies, however, surfaced at the same time, warning of the enormous expenses of disconnecting existing residences from the gas system. For example, the Dutch Economic Institute for the Building Sector (EIB) stated in a May 2018 research that turning the Netherlands' whole housing supply "energy neutral" over 25 years would save 250 PJ each year and cost €235 billion, or €36,000 per house on average. The National Association of Homeowners (Vereniging van Eigenaren, VVE) cautioned on January 19, 2019, that converting privately held homes "carbon neutral" was proving to be "too complex" and "too tough to fund." The price and complexities of disconnecting existing households from the gas grid have already raised doubts about the viability of meeting the Climate Accord's goals. Even the government agency (Netherlands Environmental Assessment Agency (PBL)) tasked to evaluate the feasibility of the strategies in the Accord concluded in its official evaluation that the measures proposed in the Accord would result in approximately 250,000 to 1,070,000 buildings becoming ‘gas-free,' which is far less than the 1.5 million target (Gasunie, 2020b).

In addition to the above evidence from society, many researchers have discussed the challenges of replacing the incumbent natural gas systems in households. The financial, social acceptability and policy-based challenges disincentivize green hydrogen use in Dutch households (IEA, 2019). The current research on green hydrogen in the built environment demonstrates technological improvements in electrolyzer capacity, increasing process efficiency. However, even the demonstration projects are focused on testing and improving the technologies deployed to run green hydrogen-powered dearth of literature that discusses the economic, technological and most importantly, the societal aspect of green hydrogen use in the built environment. Therefore, transition to a green hydrogen-powered building stock could be a difficult task to achieve. Furthermore, the driving concept of depending on hydrogen to support the country’s built environment remains somewhat unclear. This absence of understanding regarding hydrogen usage in households complicates policymaking and may delay meeting sustainability targets.

## 1.2 Research Questions

This study aims to compile results from theory and practice on the challenges and facilitators encountered in the use of hydrogen in the Dutch built environment. This study will also provide a probable set of actions for a future with hydrogen deployed in households.

For achieving the primary goal of this research, the following research questions should be answered:

***Q.1 "What are the barriers and enablers for the potential use of green hydrogen as a replacement for natural gas in the Dutch built environment?"***

***Q.2 "What actions could be taken to realize a green hydrogen-powered built environment in the Netherlands?"***

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

1. What is the role of green hydrogen in de-carbonization?
2. What could be the potential uses of green hydrogen in the Dutch built environment?
3. What technologies and processes could be used to bring green hydrogen to Dutch households?
4. Does the Dutch government have a strategic roadmap for green hydrogen deployment?

    4.1 What are the current and upcoming green hydrogen-based projects undertaken by the government?

    4.2 Are there any policies and regulations in place to foster green hydrogen adoption and deployment?

5. What are the barriers to the use of green hydrogen in the Dutch built environment?
6. What are the enablers to the use of green hydrogen in the Dutch built environment?

## 1.3 Scientific Relevance

A lack of knowledge about using green hydrogen for household purposes was indicated as the primary research gap for this thesis. The literature study led to formulating a comprehensive set of barriers and enablers for introducing hydrogen in the built environment. The interviews from experts working in the field of hydrogen, citizens and other field experts validated the literature study. Also, they added the barriers and enablers which have been prevalent in practice. The final set of barriers and enablers for introducing hydrogen in Dutch households could prove helpful for policy decision-makers in making a scientifically informed decision while considering the hydrogen introduction. Finally, the use of MLP to segregate barriers and enablers, such that they could give information about an approximate time horizon required to overcome them, was unique to this research. Another distinctive result from this research was tabulated data representing the barriers and enablers and suggestions to overcome them. These suggestions were uniquely represented according to the levels at which they should be executed, namely the economy, sector, and institutional levels. One of the main lessons that can be used from this research is that it is necessary to acknowledge the barriers and enablers related to a process/product from economic, technological, social and other perspectives. But integrating the analysis of the socio-technical landscape, regimes and niches could play a crucial role in understanding the transition process and thus increasing the chances of success. The MLP approach uniquely identifies the approximate timeline, the specific actors involved to make hydrogen-powered society a reality. Therefore, this research could be a valuable knowledge source and represents a necessary groundwork before delving deep into designing the market, technological and social structures for a green hydrogen economy.

## 1.4 Social Relevance

Large-scale projects, long planning horizons and the use of fossil fuels characterize the conventional power landscape. The new renewable energy environment is characterized by distributed power generation and smaller-scale projects with usually shorter planning horizons, allowing many countries to respond faster to growing energy demands. Smaller-scale distributed power generation projects are closely linked to regionally distributed economic value creation and job sector growth. The proposed research could help to promise the emergence of these small-scale, decentralized hydrogen use in the Dutch built environment. Citizens, local companies, and bottom-up projects for local renewable energy development have become game-changers. Stimulating citizen-assisted projects could help create a robust financial ownership base, driving the renewable energy market and bringing economic returns to society (Helgenberger, 2016).

# CH.2 – RESEARCH METHODOLOGY

It is critical to select a research strategy that is appropriate for the study. Two major elements emerge from examining the research questions. The first includes finding the barriers and enablers for green hydrogen use in the households, while the second entails analyzing the found barriers and enablers to comprehend the steps that should be taken to overcome them. There is a range of possible scenarios and visions for using hydrogen in households that may be used to assess the barriers and enablers involved, and the hydrogen penetration for each of the scenarios varies (Sekaran & Bougie, 2016). Thus, an exploratory research approach is used in this study. This method helps to investigate research issues that are not well-defined in the literature. Given the fuzziness and uncertainty associated with green hydrogen introduction and use, exploratory research is an appropriate technique. It also aids in the development of a holistic beginning point for analysis that encompasses all diverse viewpoints (Sekaran & Bougie, 2016).

The research has been organized into four parts to generate an overview and highlight the relationship between theory and practice: identification, investigation, synthesis, and formulation. The first stage is to get background information on potential uses of hydrogen in buildings and houses, methods to manufacture and transport it, and the existing government schemes to promote green hydrogen use/deployment in households. At this stage, also identify barriers and enablers from the existing literature. The second step involves conducting interviews to learn about the practical aspects of introducing hydrogen in a built environment (practical barriers and enablers). The third step is to synthesize the data from step 1 and step 2 by comparing them. The fourth step concerns using the data from step 3 and MLP to formulate the set of conditions and actions that could help in making hydrogen-powered households a reality.

The first two steps help in answering the first main research question, whereas the second main research question has been answered by using the methodologies described in steps 3 and step 4.

## Step 1 - Identification of existing knowledge

### Literature search criteria

At the start, the scope of the literature search was broad to cover a range of perspectives on hydrogen as a means for decarbonization. That is, literature from renewables and hydrogen, future energy system scenarios, green hydrogen economy were reviewed. Scopus was used as a literature database to find relevant articles. A variety of search strings were used to cover a good variety of themes in the review. The search procedure was carried out in stages. The preliminary investigation was done using a yearly report published by "The International Renewable Energy Agency" (IRENA); titled "Renewable Power -to-Hydrogen - Innovation Landscape Brief". This report helped to get a brief overview of potential uses of green hydrogen, i.e., processes involved, the economic and societal aspects etc.

The initial investigation was carried out with the following three keywords separately: "Hydrogen for the built environment" OR "Hydrogen for households" OR "Hydrogen for domestic use". In the first go for each of these, the time range set was between 2010 and 2015. The intent behind setting this range was to filter out the older articles that focused on using hydrogen in households. Putting the year limit mainly served two purposes; first, it helped investigate whether the proposition for using hydrogen existed back then. Second, the evolution of the initial idea from 2010 to the present could be done to examine if the earlier research gaps have been addressed. The search resulted in a total of 297 articles from which the pieces to be saved for further reading were filtered by setting the subject area filter to "Business, Management & Accounting" and "Energy". The criteria used to select articles out of the nine obtained was to go through the abstract and select papers that either described the use of hydrogen in households or discussed the economic potential or technical feasibility of using hydrogen in a built environment. A total of 20 relevant articles met the above search criteria. At this stage, the focus was to build knowledge about potential uses of hydrogen and therefore, the filter for the Netherlands was not activated.

In stage 2, the search was widened using the keywords from step 1. The search criteria included keywords like "Green Hydrogen in built environment "OR “Power-to-Hydrogen in built environment” OR “Power-to-X in built environment”, and the time range was set between 2016 and 2021. The search resulted in 1463 articles that had these words in their title, abstract or as keywords. To further narrow down the investigation, a subject area filter was put on, i.e., only “Energy” and “Business, Management and Accounting” were chosen. The number of articles was reduced to 444. To further reduce the number of pieces, those focusing on methods other than the electrolysis for hydrogen production were removed. In addition to that, a filter for "Country/Territory" was also applied wherein the articles from the countries belonging to the EU region were selected. Finally, a total of 15 articles were selected for the study.

In stage 3, inputs from step 2 and step 1 were used, i.e., the papers from the previous stages were used to get a thorough understanding of the hydrogen value chain. In stage 4, the Scopus database was referred to know about the barriers and enablers for using hydrogen in households. Here, the search terms: “Barriers and enablers Power-to-Hydrogen in built environment” OR “Barriers and enablers Hydrogen in households” OR “Barriers and enablers Green Hydrogen in households” OR "Challenges and facilitators Power-to-Hydrogen in built environment" OR “Challenges and facilitators Hydrogen in built environment” OR “Challenges and facilitators Green Hydrogen in built environment” OR “Barriers and enablers Green Hydrogen” were searched separately. The main inclusion criteria for papers at this stage were that the publication year should be between 2016 and 2021 and the subject area being limited to “Energy” and “Business, Management and Accounting”. Also, a "Country/Territory" filter was activated by selecting the countries belonging to the EU region. At the end of phase 4, a total of 20 articles were selected to be reviewed. The rest of the literature included was found from the references made in the articles found from the database.

Apart from the inquiries and the review, the research paper by Saccani et al. (2020) played a significant role. To begin, the study by Saccani et al. (2020) was critical since it provided a complete examination of the obstacles and enablers to green hydrogen usage in Italy. This enabled me to view the constraints and facilitators through the lens of the Netherlands, and more especially, the physical environment. The study begins with a thorough assessment of the literature on green hydrogen usage, techniques for manufacturing, storing, and transporting hydrogen. The review provides a good underpinning for this research since it considers all potential dimensions while excluding unimportant ones.

## Step 2 - Practical investigation (interviews)

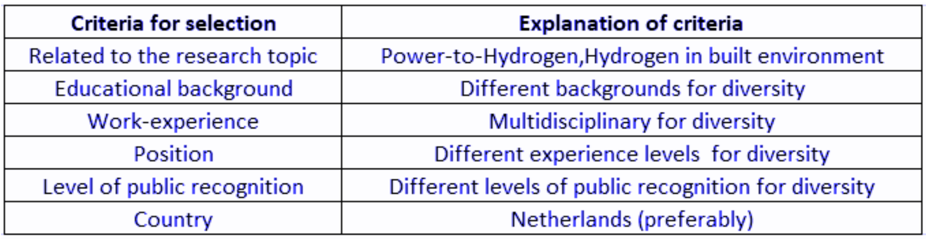
This step was done to get stakeholders' opinions and practical experiences concerning a complex topic like the transition to green hydrogen use. The semi-structured interview technique was used at this stage because it enables the development of a framework of open-ended questions to guide the discussion with participants while being unconstrained by the interviewees' answers to the questions. If an interviewee wanted to deviate from the questions posed, this was permitted. Indeed, any divergence may have resulted in the generation of data relevant to the subject that would not have been generated otherwise (Sekaran & Bougie, 2016). The semi-structured interview technique was advantageous because, although the interviewer guided the discussion, the open-ended questions more accurately represented the participants' own thinking than a closed interview, which precludes the interviewee from deviating from the particular questions addressed (Sekaran & Bougie, 2016).

The following steps for followed at this stage:

1. Research subject selection
2. Preparation and planning
3. Conduct an interview
4. Data analysis and interpretation

1. Research subject selection

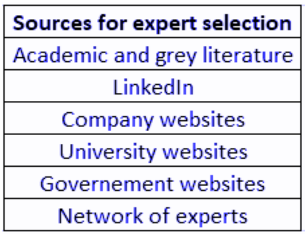
This is the starting point for the interview procedure, owing to the fact that the choice of specialists is heavily influenced by the research's major topic (Sekaran & Bougie, 2016). The use of green hydrogen as a potential replacement for natural gas in the Dutch built environment is the core focus of this study. The relevance of sampling in research is critical because if data is not obtained from people who can provide meaningful and reliable answers, the research will be flawed. The judgment sampling approach was used in this study, and it was chosen based on Sekaran & Bougie (2016) choice of sampling design. The selection of individuals in the best position to offer the information necessary is part of the judgment sampling process.



| Criteria for selection | Explanation of criteria |
|---|---|
| Related to the research topic | Power-to-Hydrogen,Hydrogen in built environment |
| Educational background | Different backgrounds for diversity |
| Work-experience | Multidisciplinary for diversity |
| Position | Different experience levels for diversity |
| Level of public recognition | Different levels of public recognition for diversity |
| Country | Netherlands (preferably) |

*Table 1 Expert selection criteria (Libakova & Sertakova, 2015)*

The experts were chosen using the aforementioned criteria (Table 1) and gathered from various sources. The experts were identified via academic and grey literature, as well as scanning the experts' LinkedIn profiles (Table 2). Furthermore, the snowballing sample method was used, which permits additional experts to be identified from the network of those already questioned who share comparable features (Sekaran & Bougie, 2016). As a result, the expert network was utilized as a significant resource for locating possible interviewees.



| Sources for expert selection |
|---|
| Academic and grey literature |
| LinkedIn |
| Company websites |
| University websites |
| Governement websites |
| Network of experts |

*Table 2 Sources for expert selection*

After the experts were identified, an invitation to participate was extended to the applicants via personal e-mail or, in the event that personal e-mail was not available, a personal message on LinkedIn. In terms of sample size, for the purposes of this study, 10 experts who are the important stakeholders for this study (Table 3) were interviewed.

| Stakeholder Category | Interviewee Reference | Role |
|---|---|---|
| Academia | A | Postdoctoral researcher : electrodes,electrolysis and other chemical processes |
| Academia | B | Masters Student : Led the team that designed a fuel to enenrgy converter device |
| Academia | C | Professsor: An avid researcher in the area of energy systems |
| Academia | D | Professsor: An avid researcher in the area of sustainability, transitions in energy |
| Society | E | Citizen from the society |
| Academia | F | Professor: A researcher in the area of innovation and complex socio-technical transition management |
| Industry | G | Professional : A compnay professional working on the combined use of renewable hydrogen and solar PV (Associated with a government project) |
| Industry | H | Professional: A company professional working on assessing the feasiblitiy of green hydrogen production on a large scale |
| Academia | I | Professor: A postdoctoral researcher working on the energy storage systems |
| Governement | J | Professional : Member of a Dutch government body working towards strengthening the National Hydrogen Programme |

*Table 3 Interviewee list with their profiles*

2. Preparation and planning

To conduct expert interviews, the researcher must be well-versed in the subject and have a clear understanding of what is being examined (Libakova & Sertakova, 2015). As a result, an extensive literature review was undertaken, allowing the researcher to get a thorough understanding of the topic under examination.

The interview questionnaire (Table 4) was an important component of the preparation for the expert interviews. Its questions were written with the following objectives in mind:

- Green Hydrogen's potential uses and major developments
- The Dutch government's policies and efforts to encourage the use of green hydrogen in the built environment.
- Identification of situations where the green hydrogen systems have been used in the built environment in the Netherlands.
- The challenges and enablers for introducing and using green hydrogen in the Dutch built environment

3. Conduct an interview

The following interview protocol (Table 4) was followed.

| **Phase** | **Things to remember** | **Content** |
|---|---|---|
| Introduction and disclaimer | To inform the interviewee about the context of the interview and his/her rights with regard to the same. | Interviewee is provided with an introduction to the goal of the study, the approximate duration of the interview and he/she is informed about his/her rights during the interview, mainly related to recording, data use, anonymity etc. |
| Interviewee introduction | To get to know the background of the interviewee | Could you please give us a short introduction of yourself, including your role in the company/organization? |
| Questions | To gauge the knowledge and potential uses of green hydrogen | We are here today to talk about the use of green hydrogen and its use. Could you please explain to us what your current understanding is about the potential of green hydrogen for the Netherlands? |

| | | |
|---|---|---|
| | To gauge the knowledge and potential uses of green hydrogen in a built environment | How beneficial could be the introduction of green hydrogen in the Dutch built environment? |
| | Try to get an answer in a serialized manner starting from production, storage, transmission and distribution. Do note if he/she talks about any problems with a technology or process in between. | What is your view on the current technologies/processes to make green hydrogen a reality in the built environment? |
| | To get knowledge on the government schemes and projects. Do ask at the end to say something about a particular project being carried out by an organization he/she is attached to. | Do you know about the efforts in terms of schemes or pilots being made by the Dutch government to promote the use of green hydrogen? |
| Questions | Inform the interviewee that he/she could describe the barriers in categories if he/she finds it comfortable and could tell the category name himself/herself.<br>Also, before talking about barriers, do talk about the Multi-Level Perspective with its levels and examples so that he/she could help in categorizing the barrier easily.<br>Suppose the interviewee forgets to suggest a solution for a particular barrier he/she discussed previously. Politely prompt him/her to say something about it. | What do you think are the most common category of barriers you know of / your organization is facing when you think of / have tried to introduce green hydrogen in a built environment? |
| | | It would be great if we could discuss in detail specific barrier categories. |
| | | It would be great if you could provide some examples when discussing the barrier. |
| | | Explain the transition concept and the Multi-Level Perspective with the three levels and examples for each. |
| | | For each of the barriers discussed, just ask at what level they think the barrier should be put at. |
| | | For each of the barriers discussed, what solutions or actions is your organization/you think could help in overcoming the barrier(s)? Please be as specific as possible about these solutions or actions. |
| | | Same set of questions repeat for enablers. |

| | | |
|---|---|---|
| | Do try to know an approximate timeline in which he/she feels the transition could happen | Could you shed some light on the green hydrogen's potential to replace natural gas in the built environment? |
| Closing | Inform the interviewee about the data usage policy, ask for permission to use the data, ask if he/she would be comfortable to approve the minutes of the meeting and also about the use of specific comments for the thesis. | Closing remarks on the future of green hydrogen in Dutch society and informing on the post-interview details. |

| |
|---|
| Importance of using renewable energy resources in the society |
| Role of green hydrogen in the built environment |
| View on natural gas and green hydrogen |
| Green hydrogen value chains and processes |
| Barriers to using green hydrogen in the built environment |
| Suggestions to overcome the barriers |
| Discussion on the Multi-Level Perspective |
| Enablers to use of green hydrogen in the built environment |
| Role of stakeholders in promoting green hydrogen use |
| Future of “Green Hydrogen Economy” in the Netherlands |

*Table 4 Interview protocol and themes*

### 4. Data analysis and interpretation

In this step, for each of the recordings of the interviews in step 3, minutes were made. These minutes are then sent to the interviewees for approval and consent to use in the research. The minutes are designed in such a way that the interviewees’ comments for each of the topics discussed are segregated according to a set of themes pre-defined for interviews and their data analysis (Table 4). Now, for each of the major topics segregated, the interviewees' comments are analyzed to get an idea of what has been the most prominent solution or suggestion for that topic and if a new suggestion could be found for that topic. In addition to that, it is imperative to keep analyzing the relative rankings provided by the interviewees for the set of barriers and enablers too. According to Sekaran & Bougie (2016), categorizing the expert’s answers facilitates the analysis, and therefore the barriers and enablers have been divided into categories: economic, technological, and social.

## Step 3 - Synthesize data from literature and interviews

A comparison was performed using the barriers and enablers acquired in step 1 and the input from practice gathered in step 2. The comparison of theory with practice aids in the creation of a final summary of both perspectives' findings.

A quick rundown of the most prevalent roadblocks and the most effective enablers (on the categorical level) was done. The interviewees were asked to rank the barriers and facilitators on a category level so that the most prominent barriers and effective enablers could be identified. An overview of the barriers and enablers discovered in theory and practice using the information from Steps 1 and 2 was created (Section -5.4 Comparing enablers and barriers (literature vs interviews)). This was done to make a final overview of barriers and enablers so as to facilitate the next stage.

## Step 4 - Formulation of an action plan

At this stage, the aim is to come up with an approximate action plan to overcome the barriers and enablers found in stage 3. This step gives the core results for the main research question 2, which focuses on the actions to be taken by stakeholders. This step started with a literature study to find theories that could be used to explain the transition to a green, hydrogen-powered built environment.

## Literature Search (Theoretical Framework)

The Scopus database was used to look for frameworks to study sustainability transitions. The search terms initially were (“Sustainability framework” AND “Transition framework”) AND (“Energy transition framework” OR “Green Hydrogen transition”). This resulted in a total of 150 articles. To be included for further study, the filtering condition was that the article covered both sustainability transition and considered an energy system. These criteria helped to filter out 50 articles. The abstracts for these 50 were studied to finally arrive at 8 articles that were deemed useful in getting information on the variety and comparison of the frameworks.

The systematic review's findings indicate that research on energy sustainability transitions mainly employed five frameworks. The most used transition framework is the MLP, followed by transition management (TM), social practice approach (SPA), strategic niche management (SNM), and innovation systems (IS). Many articles incorporated elements of many frameworks. Crivits and Paredis (2013), for example, utilized MLP and SPA.

Indeed, Markard et al. (2012) demonstrated that TM is the most often used transition framework in the field of sustainability transitions. In their analysis, the authors made no mention of SPA. The examination of the trend in the use of transition frameworks in energy sustainability research indicated that SPA usage is relatively recent. Meanwhile, SNM was one of the common frameworks to be utilized in energy transitions for sustainability research, although it remained marginal in the area (Bilali, 2017). Similarly, the methodology of IS is not used much from an energy transition perspective.

The interplay between niches, regimes, and landscapes influences the sustainability transitions in MLP (Loorbach & Rotmans, 2006). In general, articles that employ MLP focus on the dialectic relationships between developing niches and established regimes and how these interactions affect the transition to sustainability.

There were three articles that proved to be very helpful in deciding the framework to be used. The first one is from Lachman (2013); this article covered all the 5 frameworks, their advantages, critiques and comments on use-cases for the frameworks. The second article is by Markard et al. (2012), who tracks the emergence of the transitions field from the 2000s. Both the articles were helpful in narrowing down to MLP. Lachman (2013) discussed how MLP is an effective instrument for doing stakeholder analysis. Specifically, the MLP distinguishes between the regime and niche actors, who may be perceived to behave differently and give unique viewpoints on unsustainable social issues (although this difference is not absolute since regime actors may support niche projects). According to Markard et al. (2012), MLP focuses on the inclusion of niche players in a research project or policy process, thereby guaranteeing that alternatives to the status quo are addressed during analysis and decision-making. According to Lachman (2013), stakeholder-based action research utilizing the MLP eventually attempts to reclassify actors; by strengthening niche players and including them in decision-making processes, they may reorganize regime membership, resources, and power lines. Thus, the MLP assists academics by focusing on the entire system and including 'outsider' and radical viewpoints in order to generate suggestions for politicians, industry, and other players interested in bringing about societal change (Lachman, 2013). MLP research, with its multidisciplinary, long-term, and systemic approach, appears to be more capable of identifying these unintended consequences and feedback than many traditional innovation analyses, as well as emphasizing the diversity of processes and actors involved in social change (Markard et al., 2012). The third article is one written by Loorbach (2007). This article contributed to the development of logic for assessing future energy systems from a transition theory perspective. This story presented an in-depth examination of transition theory, namely the MLP, as well as a number of case studies from past Dutch transitions. Utilizing these examples aided inefficient use of the methodology for analyzing obstacles and enablers attached to a process/product and coming up with a set of actions to bring clean energy sources like hydrogen into society.

## The Multi-Level Perspective

Phasing out the natural gas with green hydrogen for households is difficult since decision-making and policy-making in this shift are anything from straightforward, as players, technology, and institutions interact in complicated ways (Kocsis & Hof, 2016). The heating transition needs a shift in the supply of renewable energy, infrastructure, domestic heating systems, and residential thermal insulation, all of which pose concerns regarding cost allocation and consumer choice (Londo et al., 2020). Along with these repercussions, the heating shift presents major financial difficulties. Natural gas is now more affordable than sustainable alternatives, and households may not always have the finances necessary to make necessary investments or to cover higher living expenditures (Nicita et al., 2020). This shift entails a lot of questions like which type of heating would result in the lowest end-user prices, the lowest societal expenditures, and the lowest emissions? To assess the effect and influence of prospective policy measures or choices for natural gas-free heating in city districts, evidence-based policymaking needs to be done.

Sustainable innovations such as hydrogen applications for the built environment may be considered innovative niche developments; niches are new developments in the socio-technical system that are expected to encounter a number of practical and institutional challenges (Rotmans et al., 2001). The primary reason for this is the fundamental and permanent modifications necessary in the energy supply infrastructure, both physically and institutionally, to enable green hydrogen energy use in the built environment. Such changes imply the occurrence of a transition. Additionally, ongoing processes such as growing societal demand for a shift away from fossil fuels and toward more affordable renewable energy production indicate that this transition is already underway: niche developments are attempting to infiltrate the built environment's current energy supply regime. Transition theory is therefore chosen to study such irreversible systemic shifts (Geels, 2002).

Transitions are defined as "processes through which society undergoes substantial change over the course of a generation or more" (Rotmans et al., 2001). Transitions denote a change from an initial dynamic equilibrium to a new dynamic equilibrium and are applicable to complex social systems such as the energy system for the built environment (Rip & Kemp, 1998). The transition under consideration in this study is from the existing (natural gas-based) energy system for the built environment to a sustainable, green hydrogen-based energy system for the built environment. Inducing, evaluating, and even guiding a transition is not a simple activity or process, owing to the non-linear changes inherent in a transition (Rotmans et al., 2001).

The transition to a sustainable green hydrogen-powered energy system for the built environment can be viewed as a systemic transformation of society's sociotechnical system. Multiple levels exist within the socio-technical system at which change can be generated. To analyze these changes at many scale levels, MLP is utilized. This viewpoint differentiates three analytical levels (Geels & Schot, 2007): niches, socio-technical regimes, and the socio-technical landscape.

a. Niche - This is where radical innovation occurs; the innovations are developed, tested, and disseminated. These are similar to 'incubation chambers' protected from market influences. These enable inquiry and experiential learning. Novelty can take the form of new technology, new laws and legislation, new organizations, or even new initiatives, thoughts, or ideas.

b. Socio-technical regime - The term regime refers to the prevailing culture, structure, and practice manifested in physical and immaterial infrastructures (such as roads and electricity grids, but also routines, actor networks, power relationships, and laws). These institutionalized frameworks provide stability to a social system and govern actors' decision-making and individual conduct. At the same time, the regime has a degree of rigidity that often precludes innovations from substantially changing the structure.

c. Socio-technical landscape -This refers to the broader societal context in which change occurs. Social values, political cultures, the environment, economic progress, and trends comprise the landscape. While the landscape level generally evolves independently, it has a direct effect on the regime and niche levels by defining the space and direction for development.

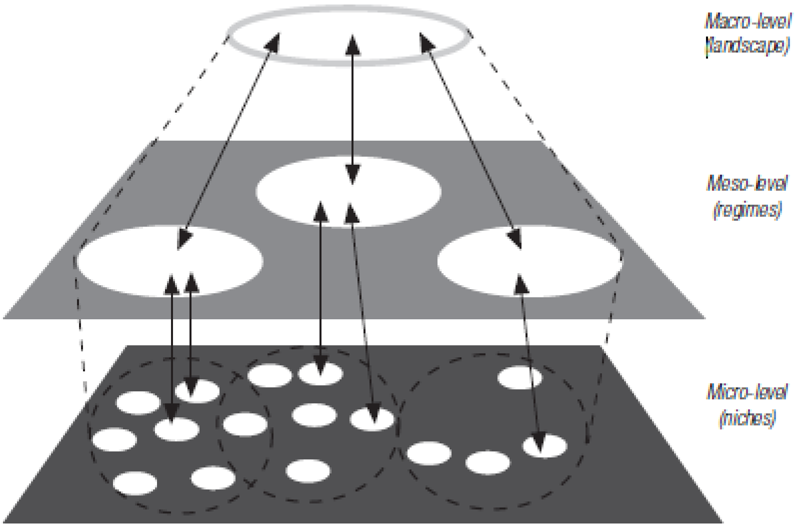


*Figure 2 The Multi-Level Perspective (Rotmans et al., 2001)*

Analyzing this perspective elucidates the levels and types of stakeholders involved in a transition to green hydrogen energy applications as a method of achieving the energy transition in the built environment.

Following from the theoretical conception, it is critical to identify barriers and their placing in the MLP in order to ascertain whether they occur at the niche or regime level. Once the barriers and enablers are identified and mapped to MLP, specific solutions and methods to overcome barriers to green hydrogen use can be discussed in order to facilitate socio-technical transitions, altering the socio-technical regimes of the Dutch built environment. The following logic underpins the use of the aforementioned steps:

1. Because barriers to green hydrogen usage are uniquely present at different levels of the MLP-framework (figure 2), they may be resolved by targeted action by the appropriate actors operating at the same level as the detected barrier.

2. Addressing obstacles to green hydrogen usage at the appropriate level of the MLP (regime/niche) can speed the transition to sustainable building stock.

The overview of barriers and enablers created at step 3 would be mapped on the levels according to the MLP. The mapping of a particular barrier/enabler to a level would be based on the following rule: whether they could be directly influenced by the firms (niche level) or whether they happened at a more substantial sector level outside the firm's sphere of control (regime level). The socio-technical landscape does not change easily in the short term and takes around 15-30 years to transform (Rotmans & Loorbach, 2009). Therefore, for this research, the mapping of barriers would be limited to niche and regime levels so that they could be overcome in the short term.

For instance, the technological barrier associated with lack of maintenance and repair networks was placed at the regime level since it cannot be managed or influenced directly by the actions of a particular research institution. Rather it requires an intervention from the Dutch government and other regime level actors like municipalities to overcome the barrier. Separating barriers and enablers at various levels added a key piece of information to the concerned barrier. The information is a rough time frame for resolving the concerned barrier. Continuing from the previous example, the lack of maintenance and repair networks was mapped at the regime level, indicating that approximately a period of 10-15 years might be required to overcome the barrier.

After segregating barriers and enablers at various levels on the MLP, the next stage was to generate ideas for overcoming the hurdles at various levels. Additionally, these recommendations were mapped on the MLP to assist us in comprehending the approximate timeline and identifying players who may work on the suggestions in the future (Section - 6.2 Mapping the suggestions on Multi-Level Perspective). Continuing with the previous example of lack of maintenance and repair networks, the respondents recommended establishing extensive maintenance and repair networks across the country. This recommendation can now be mapped to a specialized level. Thus, the suggestion/action now has two pieces of information: a possible time horizon (derived from the associated barrier mapping) and a list of possible players, i.e., the Dutch government, municipalities, private and public industry consortiums etc.

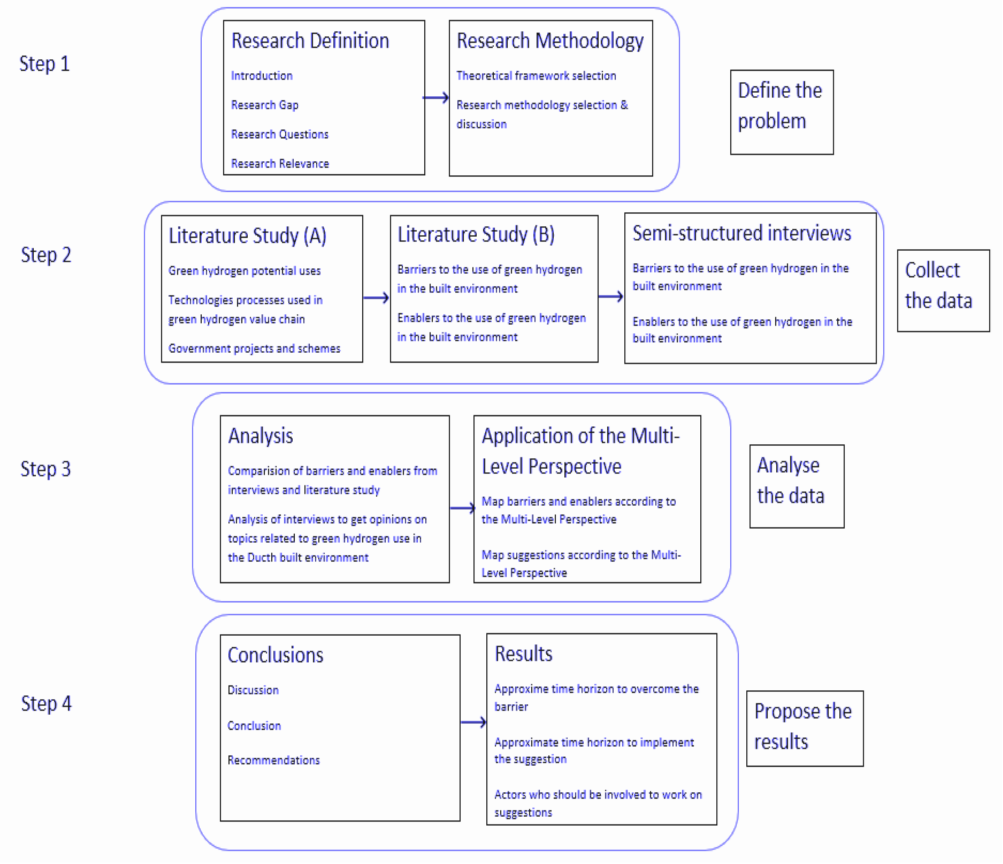


*Figure 3 Research Flow*

# Limitations of the research

- The idea of using green hydrogen is broad, and it is difficult to include everything owing to time limitations in the study. As a result, the classifications are restricted to economic, technological, and social categories. Extensive discussion of technology, for instance, is omitted but should be included in future studies. The fast-growing body of literature has a major impact on the results presented in this study and should be considered by the reader.

- The number of businesses devoted exclusively to the use of electrolysis in the Dutch built environment is few. This restricts the interviewees' capacity to offer vast and varied input for the study, which has ramifications for the research process and result. The study methodology is based on a review of the literature and conversation with specialists. A bias may arise as a result of the expert being associated with a particular component of the green hydrogen value chain and therefore giving priority to relevant barriers and enablers during discussion.

- The transformation of the Dutch built environment to a green hydrogen economy is not only the responsibility of commercial actors and the government; society, as well as the environment and context in which the change must occur, play a significant role. This subject should thus be carefully studied, taking into account all relevant stakeholders. The viewpoint of members of society and examination of the context/environment are restricted in this study. As a result, the list of identified barriers and enablers in the transition to a green hydrogen society might be incomplete. The interview technique employed is incapable of quantifying answers; only comparisons are available. Owing to the narrative nature of qualitative research, the findings cannot be completely reproduced due to the inclusion of human views.

- Due to the present pandemic situation and rules, interviews were done online. This could impact the quality of research in two ways: First, only a limited number of interviews (10) could be taken in the limited timeframe, though a large pool of experts was contacted, the online setting restricted the response from individuals. Secondly, participating in an online interview requires quite a high level of motivation and concentration. The same is true for the interviewers who have to ask all their questions under considerable time pressure.

## Research Ethics

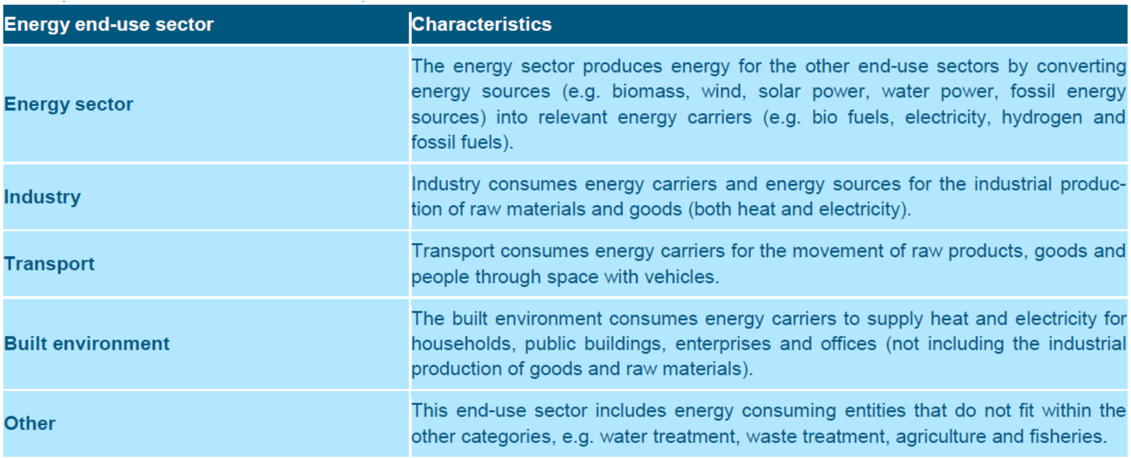
Semi-structured interviews were used to conduct the expert consultation. Interaction between the interviewer and the participants is essential to exchange knowledge and information. The researcher has a variety of tasks because of this. First and foremost, the respondents' mental and physical safety was maintained for the purposes of this study. Furthermore, specific rules were followed during the data collection and analysis procedure. Specifically, the aim of the interview was clarified at the start of the process, and space was left open in case more information or clarifications were required. Permission to record the interview and use excerpts from the transcripts was also requested. Furthermore, for concerns of privacy, the names of the participants were not revealed (Sekaran & Bougie, 2016).

# CH.3 – LITERATURE STUDY

This section starts with providing information on the role of hydrogen in the de-carbonization of the economy. Followed by that, it narrows the focus on the potential uses of hydrogen in the Dutch built environment. The processes concerning the production, storage, transmission, and distribution of hydrogen in the households are discussed. Next, the Dutch hydrogen landscape is discussed to get to know the stakeholders associated with the hydrogen value chain and the government projects, policies and regulations for using hydrogen have been described.

## 3.1 Green hydrogen and its use

Green hydrogen energy applications are contingent upon the features of energy supply and demand patterns in the built environment in the Netherlands. The built environment is one of the so-called end-use sectors of the energy supply system (Figure 4). The built environment consumes energy to meet three primary energy demands: space heating, tap water heating, and electricity generation.



| Energy end-use sector | Characteristics |
|---|---|
| **Energy sector** | The energy sector produces energy for the other end-use sectors by converting energy sources (e.g. biomass, wind, solar power, water power, fossil energy sources) into relevant energy carriers (e.g. bio fuels, electricity, hydrogen and fossil fuels). |
| **Industry** | Industry consumes energy carriers and energy sources for the industrial production of raw materials and goods (both heat and electricity). |
| **Transport** | Transport consumes energy carriers for the movement of raw products, goods and people through space with vehicles. |
| **Built environment** | The built environment consumes energy carriers to supply heat and electricity for households, public buildings, enterprises and offices (not including the industrial production of goods and raw materials). |
| **Other** | This end-use sector includes energy consuming entities that do not fit within the other categories, e.g. water treatment, waste treatment, agriculture and fisheries. |

*Figure 4 Energy-end use by sectors (Netherlands) (IEA, 2019)*

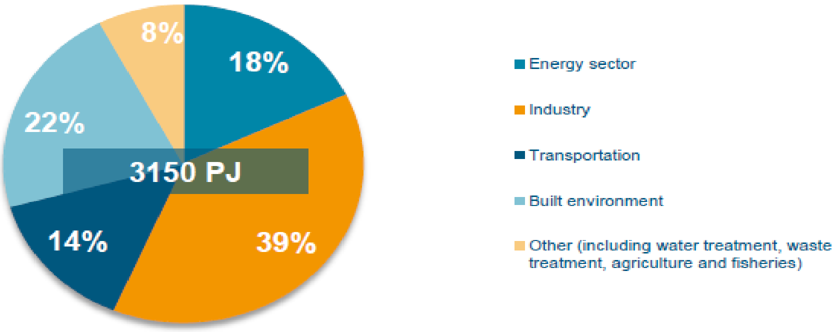


*Figure 5 Distribution of energy end-use by sector (IEA, 2019)*

## 3.2 Intermittency in the built environment

When compared to other end-use industries, the built environment's energy consumption demands are significantly more volatile on a daily and seasonal basis. Households, public buildings, businesses, and workplaces often heat their facilities only when the weather is cold (during the winter), and electronic equipment such as lamps, televisions, and kitchen appliances are typically turned off at night. Figure 6 shows this by showing the variation in energy usage in a typical neighbourhood in the Netherlands over the course of 2017. Due to the fact that the existing energy supply system is built on the controlled burning of fossil fuels, the energy sector can accommodate these fluctuations in energy demand by simply utilizing more or fewer energy carriers. However, most sustainable energy sources, particularly wind and solar, are susceptible to daily and seasonal supply fluctuations. This creates an intermittency issue; it is quite possible that while energy demand is high, supply is low, and vice versa.

The preceding facts suggest that significant system integration is required; such a system must be capable of converting heat to electricity and vice versa in order to enhance the network's adaptive capacity and, therefore, the security of energy supply (Smale et al., 2017).

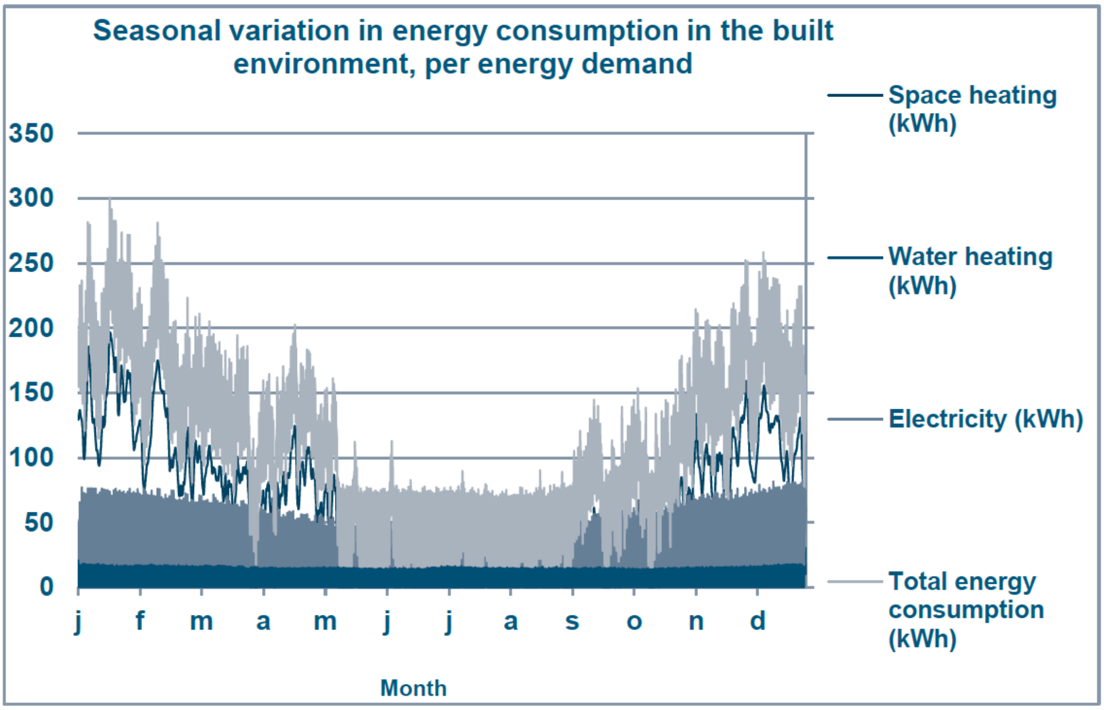


*Figure 6 Variation in the consumption-pattern (built environment) (IEA, 2019)*

## 3.3 Hydrogen production

As discussed in the previous sub-section, depending upon the energy source used, the hydrogen produced may vary. Currently, the blue hydrogen generated using steam methane reforming dominates the Dutch market. But there is a need to shift to green hydrogen that is created by electrolyzing water to produce hydrogen and oxygen. With the cost of renewable energy sources like wind and solar energy declining, the use of these to produce green hydrogen has been growing.

Hydrogen may be collected from fossil fuels and biomass, as well as from water (Figure 7). Today, about 275 million tonnes (Mt) of energy is used in the manufacture of hydrogen (2% of the world's total primary energy consumption). Natural gas is being used for producing (3/4) th of the total hydrogen production, followed by coal and respectively (Farchmin, 2016).

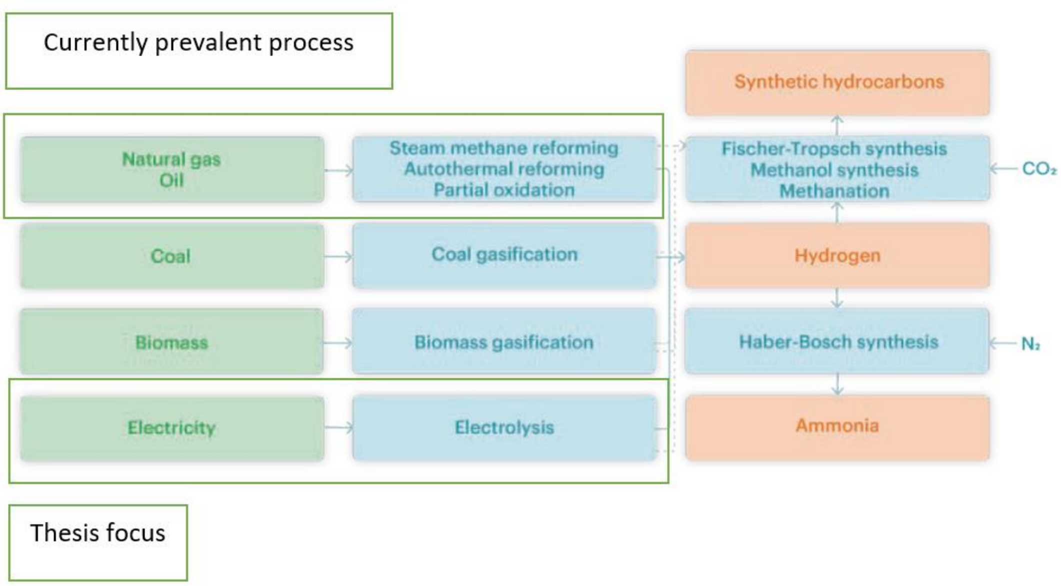
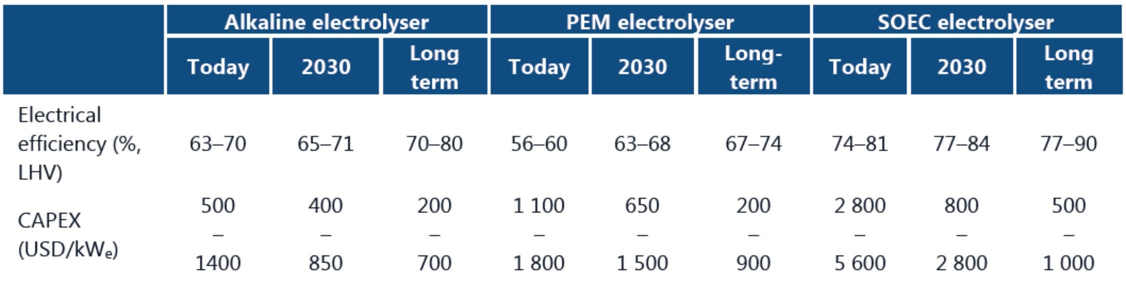


*Figure 7 Hydrogen production pathways (FCHJHU, 2017)*

Water electrolysis is a chemical reaction in which water is divided into hydrogen and oxygen. Today, a very diminutive amount (about 0.1%) of green hydrogen is produced through the clean way (IEA, 2019).

The figure below showcases the capital expenditure (CAPEX) and efficiencies for the electrolysis process and depicts the future scope associated with the use of PEM electrolyzers for hydrogen production.



| | Alkaline electrolyser | | | PEM electrolyser | | | SOEC electrolyser | | |
|---|---|---|---|---|---|---|---|---|---|
| | Today | 2030 | Long term | Today | 2030 | Long-term | Today | 2030 | Long term |
| Electrical efficiency (%, LHV) | 63–70 | 65–71 | 70–80 | 56–60 | 63–68 | 67–74 | 74–81 | 77–84 | 77–90 |
| CAPEX (USD/kW$_e$) | 500 – 1400 | 400 – 850 | 200 – 700 | 1 100 – 1 800 | 650 – 1 500 | 200 – 900 | 2 800 – 5 600 | 800 – 2 800 | 500 – 1 000 |

*Figure 8 Comparison of electrolysers (FCHJHU, 2017)*

## 3.4 Green hydrogen value chain

Green hydrogen provides flexibility due to its ability to store huge amounts of energy for extended periods of time. This calls for developing necessary transmission and distribution infrastructure. Presently, the common ways to store hydrogen is in a compressed state (gas) or in a liquid state. The most common transportation options used now are trucks and pipelines, and the most being used at the site of production (Medved et al., 2021). The competitiveness of various alternatives will be determined by the distance over which hydrogen is carried, as well as the size and ultimate usage of the hydrogen.

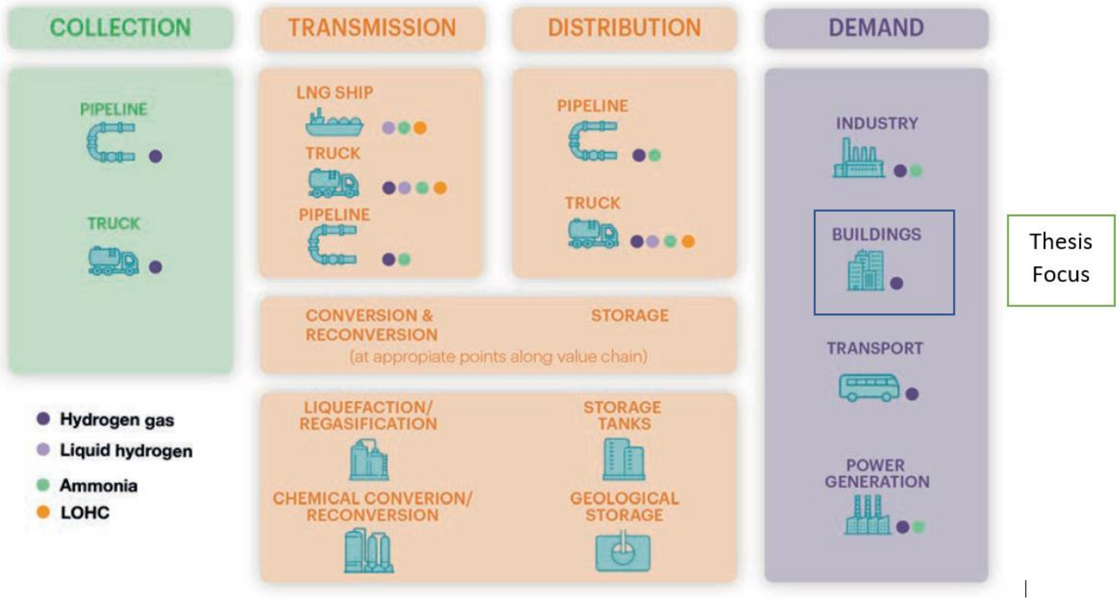


*Figure 9 Hydrogen storage, distribution & transmission (FCHJHU, 2017)*

*LOHC -Liquid Organic Hydrogen Carriers

## 3.5 Dutch transmission, distribution and storage network

The Netherlands has a substantial gas infrastructure, with around over 250 onshore and offshore production sites, 135,532 kilometres of pipelines, and connections to over 90% of homes, the majority of commercial premises, many industrial sites, and gas-fired power plants. The Dutch gas system is rather unusual in that it includes distinct networks for low calorific gas (L-gas) and high calorific gas (H-gas). Each of the networks for L-gas and H-gas has its own supply sources, pipelines, storage facilities, and related equipment. Four blending facilities in the Dutch gas system utilize nitrogen to convert the high calorific output to a low calorific one, allowing the high calorific network to provide low calorific gas. In the Netherlands, industrial customers and gas-fired power plants mainly utilize high calorific output, but there is significant industrial demand for low calorific gas also (Klimaat, 2020b).

### 3.5.1 Transmission

In the Netherlands, almost all residential and business customers are linked to the low calorific gas network. Gasunie Transport Services operates a high-pressure network and a medium-pressure network (Klimaat, 2020b).

### 3.5.2 Distribution

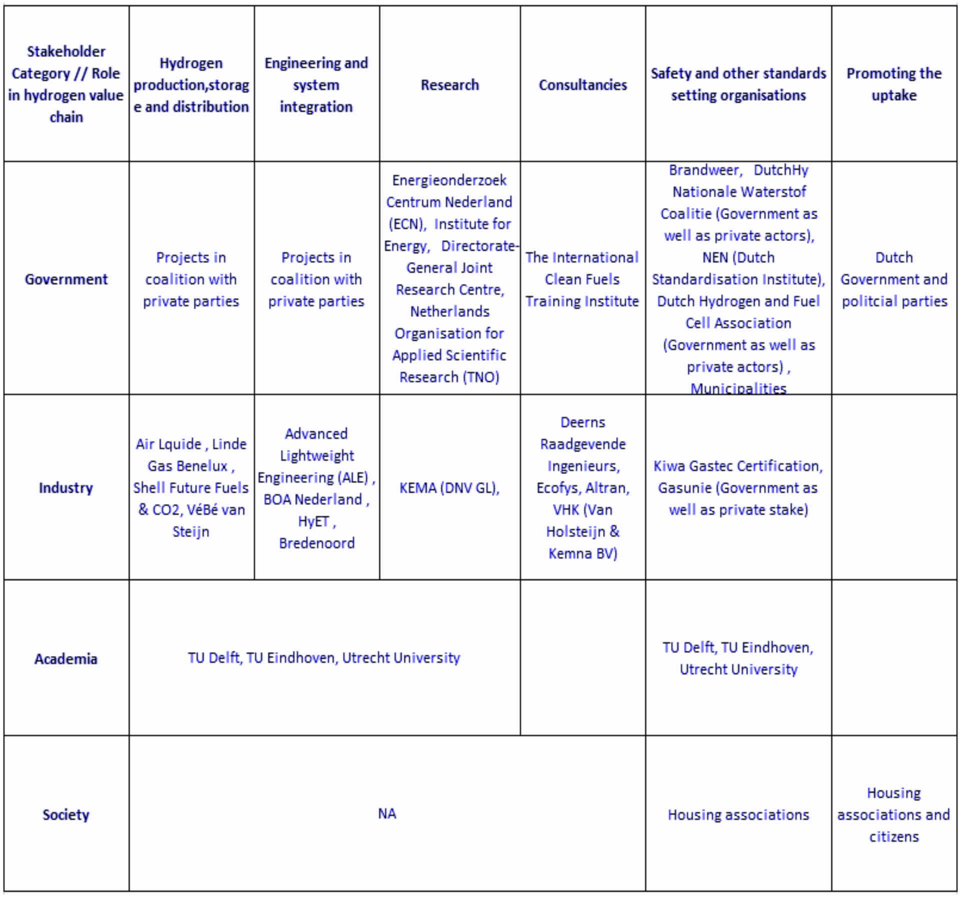
Around 100,000 kilometres of pipes link the low-pressure gas distribution network to millions of customers. The low-pressure network is largely used to carry low calorific gas and is primarily used for residential, commercial, and agricultural (greenhouse) heating. Eight distribution system operators (DSO) manage and maintain the distribution network, all of which are controlled by regional and municipal governments (Klimaat, 2020b).

### 3.5.3 Storage

The Netherlands has significant gas storage, which is utilized to accommodate seasonal demand fluctuations (particularly in connection with increasing winter heating needs) and run the trading operations along with ensuring regional security. The Netherlands has 5 underground natural gas storage facilities with a total capacity of 14 billion cubic meters. Four facilities are depleted gas fields that are used to meet seasonal and short-term demand spikes. One of the facilities is a salt cavern that is utilized to handle only short-term surges. Apart from gas storage in the Netherlands, the transmission system has an extra 6.1 billion cubic meters of storage capacity in German salt caverns. With the decision not to continue the production from Groningen, storage sites will be an important aspect in ensuring supply security (Klimaat, 2020b).

## 3.6 Green hydrogen ecosystem (Netherlands)

The stakeholders for the Dutch green hydrogen ecosystem have been done based on their expertise and function. This was done to make the selection of interviewees quite diverse based on their expertise in the hydrogen value chain:



| Stakeholder Category // Role in hydrogen value chain | Hydrogen production,storage and distribution | Engineering and system integration | Research | Consultancies | Safety and other standards setting organisations | Promoting the uptake |
|---|---|---|---|---|---|---|
| **Government** | Projects in coalition with private parties | Projects in coalition with private parties | Energieonderzoek Centrum Nederland (ECN), Institute for Energy, Directorate-General Joint Research Centre, Netherlands Organisation for Applied Scientific Research (TNO) | The International Clean Fuels Training Institute | Brandweer, DutchHy Nationale Waterstof Coalitie (Government as well as private actors), NEN (Dutch Standardisation Institute), Dutch Hydrogen and Fuel Cell Association (Government as well as private actors) , Municipalities | Dutch Government and politcial parties |
| **Industry** | Air Lquide , Linde Gas Benelux , Shell Future Fuels & CO2, VéBé van Steijn | Advanced Lightweight Engineering (ALE) , BOA Nederland , HyET , Bredenoord | KEMA (DNV GL), | Deerns Raadgevende Ingenieurs, Ecofys, Altran, VHK (Van Holsteijn & Kemna BV) | Kiwa Gastec Certification, Gasunie (Government as well as private stake) | |
| **Academia** | TU Delft, TU Eindhoven, Utrecht University | | | | TU Delft, TU Eindhoven, Utrecht University | |
| **Society** | NA | | | | Housing associations | Housing associations and citizens |

Table 5 Stakeholders in the system

## 3.7 Dutch landscape (Hydrogen)

In a letter dated March 2020, the Dutch government laid out its national hydrogen strategy and associated policy agenda. The critical role of hydrogen in creating a carbon-free energy system is well established. The National Climate Agreement, which was signed in 2019 by the government, industry, and other stakeholders, also establishes aggressive goals for hydrogen, with important themes including upscaling, cost reduction, and innovation (Klimaat, 2020b).

The Dutch energy system is evolving, and the Dutch government views hydrogen as a potential opportunity for the economy; first and foremost because it makes the Netherlands a good and green investment option; also, the trajectory to being a leader in the use of green hydrogen entails a learning process for businesses and knowledge institutions. It has been discussed that there several advantages associated with the gas network of the Netherlands like vast undeveloped gas fields in the North Sea that could store hydrogen and carbon dioxide, substantial offshore wind installations that can eventually integrate to produce clean energy, and extensive natural gas infrastructure that can be used to transport hydrogen with little modification. Additionally, the Netherlands has significant industries on the retail side, such as the Shell refinery, Yara, and Tata Steel (Gasunie, 2021).

# CH.4 – RESULTS FROM LITERATURE STUDY

This section reports the literature-based barriers and enablers for green hydrogen transition and partially answers the sub-research questions 5 and 6.

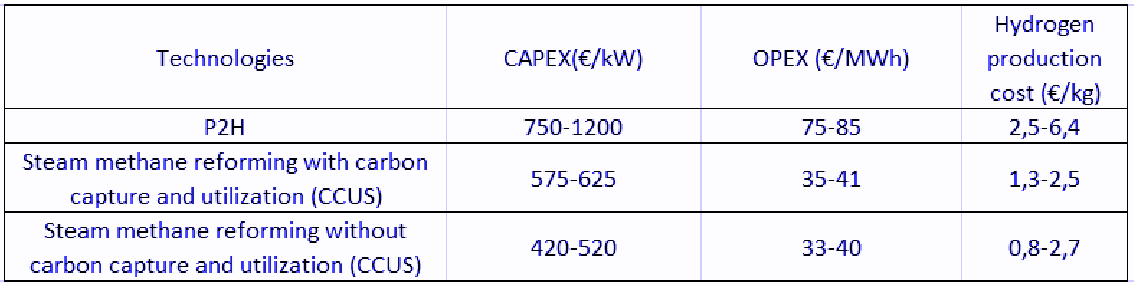
## 4.1 Enablers & Barriers

### 4.1.1 Economic Barriers

The primary economic constraints, according to the literature, are.

- High initial investments (CAPEX),
- High operational costs (OPEX),
- High expenses on storage, transportation and distribution.

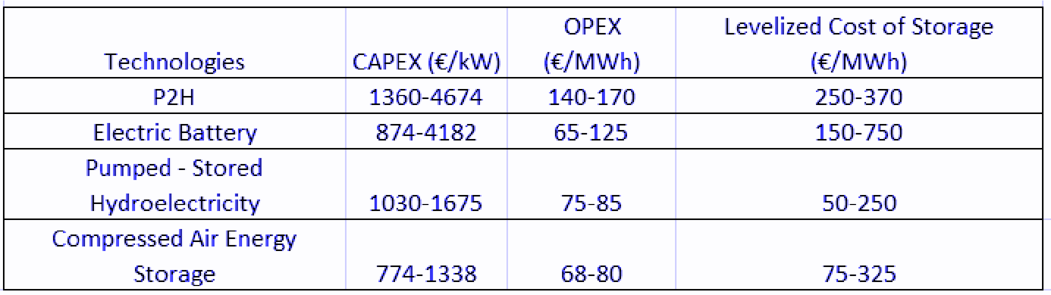
For the hydrogen generation system using PEM electrolyser, table 6 shows a comparison of CAPEX and OPEX. In addition, Power-to-Hydrogen for green hydrogen production is compared to steam methane reforming with and without carbon capture, utilisation and storage (prevalent method).



| Technologies | CAPEX(€/kW) | OPEX (€/MWh) | Hydrogen production cost (€/kg) |
|---|---|---|---|
| P2H | 750-1200 | 75-85 | 2,5-6,4 |
| Steam methane reforming with carbon capture and utilization (CCUS) | 575-625 | 35-41 | 1,3-2,5 |
| Steam methane reforming without carbon capture and utilization (CCUS) | 420-520 | 33-40 | 0,8-2,7 |

*Table 6 CAPEX and OPEX for hydrogen production processes (Saccani et al., 2020)*

In the data (Table 7) given below, we see the costs involved in using hydrogen as a storage medium and its comparison with the other prevalent technologies being used.



| Technologies | CAPEX (€/kW) | OPEX (€/MWh) | Levelized Cost of Storage (€/MWh) |
|---|---|---|---|
| P2H | 1360-4674 | 140-170 | 250-370 |
| Electric Battery | 874-4182 | 65-125 | 150-750 |
| Pumped - Stored Hydroelectricity | 1030-1675 | 75-85 | 50-250 |
| Compressed Air Energy Storage | 774-1338 | 68-80 | 75-325 |

*Table 7 CAPEX and OPEX for a unit of power stored (Saccani et al., 2020)*

Green hydrogen is currently experiencing higher CAPEX and OPEX, which is deterring investment. The data shows that the high CAPEX has a detrimental impact on hydrogen investment decisions. Because green hydrogen development cannot be funded solely by private investors, governmental financing is both necessary and a significant barrier to long-term investment in green hydrogen. Furthermore, OPEX could be a stumbling block: electricity is required for water electrolysis, hydrogen storage operations, and plant auxiliaries (i.e., compressors). Electrolysers and other equipment also need routine and emergency repair. The time it takes for green hydrogen production and storage plants to pay for themselves is determined by the unique business case. However, depending on the principal use, the payback period of the best European business cases decided by the Fuel Cells and Hydrogen Joint Undertaking (FCHJU) ranges from 3 to 11 years, assuming a gas grid injection tariff of 90 euros/MWh (FCHJHU, 2017).

We have seen the CAPEX and OPEX related to the hydrogen production and storage systems, which represents the most straightforward configuration of a Power-to-Hydrogen system. However, the STORE&GO project initiated under the European Union’s “Horizon 2020” program presents one of the most detailed accounts of the economic costs associated with a Power-to-Gas system to produce methane and inject it back to the grid (IEA, 2019). The Power-to-Gas system described below gives a breakdown of the system costs associated and provides a good idea about the economic barriers.

## System Description

An electrolyser converts electricity into green hydrogen in a Power-to-Gas plant. A methanation reactor can be used to convert it into methane. Many different costs are involved in producing hydrogen or methane in a Power-to-Gas plant, including investment costs, operational expenses, and feed-stock expenses. The essential components associated with a Power-to-Gas plant are depicted in Figure 10. Within the black dotted box is a Power-to-Hydrogen plant, which includes an electrolyser stack and equipment such as a power conversion system, water treatment, and gas purification. These, along with other components such as piping, structure housing, and monitoring equipment, make up the electrolyser's balance of plant (BoP). The entire system is referred to as the electrolyser system. The hydrogen is kept in a hydrogen storage facility, which usually requires the use of a compressor. If the hydrogen produced needs to be converted to methane, additional equipment such as a methanation reactor with a BoP and a carbon dioxide storage tank with a compressor is required. Electricity, water, and carbon dioxide are the different feedstocks required in Power-to-Gas plants, whereas hydrogen, methane, oxygen, and heat are the results (Momeni et al., 2021).

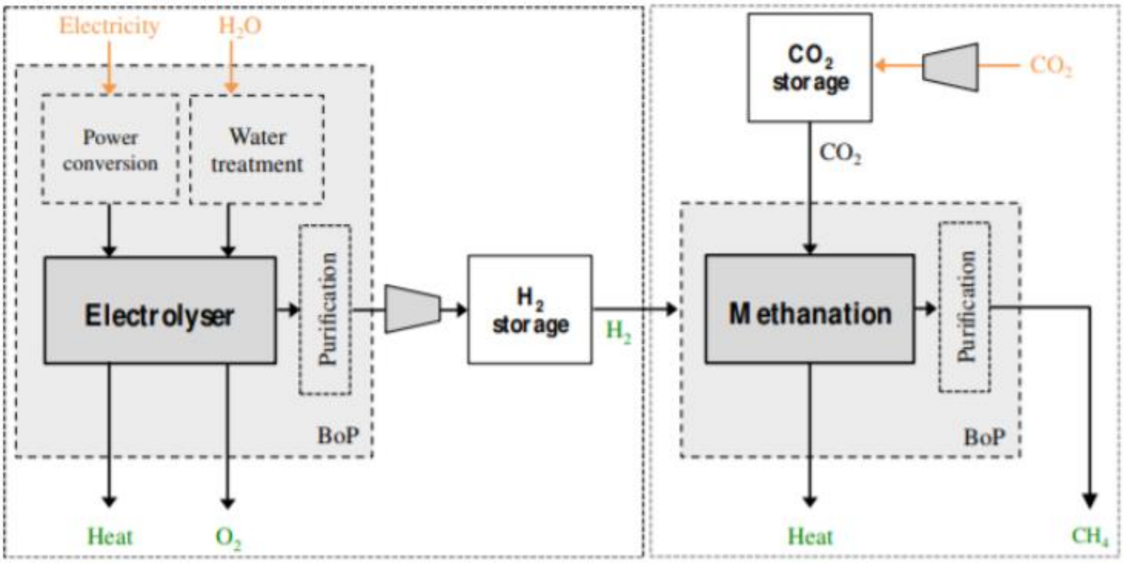


*Figure 10 Power-to-Gas plant producing methane and hydrogen (Momeni et al., 2021)*

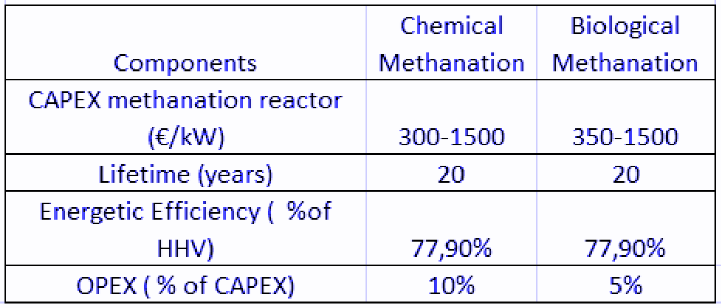
## Cost Components

The major cost components of the system described above (Figure 10) are as follows:

- Electrolyser cost (Table 6)
- Methanation reactor cost
- Carbon dioxide supply and storage cost
- Compressor cost
- Pipeline cost
- Gas-grid injection cost
- Miscellaneous cost

## Methanation reactor costs

The hydrogen produced in an electrolyser can be used directly in the chemical or transportation industries, but it can also be transformed into methane. Because methane has numerous applications and our contemporary economy is mainly built on natural gas, a gas mixture predominantly composed of methane, this conversion provides multiple advantages. A methanation reactor, like a carbon dioxide source, is necessary for the conversion of hydrogen into methane. Biological methanation and catalytic thermochemical methanation are the two types of methanation technology. The STORE&GO project discusses both technologies (Nicita et al., 2020).

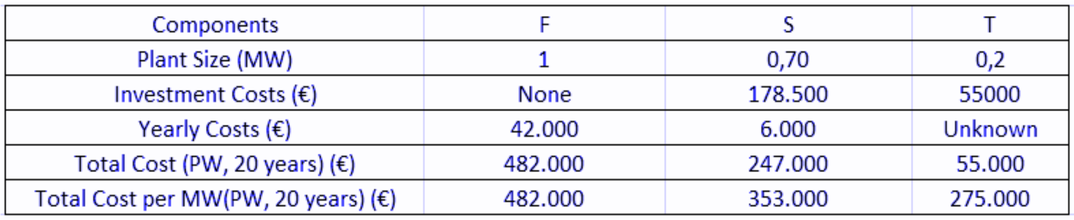


| Components | Chemical Methanation | Biological Methanation |
|---|---|---|
| CAPEX methanation reactor (€/kW) | 300-1500 | 350-1500 |
| Lifetime (years) | 20 | 20 |
| Energetic Efficiency ( %of HHV) | 77,90% | 77,90% |
| OPEX ( % of CAPEX) | 10% | 5% |

*Table 8 Cost parameters for a methanation reactor (Nicita et al., 2020)*

## Carbon dioxide storage and capture costs

A supply of carbon dioxide is required to convert hydrogen to methane. Therefore, a storage facility must be built to ensure a constant supply of carbon dioxide to the reactor. The size of the storage facility is determined by the carbon dioxide source, distance from the carbon dioxide source to the Power-to-Gas plant, and delivery method. Carbon dioxide is commonly stored in a storage tank as a liquid (Huang et al., 2017).



| Components | F | S | T |
|---|---|---|---|
| Plant Size (MW) | 1 | 0,70 | 0,2 |
| Investment Costs (€) | None | 178.500 | 55000 |
| Yearly Costs (€) | 42.000 | 6.000 | Unknown |
| Total Cost (PW, 20 years) (€) | 482.000 | 247.000 | 55.000 |
| Total Cost per MW(PW, 20 years) (€) | 482.000 | 353.000 | 275.000 |

*Table 9 Carbon dioxide storage costs in various settings (Huang et al., 2017)*

In Table 9, F represents a demonstration plant with a 30 m$^3$ liquefied carbon dioxide storage tank erected to assure a continuous supply of carbon dioxide to the plant. The tank stores carbon dioxide at a pressure of 16–20 bar at –24 °C and can run the plant for 11 days at full load without needing to be refilled. Carbon dioxide is delivered by truck. S represents a demonstration plant with a 2 m$^3$ (16 bar) buffer tank. Investment costs are estimated to be over €17,000, according to reports. A compressor and pipeline are also required in addition to the carbon dioxide storage tank. The prices are estimated to be €102,000 and €59,500, respectively, for a total investment cost of €178,500 in carbon dioxide storage. Every 2000 hours of operation, the compressor requires service, which is estimated to cost €1,500 (Huang et al., 2017). Finally, it represents a demonstration plant with an air capture facility that transports carbon dioxide. The carbon dioxide that is generated will be compressed and kept in a buffer tank. A gas balloon, compressor, and buffer tank cost €55,000 to purchase. The operational costs have yet to be determined.

## Compression costs

To inject hydrogen, methane, or carbon dioxide into a storage tank, a compressor is required. The absolute pressure of the produced gas and the pressure in the grid determine whether a compressor is necessary for the injection in the natural gas grid. For different scenarios, different compressors are required, and the design and costs are determined by the pressure difference to be overcome, the flow rate employed, and the type of gas to be compressed. Compressors for hydrogen, methane, and carbon dioxide may be required in Power-to-Gas facilities (Burre et al., 2020).

| Components | Range |
|---|---|
| CAPEX hydrogen compressors (€/kW) | 300-18500 |
| Lifetime | 10-12 years |
| OPEX ( % of CAPEX) | 1,5-4% |

*Table 10 Cost parameters for hydrogen compression  (Burre et al., 2020)*

## Pipeline costs

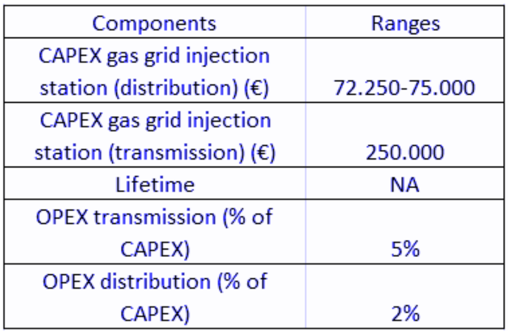
The cost of a pipeline is determined not only by the distance to be covered but also by the pressure, gas flow, surrounding areas to be traversed, and the type of gas to be conveyed. As a result, distinguishing between hydrogen and methane, transmission (high-pressure) and distribution (low-pressure) pipelines, and rural and urban areas is critical (Nicita et al., 2020).

| Components | Transmission | Distribution | | |
|---|---|---|---|---|
| | | Rural | Medium | Urban |
| CAPEX methane pipeline (€/km) | 350.000 | 100.000 | 300.000 | 500.000 |
| CAPEX methane pipeline (€/km) | 600.000 | 350.000 | 450.000 | 550.000 |
| Lifetime | 60-80 years | | | |
| OPEX (% of CAPEX) | 2% | | | |

*Table 11 Cost estimates for transmission & distribution (Nicita et al., 2020)*

## Gas-grid injection costs

A Power-to-Gas plant's hydrogen can be pumped into the natural gas system. However, because it affects the combustion behaviour of the gas in the grid, it can only be admixed up to a certain point without causing major material integrity issues. The permitted limit varies by area and is determined by both the gas grid infrastructure and the unique end-users. The amount of hydrogen that can be injected is determined by the admixture limit, combined with location-specific grid features (pipeline flow, pressure, diameter, connected producers and end-users). The changing energy density of the gas in the grid is another critical effect of hydrogen mixing in the natural gas grid. Because hydrogen has a volumetric energy density of one-third of natural gas, it requires a higher flow rate to meet demand. Without the limits that hydrogen has, methane can be pumped into the natural gas grid. However, before it can be injected, the produced gas must meet specific quality requirements, and injection may be limited owing to pipeline constraints. Thus, there are both capital and operating costs associated with gas quality measurement equipment. Similarly, a transmission grid injection point is more expensive than a distribution grid injection point (investment costs) (Farchmin, 2016). Table 12 shows the estimated investment and operational costs of a gas grid injection station, with the distribution grid (low pressure) and transmission grid (high pressure) separated (high pressure).



| Components | Ranges |
|---|---|
| CAPEX gas grid injection station (distribution) (€) | 72.250-75.000 |
| CAPEX gas grid injection station (transmission) (€) | 250.000 |
| Lifetime | NA |
| OPEX transmission (% of CAPEX) | 5% |
| OPEX distribution (% of CAPEX) | 2% |

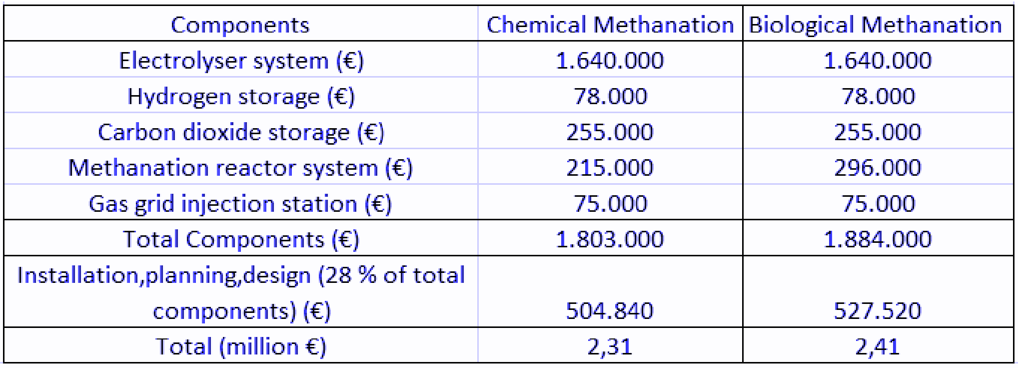
*Table 12 Cost parameters for gas-grid injection (Farchmin, 2016)*

## Miscellaneous Costs

Installation, land preparation, project planning, design, engineering, civil and site, control and safety, and other expenditures must be added to the general investment expenses for all distinct components. These expenses are typically stated as a proportion of overall investment expenses.

## Total Cost Assessment

Now, summing up the costs discussed above for a system with the following specifications, a storage tank with a capacity of 780 m$^3$ of hydrogen for a 1 MW electrolyser with a 69% efficiency. For storage in a steel tank, investment expenses are estimated to be 100 €/m3. The total investment expenses for hydrogen storage are therefore €78,000. A hydrogen compressor is not expected to be necessary. Therefore, the CO2 storage expenses are estimated to be €255,000 for a storage tank, compressor, and pipeline. We assume investment costs of 400 and 550 €/kW SNG for chemical and biological methanation, respectively, for the methanation reactor. Assuming efficiencies of 69% for the electrolyser and 77.9% for methanation (100% conversion), for a combined efficiency of 53.8%, investment costs for chemical and biological methanation are 215 and 296 €/kWel, respectively. The produced methane is assumed to be injected into a local distribution grid, with a cost of €75,000 for the injection point and measurement equipment (Medved et al., 2021).



| Components | Chemical Methanation | Biological Methanation |
|---|---|---|
| Electrolyser system (€) | 1.640.000 | 1.640.000 |
| Hydrogen storage (€) | 78.000 | 78.000 |
| Carbon dioxide storage (€) | 255.000 | 255.000 |
| Methanation reactor system (€) | 215.000 | 296.000 |
| Gas grid injection station (€) | 75.000 | 75.000 |
| Total Components (€) | 1.803.000 | 1.884.000 |
| Installation,planning,design (28 % of total components) (€) | 504.840 | 527.520 |
| Total (million €) | 2,31 | 2,41 |

*Table 13 Costs for Power-to-Gas plant (1MW electrolyser)(Medved et al., 2021)*

## 4.1.2 Technical Barriers

### Lack of hydrogen storage infrastructure

Green hydrogen is not currently recognized as a storage option according to the EU regulations, incentives, tax breaks; it is difficult to use financial instruments for boosting the uptake of hydrogen generation and storage. In the case of batteries, however, a distinct scenario happens. At the moment, public support in the EU Member States is mostly focused on batteries. Only a few Member States have established direct investment support schemes for energy storage, most of which are aimed at modest installations (usually home batteries). Indirect storage support comes mostly from another regulatory scheme or practice; prosumers, for example, are pushed to invest in batteries in order to boost their self-consumption and avoid low feed-in prices, as well as to lower grid costs and related surcharges in various countries. Most Member States currently lack a comprehensive national regulatory framework for storage; policy instruments and actions applicable to storage are dispersed across several laws and regulations and appear to approach storage without a clear and consistent vision. This results in non-harmonised regulations, as well as incoherent and complex frameworks in some circumstances (Klimaat, 2020b).

We can look at Pumped Hydroelectricity Storage (PHS), which is the most widely used electricity storage technology in the several Member States. Pumped-hydro storage is a unique example in which the regulatory process might operate as a roadblock due to its high environmental impact. Depending on their technical characteristics and influence on the environment (including the soil), safety, fire threats, public health, and/or landscape, storage facilities may be subject to specific permitting regulations. Therefore, when it comes to storage, the approval process is not present as a separate framework rather is dependent on characteristics/storage type. These characteristics are a part of a myriad of frameworks like safety, energy efficiency, operating conditions etc. This process of checking the concerned regulation makes the process cumbersome (Burre et al., 2020).

Complying with safety and security regulations (for example, fire prevention) has an impact on the economic and technological viability of storage and can thus function as a barrier to specific storage types, such as batteries and hydrogen. Although the manufacturing industry is responsible for the production of storage components, installation businesses are responsible for ensuring the safety of consumers. Standards for safety and security are necessary, but they must be based on actual dangers in order to prevent undermining storage adoption. In the Netherlands, for example, the lack of a comprehensive national permission rule that includes energy storage allows municipal governments to set extremely tight limitations on storage installations. This results in different restrictions depending on the region, as well as uncertainty for potential storage asset investors (Klimaat, 2020b).

## Problems in blending with natural gas

Injecting hydrogen in the existing gas network is considered a step toward a more sustainable energy mix. The concept is to feed hydrogen into the current gas network, produced using electrolysis of water using excess or off-peak electricity. This would serve as a hydrogen transportation and storage system. This is possible with relatively low concentrations of hydrogen, less than 5%–15% by volume, without risking at the end-user place (Haines, n.d.).

## Chemical properties (Hydrogen vs Natural gas)

On a volumetric level, hydrogen has a substantially lower energy density than natural gas. As a result, end-users of mixed gas would require a greater volume of gas than end-users of purely natural gas to achieve the same number of British Thermal Units. As a result, a 5% hydrogen mix by volume does not automatically translate into a 5% reduction in fossil fuel usage. As the amount of hydrogen combined increases, the average calorific content of the blended gas decreases, requiring a larger volume of blended gas to provide the same energy needs. For example, blending 5% hydrogen by volume would only displace 1.6% of natural gas demand (Mulder et al., 2019).

## Pipe embrittlement issues

Hydrogen embrittlement, which can develop in iron and steel pipes and lead to the spread of cracks in the pipework, is an issue with the direct injection of hydrogen into the natural gas network. It is widely agreed that low-concentration hydrogen injections into the distribution network pose no substantial safety risks. Although the exact number is debatable, several studies show that a hydrogen blend of up to 15–20 % by volume should be acceptable. Meanwhile, many authorities appear to have set arbitrary limits on the quantity of hydrogen allowed in the blend. Because high-pressure transmission grids, which are commonly composed of high strength steel, are expected to increase the effects of hydrogen embrittlement, allowed levels in high-pressure transmission grids are normally lower than in distribution grids. If hydrogen must be transported over larger distances via pipeline, it is probable that a purpose-built pipeline network will be necessary (Haines, n.d.).

## Pressure issues

Adding hydrogen to natural gas pipes lowers the pipeline's energy delivery. At greater pressures, the effect becomes more dramatic because hydrogen is less compressible than natural gas. To manage the lower energy delivery in gas networks, either peak energy demand must be minimized, or higher flow rates must be used (resulting in larger pressure drops and hence higher compression requirements) (Haines, n.d.).

## Household safety issues

In most households, gas from the distribution system is used for cooking and/or heating. When it comes to hydrogen in the home, there are additional safety issues, mainly with leaks and the possibility of ignition.

Hydrogen, for example, has a larger danger of ignition than natural gas; therefore, it may be essential to add an odorant to hydrogen to improve detectability, much as it is with natural gas. A colourant may also be required because, unlike natural gas, a pure hydrogen flame is nearly invisible. Several projects, like the NaturalHy project, have looked into the impact of hydrogen on the performance of household appliances. While most modern appliances should be able to burn hydrogen blends up to 20% by volume, above that level, appliances will most likely need to be adjusted or replaced, which would be a big undertaking (Haines, n.d.).

Working with hydrogen carries some hazards since if hydrogen is mistakenly discharged and the hydrogen cloud comes into contact with an ignition source, dangerous phenomena such as jet flames or explosions can occur. The consequences of discharged hydrogen igniting or not igniting are depicted in the form of an event tree below. A simplified event tree for the continuous discharge of compressed hydrogen is shown in Figure 11 (Gigler et al., n.d.).

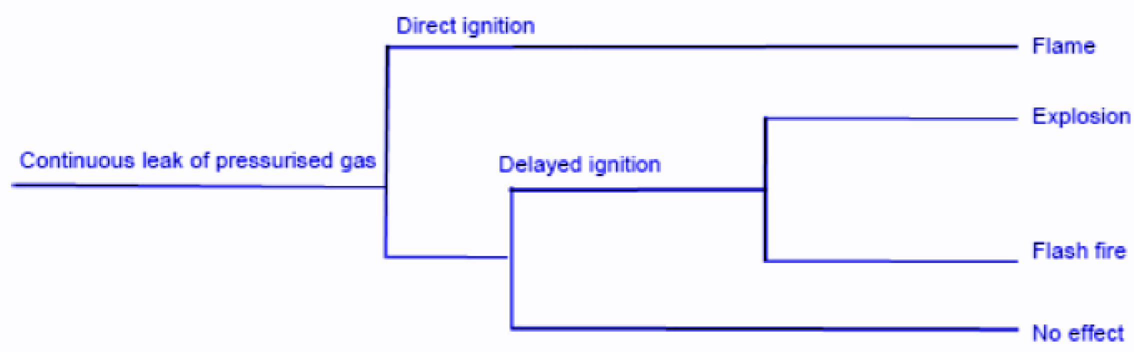


*Figure 11 Event tree for a hydrogen leakage scenario (Gigler et al., n.d.)*

A drop in pressure happens at the site of release, and the hydrogen molecules adjust to the ambient pressure. The hydrogen gas can be ignited immediately or after some time has passed.

- When hydrogen is expelled from an aperture and ignited directly, it produces an invisible jet flame with a certain size and direction. Jet flames have the potential to injure humans as well as damage neighbouring items and structures, resulting in secondary impacts. Because the pressure at which hydrogen is released is very low, the jet flame will be small (in the centimetre range) when it is discharged indoors (Gigler et al., n.d.).

- When you use delayed ignition, there is a delay between when the hydrogen is released and when it is ignited. Hydrogen reacts with air during this time, forming a potentially combustible combination. If the hydrogen cloud is exposed to the elements and ignites, the cloud will burn (flash fire), with no overpressure effects expected, simply heat impacts (Gigler et al., n.d.).

- If a hydrogen cloud is ignited in a confined place, such as a house, the cloud will explode with overpressure effects at ignition and at a sufficiently high concentration. These effects can cause significant damage by hurling debris or causing the structure of the building or surrounding buildings to collapse. Although fires and subsequent fires cannot be ruled out, the overpressure impacts of an explosion extend beyond the thermal effects of the explosion(Gigler et al., n.d.).

## Noise emissions

Additional restrictions may be enforced due to noise emissions and line bend forces. Because the flow velocity must be increased in proportion to the speed of sound in the mixture to retain the same energy transport, the noise of a line will somewhat increase. This rise in Mach number will result in noise emission (Mulder et al., 2019).

## Metering issues

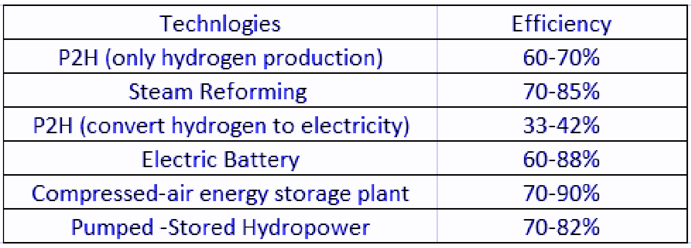
Variations in the communicated fuel qualities may occur when hydrogen is injected into the natural gas infrastructure. As a result, the energy bill computation withs time-variable injection into the grid, the measurement and management of natural gas and hydrogen mixture composition become critical. In order to calculate the quantity of energy transferred, the calorific value of the mixture must be checked. Process Gas Chromatographs (PGC) could be employed within this scope, according to state of the art. Helium is used as a carrier gas in these devices; however, it has a thermal conductivity similar to hydrogen. Helium is used as a carrier gas in these devices; however, it has a thermal conductivity similar to hydrogen. As a result, because the detection technique of such equipment is based on a differential in thermal conductivity, certification or rebuilding is required to accurately execute energy measurements (Mulder et al., 2019). However, there are two scenarios that can occur:

- Injection of hydrogen into the transmission network. Because the energy of the delivered mixture is measured before it enters the distribution networks in this instance, PGC overhauling, and certification can be confined to those instruments situated at the plant boundary limit between the natural gas transmission and distribution networks. In fact, there is no fluctuation in mixture qualities along with the distribution network since no injection occurs (Dominguez et al., 2021).

- Injection of hydrogen into the distribution system. In contrast to the preceding example, mixing attributes can alter as the network progresses. As a result, there could be a quality mismatch between the users on the same network. Without any substantial difference in volumetric flow rate measurements or structural damage were observed in diaphragm meters up to a hydrogen concentration of 15%, the change in gas composition could cause an energy meter-based inaccuracy greater than the maximum allowed. As a result, end-users should be offered a system that can measure combination qualities. Sensors should be considered to provide continuous monitoring because PGCs are too expensive and complex. Despite the fact that numerous sensors for hydrogen detection are currently on the market, no cost-effective solution for measuring the concentration of hydrogen in a mixture stream appears to be feasible in the current state of the art (Dominguez et al., 2021).

## Low electrolysis efficiency

Several experts believe that the fundamental technological barrier is the comparatively low efficiency of water electrolysis compared to alternative storage competitors. Furthermore, for high compression work, a low hydrogen energy density is required, which affects the overall cycle efficiency and puts a relatively significant strain on the operation for effective storage and transportation, as well as application in the mobility sector. The efficiency of Power-to-Hydrogen is compared to that of other technologies in table 16. Compression, even if it is the only means to raise gas density, results in an additional energy loss due to the isentropic compressor's efficiency. Commercial hydrogen compressors, for example, claim efficiency of 65–85% up to 70 bar, but values as low as 52 % can be achieved at higher pressures of up to 350 bar (Saccani et al., 2020).



| Technlogies | Efficiency |
|---|---|
| P2H (only hydrogen production) | 60-70% |
| Steam Reforming | 70-85% |
| P2H (convert hydrogen to electricity) | 33-42% |
| Electric Battery | 60-88% |
| Compressed-air energy storage plant | 70-90% |
| Pumped -Stored Hydropower | 70-82% |

*Table 14 Efficiency comparison (Saccani et al., 2020)*

## Lack of maintenance and repair network availability

The operation of a large-scale electrolysis system entails, first and foremost, a significant and long-term investment by the client or operator, which is accompanied by high expectations. Aside from this investment, operation and maintenance expenditures have a significant impact on economics. The “overall equipment effectiveness (OEE)” is a critical performance metric that is calculated by multiplying availability, productivity, and quality rates. After commissioning, the major difficulties for service and support are lowering operational costs, protecting the investment, and ensuring availability. The presence of an all-encompassing service organization is a key requirement for achieving this. That does not exclude the development department's experts, who can diagnose and repair any problem. Local service technicians with the correct mix of electrical and process knowledge must be accessible as the installed base grows. The electrolysis system's complexity must be mirrored in a simple and effective service model. This isn't about ordinary services like a toll-free number or on-site maintenance. The goal is to totally avoid unplanned shutdowns during the system's lifetime. While the stack of a PEM system is essentially maintenance-free, components that are subjected to mechanical stress during operation, such as pumps, ventilators, and certain valves, are critical in terms of availability. Measures such as preventive maintenance, inspection programs, integrated condition monitoring systems, and the availability of repair and spare parts at any time during the life of the machine (Saccani et al., 2020).

### 4.1.3 Social Barriers

In the Netherlands, methane is the most common energy source for domestic usage. Natural gas is widely regarded as a safe and dependable commodity for use in heating buildings. As a result, it's plausible to assume that the identical reaction will take place when green hydrogen becomes dominant. On the contrary, if a redesigning of household equipment is required, it is unlikely that the house owners would accept the associated financial investment unless it is accompanied by incentives or tax credits (Klimaat, 2020b).

Jan Gutteling, a psychologist at Twente University in the Netherlands, is a specialist who investigates the social dynamics surrounding the introduction of new technologies. According to Gutteling, the Dutch government is taking a cautious approach to the use of hydrogen as a fuel. The grounds for this are lessons learned from previous significant infrastructure projects, such as the expansion of Schiphol Airport and the construction of a new rail connection for cargo transit, both of which sparked widespread opposition in society. The government is even more hesitant because of hydrogen's negative reputation, which stems from a single instance, the 1937 Hindenburg disaster. The "decide, announce, defend" model has been mentioned by Gutteling. In this model, the government bodies make decisions with only a few stakeholders initially. The news of this decision sparks widespread resistance, forcing the government to take a defensive stance. Other stakeholders may express their opinions, but they are unable to influence policy. This leads to cynicism and unnecessarily strong resistance (Glanz & Schönauer, 2021).

All parties agree that one of the most difficult problems is gaining social acceptance. The demand for additional infrastructure, as well as the view that hydrogen-based technologies are risky, are the key difficulties in terms of social acceptance for hydrogen introduction.

From the standpoint of stakeholders, the social acceptance of hydrogen can be examined on three levels (Glanz & Schönauer, 2021).

Level 1 - It is concerned with the general acceptance of hydrogen technologies and carbon capture, utilisation and storage as a part of the energy transition.

Level 2 - The acceptance of the implementation and its effects.

Level 3 - The acceptance of the implementation planning process, i.e. perceived fairness of the planning process and the trust placed on the important stakeholders.

Level 1 - Acceptance of hydrogen-based decarbonisation as part of the energy transition - Stakeholders anticipate a lack of public acceptance of hydrogen as a means of decarbonizing the energy sector. Green hydrogen is expected to be more popular than blue or conventional hydrogen. Stakeholders consider public awareness of hydrogen technology to be low. Because of its poor market penetration and absence in consumers' daily lives, knowledge of hydrogen technology is considered low in society. Nonetheless, it is estimated that many people have heard of it and have a general notion about it, but in public, the technology is rarely discussed, except in the context of mobility. Some stakeholders see a lack of social acceptance of energy technology and/or large-scale infrastructure as a paradox, which they attribute to a variety of factors, including a lack of information (Glanz & Schönauer, 2021).

Level 2 - Acceptance of the implementation process and its outcomes. On a personal level, stakeholders mainly mentioned risk perception of the technologies and infrastructure effects while discussing the implementation and consequences of a hydrogen chain. Because of differing assumptions about public risk perceptions of hydrogen, the predicted uptake of hydrogen technology varies per stakeholder. There have been a variety of views from the stakeholders'; for instance, they anticipate a high level of risk perception due to the hydrogen's reputation as a highly explosive material that is dangerous to use. In contrast, the social opinion of hydrogen storage technology has been favourable as compared to natural gas storage facilities, which are thought to be a bit risky for communities and the environment. This could be due to the fact that hydrogen storage sites do not yet have the same level of popularity and use as natural gas storage sites. It is believed that new pipeline infrastructure would be unpopular and would result in NIMBY impacts as well as concerns about landscape and environmental preservation. To improve acceptance, all stakeholders believe that avoiding new large-scale infrastructure and relying on current infrastructure is critical. However, some stakeholders claim that utilizing existing infrastructure does not automatically result in increased adoption. Acceptance will be even lower if additional dangers are connected with infrastructure retrofitting and modification (Glanz & Schönauer, 2021).

At this point, in terms of social acceptance, a very contradictory argumentation is used, which can be seen in principle in the discussion and implementation of the energy transition: first, the citizens follow the transition discourse, and then we witness the NIMBY effect.

Level 3 - Acceptance of implementation planning process and the trust placed in the stakeholders - The population trusts some stakeholder groups more than others. These organizations include (environmental) non-governmental organizations (NGOs) and local stakeholders, such as local politicians and investors who are supposed to represent local and civic interests. Non-local stakeholders and huge (energy) firms, on the other hand, are less trusted due to a lack of attribution. This trust divide is a conundrum because those with financial means for investments aren't always the most trustworthy (Huijts & van Wee, 2015).

It has been emphasized by the authors that it is necessary to get approval on the planning processes in addition to project and technology adoption. Which stakeholders are included in the planning process, and whether public participation is possible are expected to have a significant impact on its adoption? There have been some differences in views over the inclusion of the public in planning procedures, especially for large-scale infrastructure projects. Furthermore, stakeholders interpret communication in a variety of ways. Authors had also suggested the need to educate people because there have been instances when the facts on which public rejection happened were inconsistent or the fact that the lack of acceptance is due to NIMBYism.

### 4.1.4 Economic Enablers

#### Public Investment

The high CAPEX has a detrimental impact on decision-makers when it comes to hydrogen investment. In comparison to other EU member states, the Netherlands has a very high level of public investment: public investment in 2020 was 3.4% of GDP, while the eurozone average was 2.8% (i.e., France 3.5%, Germany 2.5%, Sweden 4.9%). The public investment prediction for 2021 suggests a minor increase in public investment in the Netherlands to roughly 3.5%, while the euro area average remains unchanged. Because green hydrogen development cannot be funded solely by private investors, the Netherlands current trend in public investment is a positive sign that long-term investment in green hydrogen is on the way (Saccani et al., 2020).

#### Incentives & Subsidies

#### SDE+ & SDE ++

The main policy instrument revitalizing the implementation of renewables is the Stimulation of Sustainable Energy Production (SDE+) subsidy scheme. SDE+ was founded in 2011 to encourage the production of sustainable electricity, gases, and heat. SDE+ will be replaced by the Sustainable Energy Transition Incentive Scheme (SDE++) in 2020. This scheme encourages and covers many technologies that could cut gaseous emissions of any form. Under SDE+ and SDE++, funding is distributed through competitive technology-neutral auctions that accept bids from private firms, institutions, and non-profits. SDE++ auctions will accept bids from technologies aimed at producing low-carbon hydrogen, starting in the second half of 2020. Every year, the technologies that are qualified to participate in SDE++ auctions will be evaluated. The level of support under SDE+ is set by a sliding feed-in premium method that accounts for the difference between the cost of renewable energy production and the applicable market price for electricity, gas, or heat. The difference between the base tariff awarded per tonne of carbon dioxide equivalent averted and an estimated market remuneration is covered by SDE++. Subsidies are not given to projects until they begin producing green energy or lowering emissions. The Surcharge for Sustainable Energy Act Levy (ODE), an additional charge on all taxed energy consumption, provides funds for SDE+ and SDE++. Till the last year, the housing sector provided half of the ODE funding, with businesses providing the remaining. This year, it is expected that the ODE funding would change to businesses provide (2/3) rd of the funding and consumers provide (1/3) rd of the total funding. This is a good move from the Dutch government towards increasing the consumer base (Klimaat, 2020b).

## Energy Innovation Goals (MMIPs)

The Mission-Oriented Integral Knowledge and Innovation Agenda (IKIA), designed in 2019 and completely implemented in 2020, is the core of the new energy RD&D program. IKIA identifies the Climate Agreement's innovation goals and transforms them into thirteen Multiannual Mission-driven Innovation Programs (MMIPs).

IKIA's has been made to foster innovation to eradicate the climate change problem and achieve the Climate Agreement goals by 2050. MMIPs are designed to encourage research at all levels of technological readiness, from introductory groundwork to the development and market introduction of cost-effective GHG reduction technologies, while considering national expertise and human capital, export potential, social circumstances and preferences, and spatial integration issues. There are 13 MMIPS, with the thirteenth one being focused on involving society in the climate change innovation process.(Klimaat, 2020b). Support for low-carbon hydrogen is mentioned in three of the MMIPs, namely MMIP 6 (promoting the RD&D on hydrogen chain generation), MMIP 8 ( lowering the costs of electrolysers to cheaper produce green hydrogen), MMIP 9 (Working on making sustainable mobility using hydrogen a reality)(Klimaat, 2020b).

## DEI+ Scheme

The aim of the DEI+ (Demonstration Energy Innovation) grant scheme is to focus on energy sector breakthroughs that could enable the Dutch firms to be successful worldwide with the products, services, or processes developed. The demonstration project should use the technology that could help the Dutch economy through increased revenue, job creation, exports etc. Projects aiming at integrating green hydrogen in spatial planning, natural gas-free houses, buildings, and neighbourhoods running on green hydrogen all qualify for the DEI+ funding. (Klimaat, 2020b).

## Renewable Energy Scheme (HER)

The Renewable Energy Scheme (HER) helps to achieve the 2030 energy sector targets in a cost-effective manner by sponsoring innovative initiatives aimed at lowering the cost of renewable energy technology and, as a result, lowering the cost of renewable energy production support programs. The common project themes financed under this scheme are the ones focusing on energy storage and generation, smart grid projects with de-centralised production etc. (Klimaat, 2020b).

## Guarantees of Origin

The Hydrogen Strategy outlined in 2020 emphasizes the importance of coordinated network development for electricity, natural gas, and hydrogen. A blending mandate for the gas system is one option for increasing demand for low-carbon hydrogen, according to the Strategy (either physically or through certificates). In collaboration with Gasunie, DSOs, and natural gas users, the government will research technical, regulatory, safety, and price implications of physical and administrative hydrogen mixing possibilities. The

Hydrogen Strategy sees into the use of guarantees of origin (GOs) for creating the demand for green hydrogen. The EU Renewable Energy Directive mandates the construction of EU-wide hydrogen GO system and establishes a framework for its implementation. The Netherlands is seeking EU member state cooperation to build an EU-wide GO system as rapidly as possible and will incorporate European norms and techniques into its national GO system as much as possible. Vertogas, the Dutch business in charge of green gas GOs, has been tasked by the government with developing the Dutch hydrogen GO system (Hafner et al., 2020).

### Eliminating the double taxation

The problem of double taxation, which prohibits storage from realizing its full potential. Double taxation creates a severe disincentive to take advantage of a storage system's flexibility. Electricity producers and customers are both taxed under the current system. In the double taxation regime, buying as selling power is taxable. However, if the tax structure is modified, the government may lose money and will need to find a mechanism to compensate for it, maybe through new taxes. The EU’s Strategy for Energy System Integration Report was published in 2020, where it was explicitly announced that the member states should start working towards ending the double taxation system as it disincentives energy storage. Though a detailed justification from the Dutch government has not come yet, it is a good move towards the adoption of hydrogen-based storage systems (Hafner et al., 2020).

## 4.1.5 Technical Enablers

### Pilot Projects

The use of hydrogen in households is a viable alternative. Many issues remain unanswered because it is unclear whether or not these applications will be forthcoming, and if so, in what form. For example, we could envision green hydrogen being delivered at individual households or being delivered to an aggregated station from where it could be distributed according to the individual needs like cooking, heating. It could also be the case that green hydrogen blended with natural gas is being used to transition to a pure green hydrogen-powered environment. These alternatives are possible, and the Dutch government has started a number of pilot projects as a step towards making green hydrogen a reality in the community space. Some of the prominent projects in the Netherlands are described below.

In Rozenburg, the grid operator Stedin is conducting a pilot to heat homes using 100% green hydrogen. The delivery to private residences is done using an existing gas pipeline. The pipeline has been tested in phases for this purpose, with nitrogen being utilized for the initial test. Following the success of the initial tests, the next step of testing was carried out using 100% hydrogen, which also proved to be successful. At the moment, hydrogen is used to heat 40 residential houses. Another initiative involves a collaboration between companies such as Stedin, Eneco, Gasunie, Deltawind, and the Province of South Holland to investigate the feasibility of constructing a green hydrogen city. The project's goal is to transition the entire village of Stad aan 't Haringvliet (which has 600 residents) to hydrogen by 2025. The project is currently in the investigation stage, during which each project participant has their own task. Another project is being constructed in Hoogeveen, in the province of Drenthe, where the first totally hydrogen-connected residential neighbourhood will be built. The project is divided into two phases: the first (2020-2021) will see 16 residential dwellings erected with a shared hydrogen plant. Electrolysis is used to manufacture hydrogen, with power provided by solar panels installed on the rooftops of all 16 dwellings. The second phase (2021-2022) will see the construction of 80 residential homes, each with solar panels; however, these 80 homes will be supplied with hydrogen from the neighbouring Hystock hydrogen factory. A recently built gas pipeline will transmit the hydrogen from the plant to the dwellings. The goal is to show that hydrogen can be transported safely through gas pipelines (Weijden & Jonk, 2020).

### Net-Metering/Behind -the -meter storage

Supporting view - A net-metering approach in the Netherlands encourages small-scale PV development. A value-based price is paid per kWh of PV generation when PV generation surpasses a consumer's total yearly electricity use. Furthermore, the energy tax and the ODE levy do not apply to residential self-consumption of power. Households benefit from the PV net-metering plan since the levelized cost of energy (LCOE) for small-scale PV is lower compared to high power prices. Thus, it allows and promotes the integration of renewable energy sources like solar power with a community-based Power-to-Hydrogen setup (Londo et al., 2020).

Opposing view - Net metering for small-scale consumers (often residences with a behind-the-meter manufacturing unit) discourages aggressive market involvement. It also reduces the appeal of hybrid solutions that combine a storage and production unit to boost self-consumption. As a result, net metering is a significant impediment to behind-the-meter storage. New net metering solutions for active consumers are limited under the new electricity market Directive. Multiple Member States still have net metering, which is a significant impediment to the implementation of small-scale storage combined with distributed power generation units(Londo et al., 2020).

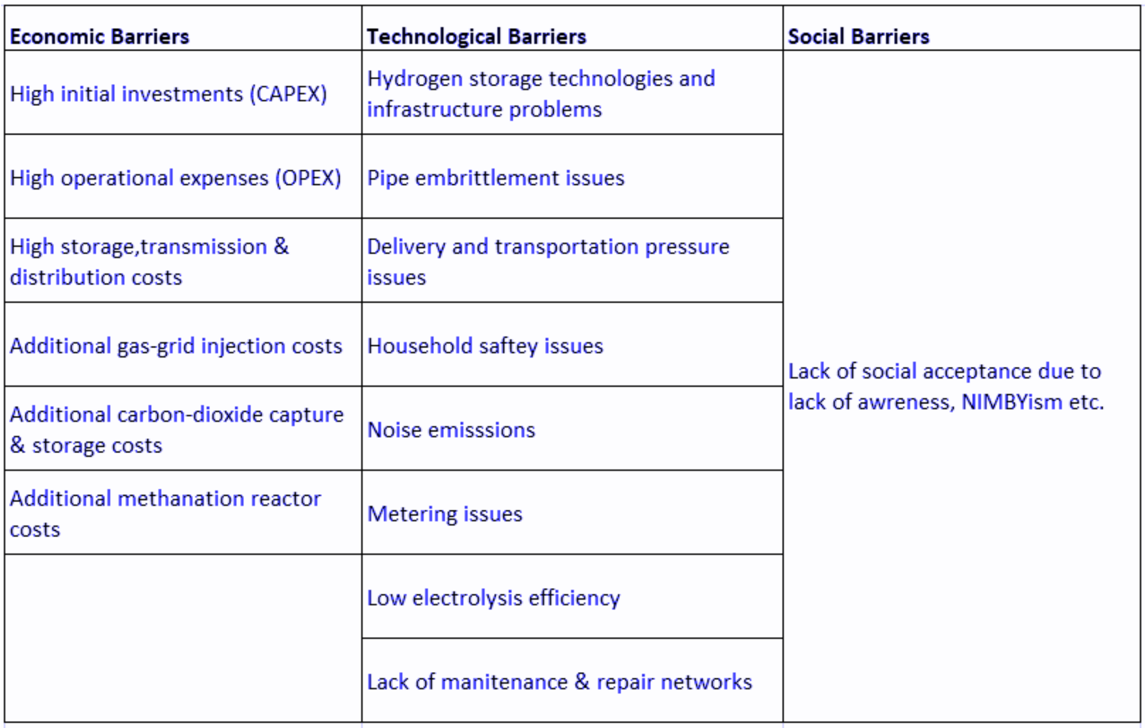
### Reduce/Eliminate Natural Gas

Transition to low-carbon heating for the built environment has been laid down as a target in the Climate Agreement. District heating with renewables, heat pumps is among the possibilities to phase out natural gas heating. The government is expected to raise the natural gas taxes by up to 43% by 2026 (compared to 2019 levels), lowering electricity taxes, providing subsidies through a national heat fund, and funding innovative projects aimed at lowering the cost of renewable heat (Klimaat, 2020a).

The shift will take place on a district basis, according to the housing characteristics and availability of resources. The Natural Gas-Free Districts program, which is being driven by the Gemeente Amsterdam, has begun to identify obstacles, establish knowledge, and best practices to shift away from natural gas. It is expected that roughly 100 pilot neighbourhoods should have made the switch from natural gas to electricity by 2026. By 2030, these pilots and other district-based methods should have resulted in 1.5 million restored homes. The Dutch Heat Act is undergoing extensive revisions to enable the transition away from natural gas heating. It is expected to be published in 2022. Market design, heat tariff control, and emissions reduction standards will all be affected by the amendment, which will also outline the duties and obligations of municipalities and network operators (Amsterdam, 2020).

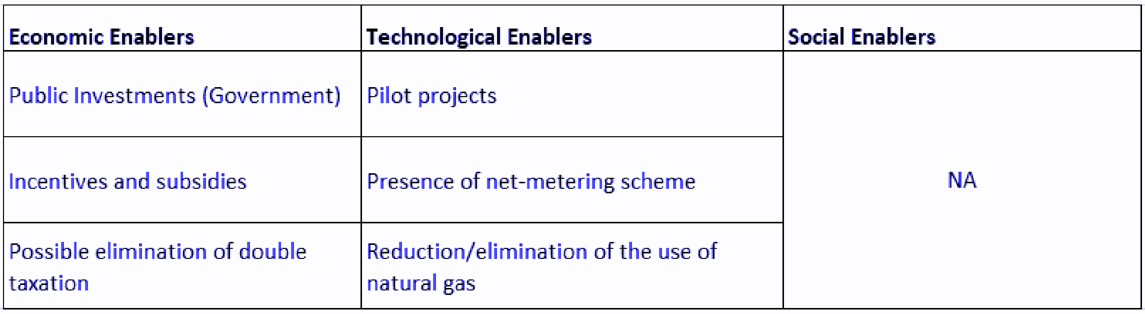
## 4.2 Overview of enablers and barriers (literature)

Based on the results of the literature study done in Section 4.1 Enablers & Barriers. An overview of enablers and barriers concerning the use of green hydrogen in building stock is presented below.



| **Economic Barriers** | **Technological Barriers** | **Social Barriers** |
|---|---|---|
| High initial investments (CAPEX) | Hydrogen storage technologies and infrastructure problems | Lack of social acceptance due to lack of awreness, NIMBYism etc. |
| High operational expenses (OPEX) | Pipe embrittlement issues | |
| High storage,transmission & distribution costs | Delivery and transportation pressure issues | |
| Additional gas-grid injection costs | Household saftey issues | |
| Additional carbon-dioxide capture & storage costs | Noise emisssions | |
| Additional methanation reactor costs | Metering issues | |
| | Low electrolysis efficiency | |
| | Lack of manitenance & repair networks | |

*Table 15 Barriers from literature*



| **Economic Enablers** | **Technological Enablers** | **Social Enablers** |
|---|---|---|
| Public Investments (Government) | Pilot projects | NA |
| Incentives and subsidies | Presence of net-metering scheme | |
| Possible elimination of double taxation | Reduction/elimination of the use of natural gas | |

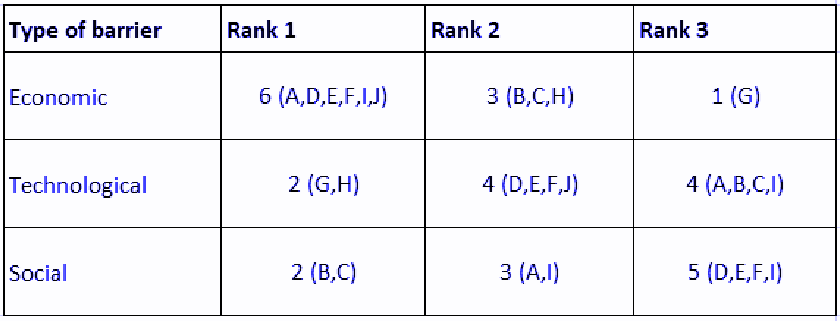
*Table 16 Enablers from literature*

# CH.5 – RESULTS FROM INTERVIEWS

This section summarizes the study's major results and explains their significance. The barriers and enablers identified during the interviews are presented, along with the suggestions to overcome these barriers. The barriers and enablers are combined, and those that appear more than once are filtered out. The most frequently mentioned barriers are those that numerous stakeholders may encounter, making them critical to address.

## 5.1 Barriers from interviews

Before delving into each of the categories of barriers, the interviewees were asked to rank the categories of barriers and enablers, i.e., which type of barriers they considered to be most essential to address and which enablers could be helpful in addressing the critical barriers. Table 17 shows the distribution of how each of the barriers was ranked by the respondents.



| Type of barrier | Rank 1 | Rank 2 | Rank 3 |
|---|---|---|---|
| Economic | 6 (A,D,E,F,I,J) | 3 (B,C,H) | 1 (G) |
| Technological | 2 (G,H) | 4 (D,E,F,J) | 4 (A,B,C,I) |
| Social | 2 (B,C) | 3 (A,I) | 5 (D,E,F,I) |

*Table 17 Ranking of barriers (Frequency-based)*

### Economic Barriers

The barrier referred to as "High investment costs (CAPEX)" is viewed as a catch-all category of economic barriers by the interviewees. Meaning; the barrier was mentioned to be one of the most important amongst the other economic barriers. The high cost of the electrolyser and system prevents the company/individual from making such a large capital investment at the start. Then, an associated cost was mentioned, i.e., the "High operational expenses (OPEX)," which accounts for nearly 25%-30% of the total system costs. Additionally, the costs associated with carbon dioxide storage and capture was also mentioned by the interviewees.

.

Interviewee A added another essential barrier that could be added to the economic barrier list. He talks about the “EU Hydrogen Strategy”, which is aimed at reducing the cost of generating green hydrogen in Europe from €2.5 to €5.5 per kilogram to €1.1 to €2.4 per kilogram by 2030. He questions the validity of the cost goal by giving reference to the presence of competitors in the market, though he is assured that because of technological advancements, the cost of green hydrogen will go down. However, there is a snag. The “EU Hydrogen Strategy” aims to reduce the cost of electrolysers from €900 per kW to €450 per kW or less by 2030. However, leading Chinese manufacturers are already selling equipment at the cost of €10 per kilowatt-hour. While Chinese manufacturers benefit from lower raw material and labour costs, they have also concentrated on more established alkaline electrolysers. However, the EU spent the better part of a decade developing solid oxide and proton exchange membrane (PEM) technologies, the latter of which can ramp up and down in tenths of a second. These are more costly than alkaline and still a long way behind in terms of scale.

Interviewee A based on the facts stated above, questions the goal set in the EU Hydrogen Strategy:

> *"Is the goal realistic? Can the EU keep up with the cost of Chinese electrolysers? Most likely not. Is it capable of meeting its cost goals without doing so? Most likely not. "*

On the other hand, interviewee B justified the investments being made by the governments and the EU:

> *"The energy industry is enormous, while around $11 trillion over 30 years is a large sum, it is not startlingly large when required for the whole energy system."*

According to him, the high cost is due to three factors: the electricity used to produce the hydrogen, the construction of solar panels and wind turbines to do so cleanly account for more than half; the electrolysers, the machines that generate the large amounts of electricity; and the transportation, such as pipelines and shipping. He added that -

> *"It is not good to consider the cost of green hydrogen as an "energy return on investment" when it is critical for the world to achieve net-zero emissions quickly'. In order for hydrogen to "pay for itself," it will need to be utilized extensively."*

Interviewee C added another point to the economic barriers list. According to him, one of the most perplexing areas of concern is the demonstration and implementation phases. The funding for a new subject is frequently available at the early stage of investment. Indeed, it is during the demonstration phase, the implementation and upscaling phases, that operational costs exceed those of “traditional” (often fossil or fossil-based) alternatives significantly. Costs rapidly increase because of the desired upscaling of production and application. As a result, funding that is solely dedicated to investment is no longer sufficient.

Interviewee H presented the difficulties associated with the implementation of a green hydrogen infrastructure outside the industrial environment by stating several comparison facts:

> *“Hydrogen, of course, is irreplaceable as a chemical feedstock. However, as an energy storage medium, it has a round-trip efficiency of just 50% — much less than batteries. Hydrogen is four*

> *times as expensive as natural gas as a source of heat. Setting a hydrogen pipeline network is much more expensive than electricity lines, which prevents its introduction in the built environment.".*

According to him, hydrogen could be used to decarbonise those areas of the energy system that electricity could not reach.

## Technical Barriers

The interviewees identified the following barriers as significant: low electrolysis efficiency and limited hydrogen storage options. According to the interviewees, decreased electrolysis efficiency is the primary reason for the technology's lack of adoption in comparison to other technologies on the market. On the other hand, they emphasized that the process's learning rate and efficiency would improve in the coming years. Efficiency improvement is an incremental process that we cannot control and is assumed to occur in the future. The interviewees were confident that injecting hydrogen into the gas grid in the Netherlands would not be difficult due to the country's extensive pipeline network. It is feasible to implement in the short term (by 2025) once the necessary safety tests and regulations are in place. On the other hand, due to the complexity of the electrolysis systems and associated devices, the repair and maintenance networks should be well established in the market. Because the economic viability of the system is contingent on the electrolyser's operating hours, it is critical to implement a predictive maintenance system. Interviewee G emphasized the importance of blending:

> *"One explanation for the high level of interest and excitement for green hydrogen is that the infrastructure is already in place in the Netherlands. With hydrogen at a concentration of approximately 10%, it is feasible to simply mix it into natural gas pipes today, and it works well."*

A new viewpoint about the technical barriers was added by interviewee E, who questioned the entire notion of utilizing excess renewable energy to create hydrogen. Interviewee E was of the view that for a highly linked, continent-scale energy system, the only thing that counts is producing the cheapest green hydrogen feasible; otherwise, producers utilizing the cheapest renewable energy at high-capacity factors and distributing it through the pipeline would outcompete you. He also explained the statement with an example:

> *"Consider, for argument's sake, a grid with a high proportion of renewable energy such that curtailment approaches 30%. It is possible that wind or solar energy with levelized costs of € 17/MWh may nevertheless be marketed economically for € 25/MWh, less than half the cost of any alternative. However, running an electrolyser only on curtailed electricity would be completely uneconomic."*

Through an example, interviewee E also emphasized the importance of high electrolyser working hours to justify the economic investments done.

Another technical uncertainty was pointed out by interviewee F, who, with the help of some data, emphasized a technological uncertainty that might be difficult to achieve in the short term (by 2025). Interviewee F:

> *"The working estimate for electrolyser capacity in the EU for 2050 is approximately 500 GW. To put it in perspective, the highest peak electrical load ever recorded for the whole European continent was around 546 GW. The hydrogen plan has the potential to double Europe's electricity consumption, double its electricity supply, double its electricity distribution capacity, and create an EU wide hydrogen pipeline network which might look hazy in the short term."*

### Social Barriers

The social barriers discussed in theory were also emphasized by the interviewees. They also deemed social acceptance of green hydrogen in society to be one of the major challenges in addition to the prevalent NIMBYism reaction. The emphasis was on the lack of awareness amongst the citizens, which might be the factor that should be addressed on priority.

## 5.2 Enablers from interviews

### Economic Enablers

The interviewees considered the incentives and subsidies offered by the government to be the most powerful weapon that could be used to effectively tackle the barriers due to the high investments (CAPEX) and operating costs (OPEX). The second most talked about enabler was the public funding from the government, which is an essential motivator for private and public research organisations to look towards the green hydrogen in the built environment. Interviewee D was confident of the fact that the cost of green hydrogen would decrease in the future and market conditions would improve:

> *"By 2050, the green hydrogen will be available at costs between $0.7 and $0.9 per kilo, combined with the ability to operate at high-capacity factors, lower capital costs with. I would not be shocked if it fell below that level."*

### Technical Enablers

The interviewees considered the pilot projects undertaken by the government and the private players to be game changer for reducing the overall cost of green hydrogen production. The interviewees also had varied opinions on the net-metering scheme, while most of them considered it to be a hampering scheme that beats the purpose of having green hydrogen as a storage medium. There were some who considered it to be a promoter of small-scale PV along with a green hydrogen production setup at buildings. One of the interviewees (E) also mentioned a rather different approach to making green hydrogen. He was of the view that instead of relying only on excess renewable electricity, there should be a system to pass on excess grid electricity for green hydrogen production and subsequent storage. But he also emphasized that a system has to be in place to decide how green this hydrogen is produced from the grid electricity. There were opposing views on curtailing the use of natural gas to promote green hydrogen, and this has been discussed in detail in section 5.7 Natural Gas - Short-term help or an inhibitor.

### Social Enablers

The interviewees gave quite a good number of present and potential social enablers to support the introduction of green hydrogen in the built environment. The unique point about the discussions related to social enablers was that there were some points made that were not directly an enabler but promoted the uptake. Interviewee F talked about the social advantage associated with the use of green hydrogen in our daily life. Interviewee F:

> *"Additionally, individuals must consider the societal advantages associated with the production of green hydrogen, such as the replacement of diesel in vehicles and the resulting improvement in local air quality, particularly in towns near major shipping hubs."*

Interviewee G also underlined the significance of political support and policy signals. Interviewee G:

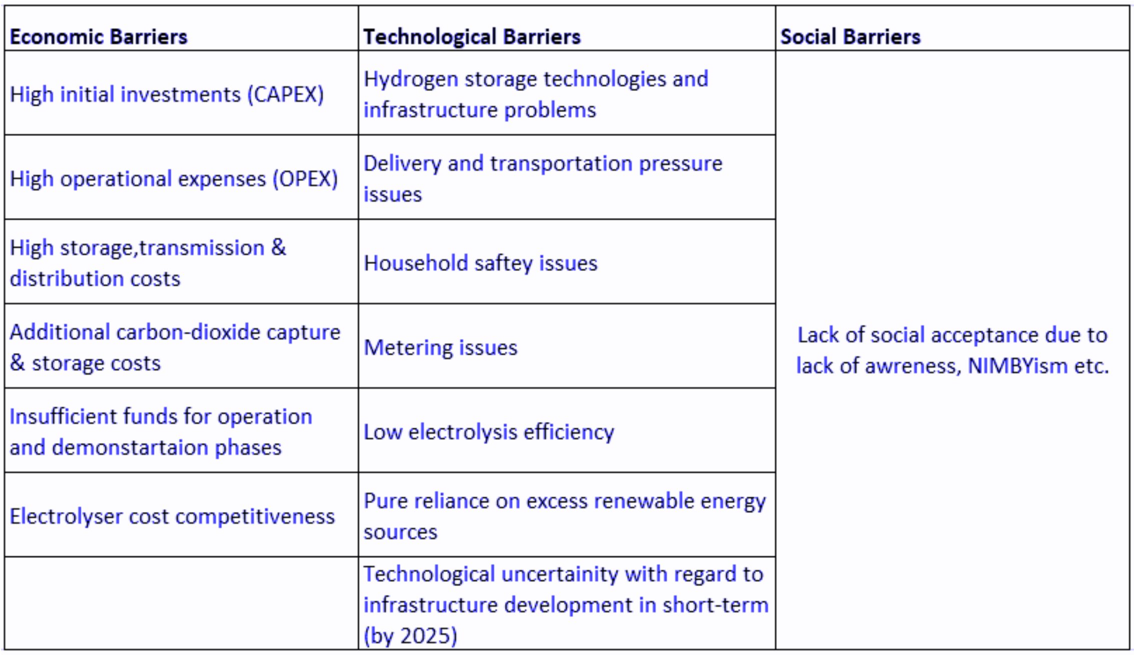
> "*In April 2020, the Dutch government under its National Climate Agreement set ambitious targets for hydrogen. In a letter pledged to the House of Representatives, the government intends to underline the importance of green hydrogen and the instruments to integrate it into the energy mix. The drivers, political signals and government policies are critical for market development.*"

Interviewee H explained the importance of policies or formal statements, as well as signals from governments such as long-term commitments or targets that tend to motivate private sector investments in built environment-based hydrogen projects. Interviewee, I explained how knowledge exchange through networks would be helpful in building a common public consensus. He said that:

> *"By freely disseminating knowledge about best practices in green hydrogen consumption and production will help to speed up learning by connecting disparate intellectual resources and stakeholders. Partnerships and coalitions are also essential they bring together many actor's knowledge, financial, and technological resources."*

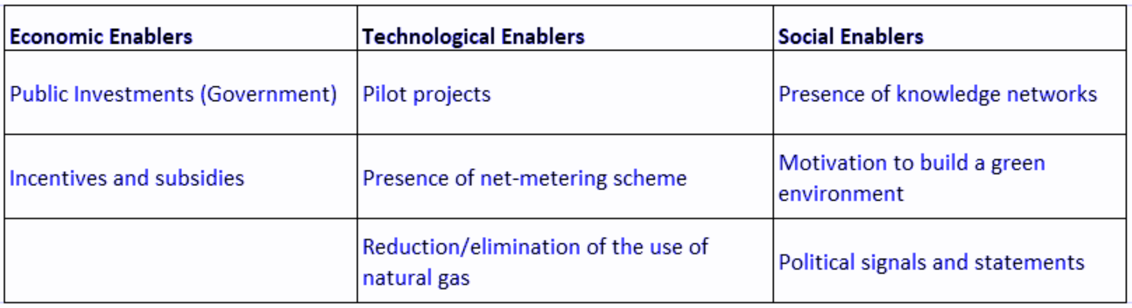
## 5.3 Overview of enablers and barriers (interviews)

Based on the interviews with the stakeholders. An overview of enablers and barriers concerning the use of green hydrogen in building stock is presented below.



| Economic Barriers | Technological Barriers | Social Barriers |
|---|---|---|
| High initial investments (CAPEX) | Hydrogen storage technologies and infrastructure problems | Lack of social acceptance due to lack of awreness, NIMBYism etc. |
| High operational expenses (OPEX) | Delivery and transportation pressure issues | |
| High storage,transmission & distribution costs | Household saftey issues | |
| Additional carbon-dioxide capture & storage costs | Metering issues | |
| Insufficient funds for operation and demonstartaion phases | Low electrolysis efficiency | |
| Electrolyser cost competitiveness | Pure reliance on excess renewable energy sources | |
| | Technological uncertainity with regard to infrastructure development in short-term (by 2025) | |

*Table 18 Barriers from interviews*



| Economic Enablers | Technological Enablers | Social Enablers |
|---|---|---|
| Public Investments (Government) | Pilot projects | Presence of knowledge networks |
| Incentives and subsidies | Presence of net-metering scheme | Motivation to build a green environment |
| | Reduction/elimination of the use of natural gas | Political signals and statements |

*Table 19 Enablers from interviews*

## 5.4 Comparing enablers and barriers (literature vs interviews)

| Category | Barrier | Literature | Interviews |
|---|---|---|---|
| Economic | High initial investments (CAPEX) | Yes | Yes |
| | High operational expenses (OPEX) | Yes | Yes |
| | High storage, transmission & distribution costs | Yes | Yes |
| | Additional gas-grid injection costs | Yes | |
| | Additional carbon-dioxide capture & storage costs | Yes | Yes |
| | Additional methanation reactor costs | Yes | |
| | Electrolyser cost competitiveness | | Yes |
| | Insufficient funds for operation and demonstration phases | | Yes |

|  |  |  |  |
|---|---|---|---|
| Technological | Hydrogen storage technologies and infrastructure problems | Yes | Yes |
|  | Pipe embrittlement issues | Yes |  |
|  | Delivery and transportation pressure issues | Yes | Yes |
|  | Household safety issues | Yes | Yes |
|  | Noise emissions | Yes |  |
|  | Metering issues | Yes | Yes |
|  | Low electrolysis efficiency | Yes | Yes |
|  | Lack of maintenance & repair networks | Yes |  |
|  | Pure reliance on excess renewable energy sources |  | Yes |
|  | Technological uncertainty with regard to infrastructure development in the short term (by 2025) |  | Yes |
| Social | Social acceptance issues | Yes | Yes |

*Table 20 Comparison of barriers*

| Category | Enabler | Literature | Interviews |
|---|---|---|---|
| Economic | Public Investments (Government) | Yes | Yes |
|  | Incentives and subsidies | Yes | Yes |
|  | Possible elimination of double taxation | Yes |  |
| Technological | Pilot projects | Yes | Yes |
|  | Presence of net-metering scheme | Yes | Yes |
|  | Reduction/elimination of the use of natural gas | Yes | Yes |
| Social | Presence of knowledge networks |  | Yes |
|  | Motivation to build a green environment |  | Yes |
|  | Political signals and statements |  | Yes |

*Table 21 Comparison of enablers*

## Barriers

A total of 18 barriers were found from interviews and the literature study. The interviewees ranked the economic barriers as the ones needing immediate attention, followed by the social barriers and were neutral on the technological barriers as they felt that these would improve over time as the learning curves of the associated technologies improve.

| **Barriers Category** | **Rank** |
|---|---|
| Economic | 1 |
| Social | 2 |
| Technological | 3 |

*Table 22 Ranking of barriers*

There was an overlap between theory and practice concerning the initial investments required (CAPEX) and operational expenses (OPEX) as the most critical economic barriers. The theory goes into greater detail about the various cost-related barriers, such as CAPEX, OPEX, and storage and transportation costs, that make pre-financing difficult, but the interviewees consider the initial investments (CAPEX) to be the economic barrier that should be addressed first. The respondents and the literature study also agreed on the storage, transmission, and distribution costs as an economic barrier to green hydrogen use in households. The interviewees suggested some additional economic barriers, like the lack of funds in the operation phase of the green hydrogen usage projects, which could be a probable cause of scarce demonstration projects for hydrogen use in the households. Moving to the technological barriers, the interviewees and the researchers were concerned about the storage, transportation, distribution, and safety-related issues when using hydrogen in the Dutch households. There were some comments from the experts concerning the over-reliance on excess renewable energy sources like solar and wind power for hydrogen production. They were worried about the supply and demand mismatch if hydrogen production only uses extra renewable resources. Social acceptance was also deemed a significant barrier. The interviewed experts and the theory considered persuading the society to use hydrogen in the households to be a challenge because of safety issues discussed in the technological barriers and the high upfront costs associated with the system installation.

## Enablers

A total of 9 enablers were found from interviews and the literature study. The interviewees ranked the economic enablers as the ones that could be most effectively used to promote green hydrogen use. The next focus was on the technological enablers, mainly the pilot projects. The objective should be to provide room for ancillary research in higher TRL technologies and processes, as well as for lower TRL technologies and processes that enable breakthroughs that could translate into a product/technology for society. The social enablers underlined the need of integrating green hydrogen into society by demonstrating actual instances of hydrogen projects in existing building stock that may serve as models for future scale. This means that these initiatives must prioritize social actors' engagement, including properly prepared information packages and knowledge exchange, to get the maximum amount of support for the projects.

| **Enablers Category** | **Rank** |
|---|---|
| Economic | 1 |
| Technological | 2 |
| Social | 3 |

*Table 23 Ranking of enablers*

The economic enablers like the government investment schemes and subsidies were mentioned by both the interviewees and in the literature study. In addition, the literature study talked about the double taxation regime where the households or businesses were taxed for both buying and producing the electricity to be a disincentive. From 2020 onwards, the Dutch government would start working towards ending this regime. This was deemed to be a positive sign for promoting small-scale hydrogen storage systems. Also, the role of natural gas in promoting hydrogen usage in households was ambiguous as the literature considered eliminating/reducing the use of natural gas as an enabler for hydrogen penetration into society. In contrast, the interviewees regarded natural gas to be important in promoting hydrogen usage through blending. The literature study did not show any social enablers for promoting hydrogen usage in Dutch households. But the innovation and diffusion experts emphasised strengthening the knowledge networks and the motivation to have a green environment as forces that would prompt users to adopt hydrogen. In addition, the policy signals and statements from political leaders could also prove beneficial for promoting hydrogen usage in households.

## 5.5 Renewable Energy Contribution

All the respondents agreed that the Netherlands is putting a greater emphasis on renewable energy sources, and Dutch energy policy reflects this. Interviewees and the literature depict the growth in solar PV and wind energy output in the Netherlands over the past few decades. Even though there is a lot of discussion about integrating renewable energy sources, the belief is that the shift is not yet complete. In the Netherlands, for example, interviewee D talked about the technological lock-in with fossil fuels and natural gas. Interviewee J also mentioned that the Netherlands still uses natural gas as one of the main sources to power the built environment.

In addition, the traditional sources of energy are still being used in many end-use sectors. Only 11% of the domestic natural gas supply (the single most frequently utilized energy source in the Netherlands) flowed to power plants in 2014. (IEA, 2017). Several respondents emphasized the fact that electricity has a little part in the entire Dutch energy system. Interviewee I, for example, said, even though the numbers cited may not be completely accurate:

> *"For heating and cooking, we transfer 80% of the energy we carry as a business to our consumers through the gas infrastructure. Many people don't realize this; they believe it's all about power.*

> *Although we hear about decentralized renewable energy, the gas grid transports 80% of the energy."*

In terms of energy production, wind and solar together produced just 8% of total electricity in 2015 (IEA, 2017). Interviewee A made a point regarding the integration of wind and solar power with green hydrogen production.

> *"Electrolysis could gain an advantage by using solar energy to produce hydrogen. Due to the fact that solar energy accounts for just a small portion of overall power generation in the Netherlands, redirecting solar energy to hydrogen production does not result in a reduction in greenhouse gas emissions. That may change if solar energy production is increased in the future."*

## 5.6 Green hydrogen as a decarboniser

Regarding the use of green hydrogen for decarbonisation, the interviewees were mostly positive, but there were some problems that were highlighted. Interviewee A was very confident about the role of green hydrogen in decarbonisation which was evident in his comment:

> *"The most abundant element in the universe seems to be the panacea for all energy problems. It could be manufactured wherever there is access to power and water. It can produce either heat or electricity. It can be generated, stored, transported, and utilized without polluting the environment or emitting carbon dioxide."*

Interviewee B was a little sceptical on the effectiveness of green hydrogen for decarbonisation:

> "*Hydrogen is only as clean as the energy used to produce it.*"

Interviewee C, however, mentioned an entirely different aspect of having green hydrogen as a fuel:

> *"Due to the fact that hydrogen may be produced geographically dispersed by anyone, no OPEC cartel could ever control supply or price. There will never be another energy war."*

Interviewee E cautioned about the possible green hydrogen hype in his statement:

> *"We know that green hydrogen may theoretically be utilized in a variety of applications. It will not, however, happen magically in areas like the built environment that do not presently utilize it just because it is green. Hydrogen will have to win steadily dealing with each of the end-use sectors, and this would not be easy. Not only must it outperform the current technology, but it must*

> *also outperform all alternative zero-carbon options for that use case. This is the point at which hydrogen hype meets reality."*

Interviewee F was positive about the green hydrogen usage and even called it a "Swiss Army Knife" for the clean energy transition. She also believed that integration of solar and wind power for hydrogen production at the household level with green hydrogen would be very beneficial in the future:

> *"Solar and wind energy, and particularly batteries, have experienced dramatic cost reductions over the past years; thus, green hydrogen, with its high energy density and help from renewable sources, is anticipated to fill the gaps for making our households clean and green."*

## 5.7 Natural Gas - Short-term help or an inhibitor

As mentioned in the discussion of interview results, the use of natural gas was reduced or eliminated to promote the use of green hydrogen in the literature, but the interviewees had a different view on this. The literature talks about natural gas as not an emission-free fuel. Natural gas accounted for about 22% of carbon dioxide emissions in 2020, and its proportion is increasing (Londo et al., 2020). Another problem is fugitive emissions, particularly methane leakage. According to interviewee G, the natural gas's story is changing in both areas, from cleaner than coal to worse than renewables. Other regulatory obstacles to gas are also developing, typically on a municipality level. He also talked about the fact that the Netherlands has already prohibited gas connections in newly constructed buildings. The next frontier in decarbonization efforts is displacing gas used in residential and commercial buildings. In this category, the primary low-carbon alternatives for decarbonizing heating include electrification through heat pumps or direct electric heating, district heating, or green gases such as biogas and hydrogen (Klimaat, 2020b).

However, the interviewees feel that switching to any of these will not be cheap or simple but will be essential if deep decarbonization is to be achieved. In the short term, the focus should be on methane monitoring and reduction, as well as appropriate business practices across the value chain. For precise accounting of methane emissions, an integrated strategy using drones, satellites, aeroplanes, and on-site sensors is needed.

Interviewee B talked about carbon capture and storage as a relevant option, though it is not a zero-emissions technology. He said that:

> *"Capturing 90% of emissions is an excellent start, but inadequate in light of the need for yearly net negative emissions. Carbon capture and storage will also be ineffective in markets that lack natural carbon dioxide storage or a market for the carbon dioxide."*

Interviewee G talks about hydrogen blending. Blending provides a near-term chance to decrease emissions without affecting the business. Blending natural gas with 20% renewable hydrogen (by volume) would result in a 7% reduction in carbon dioxide emissions from combustion (approximate data). Blending is a necessary but not sufficient condition for deep decarbonization. Interviewee H talked about the existing gas infrastructure which can handle green hydrogen mixes, but today's turbines, pipe materials, seals, compressors, valves, and appliances are not capable of running on pure hydrogen. Unless natural gas infrastructure is hydrogen-ready, today's investments in natural gas infrastructure risk becoming stranded. Similarly, appliances such as ovens, boilers, and heaters will need to be hydrogen ready.

Interviewee H also talked about the urgency of readying the infrastructure for blending:

> *"There is a genuine risk that gas firms will promote the story that their infrastructure is necessary for a net-zero future without making the necessary investments. As a consequence, there will be uncertainty and delay — and the climate does not have time for that. As a result, gas firms must develop a clear road map for bringing their systems up to net zero. Everything else is background noise. They will need to do so with the understanding that taking significant action now does not ensure future success. Transitions are often tumultuous and disruptive, rather than seamless.*"

## 5.8 Policies to support renewable energy sources

The discussion on the policies by the Dutch government to promote clean energy was backed with facts. According to interviewees, the Dutch Government has been trying to promote sustainable and secure energy supply by working on policy instruments, specifically the financial ones. Interviewee J saw promoting the subsidies to support the production of clean energy sources like green hydrogen as an essential instrument in the transition to a green hydrogen-powered built environment. According to him, sustainable production subsidies:

> *"It is necessary to subsidize the energy output to build on a business model for projects. Production subsidies are close the gap between energy production investments and the average wholesale market price per kWh."*

Interviewee C also mentioned that the main production subsidies in the market which are prevalent and have been successful are MEP and SDE++. Largely, the interviewees had a positive comment on the subsidies being provided by the Ministry of Economic Affairs to promote the addition of green hydrogen and other clean fuels to the energy mix.

## 5.9 Taxation System

Several respondents also mentioned how the present energy tax structure impedes the incorporation of energy storage technologies such as green hydrogen. Interviewee C believes that the present system, which charges both users and suppliers of energy, is preventing battery integration; he described how it works:

> *"Electricity is taxed regardless of whether it is purchased by a customer or a business. If you sell it, you are a producer and must pay tax on it. Thus, if you own a battery and charge or discharge it frequently throughout the day, you are subject to tax on both the purchase and sale of the battery, resulting in a double tax."*

The present system, according to interviewee J, holds energy storage systems back:

> *"There are additional legal factors that make energy storage devices difficult to implement. The tax and the pricing system are too old to support modern energy storage techniques like green hydrogen, pumped hydro-storage etc. They ought to be altered."*

Interviewee, I said that there is a need to re-configure the taxation regime:

> *"For example, you take a unit of energy from the grid and store it; you pay the tax. Now, when you return it back to the grid, you again have to pay the tax. This needs to be addressed immediately."*

But interviewee I also wanted the government to cautiously change the tax structure without losing income and, if possible, propose a new tax structure that could compensate for the deviation from the current one. Interviewee A, on the other hand, said that the revenue from energy taxes was very modest in comparison to the entire tax revenue to the government and that altering the tax structure might reduce overall society expenses. In reality, environmental taxes and levies brought in 23.9 billion euros in 2014, accounting for 9% of total government tax collections (including social contributions), with individuals paying 66% and businesses contributing 34% (the Netherlands, 2015). According to Klimaat (2020b), the Netherlands has one of the largest shares of environmental taxes and levies in overall taxes in Europe.

Furthermore, many respondents believed that the existing "stepped" tax structure hampered storage. This method distinguishes between several types of energy users, ranging from small businesses (using less than 10,000 kWh per year) to big businesses (using more than 10 million kWh per year), with many levels in between (Belastingdienst, 2021). Large customers pay a lower proportionate tax on used energy than small consumers, which may act as a deterrent to large consumers investing in storage. This approach, according to interviewee B, is an "old tax regime", and he sees no change in the energy consumption from individuals and businesses because of this regime:

> *"You have to keep in mind that emission is an emission. Whether a small firm produces it or a large one, it should be discouraged at all costs. This differentiation prompts the large companies to refrain from using clean sources or any energy storage media."*

Interviewee B explains the drawback of price differentials with an example where he talks about a firm that consumes more energy than necessary to pay less tax by moving into a lower rate bracket, rather than consuming less and investing in developing energy storage technologies like green hydrogen. Interviewee D, from an economic perspective, was of the view that this structure is in place to keeps Dutch companies remain competitive in the market. Interviewee G liked the “stepped taxation” as it helps to segregate and view the minutes of consumption. Interviewee F said that to achieve the targets of the climate agreement, either the companies need an alternate clean solution or government should force emission reductions.

## 5.10 Green hydrogen for the built environment

The interviewees emphasized the role of green hydrogen in the built environment. One of the interviewees referred to the fact that the transportation sector has been expected to carry the burden of the responsibility for greenhouse gas reduction, even though it accounts for just one-third of greenhouse gas emissions. He asserted that if we are serious about addressing climate change, we must also phase out fossil fuels/natural gas from non-vehicular uses. While the concept of pumping green hydrogen directly into homes or businesses may sound far-fetched, it is feasible. Interviewee A stressed the addition of green hydrogen to the existing liquid natural gas system as a start. Interviewee A:

> *“While hydrogen's flammability raises safety issues, with the appropriate safeguards in place, these worries may be addressed – electricity is hazardous, but we all use it.”*

Interviewee C was in favour of using green hydrogen in the community space but was of the view that in the next 2-5 years, heat pumps would be a better choice for decarbonisation in the built environment.

> *“Heat pumps are the game changer, generating about four times the amount of heat per unit of wind or solar energy as a hydrogen boiler or furnace. Hot water can be stored considerably more cheaply than hydrogen or energy in advance of a cold snap, and thermal batteries are advancing rapidly. Where there is a possibility of dangerously low temperatures, hybrid heat pumps seem to be an elegant answer.”*

He also said that a legitimate issue with heat pumps is upgrading hundreds of millions of households and businesses globally to heat pumps at a global cost of billions of dollars will take time. And finally zeroed into the idea of incorporating green hydrogen into the natural gas system. Interviewee B even supported the use of green hydrogen in the built environment but called it a “distant, utopian dream”. He even gave an idea about an imaginary “Worldwide Hydrogen Energy Web” where millions of users on regional and local levels would trade and use hydrogen, forming a decentralised system.

## 5.11 Communities

A lot of respondents mentioned the importance of communities and community-scale storage. Local community participation, according to interviewee B, is critical in assisting with the integration of clean energy sources and achieving a goal of total self-sufficiency. Interviewee B believed that community-level storage would be simpler to deploy for many homes than a distributed and individualistic small-scale storage:

> *"Bigger the scale, better would be the cost feasibility. It's more difficult to afford for one family than it is for hundreds."*

But this notion of aggregation leaves us with a question of who should implement such a large-scale storage system? Interviewee B talked about a combined effort from the municipalities, housing associations, the government, and the citizens to make the implementation possible. The vision making should be with the government and the DSOs, TSOs, whereas the implantation charge should be taken by the municipalities.

Interviewee C also mentioned a cooperative of farmers who own and run renewable energy sources and energy storage systems to provide clean energy to a community of approximately 300-400 people. While Interviewee D mentioned a private entity that develops, owns, and operates community storage and sells services to the grid operator. These two examples show the potential to integrate green hydrogen production with renewable energy sources in the community setup mentioned above.

## 5.12 Dutch national government and private players

Interviewees believed that apart from its role to financially support the transition, there have been instances when lacking information flow within the layers (national, provincial, local) as well as a lack of strong governmental leadership. Interviewee A, for example, highlighted the government's "rather irregular approach" in terms of financing for wind technology, in which funding regimes changed many times, making it difficult for investors. Short-term policy solutions, according to interviewee A, are problematic.

> *"There is no long-term assurance with long-term commitments — and this is the essential factor. Everyone – even big business – is pressing the government for a long-term commitment to specific regulations. However, political parties often have other, more popular, items they wish to offer to people in the Netherlands."*

Furthermore, Interviewee A mentioned how the Netherlands' high number of municipalities (about 400) made information exchange and collaboration crucial. The issue, as stated by interviewee C, is that each municipality has its own objective, making the energy transition difficult. Furthermore, Interviewee G explained with an example the process of obtaining a municipality's approval to pilot an innovative battery project, where a lack of shared information or a common regulation to govern a new project hampers the introduction and approval. According to this interviewee:

> *"In policy instruments, the flow battery as a notion is unknown. As a result, this is a stumbling block since each municipality must determine whether or not they need to be concerned about the battery and what steps must be taken to provide a safe environment. It would be beneficial if there was a regulation for this kind of equipment in the law that allowed towns to easily determine what criteria are required for a safe scenario with a battery placed inside their municipality."*

They went on to argue that sharing information was becoming more important as a means of bridging knowledge gaps and that more standards for emerging technologies were needed. Interviewee B concurred, saying that the government should be encouraged to take a larger role in standards development. Interviewee B also felt that financing for pilot programs would be beneficial, as previously indicated. Pilot schemes are also beneficial, according to this respondent since their pilot status allows them to circumvent existing laws in certain cases.

While there were some critical remarks regarding the government's involvement, they were not entirely negative. For example, interviewee E characterized municipalities as workspaces for innovation in which society could be easily integrated. The provincial and local municipalities have supported European energy goals. This, according to interviewee F, is a "really positive indication" to the interviewee. Although this respondent admitted that the government would make errors and that meeting goals would take time, they were generally optimistic about the government's involvement.

Cooperation between the government and big industries or companies was also mentioned by many respondents as being essential. Interviewee G believed that sometimes corporations are faster than the governments in adopting innovations and working in the right direction. Interviewee B concurred, believing that corporations are very open to changes and adjust fast as compared to the incumbent governments. Therefore, he saw a collaboration between government and private players on research projects and investments to be good news for the upcoming transition. However, these views may appear to contradict the earlier findings regarding the taxation regime; when the belief was that the big companies are reluctant to invest and research on energy storage solutions like green hydrogen.

## 5.13 Sector coupling a futuristic option

Furthermore, in addition to discussing green hydrogen and related technologies, several respondents stressed the necessity of interconnecting various sectors (for example, electricity, gas, heat, and mobility) in order to achieve a successful energy transition. A unique viewpoint was that the final aim is to have an emission-free environment and not necessarily a green hydrogen-powered environment. According to interviewee E:

> *“You wouldn't say, "We want hydrogen there," simply because it's green - it's pointless. It's only meaningful if it's both commercially and systemically feasible. You may have as much solar and wind as you want - it's the objective, after all, to decrease emissions. ”*

This respondent, on the other hand, acknowledged the importance of flexibility associated with the use of green hydrogen in a built environment:

> *“Level the field for other technologies too, try to integrate the flexibility associated with green hydrogen with other clean technologies.”*

Interviewee H said that the linkage between technologies could help in fastening the transition rather than being dependent on a single technology. Interviewee E talked about “Power-to-X” technologies in general. Here, X could be any fuel like electricity, methane gas or any other industrial gas that could be beneficial. Interviewees F indicated that developing a decarbonized energy system that is linked and beneficial to the industry, the power sector, and society is attainable using sector coupling. The higher power demand from industry will contribute to the energy system's flexibility by mitigating the effects of the increased amount of renewable energy from the individual or a community and therefore assisting in the stabilization of electricity prices. Certain industrial processes, such as process heat generation and hydrogen synthesis, may benefit the households by sharing the excess with the built environment and order to operate at the lowest possible cost. This will benefit the industry, accelerate the use of renewable energy, and ultimately benefit the world. Interviewee H said that there is a certainty that the future power supply system will be very complicated to regulate, balance, and optimize than today. Renewable energy sources will always be intermittent; as a result, the energy system must be adaptable, durable, and efficient in order to address this power problem. This could be solved with sector coupling.

## 5.14 Actions to overcome barriers

As seen in

Table 24, 23 distinct actions were discovered in the interviews and literature review. The respondents underlined the need of developing a business model for green hydrogen in the built environment and establishing standards for the activities involved in the green hydrogen value chain. Specific suggestions were made for barriers that were only addressed in the literature, and a similar pattern was seen for barriers that were only discussed in the interviews. Several ideas were made that might be utilized to tackle numerous obstacles. Table 24 below summarizes the recommendations made to overcome the hurdles and provides a summary of the most significant recommendations.

| **Suggestion** | **Barriers addressed** |
|---|---|
| Look for short-term and long-term storage solutions for green hydrogen | 1. High initial investments (CAPEX)<br>2. High operational expenses (OPEX)<br>3. High storage, transmission and distribution costs<br>4. Lack of green hydrogen storage infrastructure |
| Scaling the green hydrogen production and looking into other production methods | 1. High initial investments (CAPEX)<br>2. High operational expenses (OPEX) |
| Making the natural gas infrastructure ready for hydrogen/blended natural gas | 1. High initial investments (CAPEX)<br>2. High operational expenses (OPEX)<br>3. High storage, transmission and distribution costs<br>4. Pure reliance on excess renewable energy sources<br>5. Technological uncertainty with regard to infrastructure development in the short term (by 2025) |
| Process improvements in the electrolyser technology and optimisation of BOP (Balance of Plant) | 1. High initial investments (CAPEX)<br>2. High operational expenses (OPEX)<br>3. Low electrolysis efficiency |
| Developing a market model keeping in mind the entire green hydrogen value chain | 1. High initial investments (CAPEX)<br>2. High operational expenses (OPEX)<br>3. High storage, transmission and distribution costs |
| Establish regulations associated with the green hydrogen value chain in the built environment | 1. High storage, transmission and distribution costs |
| Establishment of standards for the use of hydrogen | 1. High storage, transmission and distribution costs<br>2. Household safety issues<br>3. Metering issues |
| Gas quality assessment and end-user acceptance | 1. High storage, transmission and distribution costs |
| Developing cost-effective techniques for carbon dioxide capture and try to develop techniques like adsorption | 1.Additional carbon-dioxide capture & storage costs |
| An optional and short-term solution for transporting hydrogen is by converting it to methane. Develop the capability to blend higher hydrogen concentrations to avoid this | 1. Additional methanation reactor costs |

| | |
|---|---|
| cost. | |
| Promote research for electrolysers at the research institutions to fasten the learning rate | 1. Electrolyser cost competitiveness |
| Establish regulations on the limited use of electrolysers from other countries to promote the use of locally manufactured electrolysers or make procurement of foreign electrolysers more cost-effective | 1. Electrolyser cost competitiveness |
| Government should launch schemes aimed at helping the projects in their operation and demonstration phase. The current schemes make provision for funding the operation and demonstration phase sufficiently. | 1. Insufficient funds for operation and demonstration phases |
| Research is needed to find materials that could sustain a mixture of hydrogen and natural gas | 1. Pipe embrittlement issues<br>2. Delivery and transportation pressure issues |
| Establishment of standards aimed at the pressure required at each stage of storage, transmission and distribution | 1. Delivery and transportation pressure issues |
| Establishment of standards for the use of hydrogen in households and indoor environments | 1. Household safety issues |
| Digitisation in energy transition should be promoted | 1. Household safety issues |
| Promote human capital development | 1. Household safety issues |
| Research is needed to eliminate or lower the noise emissions related to gas flow and other processes | 1. Noise emissions |
| Innovate to develop devices and methods to accurately measure the consumption according to the calorific value of the end-product and pressure | 1. Household safety issues<br>2. Metering issues |
| Establish standards for charging customers ranging from individual households to big apartment buildings | 1. Metering issues |
| Establish extensive maintenance and repair networks in collaboration with government, municipalities and private players | 1. Lack of maintenance and repair networks |
| For the short-term (2025), do not eliminate the use of natural gas. Develop the hydrogen network such that they have a symbiotic relation to natural gas. | 1. Pure reliance on excess renewable energy sources<br>2. Technological uncertainty with regard to infrastructure development in the short term (by 2025) |
| Involving the society in a societal transition | 1. Social acceptance issues |

| | |
|---|---|
| and the concept of regional embedding | 2. Household safety issues |
| Take into account the social consequences of green hydrogen use in an area before the actual introduction | 1. Social acceptance issues<br>2. Household safety issues |

*Table 24 Suggestions to overcome barriers*

Here is a short discussion on some of the specific suggestions made by the interviewees and the literature.

*Suggestion* - Establish regulations associated with the green hydrogen value chain in the built environment
*Innovation need/Required conditions* - Eliminating hydrogen-related obstacles in current legal frameworks and administrative procedures. Work towards simplifying the authorisation and sanction of permits for the carrying out demonstration and pilot projects for green hydrogen use, safety etc. and eliminating obstacles in the Renewable Energy Directive (RED II) that prevent the efficient production of green hydrogen through grid-connected electrolysers (Gigler et al., n.d.).
*Reinforced by* -Literature (FCHJHU, 2017) and all the interviewees.

*Suggestion* - Establishment of standards for the use of hydrogen
*Innovation need/Required conditions* - Standards are critical for ensuring that technology and processes are secure, dependable, safe and energy-efficient, as well as for assuring their uninterrupted operation. Standards provide a unified platform for development and innovation. They also contribute to the improvement of lives and the acceleration of development by fostering the growth of new technology.
*Reinforced by* -Literature (IEA, 2019) and all the interviewees.

*Suggestion* - Gas quality assessment and end-user acceptance
*Innovation need/Required conditions* - Identifying the required/desired gas quality to facilitate the decision on what changes need to be done in the end-user equipment, establishing the most cost-effective techno-economic requirements. This step should be taken at both regime as well as niche levels; at the regime level, a superficial assessment is needed, whereas a detailed assessment would be necessary for the operational phase.
*Reinforced by* -Literature (Gigler et al., n.d.) and all the interviewees.

*Suggestion* - Promote human capital development
*Innovation need/Required conditions* - Hydrogen energy is a relatively young field of study. While hydrogen has been used extensively in industry for decades, it is a novel technology coming to its application in the built environment, energy storage and transportation. The industrial sector is already experiencing severe shortages of skilled people with the necessary skills. Therefore, it is critical to undertake initiatives that focus on developing specialized knowledge and skills. This translates to getting knowledge about working with gases, high pressure etc. and spans multiple disciplines (infrastructure,

storage, technology applications). These efforts should be expanded: further hydrogen education packages should be implemented in schools and other educational institutions. The objective is to carry out these actions in collaboration with other sectors, where the greatest links to relevant businesses, knowledge institutions, and sectors exist.
*Reinforced by* - Interviewees A, C, E, F, G.

*Suggestion* - Digitisation in energy transition should be promoted
*Innovation need/Required conditions* - We cannot overstate the significance of digitalization. When used in the built environment, hydrogen's greatest advantages are the tasks it can do inside the system, including offering flexibility, transporting huge amounts of energy and storage. Technological applications such as dynamic pressure control and improved network modelling will be essential for integrating hydrogen into the built environment. Fostering digitisation in the green hydrogen chain would enable the processes to become safe, efficient and could also solve a lot of technological barriers discussed (IEA, 2019). However, green hydrogen is inextricably linked to the many applications that are driving the digital technology agenda.
*Reinforced by* - Literature only (Gigler et al., n.d.).

*Suggestion*- Involving the society in a societal transition and the concept of regional embedding
*Innovation need/Required conditions* - Cooperation on the energy transition should be concentrated on the transition's "landing pads." These are, in general, physical places ranging from towns and regions to industrial parks and distribution hubs. The sites provide great chances to demonstrate the capabilities of any change to all the stakeholders in society and to assess the success of innovations. The result is an array of feedbacks that must be included in the development of the next, better iteration of the product, idea, or service.

Regional integration is essential since practical initiatives (in this instance, pilots, demonstrations, and implementation projects) constitute a key component of the program. In many instances, the technology has progressed enough to allow for testing and use in reality; in other circumstances, it is already ready for deployment. Due to the novelty of these products and services, it is essential to incorporate the needs of all the stakeholders at every stage of the introduction. Otherwise, there is uncertainty about the actors getting an impression that they were not engaged and informed about the innovation (Source: Interviewees F, I). The demonstration or small-scale projects should be obliged to involve the citizens of the society at some of their planning and execution levels. This obligation could be strictly enforced to get the next rounds of funding (Source: G).
*Reinforced by* - Literature (Glanz & Schönauer, 2021) and interviewees F, G and I.

*Suggestion*- Taking into account the consequences of green hydrogen introduction
*Innovation need/Required conditions* - Another issue that warrants consideration is the possible social and ecological consequences of large-scale hydrogen deployment in a region. If hydrogen consumption

continues to increase at the anticipated rate and large-scale production starts, for example, in regions with strong solar and/or wind potential. It is advised to study the socio-societal and ecological consequences that will happen (Hafner et al., 2020). Local flora and fauna preservation, the ecological impact of green hydrogen generation and the implications of hydrogen storage, transport and distribution for the nearby area should be well-researched before the implementation of a project.
*Reinforced by* - Literature only (Glanz & Schönauer, 2021).

*Suggestion* -Look for long-term storage solutions for hydrogen
*Innovation need/Required conditions* – There are a lot of salt caverns, depleted oil and gas fields in and near the Netherlands. The problem to be addressed is when introducing green hydrogen in the built environment, is the provision of large-scale storage a requirement or not. In addition, investigating the possibilities entails addressing issues such as: are chemical interactions between hydrogen, the reservoir possible, hydrogen reactions with microbes, the effectiveness of the seals and resistance of the materials employed in the gas fields to hydrogen corrosion (Burre et al., 2020).
*Reinforced by* – Literature (Burre et al., 2020) and interviewees A, C, G, J.

*Suggestion* - Scaling the green hydrogen production and looking into other production methods
*Innovation need/Required conditions* - Look into ways to translate laboratory research to large-scale and mass production. Scaling the electrolysis to make it economically feasible, planning demonstration projects amid the NIMBYism discussed in the social barriers. Other factors to be researched are the problem of intermittency associated with renewable resources. The academic community, in collaboration with the business community, should try to weed out this problem to make green hydrogen a reality in the community sphere.
*Reinforced by* - Literature (IEA, 2019) and all the interviewees.

*Suggestion* - Look for a solution focused on short-term and localised storage of hydrogen
*Innovation need/Required conditions* - It is imperative to approximate the required storage capacity in relation to seasonal impacts, as well as the influence of dynamic operations. Hydrogen storage systems, like tanks and underground storage systems, are one of the possible solutions for decentralised community storage. New materials and manufacturing methods need to be adopted/researched to enable lighter and more affordable high-pressure tanks (>800 bar), allowing tanks to be produced in a variety of forms for effective and safe vehicle application. Other than under high pressure, small-scale storage methods include liquid and cryo-compressed (supercritical) storage and liquid organic hydrogen carriers, which are still in their development phase(Glanz & Schönauer, 2021).
*Reinforced by* – Literature (Burre et al., 2020) and all the interviewees.

*Suggestion* - Making the natural gas infrastructure ready for hydrogen/blended natural gas
*Innovation need/Required conditions* – Research should focus on the changes required (technical, organizational, and legal), the scope of a large-scale conversion, and the associated costs that have to be

extensively studied. Research on the embrittlement of materials (pipes, etc.), the effectiveness of odorization and if there. As long as certain safeguards are taken, the current gas infrastructure is theoretically capable of handling low hydrogen concentrations in the Netherlands (van der Roest et al., 2020). Concerns include whether existing constituents of the gas network are capable of handling hydrogen. The feasibility has to be checked under controlled circumstances to determine the long-term impacts of hydrogen addition to natural gas on current Dutch household appliances. In addition, electrochemical hydrogen purification techniques would have to be developed to enable the selective purification of hydrogen from a gas flow. The objective is to scale up while reducing costs and increasing sensitivity to contamination via the use of various membranes. Testing is required to reduce the noise effects that occur because of the increased volume flow while the energy supplied remains constant. This was also covered as one of the barriers to its uptake in society. In the United Kingdom, the study is being conducted on the hazards (including igniting risks) associated with and in the case of pure hydrogen leaks in households and distribution networks. The objective is to obtain insight into how the safety and risk factors associated with natural gas compared to those associated with propane. The studies being carried out in the UK could be helpful as groundwork while testing the gas networks in the Netherlands.
*Reinforced by* – Literature (FCHJHU, 2017) and all the interviewees.

*Suggestion* - Process improvements in the electrolyser technology and optimisation of BOP (Balance of Plant)
*Innovation need/Required conditions* - While alkaline and polymer electrolyte membrane electrolysis is now at TRL 7-9 and on the verge of demonstration, this should be accelerated (Glanz & Schönauer, 2021). It is essential to understand and insight into the behaviour and lifespan of proton exchange membranes, as well as the maintenance expenses connected with them. BOP cost savings and technological optimization (Balance of Plant) are a technological priority.
*Reinforced by* – Literature (Glanz & Schönauer, 2021) and all the interviewees.

*Suggestion* - Developing a market model keeping in mind the entire green hydrogen value chain
*Innovation need/Required conditions* - Develop future-proof business and market models, as well as methods for incorporating the full value chain from manufacturing to end-use into the model. Develop market models that enable inhabitants' individual choices (in the built environment) and ways for paying for and billing the advantages of specific services such as hydrogen storage, demand-side response, and imbalance optimization, among others (Lemke et al., 2015)—evaluating the commercial viability of electrolysis's by-products, such as oxygen, heat.
*Reinforced by* - Literature (FCHJHU, 2017) and all the interviewees.

# CH.6 – APPLICATION OF THE MULTI-LEVEL PERSPECTIVE

## 6.1 Barriers and enablers on the Multi-Level Perspective

Next, the barriers and enablers would be mapped on the three levels of the MLP.

### Revisiting the three levels

#### Landscape

The socio-technical landscape, in this case, is the external factors linked to decarbonisation and climate change which affects or puts pressure on the Dutch economy. For example, in recent years, a variety of international organizations have formed to further the hydrogen alternative, and the International Energy Agency (IEA) has voiced excitement about hydrogen's potential role in a sustainable society. Organisations like the Hydrogen Europe and the Hydrogen Council on an international level work towards making a green hydrogen-powered future. Additionally, there are a number of worldwide initiatives involving Dutch organizations. Through surveys, research, continued development, and implementation, all these initiatives are contributing to the development of a shared vision for hydrogen's role in the energy transition. Knowledge exchange on a bilateral level with countries like Germany, the United Kingdom, Belgium etc., could be beneficial in initiating a landscape-level change. Therefore, landscape-level may be thought of as the broader framework within which the built environment's energy transition occurs (Geels, 2011). The landscape is shaped by large-scale and gradual changes, such as those seen in culture and (scientific) paradigms.

#### Regime

The standards, practices and cultures are created at the regime level (both official and informal) based on common ideas and assumptions. This level presents the greatest challenge in terms of enforcing change since it is populated by (governmental and non-governmental) organizations and institutions dedicated to optimizing the current system (Rotmans et al., 2001). Rather than system innovation, strategies are geared at "optimization and protection of investments" (Van der Brugge et al., 2005). The present paradigm is that the built environment's energy requirement is met by electricity and heat generated by the controlled combustion of fossil fuels (coal, natural gas, and oil). Addressing these challenges would need major modifications to both the physical and institutional structures. Culture change takes time, which implies that the environment has a significant impact on the speed of the transformation. Changes in ideas and cultures have a cascading effect on regimes.

#### Niche

Individual stakeholders, such as small businesses, institutions, and inventors, generate new ideas and technology at the niche level. These technologies represent a considerable divergence from established practices and are geared at system innovation. Their objective is for their innovative technologies to finally be adopted at the regime level, replacing, or complementing existing technologies.

The multi-level viewpoint illuminates the types of stakeholders that are most pertinent to this investigation. These are the regime-level stakeholders who are active in tactical governance activities, are motivated by common interests, develop mid-term initiatives, plans, institutions, and laws, and are preoccupied with optimizing the system's current condition (Van der Brugge et al., 2004). However, while the conservative attitude of regime stakeholders appears to oppose the pursuit of niches (status quo vs innovation), regime stakeholders are critical in overcoming cultural obstacles. Stakeholders in the regime may design institutions that will enable society to improve confidence, engagement, and experience with green hydrogen energy uses in the built environment (Meadowcroft, 2009).

| **Barriers** | **Enablers** |
|---|---|
| **Niche** | |
| High initial investments (CAPEX) [E] | Public and private pilot projects [T] |
| High operational expenses (OPEX) [E] | |
| Additional costs for carbon dioxide storage and capture [E] | |
| Additional costs when using a methanation reactor [E] | |
| Hydrogen storage technologies and infrastructure problems [T] | |
| Pipe embrittlement issues [T] | |
| Delivery and transportation pressure issues [T] | |
| Noise emissions [T] | |
| Metering issues [T] | |
| Low electrolysis efficiency [T] | |
| High storage, transmission and distribution costs [E] | |

| **Regime** | |
|---|---|
| High storage, transmission and distribution costs [E] | Public Investments (Government) [E] |
| Insufficient funds for operation and demonstration phases [E] | Incentives and subsidies [E] |
| Lack of maintenance and repair networks [T] | Possible elimination of double taxation system [E] |
| Technological uncertainty about infrastructure development in the short-term (2025) [T] | Presence of the net-metering scheme [T] |
| Social acceptance issues [S] | Reduction/elimination of the use of natural gas [T] |
| | Motivation to build a green environment [S] |
| | Political signals and statements [S] |

*Table 25 Mapping barriers and enablers on the Multi-Level Perspective*

## Inferences from mapping barriers and enablers

According to the MLP paradigm, the initial premise for the MLP's barrier positioning was that social barriers would occur mostly at the regime level since they would be outside the firm's immediate sphere of control. As seen in Table 25, this is largely accurate. Additionally, impediments to system and process cost reduction were on the specialized niches since they may be investigated and overcome by institutions and individual actors. However, it was stated that the barrier of "high storage, transmission, and distribution costs" exists at both the regime and niche levels. According to interviewee C, it is preferable to establish this barrier at the niche level since experimentation and innovation occurring at this level may assist in lower prices and overcome this barrier. However, he argues that even with cost reductions and innovation in technology and procedures, the three processes (storage, transmission, and distribution) at issue here cannot be simplified due to a lack of rules and standards regulating transmission, distribution, and storage. As a result, it should be put at both levels, and actions at both levels by concerned parties must be coordinated. Barriers focused on standardisation and regulations and technical barriers both conform to the initial premise for these barriers, namely, that hurdles linked to regulation formation would occur at a broader regime level, and those technological barriers would occur at both the regime and niche level. In this scenario, impediments such as "lack of maintenance and repair networks" occur at the regime level, outside of companies' spheres of control. At the same time, those aimed towards technological advancements would be considered niche.

It is evident from Table 25, that for barriers the (niche/regime) ratio is (70%: 30%) whereas for enablers the (niche/regime) ratio is (12%: 88%). This means that green hydrogen being a novel product for the built environment requires a lot of effort to be put in by the institutions at the niche level. This would be essential so that technological niches may break into the regime level and make the use of green hydrogen possible in the Dutch built environment.

## 6.2 Mapping the suggestions on Multi-Level Perspective

After segregating barriers and enablers at various levels on the MLP, the next step is to map the suggestions made to overcome each of the barriers on the MLP. This step is aimed at generating ideas for overcoming hurdles at various levels. Mapping these recommendations on the MLP assists in comprehending the approximate timeline and identifying players who may work on the suggestions in the future. For example, one of the technological barriers to green hydrogen setup implementation in the built environment is the lack of maintenance and repair networks; the respondents recommended establishing extensive maintenance and repair networks across the country. This recommendation can now be mapped to a specialized level. Thus, the suggestion/action now has two pieces of information: a possible time horizon (derived from the associated barrier mapping) and a list of possible players, i.e., the Dutch government, municipalities, private and public industry consortiums etc. These suggestions, with approximate timelines and the actors, could be developed into a complete action plan to guide the stakeholders in making green hydrogen use in Dutch households a reality. An extensive table with all the barriers and the respective suggestions, timelines has been included in the appendix at the end.

### Inferences from mapping suggestions

It is evident from Table (27) that suggestions that should be worked on at the niche level account for 41% of the total; the suggestions to be worked on at the regime level accounts for 37% of the total. There is a third category of suggestions that needs a unified approach, i.e., it should be worked on at both the niche and regime level simultaneously (accounts for 22% of total).

Surprisingly, the MLP has a significant resonance with the geographical dimensions of the Dutch energy planning system. The Dutch national government establishes long-term strategic goals and is obligated to carry out and protect national interests and is therefore partially guided by the EU. The national government initiatives are included in the National Spatial Strategy and the Energieagenda (Rijksover-heid, 2016b) and are consistent with landscape-level actions. The provinces appear to correspond to regime-level stakeholders, where tactical governance operations occur. The government's strategic vision may be viewed as a translation of national interest and strategic visions into regional visions and more concrete plans and initiatives, with a (10-12) year time horizon. Provinces are critical players at the regime level since they influence the construction of institutions that facilitate the removal of barriers and the creation of niches. Municipalities legally take on a comparable function to provinces, but on a smaller scale. Local efforts must be formally connected with provincial objectives (Rijksoverheid, 2014). This alignment may be viewed as a translation from a regional perspective to a local one since it corresponds to extracting the ground level plan from tactical activities during the transition (Loorbach, 2010). Municipalities, on the other hand, can be involved in innovative projects in terms of finance and exposure if they are implementing initiatives including sustainable creative niches, for instance, in the case of the hydrogen-heated Nijstad-Oost new development project in Hogeveen (Gemeente Hogeveen, 2018a).

Thus, there is overlap between stakeholders and the tasks they conduct at various stages of transition, which is particularly evident in the context of the energy transition in the built environment. This overlap is advantageous since it enables the scaling-up of low-carbon efforts. Thus, the national government is involved in all three layers of the transition process: the macro-long-term strategic vision at the landscape level, the tactical plans to implement these long-term visions at the regime level, and finally, the niches created, for example, in collaboration with major energy sector players.

# CH.7 - CONCLUSION

The goal of this study was to explore possibilities and problems associated with the transition of the Dutch built environment to green hydrogen-powered dwellings. This investigation was motivated by two factors: Since the Ministry of Economic Affairs and Climate Policy announced its intention to phase out gas extraction in Groningen, a widespread sense of urgency has developed to transition away from the current fossil-fuel-based energy supply system (Klimaat, 2020). As a result of this momentum, stakeholders have become more receptive to green hydrogen and other sustainable energy solutions. Additionally, the emergence of green hydrogen as a viable industrial alternative to fossil fuels inspired the researchers to investigate the feasibility of using green hydrogen to decarbonize the built environment. Additionally, the research addressed a significant vacuum in the academic literature by failing to provide a comprehensive view for stakeholders to determine whether their business models are amenable to tapping the Dutch household energy market and substituting green hydrogen for natural gas. Although using natural gas for residential uses may be deemed unsustainable in the era of sustainability, the emphasis for household use is economical energy supply, which makes natural gas an excellent alternative now. The research identifies the important factors for green hydrogen introduction in the Netherlands by integrating technology, management, and social aspects.

A comparison of the data from two sources (literature and interviews) helped to create an overview of barriers and enablers. This would serve as a foundational work for the researchers as it summarises the barriers and enablers from the economic, technological, and social perspective, which has been a research gap because most of the literature is focused on improving the technological impediments related to green hydrogen introduction. (See Section - 4.2 Overview of enablers and barriers (literature)).

For the second research question, to come with possible actions that could bring green hydrogen in the Dutch built environment, the MLP was used. The shift from a natural gas-powered environment to a green hydrogen-powered environment is envisioned as a transition. This transition could be possible when there is alignment between the different levels of the society (niche, regime and landscape). The barriers and enablers previously summarised and the corresponding suggestions from interviews were mapped on the three levels. This resulted in an approximate set of actions along with the required timeline and the actors who could work to overcome the barriers. (See Section - 6.1 Barriers and enablers on the Multi-Level Perspective and 6.2 Mapping the suggestions on Multi-Level Perspective). The mapping of barriers and enablers according to the MLP shows a big divide between enablers and barriers, around 70% of the barriers are currently at the niche level, whereas around 88% of the enablers are present at the regime level to support the transition. This divide must be filled in for a smooth transition to green hydrogen. By mapping suggestions on the MLP, it was expected that we could get a clear picture on how to proceed with implementing them, i.e., taking a top-down approach or a bottom-up approach but surprisingly, the results were balanced. There is no clear indication about the suggestions that should be prioritised because of the third category of suggestions that were found during the research, which is the ones that need combined efforts from both niche and regime level players.

The uncertainties surrounding the energy transition in the built environment contributes to its complexity. Stakeholders are hesitant to support hydrogen energy applications in the built environment due to a lack of laws governing hydrogen usage in the built environment and significant gaps in the legislation impeding the transportation and manufacture of sufficient quantities of green hydrogen. In the absence of common objectives and interests, pilots may fail, impeding the development of green hydrogen energy applications in the built environment. This divergence in the views was described effectively in one of the interviews: market players perceive it as a project to obtain subsidies for something they would have done otherwise, but research institutes and TSOs view it more as a learning exercise, with a strong emphasis on knowledge acquisition.

This study established is that a substantial number of stakeholders are not only at the landscape, regime, or niche level. They are active at both the landscape and regime levels, or at both the niche and regime levels, or occasionally at all levels. Both public and private actors appear to play distinct roles in growth. This remark was also expressed during the various semi-structured interviews and may be seen as a potential positive for facilitating green hydrogen energy uses in the built environment. Therefore, stakeholders (mostly public stakeholders) should function as launching consumers for such applications, generating initial demand, and demonstrating that green hydrogen energy applications for the built environment operate in practice, not only on paper.

# CH.8 - RECOMMENDATIONS

## For science

As a result of segregating barriers and enablers, we found that most of the barriers are present on the niche level, i.e., 70% of the total. As a next step, efforts to eradicate these barriers have also been discussed; now, investigation needs to be done to find out the processes through which niches could transition to the regime level. Each of the barriers on the niche level is related to a specific research area, for example, storage-related barriers, safety-related barriers etc. When the suggestion made to eradicate the barrier is implemented, the research done in the niches will result in new technologies and processes which should transition from niche to regime level to become the dominant practice, and the phenomena involved here need to be analysed carefully. This research might potentially yield more relevant insights if conducted as a case study on one of the Netherlands' pilots or demonstration projects. Though this was not achievable owing to the pandemic circumstances, it might be extremely beneficial in the future for studying the process in its natural context and for generalizing the research conclusions. Extensive research that focuses on green hydrogen in all energy end-use sectors from either a transition or a future-oriented viewpoint would be fascinating to gain more insight into the sector coupling potential.

## For European Union (EU)

The EU has been playing a more directive role in energy planning. The EU establishes targets that must be implemented on a national scale by its member states (European Commission, 2010) and thus does not interfere with member states' competence to design policies for the energy supply system and the built environment to accomplish these goals (SER, 2013). However, the EU may be a significant participant in facilitating hydrogen energy uses. The EU might offer (significant) financial support to larger pilot initiatives in member states. According to one of the respondents (C), several of the larger market stakeholders are waiting for the European Commission to initiate further large-scale pilot initiatives. Additionally, it is envisaged that the Netherlands would seek assistance from neighbouring countries and the EU to resolve the 'chicken or egg' problem associated with green hydrogen energy.

## For Dutch Government

The Dutch government plays a critical role in facilitating green hydrogen applications in the energy transition for the built environment by defining long-term, explicit goals, facilitating finance, and adapting legislative and regulatory frameworks. The government has played a role in establishing a long-term strategy for the use of green hydrogen by developing a National Hydrogen Program by 2021. The shift from SDE+ to SDE++ was a critical step in incorporating green hydrogen projects into incentive and subsidy programs. It is up to the national government to adjust the legal, regulatory, and tax structures. Among these improvements is enacting required amendments to the Gas Act to allow the transportation of green hydrogen gas inside the current natural gas system. This must be accomplished with the assistance of officials from Gasunie to make the current gas network compatible with green hydrogen, investigate blending options, and establish use guidelines. In addition, 37% of the suggestions made by the literature study and the interviewees are to be carried out by regime level actors, mainly the Dutch government and 22% of the suggestions require a unified approach from the regime as well as niche level actors. This highlights the importance of the involvement of the Dutch government in making green hydrogen a part of Dutch society.

## For Municipalities

Municipalities often place a greater emphasis on the creation and execution of programs related to the energy transition in the built environment. To begin, governments establish neighbourhood-specific plans and regulations, i.e., regional plans for each community. Additionally, it is critical to incorporate specific locally tailored financial stimulation measures into the design process and to bring stakeholders together. This should be the main focus of municipalities because this could help in overcoming the economic barriers associated with green hydrogen introduction.

## For private players

TSOs are another critical set of stakeholders in the energy transition in the built environment. In the Netherlands, there are two types of TSOs: national TSOs (Gasunie and TenneT) and regional TSOs (of which there are seven, which are responsible for regional grids of both natural gas and electricity). TSOs oversee transporting energy from producers to consumers (CE Delft, 2017).

Historically, TSOs have been tasked with the responsibility of facilitating the building, administration, and maintenance of electrical and (natural) gas grids. However, regional TSOs have a dominating role to play since, as complexity increases, the TSO's advising function becomes increasingly essential for other stakeholders when making choices. TSOs have in-depth knowledge of the energy supply system and are best equipped to address the problems associated with various sustainable energy options. Municipalities will undoubtedly require expertise and capacity to effect change. The extent to which TSOs are involved might have a significant influence on the pace of the built environment's energy transition.

Finally, private actors (industries, consultancies, etc.) are essential to facilitate green hydrogen use in Dutch society. They are the primary developers of commercially viable products and bringing new applications to market. They are deemed critical for the development of competitive new technologies in the EU's ambitious document Energy 2020 and the Dutch ministry's Energieagenda.

Prior to investing in new technology or application, private players should consider the potential for (long-term) profit. In other words, it is critical to establish business models that demonstrate the profitability of the green hydrogen value chain for the built environment. While governments are obligated to execute pilots spatially, the technology employed in the pilots must be scalable to broader applications, which is where private sector involvement is critical.

# REFERENCES

Acar, C., & Dincer, I. (2019). Review and evaluation of hydrogen production options for better environment. *Journal of Cleaner Production*, *218*, 835–849. https://doi.org/10.1016/j.jclepro.2019.02.046

Amsterdam. (2020). *Policy: Phasing out natural gas* [Webpagina]. English Site; Gemeente Amsterdam. https://www.amsterdam.nl/en/policy/sustainability/policy-phasing-out/

Asselt, M. V. (2000). *Perspectives on Uncertainty and Risk: The PRIMA Approach to Decision Support*. Springer Netherlands. https://doi.org/10.1007/978-94-017-2583-5

Behling, N., Williams, M. C., & Managi, S. (2015). Fuel cells and the hydrogen revolution: Analysis of a strategic plan in Japan. *Economic Analysis and Policy*, *48*, 204–221. https://doi.org/10.1016/j.eap.2015.10.002

Belastingdienst. (2021). *Tables of rates for environmental taxes*. https://www.belastingdienst.nl/wps/wcm/connect/bldcontentnl/belastingdienst/zakelijk/overige_belastingen/belastingen_op_milieugrondslag/tarieven_milieubelastingen/tabellen_tarieven_milieubelastingen

Bennoua, S., Le Duigou, A., Quéméré, M.-M., & Dautremont, S. (2015). Role of hydrogen in resolving electricity grid issues. *International Journal of Hydrogen Energy*, *40*(23), 7231–7245. https://doi.org/10.1016/j.ijhydene.2015.03.137

Blok, K. (2007, April). *Introduction to Energy Analysis | Techne Press*. http://www.technepress.nl/publications.php?id=17

Burre, J., Bongartz, D., Brée, L., Roh, K., & Mitsos, A. (2020). Power-to-X: Between Electricity Storage, e-Production, and Demand Side Management. *Chemie Ingenieur Technik*, *92*(1–2), 74–84. https://doi.org/10.1002/cite.201900102

Carayannis, E. G., Barth, T. D., & Campbell, D. F. (2012). The Quintuple Helix innovation model: Global warming as a challenge and driver for innovation. *Journal of Innovation and Entrepreneurship*, *1*(1), 2. https://doi.org/10.1186/2192-5372-1-2

Cerniauskas, S., Grube, T., Praktiknjo, A., Stolten, D., & Robinius, M. (2019). Future Hydrogen Markets for Transportation and Industry: The Impact of CO2 Taxes. *Energies*, *12*(24), 4707. https://doi.org/10.3390/en12244707

Cipriani, G., Di Dio, V., Genduso, F., La Cascia, D., Liga, R., Miceli, R., & Ricco Galluzzo, G. (2014). Perspective on hydrogen energy carrier and its automotive applications. *International Journal of Hydrogen Energy*, *39*(16), 8482–8494. https://doi.org/10.1016/j.ijhydene.2014.03.174

Crang, M. (2002). Qualitative methods: The new orthodoxy? *Progress in Human Geography.*, *26*(5), 647–655. https://doi.org/10.1191/0309132502ph392pr

Dominguez, C., Orehounig, K., & Carmeliet, J. (2021). Understanding the path towards a clean energy transition and post-electrification patterns of rural households. *Energy for Sustainable Development*, *61*, 46–64. https://doi.org/10.1016/j.esd.2021.01.002

Farchmin, F. (2016). Development of Large Scale Electrolysis Systems: Necessity and Approach. In J. Töpler & J. Lehmann (Eds.), *Hydrogen and Fuel Cell: Technologies and Market Perspectives* (pp. 209–222). Springer. https://doi.org/10.1007/978-3-662-44972-1_12

FCHJHU. (2017, June). *STUDY ON EARLY BUSINESS CASES FOR H2 IN ENERGY STORAGE AND MORE BROADLY POWER TO H2 APPLICATIONS | www.fch.europa.eu*. https://www.fch.europa.eu/publications/study-early-business-cases-h2-energy-storage-and-more-broadly-power-h2-applications

Gasunie. (2020a). *Hydrogen projects*. Gasunie. https://www.gasunie.nl/en/expertise/hydrogen/hydrogen-projects

Gasunie. (2020b). *HyStock*. Gasunie. https://www.gasunie.nl/en/expertise/hydrogen/hystock

Gasunie. (2021, March 17). *Another step closer to hydrogen backbone in port of Rotterdam*. Gasunie. https://www.gasunie.nl/en/news/another-step-closer-to-hydrogen-backbone-in-port-of-rotterdam

Geels, F. W. (2002). Technological transitions as evolutionary reconfiguration processes: A multi-level perspective and a case-study. *Research Policy*, *31*(8), 1257–1274. https://doi.org/10.1016/S0048-7333(02)00062-8

Geels, F. W., & Schot, J. (2007). Typology of sociotechnical transition pathways. *Research Policy*, *36*(3), 399–417. https://doi.org/10.1016/j.respol.2007.01.003

Gigler, J., Weeda, M., Hoogma, R., & de Boer, J. (n.d.). *Hydrogen for the energy transition*. 148.

Glanz, S., & Schönauer, A.-L. (2021). Towards a Low-Carbon Society via Hydrogen and Carbon Capture and Storage: Social Acceptance from a Stakeholder Perspective. *Journal of Sustainable Development of Energy, Water and Environment Systems*, *9*(1), 0–0. https://doi.org/10.13044/j.sdewes.d8.0322

Hafner, S., Anger-Kraavi, A., Monasterolo, I., & Jones, A. (2020a). Emergence of New Economics Energy Transition Models: A Review. *Ecological Economics*, *177*, 106779. https://doi.org/10.1016/j.ecolecon.2020.106779

Hafner, S., Anger-Kraavi, A., Monasterolo, I., & Jones, A. (2020b). Emergence of New Economics Energy Transition Models: A Review. *Ecological Economics*, *177*, 106779. https://doi.org/10.1016/j.ecolecon.2020.106779

Haines, M. R. (n.d.). *Reduction of CO2 emissions by adding hydrogen to natural gas*. 104.

Helgenberger, S. (2016, May 10). *Social Benefits of Renewable Energies | Institute for Advanced Sustainability Studies*. https://www.iass-potsdam.de/en/blog/2016/10/social-benefits-renewable-energies

Huang, Z., Yu, H., Peng, Z., & Feng, Y. (2017). Planning community energy system in the industry 4.0 era: Achievements, challenges and a potential solution. *Renewable and Sustainable Energy Reviews*, *78*, 710–721. https://doi.org/10.1016/j.rser.2017.04.004

Huijts, N. M. A., Molin, E. J. E., & Steg, L. (2012a). Psychological factors influencing sustainable energy technology acceptance: A review-based comprehensive framework. *Renewable and Sustainable Energy Reviews*, *16*(1), 525–531. https://doi.org/10.1016/j.rser.2011.08.018

Huijts, N. M. A., & van Wee, B. (2015). The evaluation of hydrogen fuel stations by citizens: The interrelated effects of socio-demographic, spatial and psychological variables. *International Journal of Hydrogen Energy*, *40*(33), 10367–10381. https://doi.org/10.1016/j.ijhydene.2015.06.131

IEA. (2019, June 9). *The Future of Hydrogen – Analysis*. IEA. https://www.iea.org/reports/the-future-of-hydrogen

Klimaat, M. van E. Z. en. (2020a, April 6). *Government Strategy on Hydrogen—Publication—Government.nl* [Publicatie]. Ministerie van Algemene Zaken. https://www.government.nl/documents/publications/2020/04/06/government-strategy-on-hydrogen

Klimaat, M. van E. Z. en. (2020b, September 29). *Netherlands In-Depth Review 2020—Rapport—Rijksoverheid.nl* [Rapport]. Ministerie van Algemene Zaken. https://www.rijksoverheid.nl/documenten/rapporten/2020/09/29/netherlands-in-depth-review-2020

Kocsis, V., & Hof, B. (2016). Energy policy evaluation in practice: The case of production subsidies and DEN-B in the Netherlands. *Environment, Development and Sustainability: A Multidisciplinary Approach to the Theory and Practice of Sustainable Development*, *18*(5), 1433–1455.

Krozer, Y. (2008). *Innovations and the Environment*. Springer-Verlag. https://doi.org/10.1007/978-1-84800-197-8

Lemke, C., Grueger, F., & Arnhold, O. (2015). MELY: Market Model for Water Electrolysis – Electrolysis' Economic Potential given its Technological Feasibility. *Energy Procedia*, *73*, 59–68. https://doi.org/10.1016/j.egypro.2015.07.562

Libakova, N., & Sertakova, E. (2015). The Method of Expert Interview as an Effective Research Procedure of Studying the Indigenous Peoples of the North. *Journal of Siberian Federal University. Humanities & Social Sciences*, 114–129. https://doi.org/10.17516/1997-1370-2015-8-1-114-129

Londo, M., Matton, R., Usmani, O., van Klaveren, M., Tigchelaar, C., & Brunsting, S. (2020). Alternatives for current net metering policy for solar PV in the Netherlands: A comparison of impacts on business case and purchasing behaviour of private homeowners, and on governmental costs. *Renewable Energy*, *147*, 903–915. https://doi.org/10.1016/j.renene.2019.09.062

Loorbach, D., & Rotmans, J. (2006). *Managing Transitions for Sustainable Development* (Vol. 44, pp. 187–206). https://doi.org/10.1007/1-4020-4418-6_10

Meadowcroft, J. (2009). What about the politics? Sustainable development, transition management, and long term energy transitions. *Policy Sciences*, *42*(4), 323–340.

Medved, S., Domjan, S., & Arkar, C. (2021). Contribution of energy storage to the transition from net zero to zero energy buildings. *Energy and Buildings*, *236*, 110751. https://doi.org/10.1016/j.enbuild.2021.110751

Mirza, F. (2012). *Alan Bryman-Social Research Methods, 4th Edition-Oxford University Press (2012).pdf*. https://www.academia.edu/38228560/Alan_Bryman_Social_Research_Methods_4th_Edition_Oxford_University_Press_2012_pdf

*Mks-studie-ptg-transport-status-quo-and-perspectives-for-development.pdf*. (n.d.). Retrieved 17 August 2021, from https://www.bmvi.de/SharedDocs/EN/Documents/MKS/mks-studie-ptg-transport-status-quo-and-perspectives-for-development.pdf?__blob=publicationFile

Momeni, M., Soltani, M., Hosseinpour, M., & Nathwani, J. (2021). A comprehensive analysis of a power-to-gas energy storage unit utilizing captured carbon dioxide as a raw material in a large-scale power plant. *Energy Conversion and Management*, *227*, 113613. https://doi.org/10.1016/j.enconman.2020.113613

Mulder, M., Perey, P. L., & Moraga, J. L. (2019). *Outlook for a Dutch hydrogen market: Economic conditions and scenarois*. Centre for Energy Economics Research, University of Groningen.

Netherlands, S. (2015). *Green growth in the Netherlands 2015* [Webpagina]. Statistics Netherlands. https://www.cbs.nl/en-gb/publication/2015/49/green-growth-in-the-netherlands-2015

Nicita, A., Maggio, G., Andaloro, A. P. F., & Squadrito, G. (2020, April 14). *Green hydrogen as feedstock: Financial analysis of a photovoltaic-powered electrolysis plant—ScienceDirect*. https://www.sciencedirect.com/science/article/abs/pii/S036031992030625X?via%3Dihub

Nikolaidis, P., & Poullikkas, A. (2017). A comparative overview of hydrogen production processes. *Renewable and Sustainable Energy Reviews*, *67*, 597–611. https://doi.org/10.1016/j.rser.2016.09.044

Ohlig, K., & Decker, L. (2014). The latest developments and outlook for hydrogen liquefaction technology. *AIP Conference Proceedings*, *1573*(1), 1311–1317. https://doi.org/10.1063/1.4860858

Raven, R. P. J. M. (2005). *Strategic niche management for biomass: A comparative study on the experimental introduction of bioenergy technologies in the Netherlands and Denmark*. https://doi.org/10.6100/IR590593

Rip, A., & Kemp, R. (1998). Technological change. *Human Choice and Climate Change: Vol. II, Resources and Technology*, 327–399.

Rotmans, J., Kemp, R., & van Asselt, M. (2001). More evolution than revolution: Transition management in public policy. *Foresight*, *3*(1), 15–31. https://doi.org/10.1108/14636680110803003

Rotmans, J., & Loorbach, D. (2009). Complexity and Transition Management. *Journal of Industrial Ecology*, *13*(2), 184–196. https://doi.org/10.1111/j.1530-9290.2009.00116.x

Saccani, C., Pellegrini, M., & Guzzini, A. (2020). Analysis of the Existing Barriers for the Market Development of Power to Hydrogen (P2H) in Italy. *Energies*, *13*(18), 4835. https://doi.org/10.3390/en13184835

Schnuelle, C., Kisjes, K., Stuehrmann, T., Thier, P., Nikolic, I., von Gleich, A., & Goessling-Reisemann, S. (2020). From Niche to Market—An Agent-Based Modeling Approach for the Economic Uptake of Electro-Fuels (Power-to-Fuel) in the German Energy System. *Energies*, *13*(20), 5522. https://doi.org/10.3390/en13205522

Schroot, B. (2021, April 26). The Netherlands: A Blue Hydrogen economy now will ease a transition to Green. *Energy Post*. https://energypost.eu/the-netherlands-a-blue-hydrogen-economy-now-will-ease-a-transition-to-green/

Sekaran, U., & Bougie, R. (2016, June). *Research Methods For Business: A Skill Building Approach, 7th Edition | Wiley*. Wiley.Com. https://www.wiley.com/en-al/Research+Methods+For+Business%3A+A+Skill+Building+Approach%2C+7th+Edition-p-9781119266846

Singh, S., Jain, S., Ps, V., Tiwari, A. K., Nouni, M. R., Pandey, J. K., & Goel, S. (2015). Hydrogen: A sustainable fuel for future of the transport sector. *Renewable and Sustainable Energy Reviews*, *51*, 623–633. https://doi.org/10.1016/j.rser.2015.06.040

Thomas, G. (2009). How to Do Your Research Project: A Guide for Students in Education and Applied Social Sciences. *Undefined*. https://www.semanticscholar.org/paper/How-to-Do-Your-Research-Project%3A-A-Guide-for-in-and-Thomas/daf476352ceb922415ae020326352e255b36e9ef

Trencher, G., & Edianto, A. (2021). Drivers and Barriers to the Adoption of Fuel Cell Passenger Vehicles and Buses in Germany. *Energies*, *14*(4), 833. https://doi.org/10.3390/en14040833

Van Audenhove, L. (2009, February 13). *Expert Interviews and Interview Techniques for Policy Analysis*. Vrije Universiteit Brussel. https://researchportal.vub.be/en/activities/expert-interviews-and-interview-techniques-for-policy-analysis-2

van der Brugge, R. (2009). *Transition dynamics in social-ecological systems: The case of Dutch water management*. https://repub.eur.nl/pub/16186/

van der Roest, E., Snip, L., Fens, T., & van Wijk, A. (2020). Introducing Power-to-H3: Combining renewable electricity with heat, water and hydrogen production and storage in a neighbourhood. *Applied Energy*, *257*, 114024. https://doi.org/10.1016/j.apenergy.2019.114024

Weijden, C. van der, & Jonk, M. (2020, September 8). *Hydrogen law and regulation in the Netherlands | CMS Expert Guides*. https://cms.law/en/int/expert-guides/cms-expert-guide-to-hydrogen/netherlands

Whalen, C. (2017a, July). *Hydrogen made by the electrolysis of water is now cost-competitive and gives us another building block for the low-carbon economy*. Carbon Commentary. https://www.carboncommentary.com/blog/2017/7/5/hydrogen-made-by-the-electrolysis-of-water-is-now-cost-competitive-and-gives-us-another-building-block-for-the-low-carbon-economy

Whalen, C. (2017b, July 24). *Exytron: The world's first 'power-to-gas' system with integrated CO2 collection and reuse*. Carbon Commentary. https://www.carboncommentary.com/blog/2017/7/24/exytron-the-worlds-first-power-to-gas-system-with-integrated-co2-collection-and-reuse

# APPENDIX I – FINAL RESULTS

| **Barrier** | **Level according to the MLP** | **Approximate time to overcome the barrier** | **Condition/Suggestion** | **As suggested in the literature** | **Suggested by interviewees** | **Mapping suggestion to MLP** | **Stakeholders to be involved** | **Approximate time to realise the suggestion** | **Example** |
|---|---|---|---|---|---|---|---|---|---|
| High initial investments (CAPEX), High operational expenses (OPEX) | Niche | (0-5) years | Look for long-term as well as short-term storage solutions for hydrogen | Londo et al., 2020; IEA 2019; FCHJHU 2017 | All interviewees | Niche | Industry + Academia | (0-5) years | Gasunie, Energie Beheer Nederland B.V. (EBN), Shell, Nederlandse Olie en Gas Exploratie en Productie Associatie (NOGEPA), Technical Universities |
| | | | Increasing the scale of green hydrogen generation and exploring alternative options | Kocis and Hof 2016; Gigler et al. n.d.; IEA 2019 | All interviewees | Niche | Industry + Academia | (0-5) years | Technical universities, Vattenfall, Allego etc. |
| | | | The focus should be on making the natural gas infrastructure ready for hydrogen and blended natural gas | Gasunie 2020; Whalen 2017; Klimaat 2020 | All interviewees | Niche | Government + Industry + Academia | (0-5) years | Gasunie Transport Services, Trade Association for Dutch Gas Sector (KVGN), Universities, TNO, the Dutch government, Municipalities |
| | | | Innovating the electrolyser related techniques and optimisation of BOP (Balance of Plant) | Gasunie 2020; Whalen 2017; Klimaat 2020 | All interviewees | Niche | Industry + Academia | (0-5) years | Universities, TNO, Siemens etc. |
| | | | Develop a good business model to make the entire value chain affordable | Gasunie 2020; Whalen 2017; Klimaat | All interviewees | Regime + Niche | Government + Industry + Academia | (10-12) years | Universities, the Dutch government, TSOs and DSOs. |
| High storage, transmission & distribution costs | Regime | (10-12) years | Develop a good business model to make the entire value chain affordable | Gasunie 2020; Whalen 2017; | All interviewees | Regime + Niche | Government + Industry + Academia | (10-12) years | Universities, the Dutch government, TSOs and DSOs. |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Klimaat 2020 | | | | | |
| | | | Look for long-term as well as short-term storage solutions for hydrogen | Londo et al., 2020; IEA 2019; FCHJHU 2017 | All interviewees | Niche | Industry + Academia | (0-5) years | Gasunie, Energie Beheer Nederland B.V. (EBN), Shell, Nederlandse Olie en Gas Exploratie en Productie Associatie (NOGEPA), Technical Universities |
| | | | The focus should be on making the natural gas infrastructure ready for hydrogen and blended natural gas | Gasunie 2020; Whalen 2017; Klimaat 2020 | All interviewees | Regime + Niche | Government + Industry + Academia | (0-5) years | Gasunie Transport Services, Trade Association for Dutch Gas Sector (KVGN), Universities, TNO, the Dutch government, Municipalities |
| | | | There is a need to establish rules to govern the storage, transmission and distribution of green hydrogen and blended natural gas. This could also help in bringing down the costs. | Saccani et al. 2020; Weijden and Jonk 2020 | All interviewees | Regime | Government + Industry | (10-12) years | Netherlands Standardization Institute (NEN), Dutch Hydrogen & Fuel Cell Association (NWBA), Rijskdienst Voor Ondernemend Nederland (RVO) |
| | | | Establishment of standards for the use of hydrogen | IEA 2019; Huang et al. 2017 | All interviewees | Regime | Government | (10-12) years | Dutch Hydrogen Standards Commission |
| | | | Gas quality assessment and end-user acceptance | Gigler et al. n.d. | All interviewees | Regime + Niche | Government + Industry | (10-12) years | DNV-GL Energy, Keuringsinstituut voor WaterleidingArtikelen (Institution DNV-GL Energy, Keuringsinstituut voor WaterleidingArtikelen (Institution for the Examination of Waterworks Articles) KIWA |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Additional carbon-dioxide capture & storage costs | Niche | (0-5) years | Carbon dioxide capture and storage techniques need to be developed to make the process cost-effective | Glanz & Schonauer 2021; Cerniauskas et al.2019 | Interviewees C, G, I, J | Niche | Government + Industry + Academia | (0-5) years | CATO (CO2 capture, transport, and storage in the Netherlands), Universities, Linde |
| Additional methanation reactor costs | Niche | (0-5) years | Converting hydrogen to methane using the methanation process can be used for the short term. It is essential to make the natural gas infrastructure ready for hydrogen and blended natural gas. | Glanz & Schonauer 2021; Cerniauskas et al.2019 | NA | Niche | Industry + Academia | (0-5) years | Gasunie, Universities etc. |
| Electrolyser cost competitiveness | Regime | (10-12) years | Extensive research and innovation need to be done for electrolysers | NA | Interviewee A | Niche | Industry + Academia | (0-5) years | Siemens, Universities |
| | | | Promote the locally manufactured electrolysers | | Interviewee A | Regime | Government | (10-12) years | Dutch Government |
| Insufficient funds for operation and demonstration phases | Regime | (10-12) years | Government should launch schemes aimed at helping the projects in their operation and demonstration phase. The current schemes should make provision to fund the operation and demonstration phase sufficiently. | NA | Interviewees C, H | Regime | Government | (10-12) years | Dutch Government |
| Lack of green hydrogen storage infrastructure | Niche | (0-5) years | Look for long-term as well as short-term storage solutions for hydrogen | Londo et al., 2020; IEA 2019; FCHJHU 2017 | All interviewees | Niche | Industry + Academia | (0-5) years | Gasunie, Energie Beheer Nederland B.V. (EBN), Shell, Nederlandse Olie en Gas Exploratie en Productie Associatie (NOGEPA), Technical Universities |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Pipe embrittlement and pressure issues | Niche | (0-5) years | Research into finding materials compatible with hydrogen and blended natural gas | FCHJHU 2017; Gigler et al. n.d. | Interviewees B, E, F, H | Niche | Academia | (0-5) years | Technical universities |
| | | | Formulate standards to govern the pressure required at each stage of storage, transmission, and distribution | Nicita et al. 2020; IEA 2019 | All interviewees | Regime | Government | (10-12) years | Dutch Hydrogen Standards Commission |
| Household safety issues | Regime | (10-12) years | Formulate rules and regulations for hydrogen production, storage, transmission, and distribution in the built environment. Also, for the pressure required at each stage of storage, transmission, and distribution | IEA 2019; Huang et al. 2017 | All interviewees | Regime | Government + Industry | (10-12) years | Netherlands Standardization Institute (NEN), Dutch Hydrogen & Fuel Cell Association (NWBA), Rijskdienst Voor Ondernemend Nederland (RVO) |
| | | | Establishment of standards for the use of hydrogen in households | IEA 2019 | All interviewees | Regime | Government | (10-12) years | Dutch Hydrogen Standards Commission |
| | | | Digitisation in energy transition should be promoted | Gigler et al. n.d. | NA | Regime + Niche | Government + Industry + Academia | (10-12) years | Dutch Government, Siemens, Gasunie, TenneT, Technical Universities |
| | | | Promote human capital development | NA | Interviewees A, C, E, F, G | Regime + Niche | Government + Industry + Academia | (10-12) years | Dutch Government, Siemens, Gasunie, TenneT, Technical Universities |
| Noise emissions | Niche | (0-5) years | Innovate methods to eliminate or lower the noise emissions related to gas flow | Gigler et al. n.d. | NA | Niche | Industry + Academia | (0-5) years | Technical universities, Linde Gas, Gasunie, GasTerra etc. |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Metering issues | Niche | (0-5) years | Innovate to develop devices and methods to accurately measure the consumption according to the calorific value of the end-product and pressure | Dominguez et al. 2021 | Interviewees A, F | Niche | Industry + Academia | (0-5) years | Technical universities, Linde Gas, Gasunie, GasTerra etc. |
| | | | Establishment of standards for charging the customers | Dominguez et al. 2021 | All interviewees | Regime | Government | (10-12) years | Dutch Hydrogen Standards Commission |
| Low electrolysis efficiency | Niche | (0-5) years | Innovating the electrolyser related techniques and optimisation of BOP (Balance of Plant) | IEA 2019; FCHJHU 2017 | All interviewees | Niche | Industry + Academia | (0-5) years | Technical universities, Siemens, Gasunie etc. |
| Lack of maintenance & repair networks | Regime | (10-12 years | Establish extensive maintenance and repair networks across the country | Cipriani et al. 2021 | NA | Regime | Government + Industry | (10-12) years | The Dutch government, Municipalities, Siemens, Shell etc. |
| Heavy reliance on excess renewable energy sources & uncertainty regarding infrastructure development in the short term (by 2025) | Regime | (10-12) years | Do not phase out natural gas in the short term; rather, the network should be adjusted such that blended natural gas could be used. Practical experiments need to be done for making the system compatible with pure hydrogen in the future | NA | Interviewees E, F | Regime | Government + Industry | (10-12) years | Dutch Government, Gasunie etc. |
| | | | The focus should be on making the natural gas infrastructure ready for hydrogen and blended natural gas | NA | All interviewees | Regime + Niche | Government + Industry + Academia | (10-12) years | Gasunie Transport Services, Trade Association for Dutch Gas Sector (KVGN), Universities, TNO, the Dutch government, Municipalities |
| Social acceptance issues | Regime | (10-12) years | Society should be included in transitions and embrace the concept of regional embedding | Huijts et al. 2012 | Interviewees F, G, I | Regime | Government + Society | (10-12) years | Dutch Government, Municipalities, Housing association, Citizens etc. |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Survey on the social consequences of green hydrogen introduction in a locality before the actual introduction | Huijts et al. 2012 | NA | Regime | Government + Society | (10-12) years | Dutch Government, Municipalities, Housing association, Citizens etc. |