The deployment of hydrogen in the Netherlands

Policy advice to accelerate the hydrogen transition in the heavy industry

Dennis Hoek | Master Thesis | August 2021

This page was intentionally left blank

The deployment of hydrogen in the Netherlands

Policy advice to accelerate the hydrogen transition in the heavy industry

Master thesis submitted to Delft University of Technology

in partial fulfilment of the requirements for the degree of

MASTER OF SCIENCE

in Complex Systems Engineering and Management

Faculty of Technology, Policy and Management

by

Dennis Hoek

Student number: 4392086

To be defended in public on August 24th 2021

Graduation committee

Chairperson	: Prof. Dr. K. Blok, Engineering Systems and Services
First Supervisor	: Dr. D.J. Scholten, Economics of Technology and Innovation
Second Supervisor	: Prof. Dr. Kornelis Blok, Engineering Systems and Services
External Supervisor	: Jan Jaap Ensing, Sia Partners
External Supervisor	: Micky van Gemert, Sia Partners

Preface

Dear reader,

This Master Thesis is the final assignment of my master Complex Systems Engineering and Management at the Delft University of Technology. I conducted my thesis at Sia Partners, a Management Consultancy Firm located in Amsterdam. Sia Partners has gathered a lot of expertise about the energy sector. Therefore, this was the perfect organization to cooperate with.

I worked with love and passion on this research for the last six months, although it was not always a stroll in the park. The road to this thesis had its peaks and valleys, which are all part of the experience and learning process. I enjoyed the ride, but I could not have done this without all the advice, help, and support from the people around me. Grateful as I am, I want to thank those for everything they have done during this graduation project.

I want to thank some people in particular for this. Firstly, I would to thank Daniel Scholten for supervising the Master Thesis for the last six months. I apricated your enthusiasm and willingness to help me wherever you could. Although we never had a meeting in real life, I enjoyed our online meetings very much. Your clear vision was sometimes the light at the end of the tunnel. You always gave me confidence that everything was gone be all right. That did not stop you from giving your critical opinion, which I certainly appreciated. I would then thank Kornelis Blok for the help during the thesis and for providing helpful feedback during our meetings.

Furthermore, I would thank my supervisors, Jan Jaap Ensing and Micky van Gemert, at Sia Partners for supervising me during my thesis writing. I got a warm welcome, which I appreciated very much. You both took the time to meet with me every week a half an hour. During our meetings, we discussed my thesis problems, but gladly we could also talk about other things. You both always took the time to provide me with feedback, advice or support, even during the weekends. Luckily, we were able to meet at the office of Sia Partners in Amsterdam for the last two months, where I enjoyed working with you. Without you, writing my thesis would have been a lot more complicated and less fun.

Finally, I would like to thank my family and friends for their indispensable support and help during this graduation process and the rest of my studies. A special thanks to my parents and sisters for their trust and support, you never gave up on me. To my roommates for cooking and encouraging me during the difficult moments. Lastly, to my study buddies Jelle and Hugo, who made completing this master even more fun than it already was.

Dennis Hoek

The Hague, August 2021

Executive summary

In the Netherlands, it is envisaged that hydrogen will play a crucial role in the energy transition. Currently, the heavy industry sector is responsible for emitting most CO_2 compared to the other sectors. Especially in this heavy industry, hydrogen will become essential to make this sector sustainable. The focus of this study is on the chemical, petrochemical and refining, iron, and steel industries. Altogether, these industries emit more than 80% of the CO_2 in the Netherlands.

In general, three types of hydrogen are used: grey, blue, and green hydrogen. This study focuses on green hydrogen, as it is produced without CO_2 emissions and therefore complies with the climate goals of the Netherlands. Using green hydrogen in these industries is useful because it can accomplish easy and cost-efficient significant reductions in this sector. These industries use mainly fossil fuels to heat high-temperature processes, which can only be decarbonized with hydrogen. Furthermore, grey hydrogen is already used a lot within the chemical industries, meaning that this demand can easily be replaced by green hydrogen without too much effort. The transition must be initiated to swap the use of grey hydrogen to green hydrogen and expand the use of green hydrogen in processes that are currently based on fossil fuels.

However, some stabilizing pressures (stabilizing pressures), such as the suppliers' lack of a business case and there are more, hinder this transition and keep the incumbent regime based on fossil fuels in position. Fortunately, some destabilizing pressures (destabilizing pressures) stimulate the transition, such as the Paris Climate Agreement. Policy instruments can stimulate these destabilizing pressures and overcome stabilizing pressures. These stabilizing and destabilizing pressures must be identified first to determine which policy instruments are suitable for stimulating the hydrogen transition. To get the transition started, the Dutch government will have to deploy policy instruments. For the Dutch government, it is currently unknown which policy instruments can accomplish this. Therefore, the following research question has been formulated in this study:

Which policy instruments should the Dutch government implement to accelerate the deployment of green hydrogen in the heavy industry by 2050?

Two streams of literature are combined into an analytical framework that can assess policy instruments to answer this research question: the transition literature and the economic literature. The transition literature writes about transitions towards sustainability in socio-technical systems and prescribes the multi-level perspective (MLP). The MLP is a framework described by Geels (2002), that helps understand transition processes and identify stabilizing and destabilizing pressures by applying it to a case study. The case study conceptualizes the heavy industry sector and describes the characteristics of this socio-technical system, like the present policies, actors, infrastructure, innovations. From this analysis, the pressures are identified.

Kern (2012) used the MLP for another purpose. In his paper, the MLP is applied to ex-ante assess policy instruments to what extent it contributes to a transition. However, this stream of literature cannot give specific advice about policy instruments. To have more information about policy instruments and their effects, the economic literature is consulted.

Both strands of literature can complement each other, resulting in an analytical framework based on the multi-criteria analysis (MCA). In the analytical framework, the identified pressures from the case study

will assess selected policy instruments on the level of contribution to the hydrogen transition in the heavy industry.

Case study of the heavy industry in the Netherlands

The outcome of the case study of the heavy industry in the Netherlands is the identification of six stabilizing pressures. The first is a lack of coordination as the necessary policies and regulations are not yet to facilitate the transition. Furthermore, there is no business case for green hydrogen yet. Next, the learning process has to be stimulated, as the development of the technology is moving slow. To foster the transition, it is crucial to have powerful actors involved, for example, investors. Currently, their involvement is not sufficient.

At last, a hydrogen market has to be established to accelerate the transition. Also, one destabilizing pressure is identified: the industry sector has a lot of hydrogen experience, which positively influences the transition. These are the pressures on which the policy instruments will be assessed in this research.

Studying the economic literature results in three classes of policy instruments: regulations, economic means, and information, also called the stick, carrot, and the sermon. Within these classes, multiple forms of policy instruments are present. The case study is also used to indicate which policy instruments would be suitable to stimulate the transition. The following policy instruments will be assessed on their contribution to transition: a higher national CO_2 price for the industry sector, Carbon contracts for Difference, a subsidy of the supply, a subsidy for demand, and a financial contribution for the construction of the infrastructure. These are the policy instruments that will be assessed by the identified pressures.

Results

In the multi-criteria analysis, the five policy instruments are ranked on the six pressures. The policy instruments where the government provides financial stimulus performed well. The policy instrument that stimulates the transition as the best is the subsidy for supply, followed by the financial support for infrastructure development, CCfD, subsidy for demand, and at last higher CO_2 price.

Interpretation of results

To answer the research question, it is advisable for the Dutch government to deploy a policy mix of multiple policy instruments to impact all identified pressures positively. This research shows that a combination of a subsidy for supply, financial support for infrastructure development, and CCfD complement each other. This policy mix has therefore been found adequate to stimulate the hydrogen transition in the heavy industry in the Netherlands.

This study has shown the added value of combining two strands of literature into an analytical framework for analyzing which policy instruments can foster the hydrogen transition in the heavy industry. To make this assessment explicit for a particular transition, the indicated stabilizing and destabilizing pressures in the case study are used as criteria in this analytical framework to assess the indicated policy instruments. This study provides a piece of advice that is well suited for the particular transition.

Table of contents

List of abbreviations

AEM	Anion Exchange Membrane
AHP	Analytical Hierarchy Process
CCfD	Carbon Contracts for Difference
CCS	Carbon Capture and Storage
DEI	Demonstratie Energie en Klimaatinnovatie
EU	European Union
EU-ETS	European Emission Trading System
MCA	Multi-criteria analysis
MLP	Multi-level perspective
PEM	Polumer Electrolyte Membrane
SDE	Stimulering Duurzame Energieproductie en Klimaattransitie
SMART	Simple multi-attribute rating technique
SMR	Steam-Methane-Reforming
SOE	Solid Oxide Electrolysis

List of Figures

List of Tables

Chapter 1 Introduction

1.1 Problem description

In recent years, the Netherlands is in an energy transition. In June 2019, a National Climate Agreement was concluded, based upon the Paris Climate Agreement (2015). The main goal of the Climate Agreement is to reduce the emission of greenhouse gasses by 49% in 2030 relative to 1990 and with 95% in 2050 relative to 1990 (Dutch Government, 2019). In December 2020, EU leaders agreed on an even stricter cut of greenhouse gasses. Instead of a reduction of 49% in 2030, they want to reduce the emission by 55% in 2030 (Giesen, 2020). The new agreement once again underlines the urgency of climate change.

The Dutch government acknowledged an essential role for hydrogen in the energy transition to meet the climate goals of 2050 (Rijksoverheid, 2019). The climate agreement presented plans to develop hydrogen in the Netherlands further. In general, three types of hydrogen are well-known: grey, blue and green hydrogen. At this moment, almost all hydrogen produced globally is grey hydrogen (van der Burg, 2021). Grey hydrogen is made out of natural gas via steam-methane-reforming (SMR), a process whereby steam is reacting with natural gas (CH_4) that result in hydrogen (van der Burg, 2021). In this process, carbon dioxide is released, which is why it is called grey hydrogen (Mueller-Langer et al., 2007). If the carbon dioxide is captured and stored, e.g., via Carbon Capture and Storage (CCS), the hydrogen is referred to as blue hydrogen or low carbon-hydrogen (Rijksoverheid, 2020b). For making blue hydrogen, pre-combustion technology is used, which captures 80 – 90% of the carbon dioxide (van der Burg, 2021). The CO_2 is stored deep underground in old gas fields.

Post-combustion technology can capture all the CO_2, but this is expensive, and the process requires energy which will cause other CO_2 emissions (Westerveld, 2021a). Hydrogen can also be produced from residual gasses. The project H-vision will produce blue hydrogen consisting of 90% refinery gasses supplemented with natural gas (10%) and combined with CCS (H-vision, 2021). At last, hydrogen is in some chemical processes a by-product (Green Deal, 2021; Milieu Centraal, 2021).

Another technology to produce hydrogen is to make it from electricity through electrolysis (Dincer & Zamfirescu, 2016). Depending on the electricity source (renewable or fossil), the color of hydrogen is determined. When hydrogen is produced using grey electricity, it is also referred to as grey hydrogen, and green hydrogen means that the hydrogen used is produced with renewable electricity (Rijksoverheid, 2020b). Multiple technologies are available for electrolysis, like PEM, Alkaline, AEM, and Solid Oxide Electrolysis (SOE) (FME & TNO, 2021; TKI Nieuw Gas, 2018; TNO, n.d.). PEM and Alkaline are the two technologies that are most developed and are market-ready technologies (FME & TNO, 2021). In Figure 1, the Alkaline, PEM, and SOE technologies are visualized.

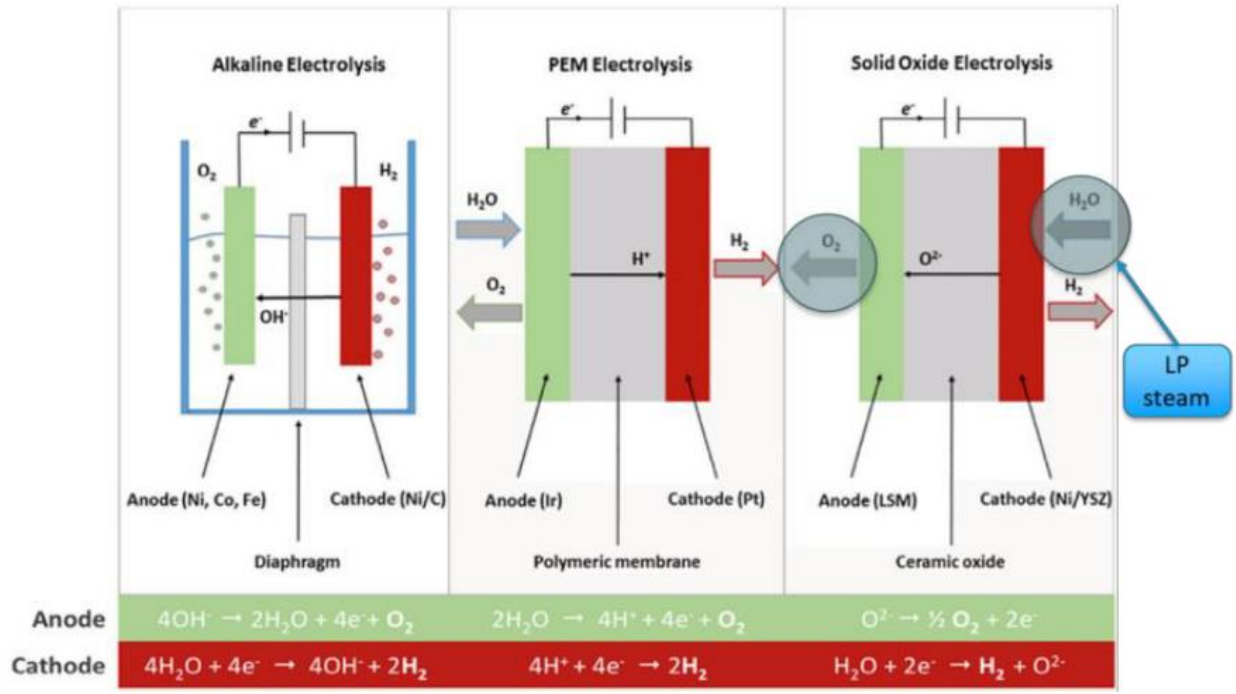

Figure 1: Three different elektrolysis technologies (Alkaline, PEM and SOE) (Millet & Grigoriev, 2013)

The Dutch government focuses on the deployment of green hydrogen (CO_2 emission-free) for the future (2050) (Dutch Government, 2019). Therefore this study will focus on green hydrogen as the ultimate end goal in 2050 and includes blue hydrogen as a possible means to achieve that goal. The use of more grey hydrogen is not included in the plans as the production process emits a lot of CO_2 (FME & TNO, 2021). However, to have a fully functional hydrogen economy running on green hydrogen, blue hydrogen could play an essential role as an intermediate step and catalyst (Sebastiaan Hers et al., 2018; Anne Geurts, personal communication, June 23, 2021 & Zofia Lukszo, personal communication, June 25, 2021). The focus is on how the supply and demand in the Netherlands can be stumilated for both, blue and green hydrogen. When in this study is talked about stimulating hydrogen, green and blue hydrogen are mentioned.

Hydrogen is an energy carrier that can significantly contribute to the energy transition (Momirlan & Veziroglu, 2002). Hydrogen can be used for multiple applications, e.g., for energy storage (seasonal or in the short term to overcome intermittency), in the built environment, in the industry, in aviation, as a fuel in the transport sector (Ehret & Bonhoff, 2015; Murthy Konda, Shah, & Brandon, 2011; Sherif, Barbir, & Veziroglu, 2005).

In April 2020, the Dutch government presented its strategy on hydrogen, which is in line with the hydrogen plans of the climate agreement (Rijksoverheid, 2020). This strategy presents plans for several sectors like ports and industry clusters, mobility, and build environment. Plans include for example subsidies schemes and research initiatives. One of the goals in this strategy is to have 3 – 4 GW installed electrolyse capacity in 2030 (Ministry of Economic Affairs and Climate Policy, 2020).

In this study, the focus is on the heavy industry sector. Significant reductions can be (easily and cost-efficient) accomplished in this sector. This sector mainly uses fossil fuels like coal and natural gas to heat processes and produce feedstocks (Dutch Government, 2019; Kiwa, 2021b; Ministry of Economic Affairs and Climate Policy, 2020; RVO & EZK, 2019). Therefore is expected that the available (green) hydrogen will be used first in the energy-intensive industry (Rotman, 2020; Stedin, 2020; van der Burg, 2021). In addition, the sector already uses a lot of grey hydrogen in its processes as feedstock, and blue or green hydrogen can easily replace this demand (Gigler et al., 2020). Many processes (temperatures above 600 degrees Celsius) are hard to be electrified (Dutch Government, 2019; Hydrogen Council, 2017). To make these processes sustainable, the companies have no alternative but hydrogen for decarbonization (van Renssen, 2020).

The idea of a hydrogen economy in the Netherlands is taking off (Rijksoverheid, 2019). Gasunie is working on a hydrogen backbone. To use hydrogen for such applications mentioned above, a fully developed hydrogen infrastructure is required (Smit, Weeda, & de Groot, 2007). This infrastructure is one part of a hydrogen supply chain (distribution). Other parts of the supply chain are the generation and utilization (Stephens-Romero & Samuelsen, 2009). Besides the infrastructure, there are several projects planned for hydrogen production, e.g., DJwels (16 million euro subsidy), H-Vision (2 billion euro investments), NortH2 (10 billion euro investments)(Savelkouls, 2021b). These projects are in the 'decision' phase and are waiting for the green light (de Laat, 2020). This green light depends primarily on whether the financing is complete (subsidies, grants, funding) because these projects have to deal with an unprofitable top (Hoogma, 2020). In other words, the investors will wait for the government's support before making a final investment decision (Beckman, 2020; Savelkouls, 2021b).

The hydrogen technologies are developing, and the projects are the result of all this effort. However, there are still significant steps to be taken. A big setback is the cancellation of the plan of the Dutch government to subsidize green hydrogen production via SDE++. The EU Commission does not approve this scheme because there is not enough renewable energy available in the Netherlands (H2Platform, 2020b). Most of the projects depend on this subsidy, and the cancellation hinders the development.

The hydrogen technology is developing in a system with many actors who have their interests (de Laat, 2020). Hydrogen is in an excellent position to play an essential role in the future in the heavy industry sector, but there are still some barriers that hold back full deployment (Moliner, Lázaro, & Suelves, 2016). Financing is at least one of them, but it is expected that there are many more. In this study, barriers will be called stabilizing pressures. These stabilizing pressures hold back the transition and need to be overcome. Drivers in this study will be called destabilizing pressures. These could foster the transition and should therefore be stimulated. This terminology is used because these terms are used in the transition literature.

1.2 Problem statement

The introduction has mentioned that the cancellation of granting subsidy via SDE++ causes a delay of the new hydrogen projects. This stabilizing pressure makes the transition more difficult because projects deal with an unprofitable top and ensures that the current technology (fossil fuels) remains in use. Overcoming the unprofitable top is not only dependent on the SDE++ subsidy scheme but has multiple causes. In addition to the unprofitable top, there are also stabilizing pressures regarding technology and regulations. Both technical and institutions are related to the costs of the development and realization of the hydrogen economy. These stabilizing pressures have to be overcome to foster the transition.

Furthermore, the developments rely on integrating the supply chain, where the infrastructure plays an important role. These are all stabilizing pressures that counterwork the deployment of green hydrogen in the heavy industry sector in the Netherlands. Nonetheless, there are also destabilizing pressures which could accelerate the transition, e.g. the pressure of the climate agreement to be almost entirely sustainable by 2050. To stimulate the transition, the Dutch government can deploy one or more policy instruments, for example, a subsidy or a tax. Policy instruments can remove stabilizing pressures, stimulate destabilizing pressures, and that paves the way for hydrogen in the heavy industry. However, it is unknown which policy instruments can accomplish this.

Therefore, the following problem is central in this study:

> The Dutch government must initiate the transition towards the use of green hydrogen in the heavy industry sector. Policy instruments could overcome these stabilizing pressures and stimulate the destabilizing pressures, but it is unknown which policy instruments can do that best.

.

1.3 Knowledge gap

At this moment, it is unknown which policy instrument the Dutch government should deploy to stimulate green hydrogen in the heavy industry. Before policy instruments can be assigned, it must be clear which stabilizing pressures and destabilizing pressures are present in the heavy industry.

The government is looking for policy instruments that can best overcome the stabilizing pressures and stimulate the destabilizing pressures to accelerate green hydrogen development in the Netherlands' heavy industry sector (Anne Melchers, personal communication, June 16, 2021). There are ideas about which steps to take to get hydrogen off the ground. There is a lot written about what there should be done to deploy hydrogen in general (developing a hydrogen economy)(Demirbas, 2017; Dunn, 2002; van Renssen, 2020) and there are reports about how to make the heavy industry sustainable (Dutch Government, 2019; SER, 2019) or written about what specific hydrogen projects (H-vision) needs (Savelkouls, 2021a; Sluijters, 2021). Nevertheless, there is no unambiguous analysis of which policy instruments the government should deploy to stimulate green hydrogen in heavy industry (Dutch Government, 2019; Ministerie van Economische Zaken en Klimaat, 2020a; Savelkouls, 2021b; Westerveld, 2021b).

The transition literature can help analyze the hydrogen transition by decomposing it into several phases and distinguishing multiple levels (Geels, 2011a, 2018). Within the transition literature, the multi-level perspective (MLP) is a framework developed to understand transition processes and is used by policymakers for selecting appropriate policy instruments to stimulate the specific transition (Alkemade et al., 2011). The MLP provides insight into how socio-technical system works and can identify stabilizing and destabilizing pressures, but it cannot provide specific advice on policy (Kern, 2012). For more detailed information on the effects of specific policies, the economic literature gives more insights.

The economic literature describes policy instruments, e.g., quotas and subsidies, and their effects (Vedung, 1998). Therefore, this literature examines the effects of certain policy instruments and is more specific than the transition literature for selecting policy instruments. However, this literature focuses on the efficiency and effectiveness of policies and does not take other aspects into account (Haas et al., 2011; Menanteau et al., 2003; Perrels, 2001).

Both strands of literature could be of value for selecting suitable policy instruments that can foster the transition. However, there is still little knowledge about combining the two fields of literature into a analytical framework to determine which policy instruments are the best for stimulating the transition. Kern (2012) used key processes extracted from the literature about MLP for assessing policy instruments but does not address case-related destabilizing pressures and stabilizing pressures. Furthermore, including case-related destabilizing pressures and stabilizing pressures, with help from the MLP, in the assessment of policy instruments has not been done before.

However, it is not for the first time that a study will evaluate policy instruments on specific criteria (Battles & Zoppoli, 2020; Konidari & Mavrakis, 2007; Wang et al., 2009)**.** This paper will contribute to the literature as there is no analytical framework yet for policy instruments to stimulate the hydrogen transition for the heavy industry sector in the Netherlands. Furthermore, combining the transition literature (MLP) to identify destabilizing pressures and stabilizing pressures with the economic literature to assess policy instruments on these destabilizing pressures and stabilizing pressures will add new insights.

1.4 Research objective and research questions

This research will look into the destabilizing pressures and stabilizing pressures obstructing the deployment of green hydrogen in the heavy industry. The objective of this research is to provide policy advice, consisting of policy instruments, for the Dutch government on how to deal with these stabilizing pressures and destabilizing pressures.

The research focuses on the hydrogen supply chain, from exploration to consumption in the heavy industry. The literature review, which can be read in chapter 3, outlines that the right policies can help overcome the stabilizing pressures and stimulate the destabilizing pressures (Demirbas, 2017; Dunn, 2002; Hisschemöller et al., 2006). The literature has no answer on how which policy instruments have to be deployed to stimulate green hydrogen in the heavy industry sector in the Netherlands. The research question that will be central in this research is:

Which policy instruments should the Dutch government implement to accelerate the deployment of green hydrogen in the heavy industry by 2050?

The main research question contains multiple concepts that can be divided into sub-questions. Answering all the sub-questions will result in a complete answer to the main research question. Per sub-question, the selected research method is presented, and the strong and weak points of the selected methods are discussed.

1. *How can a* analytical *framework be made of the transition literature and economic literature to assess policy instruments' performance?*

2. *Which policy instruments are there to stimulate the hydrogen transition in the heavy industry in the Netherlands?*

3. *What are the characteristics of the socio-technical system, the heavy industry sector in the Netherlands (niche, regime, and landscape level), and what kind of destabilizing pressures and stabilizing pressures are there?*

4. *What is the ranking of these instruments in stimulating the hydrogen transition in the Netherlands by overcoming the identified stabilizing pressures and supporting the destabilizing pressures?*

1.5 Research design

In this section, the reseach design will be explained. In Figure 3, the research design is visualized. First, the theoretical framework will be discussed. This section decribes the pieces of literature that will be used in this study. Second, per sub—question, the methodology to formulate an answer is discussed. Al the sub-questions together formulates an answer to the main research question.

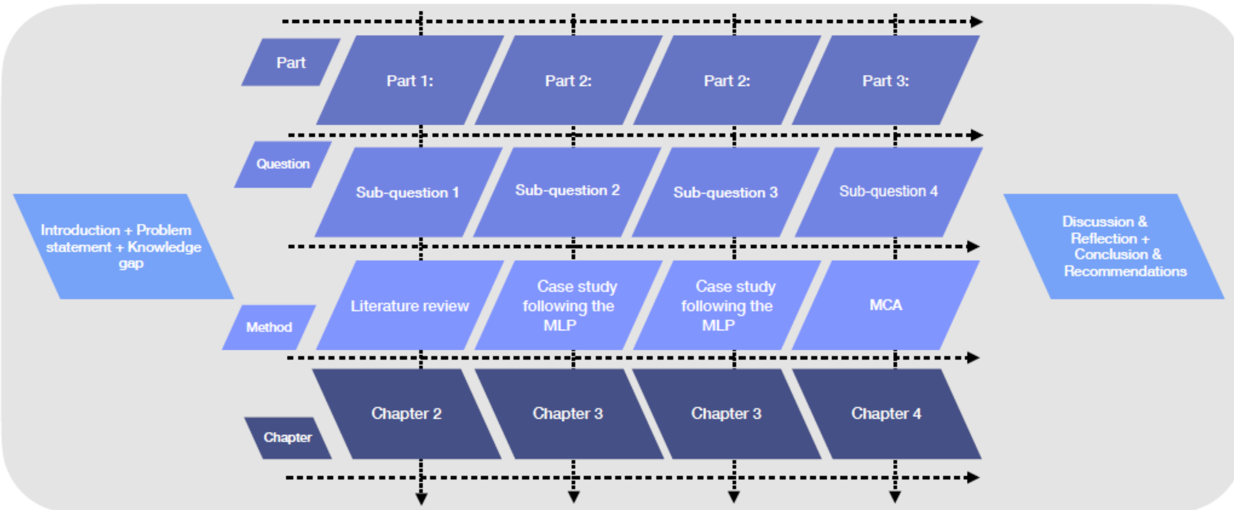

Figure 2: Research flow diagram (Own work)

1.5.1 Theoretical framework

In this section, the pieces of literature used in this research are explained. Last, it is elaborated on how these pieces of literature are used to fill in the knowledge gap.

1.5.1.1 Transition literature

The energy transition is a transition towards sustainability and requires deep structural changes in all kinds of systems, such as energy and transport (Geels, 2011). To accomplish deep structural, the configuration of elements in these systems like technology, infrastructure, markets, and scientific knowledge needs to be adapted.

The multi-level perspective from Geels (2002) is a conceptualization used to understand the transition process. The MLP can help understand technological transitions, such as the towards a hydrogen economy. According to this framework, transitions arise throughout interactions between three levels: socio-technical landscape, socio-technical regime, and niche (Geels, 2011b).

Typically, the MLP analyzes historical cases of transitions and future transitions towards sustainability (Geels, 2011). Policymakers commonly use the MLP to inform policies to stimulate the transition to sustainability (Alkemade et al., 2011). Kern (2012) uses the MLP to “ex-ante assess policies to stimulate socio-technical transitions”, meaning that the framework will be used for policy analysis (Kern, 2012, P.299). His theory will be used throughout this thesis.

In this research, the MLP will analyze the socio-technical system of the heavy industry in the Netherlands. The MLP will define the system by looking into the three prescribed levels and the interaction between them. Furthermore, the MLP will be used to assess policies on their contribution to the transition.

Despite the fact that the MLP makes insightful how the socio-technical system is set up, it cannot give detailed advice for policies as it is on a high level of abstraction (Kern, 2012). For more detailed information on the effects of specific policies, the economic literature gives more insights.

1.5.1.2 Economic literature

The SDE++ subsidy scheme is a policy instrument that the Dutch government wanted to use to stimulate the deployment of hydrogen. A policy instrument is conceived to accomplish a particular target (Hepburn, 2006). This target, which could be e.g. the realization of 3-4 GW capacity of electrolyzers in 2030 is part of a policy objective. The corresponding objective could be to stimulate the hydrogen economy. The objective and target must be in line with each other to get the desired results (Hepburn, 2006). In the literature, multiple typologies can be distinguished. In this study, the threefold arrangement of policy instruments, discussed by Vedung (1998), is applied. In this threefold, the instruments are classed as regulations, economic means, and information. These classes are also referred to as the stick, the carrot, and the sermon (Vedung, 1998). When designing and using a policy tool, "the contextual nature of the choice and specification of policy instruments is a crucial aspect" (Borrás & Edquist, 2013, P.1515)**.**

1.5.1.3 Multi-level Perspective and policy instruments

In section 1.5.1.1, the transition literature is elaborated, and section 1.5.1.2 explains the economic literature about policy instruments. By combining this literature, however, a better understanding of conducting policies can be obtained. The strong points of the MLP are that it has a broad scope and includes the timeline of the transition process. Moreover, it encounters the complexity in systems with all its stakeholders. At the same time, the economic literature excels by its predictive power of the policy instruments.

The MLP lends itself well as an overarching framework to get insight into the socio-technical environment. To analyze the problem that the transition is facing, the MLP is a valuable tool.

However, the MLP refrains from making concrete policy recommendations because the literature on transition management, wherein the MLP is outlined, has no comprehensive knowledge about policy instruments. Although the MLP is commonly used to make policy recommendations and is also used to assess policy, the economic literature has to be consulted for extensive knowledge. Literature about policy instruments comes is based on neoclassical economics and has a strong explanatory character. The economic literature is more specific about when to deploy instruments and what the effects are.

Therefore, this study tries to combine both strands of literature by complementing the strengths: the straightforward economic literature with lots of assumptions that described the effect of policy instruments and the MLP theory, which describes the complexity of a system but is at the same time hard to conceptualize and is more based on perceptions. The economic literature will form the input for the assessment to understand the effects better when a particular policy is deployed.

1.5.2 Methodology

Per sub-question, the methods that are used to formulate an answer to this particular question are explained. The sub-questions correspond with the three parts of this research. Each completed part forms the input for the next part so that eventually, an answer can be formulated to the main question.

Sub-question 1: How can a analytical framework be made of the transition literature and economic literature to assess policy instruments' performance?

The first research question will dive into the transition literature and economic instruments (section 2.1 & 2.2). A literature review is conducted to formulate an answer to this sub-question and create an analytical framework in both strands of literature. At first, in section 2.1, the transition literature is consulted to set up the y-axis of the analytical framework. Second, the economic literature about policy instruments is has been studied to set up the x-axis of the analytical framework.

Sub-question 2: Which policy instruments are there to stimulate the hydrogen transition in the heavy industry in the Netherlands?

The MLP will be used to define the socio-technical environment of the heavy industry sector (Geels, 2000). With the help of this framework, policy instruments that the Dutch government could deploy to stimulate the hydrogen transition will be analyzed via a case study. After the case study, a selection will be made. Next, an assessment of these policy instruments is conducted. In this study, an MCA is selected as a methodology for assessing the policy instruments indicated by this sub-question and ranking them. Criteria for assessing these instruments are discussed in sub-question 3.

Sub-question 3: What are the characteristics of the socio-technical system, the heavy industry sector in the Netherlands (niche, regime, and landscape level), and what kind of destabilizing pressures and stabilizing pressures are there?

The second sub-question, together with the third sub-question, will be answered by mapping the heavy industry sector in the Netherlands. First, a literature review is conducted of the transition to a hydrogen economy in general. A search strategy is set up to collect all relevant literature. Databases as ScienceDirect, Scopus, Google Scholar, and Web of Science are used to find literature. The following keywords and Boolean operators are used to collect literature written about this topic:

'barrier', 'challenge', 'obstacle', 'deployment', 'hydrogen', 'economy', 'infrastructure', 'hydrogen economy', 'Netherlands, 'Dutch', 'implement' "AND" and "OR"

The literature that is found in the online databases is assessed on relevance and quality. This review considers literature that was published after January 2000. Another limitation is the exclusion of literature written in a language other than English. No geographical limitations were imposed.

In addition to this literature review about the hydrogen transition in general, gaining case-related insights into the current situation of the heavy industry in the Netherlands is necessary for getting a clear overview of the problem and indicating the destabilizing pressures and stabilizing pressures (Geels& Kemp, 2000). Insights will be gained by doing a case study based on the MLP framework. Information and data will be gathered by doing a review of (academic) literature and reports. Literature in which the hydrogen vision for the future is described will also be used to answer the sub-questions. Data collection using documents is an effective method to collect a lot of information and data in a short period (Johannesson & Perjons, 2014). When using documents, one of the issues is that the information has to be assessed on a bias (Winchester & Salji, 2016).

The theory of Geels (2011) on (MLP) will be used to understand the dynamics of the hydrogen economy and its environment. The MLP looks at three different layers, namely, niche, regime, and landscape (Geels, 2011). In section 2.1, the transition literature is explained.

Sub-question 4: What is the ranking of these instruments in stimulating the hydrogen transition in the Netherlands by overcoming the identified stabilizing pressures and supporting the destabilizing pressures?

The next phase is assessing which policy instruments, identified by sub-question 2, can help achieve the climate goals and foster the hydrogen transition. The policy instrument will be evaluated by the destabilizing pressures and stabilizing pressures identified in sub-question 3. This will be done by using the analytical framework from sub-question 1. The MCA methodology has been found suitable for to rank the policy instruments. Applying this analysis will help in evaluating policy instruments and conducting policy advice.

When the pressures are formulated using the contextual insights from the MLP, an MCA will be conducted. An MCA is a tool to evaluate various alternatives on multiple criteria (Government, 2009). The MCA model used in this research will help in decision-making for selecting the right policy or policies in a policy mix. There are multiple alternatives for valuating policies in an MCA. The selected criteria can have the same weights (equal weight method) or have weighted coefficients (Battles & Zoppoli, 2020). Different scales can be applied to grade the policy instruments on the criteria. Two examples are a scale [0,10] or [-1, 0, +1.].

The assessment will be based on (grey) literature, reports, news articles, and academic papers. Furthermore, informational interviews will be conducted with experts who are related to the socio-technical system. Via semi-structured interviews with experts in the socio-technical system, from generation towards utilization, technology developers, and the Dutch government, more information and knowledge will be gained about the effects of policy instruments on the destabilizing pressures and stabilizing pressures. Interviews allow the researcher to go in-depth to gather detailed information and specific data (Johannesson & Perjons, 2014). One of the advantages of semi-structured interviews is that the respondent can answer in their own words. A semi-structured interview gives the interviewee room for comprehensive answers without straying too much from the topic. Moreover, this kind of interview is better suited for studies with complex issues (Johannesson & Perjons, 2014).

Two disadvantages can be identified when conducting interviews. One is that interviews cost much time. Another disadvantage is the possible interference of the researcher's personal attributes (Johannesson & Perjons, 2014). One must keep in mind that every respondent answers from their interest and perspective. Also, there is the possibility of false positives: respondents want to be polite and conceal critics from the researcher. This can be encountered by asking follow-up questions. Interviews will let the researcher ask follow-up questions to receive in-depth feedback (Johannesson & Perjons, 2014). Based on the case study, questions are derived for the interviews. These questions are asked during every interview to reduce the interference of the interviewer. Furthermore, asking the same questions makes it possible to compare opinions and perceptions. However, in an interview, some space must be left for motivations and personal experiences. This knowledge will contribute to the quality of the research.

Chapter 2 Literature review: Review of the theory

In the previous chapter, the research question and research objective are illustrated. Chapter 1 has revealed the struggle where the hydrogen sector is dealing with at this moment. It is beyond dispute that the willingness to build a hydrogen economy in the Netherlands is enormous, looking at all the projects, plans, initiatives, and active coalitions (de Laat, 2020; McDonald, 2021; Provincie Groningen, 2020; Savelkouls, 2021b). In addition to the activity in the private sector, the Dutch government revealed their intentions regarding hydrogen in the climate agreement and government strategy on hydrogen (Dutch Government, 2019; Rijksoverheid, 2020).

In this chapter, the literature on transitions and policies will be reviewed to perceive an overview of the available knowledge and answer the first sub-question. First, the literature about transitions will be evaluated. Two different approaches are commonly used to analyze socio-technical transitions in a broader aspect and making transition policy recommendations (Alkemade et al., 2011). A tradeoff will be made between these two approaches. The most suitable approach will be used in chapter 4 to analyze the transition and get insights into the destabilizing pressures and stabilizing pressures for enabling and stimulating transitions.

Subsequent the economic literature about policy instruments is discussed. This literature tells more precisely about policy instruments and their effects. Considering economic literature contributes to answering the question of which policy instruments the Dutch government can implement to stimulate the hydrogen. In the end, the multiple strands of literature are combined into an analytical framework.

2.1 Sustainable transitions

Transitions call for structural changes among huge systems (sectors) in the Netherlands. The focus is on transport, agri-food, industry, built environment, and energy (Dutch Government, 2019; Geels, 2011a). Systems that fulfill a societal function, like energy systems, are socio-technical systems (Geels, 2012). Transitions that have far-reaching effects on fulfilling societal needs are called socio-technical transitions and are deep-structural systemic, generally long-term processes. (Alkemade et al., 2011; Geels, 2011a). These transitions are complex as there are all sorts of actors involved, e.g., firms, policymakers, politicians, consumers, researchers, and engineers. It is no exception to take over 25 years to complete such transitions (Alkemade et al., 2011). Observing transitions towards sustainability entails some different characteristics in comparison with historical transitions (Geels, 2011a). Sustainable transitions can be distinguished from other transitions by three characteristics (Geels, 2011):

1. The transition is goal-oriented
2. Sustainable choices serve the collective good and can be economically less beneficial than established technologies
3. Large firms rule the essential systems that need to change with a strong position and market power.

The first one is that sustainability transitions originate from climate change, while historical transitions were often emergent. The second characteristic of sustainable transitions is that they serve a collective good and are often economically and efficiently not the best options. Meaning that when leaving things to the market, the transition will not occur by itself. Innovations will not replace the current regime without the interference of the government (Geels, 2011a). In section 2.2, possibilities to interfere are presented.

At last, the sectors mentioned above are characterized by large firms. Moreover, these firms have a strong position in the sector. Hence, these are the actors in the best position to establish innovations because they have the assets (knowledge and money) to invest in R&D. When these actors do not invest in innovations, this impacts the speed of the development of the innovation. Even when these firms are not forerunners, their vast power in the sector can significantly impact stimulation innovations (Geels, 2011a). To initiate a sustainable transition and keep it in motion calls for an interplay between technology, government, the market and, society (Geels, 2011a)**.**

A socio-technical system consists of elements that do not function on their own. These elements are maintained and created by human actors arranged in social groups (Geels, 2006). These elements are all aligned in a configuration and are dedicated to one socio-technical system. A change from one socio-technical configuration to another is also mentioned as the change from one socio-technical system to another (Geels, 2002, 2006). Elements are e.g. regulations and policies, market and user practices, infrastructure(s), culture, maintenance networks, and symbolic meaning (Geels, 2006).

To enforce a reconfiguration is a complicated process. The elements in the configuration are all linked to each other and aligned to the specific socio-technical system. The breakthrough of new technology is therefore complicated but not impossible. (Technical) Innovations can create a transition in a socio-technical system (Alkemade et al., 2011). Think about the electric car. The transitions have consequences for the actors involved. For a deeper understanding of the transition, it is of value to analyze the socio-technical system. Furthermore, when the socio-technical system is analyzed, there are possibilities to design policies to stimulate the transition (Kern, 2012; Markard & Truffer, 2008). Two streams of literature have emerged within the innovation literature, and both defined an approach for the conceptualization of transitions.

Socio-technical transitions can be analyzed and conceptualized by the multi-level perspective literature on technical transitions, and the technological innovation systems (TIS) approach (literature on innovation systems) can be used (Alkemade et al., 2011; Markard & Truffer, 2008). The MLP from Geels (2002) is a conceptualization that can be used to understand the transition processes as it looks between three levels and the alignment between them (Markard & Truffer, 2008). The TIS approach conceptualizes the development of the transition process by focusing on the innovations processes (Hekkert et al., 2007; Markard & Truffer, 2008)**.**

First, these two approaches will be discussed, and after that, the approaches will be compared.

2.1.1 Multi-level perspective

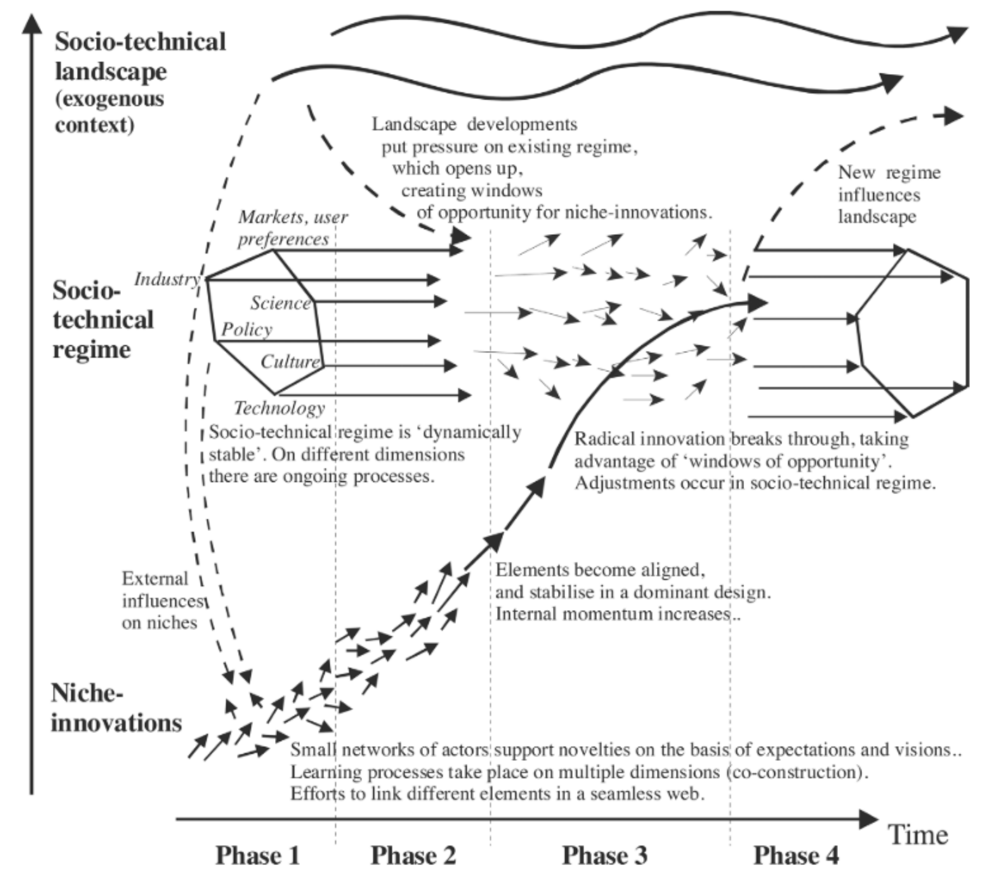

Figure 3: Dynamic MLP on system innovations, from (Geels, 2018)

For analyzing the dynamics, mechanisms, and patterns of socio-technical transitions, the MLP is a commonly used framework. The framework consists of three analytic levels (Figure 3) (Geels & Kemp, 2000):

Micro-level Technological niches

Meso-level Socio-technical regimes

Macro-level Socio-technical landscape.

The core of the MLP theory is the interdependence between the three levels (micro, meso, macro). A breakthrough of new technology or innovation will only happen if all levels sync with each other. The success of a transition is based on the interaction between developments on the three levels (Kern, 2012).

At the niche level, radical innovations take place in protected spaces. Technological niches are often experimental projects that can learn and develop in a unique environment (market niches) that stands apart from the current regime. Network formation is another vital function at the niche level. The bigger the network gets, the more actors are involved, including money to develop the new technology (Geels & Kemp, 2000). When a particular actor creates an experiment, there may be a strategic idea behind it.

Besides the intention to learn from experiments, experiments could also create awareness and support for the new technology. Sometimes the strategic intentions are known, but this could also be hidden. Niches try to pressure the regime from below and gradually become the new regime (Geels & Kemp, 2000).

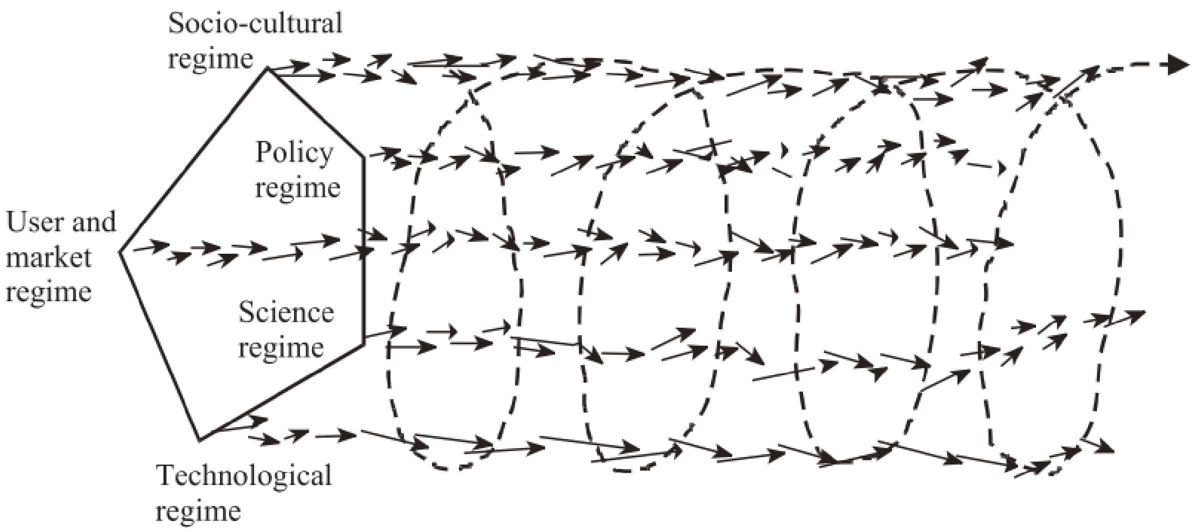

Figure 4: Alignment of ongoing processes in a socio-technical regime (Geels, 2011)

The regime is the second level and forms the core of the socio-technical system. "The current fossil-fuel based energy regime is characterized by a dominant configuration of certain technological artefacts, institutions, networks, user practices, market structures, regulatory frameworks, cultural meanings and scientific knowledge" (Kern, 2012, p. 299) as can be seen in Figure 4. Those elements anchor a particular technology. The alignment between the elements gives stability. It is hard to change one element without changing the others (Geels, 2004; Kern, 2012). This is because technological developments are often incremental and optimize a technology (e.g. combustion engine). The downside is that it provides a lock-in of the technology, which is hard for innovations to break through (Kern, 2012). At this level, the current rules and institutions are described and carried by the incumbent actors (Geels, 2002; Roberts & Geels, 2019).

The top-level is the landscape, an exogenous environment that influences and affects developments at the regime level. "Landscapes are beyond the direct influence of actors and cannot be changed at will" (Geels, 2005, p. 684). Transitions will emerge by aligning the niche, regime, and landscape level (Geels, 2005; Roberts & Geels, 2019). The following elements have an essential role in the landscape level (Geels & Kemp, 2000, p. 17):

- Material infrastructure
- Political culture and coalitions
- Social values and lifestyles
- Societal and managerial 'common sense' (e.g. companies have to be lean, green and must focus on ICT and being active and visible online)
- Macro-economic aspects
- Pervasive technologies

- Demography
- Natural environment

The MLP defines in total four different transition phases during a transition process. The four phases are (1) radical innovation, (2) innovations enter small market niches, (3) diffusion and competition with the existing regime (4) system substitution and institutionalization (Roberts & Geels, 2019). Starting with the emerges of radical innovations in niches in the context of existing regimes and landscape developments (Geels, 2005; Geels & Schot, 2007). In the second phase, the innovation is used in small markets niches, facilitating other resources for further developments (Roberts & Geels, 2019). The third phase of the transition is the breakthrough of the new technology into the regime. The breakthrough will not happen without a struggle with the existing regime. Two forces make this breakthrough possible: internal destabilizing pressures and the so-called windows of opportunity created by external circumstances. An example of an internal destabilizing pressure could be the development of hydrogen technology that causes a price decrease. Changes in the landscape level can create a window of opportunity as they pressure the regime (Geels, 2018). One can think of an aversion to fossil fuels that open up the regime for electric cars. The last phase is when the new technology takes over the old regime and adapts to the more comprehensive socio-technical regime (e.g. infrastructure, policies, and lifestyles). Eventually, the new regime will also affect the landscape level (Geels, 2005, 2018; Kern, 2012). In Figure 4, the phases are indicated in the transition process (Geels, 2018). “Although the varying role of public policies in these four transition phases has not yet been systematically analyzed, scholars have suggested that transitions are not driven by single policies but by policy mixes (Kivimaa and Virkamäki 2014; Kivimaa and Kern 2016; Rogge and Reichardt 2016), which are likely to vary over time” (Roberts & Geels, 2019, P. 5). Kern (2012) acknowledges that every level from the MLP needs another form of policy to support the transition at that specific phase.

2.1.2 Technical innovation systems (TIS)

The contribution of renewable technologies to the sustainability transition in (energy) systems can be analyzed with the TIS perspective. This tool provides insights into the successes and failures of the development and diffusion of these technologies (Wieczorek et al., 2015). Just like the MLP framework, the TIS perspective looks at the configuration of four components: actors, networks, institutions, and technology in the innovation system (Jacobsson & Karltorp, 2013). “A technological innovation system can be defined as the network of actors, rules and material artifacts that influence the speed and direction of technological change in a specific technological area” (Reichardt et al., 2016, p. 12). By analyzing the elements in the system and evaluating their contribution towards supporting an innovation. An innovation system could serve different purposes, although it consists of similar elements (Reichardt et al., 2016). In addition, the perspective focuses on crucial processes in the development of new technological fields (Wieczorek et al., 2015). In particular, the TIS approach looks at seven system functions (Hekkert et al., 2007):

1. entrepreneurial activities
2. knowledge developments
3. knowledge diffusion through networks
4. the guidance of the search
5. market formation
6. resources mobilization

7. creation of legitimacy resistance to change

Where the MLP is focusing on the interaction between the three levels, the TIS focuses on the interplay between functions (Markard & Truffer, 2008). Using these functions mentioned above, the TIS assesses and compares the innovation systems. All these functions have to function correctly for a good system functioning (Reichardt et al., 2016). The TIS approach could be of value to identify obstacles in the deployment of hydrogen in the Netherlands and formulate recommendations for policy interventions (Jacobsson & Karltorp, 2013; Reichardt et al., 2016, 2017). To do so, extensive knowledge of the current situation, the hydrogen developments in the Netherlands, is required (Jacobsson & Karltorp, 2013). The TIS approach is suitable for analyzing the impact of policy mixes on the technology innovation system. Besides, the dynamics of TIS influences the formation of the policy mix (Reichardt et al., 2016).

2.1.3 Comparison MLP & TIS

Now that both approaches are generally explained, some differences can be distinguished.

One of the differences is that the TIS approach focuses less on the battle between innovations and the existing regime and more on the development of innovation (Geels, 2011a; Roberts & Geels, 2019). When the focus is on establishing and supporting the innovation activities (formative phase), the TIS approach is very suitable. Nonetheless, this approach pays less attention to the transition from the formative to the growth phase, known as the breakthrough into the exiting systems (regime) (Roberts & Geels, 2019).

One of the strengths of the MLP is the thorough analysis of the regime level, which makes it possible to explain clearly the innovation and transition process. The MLP looks into the “interplay of stabilizing mechanisms at the regime level and (regime-) destabilizing landscape pressures combined with the emergence of radical innovations at the niche level. Thereby, the framework also leaves room for contingencies such as external shocks or disruptive changes at the landscape level” (Markard & Truffer, 2008, p. 609). While the systems environment is one of the pillars of the multi-level perspective, in the TIS approach the focus on the environment is not comprehensive (Markard & Truffer, 2008).

In this paper, the multi-level perspective framework is selected for gaining insight and conceptualize the socio-technical transition. Derived from the introduction, it became clear that the technical innovations, experiments, and pilot projects, have not started yet. However, more and more project plans are being released and are waiting on an investment decision.

Establishing niche markets is just the first phase, the challenge is to compete with existing technologies (van der Laak, Raven, & Verbong, 2007). and ensure a transition to a hydrogen economy. All four phases described by the MLP framework are essential for a successful transition. This policy advice will contain a recommendation to deploy several policy instruments that are effective to stimulate the development of the hydrogen in the heavy industry sector.

2.1.4 Application of the literature

Analyzing socio-technical transition is one way of using the MLP framework. Kern (2012) proposes another application for the MLP framework on socio-technical transitions. Instead of using the MLP as a tool to analyze socio-technical systems for giving policy recommendations, Kern (2012) uses the framework for analyzing the contribution from specific policy instruments to the transition. In his paper, Kern (2012) identified key processes essential for a socio-technical transition and conducted a framework. This framework consists of the essential processes that are derived from Geels & Schot (2007), Verbong &

Geels (2007) and Shackley & Green (2007). After that, a policy measure is assessed whether or not this policy measure promotes the key processes or not. The key processes are shown in Figure 5, the rows correspond with the levels of the MLP framework, and in the columns, the key processes identified per level are described.

Summary of analytical framework.

Niche	Learning processes E.g. learning processes have stabilised in a dominant design	Price–performance improvements E.g. price–performance improvements have been made and are believed to continue to improve	Support from powerful groups E.g. powerful actors have joined the support network	Establishing market niches E.g. innovation is used in market niches
Regime	Changes in rules E.g. belief systems, problem agenda's, guiding principles, search heuristics; relationships, behavioural norms; regulations, standards, laws	Changes in technologies E.g. in the case of electricity: resources, grid, generation plants	Changes in social networks E.g. new market entrants gain in importance compared to incumbents	
Landscape	Macro-economic trends E.g. globalisation, oils crisis	Socio-economic trends E.g. recessions, unemployment developments	Macro-political developments E.g. the 'philosophy' behind policy making	Deep cultural patterns E.g. trend towards more 'individualization'

Figure 5: Analytical framework with criteria, from (Kern, 2012)

Like the paper of Kern (2012), this paper will assess policy instruments on the contribution to the transition towards hydrogen in the heavy industry sector using the MLP framework. Kern (2012) applied his methodology on only single policy instruments. This study will evaluate multiple policy instruments, which is one of the recommendations from the paper of Kern (2012).

Per level of the framework, **destabilizing** and **stabilizing** pressures (Geels & Kemp, 2000) can be identified, which will provide insights into weaknesses and strengths of the transition from fossil fuels to green hydrogen in the heavy industry by doing an analysis of the socio-technical system (heavy industry) using the MLP. These pressures will be used to evaluate the different policy instruments. Destabilizing pressures could foster the breakthrough of niches (creating a window of opportunity) and are therefore positive. Stabilizing pressures are protecting the incumbent regime and hold back niches from a breakthrough.

As is made clear when explaining the MLP framework, when enabling transitions, the regime level and niche level are claimed to be essential (Kern, 2012). The focus is primarily on the regime's destabilization, which will create a 'windows of opportunity' for niche innovations to compete with the existing regime (Kern, 2012).

1. The destabilization is created by developments on the landscape level that enforce **destabilizing pressures** on the regime. **Stabilizing pressures** are also possible.

2. Another possibility for **destabilization** of the regime is destabilizing internal pressures. The opposite is also possible. There can also be stabilizing pressure present within the regime, which must be removed to enforce a transition (Geels, 2006; Kamp & Vanheule, 2015).

3. Niches could also destabilize pressure on the regime level from the bottom up (Geels & Kemp, 2000).

Pressures that are essential for the transition

Following the literature on MLP, the coherence between processes at niche, regime, and landscape level are denoted as essential for transitions.

Landscape

The landscape developments take place at the macro level. Driving forces behind the landscape level are macro-economic and socio-economic trends, political developments, and cultural patterns (Kern, 2012). The developments on this level are relatively slow and are external to the other two levels. Nonetheless, the landscape developments affect them. Policymakers cannot directly influence landscape pressures. However, it is meaningful to know how the developments on the landscape level can hold back or foster the transition because the landscape can impact the regime and niche (for example, environmental problems) (Geels, 2006). Therefore, the landscape will be analyzed, but no pressures will be identified in the case study. but will not be included in the

Regime

In chapter 3, an extensive analysis of the heavy industry system will be conducted to identify these case-related pressures. Formulating pressures related explicitly to this socio-technical system ensures that the evaluation process produces better-suited results than using the general key processes from Kern (2012).

Niche

It is difficult to identify specific pressures in the socio-technical system for the niche level, as they are created by all kinds of niches. To assess the effect of policy instruments at niches, the key processes identified by Kern (2012) will be used in this study. These key processes summarize the fundamental pressures that are needed to enforce a transition. The key processes identified by Kern (2012) are:

- Learning processes
- Price-performance improvements
- Support from powerful groups
- Establishing market niches

Learning processes and price-performance improvements are heavily related. For example, as we shall see, the price of hydrogen technologies can decrease by doing many (demonstration) projects and research (Dutch Government, 2019). Other vital points that need to develop are the materials used (scarcity), the design of the market, and regulations. The learning processes go hand in hand with the demonstration projects that also will result in price performance. Therefore, in this study, these two key processes are combined.

Support from powerful groups refers to the configuration of elements that have to be in place for a particular technology. Technology is not the only essential factor that needs to be changed in a transition. Powerful actors like investors are necessary to make the transition successful.

Market niches are also called protected spaces and refer to a protected environment wherein the niche can evolve over time and eventually is dominant enough to start competing with the incumbent regime. Verbong & Geels (2007) talks about incubation rooms that shield technologies from the current market. This protection is required as the innovations cannot stand on their legs because of low price/performances (Verbong & Geels, 2007). The market can be kept artificial for some time before it will intervene with the real market of the regime (van der Laak et al., 2007). Market niches are less critical for the hydrogen transition. The projects are mainly introduced in the five industrial clusters and can trade hydrogen within these clusters. Therefore, the focus is not on market niches as the innovations will be established first in the clusters (Dutch Government, 2019).

The key processes that will be used for assessment in chapter 4:

- Learning processes
- Support from powerful groups

2.2 Policy instruments

The section 2.1 about MLP has become clear that all the elements have to be in favor of the new technology. The socio-economic conditions have to be in place before an innovation is a success. Governmental policies are commonly used to shape these conditions for innovations (Hisschemöller et al., 2006). Between government and market are several possibilities for governmental policies. Hisschemöler et al. (2006) unfold four paradigms of governance for stimulating the transition towards a hydrogen economy in the Netherlands:

- Governance by policy networking (Focus on public-private partnerships)
- Governance by government (regulatory focus)
- Governance by corporate business (leave it to the market)
- Governance by challenge (planning economy).

The analysis of policy instruments is the next step in determining how the Dutch government can stimulate the hydrogen transition. To find out which policy instruments the Dutch government can deploy, a literature study will be conducted. With this will be looked at policy instruments that the Dutch government can use to steer the market (governance by challenge) (Hisschemöller et al., 2006). A threefold typology of public policy instruments from Vedung (1998) describes the policy instruments (Figure 6). The three classes that are distinguished are regulations, economic means, and information.

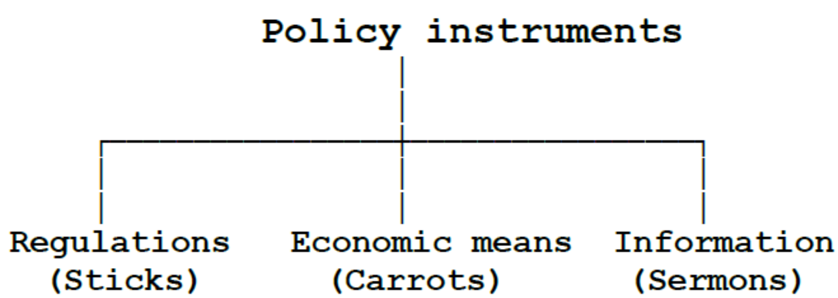

Figure 6: Threefold Typology of Policy instruments, from (Vedung, 1998)

2.2.1 Regulations

The first class is regulations, “Regulations are measures undertaken by governmental units to influence people by means of formulated rules and directives which mandate receivers to act in accordance with what is ordered in these rules and directives” (Vedung, 1998, p. 31). This class of policy instruments is also referred to as ‘sticks’. Regulations are there most often in the form of prices and quantities. Examples of this type of regulation are quotas, targets, banning, or standards. Quotas set a maximum on a quantity, targets a minimum, and banning means that a quantity of something is zero (banning diesel vehicles from the city center). Standards can be both maximum or minimum. Think about the standard of toxic ingredients in paint (Hepburn, 2006). Another example is the standard of a minimal amount of renewable energy production in the energy mix (Fankhauser et al., 2010).

Veugelers (2012) noticed that performance-based regulations are working the best in clean energy technologies. In environmental policies, legal instruments are commonly used (Oikonomou & Jepma, 2008). Regulation is an instrument of the government to control the behavior of actors, in this case, the companies that produce, transport, and use hydrogen. The instruments mentioned above are limiting the choices for the actors in place (Vedung, 1998).

2.2.2 Economic means

A vital feature of the second class, economic instruments, is exploiting markets' capability to aggregate information (Hepburn, 2006, p. 228). This class offers much more diversity in terms of instruments. Economic instruments can be distinguished into **price-based instruments** and **quantity-based instruments**. Price-based instruments were most influential in stimulating innovations in solar energy. On the other hand, Quantity-based instruments were the most effective in activating innovations in wind power technologies (Veugelers, 2012).

Deploying quantity-based instruments will eventually define a price for goods and services following the supply and demand curve. Within price-based instruments, **investment-focused strategies** and **generation-based strategies** can be distinguished (Haas et al., 2011). Furthermore, a distinction can be made between financial incentives and financial disincentives.

Price-based instruments (Vedung, 1998):

Investment focused strategies (IFS):

Financial support is provided per unit installed capacity, e.g. per MW installed capacity to produce (green) hydrogen in an electrolyzer.

Generation based strategies (GBS):

Financial support is provided as a fixed payment or per unit, e.g. per cubic meters of green hydrogen produced. Another example is a feed-in tariff.

Economic means can be provided as well in cash as in-kind (presented in Table 1, 2 & 3) (Vedung, 1998).

Table 1: Economic incentives in cash

Economic incentives in cash	
• Loan Guarantee	
○ Subsidies	
▪ R&D subsidies	
▪ Investment subsidies	IFS
○ Grants	
○ Low-interest / soft loans	IFS
○ Tax credits	IFS
○ Feed-in tariff	GBS

Table 2: Economic disincentives in cash

Economic disincentives in cash
• **Taxes**
○ **Fossil fuels**
○ **Energy use**
○ **Pollution / carbon tax**

Table 3: Economic incentives in kind

Economic incentives in kind
○ **of goods and services**
○ **Vouchers**

2.2.2.1 Subsidies

A well-known instrument is the provision of subsidies. Within this policy, instruments are multiple options to support technology. Feed-in tariffs are a form of subsidy, just as grants and (low-interest) loans. These are all examples where the government gives money for a good or service and gets nothing in return (goods or services) (Vedung, 1998). A characteristic of subsidies for specific technologies is that this instrument picks a ‘winner’ and favors a specific technology (Rosenow et al., 2017). Governments often give subsidies for research and development (R&D) in the hope that it will pay off. However, the outcome is uncertain as not all R&D efforts will end in a new technology that enters the market. Subsidies can support innovations by stimulating R&D or focusing on deploying existing technologies (SER, 2019).

Meanwhile, the effectiveness of grants, loans, and tax credits can be better determined in advance, and the government can pick specific technologies and has therefore more certainty (Oikonomou & Jepma, 2008). A risk associated with subsidies is the risk of overstimulating. According to the Secretary of State Dilan Yeşilgöz-Zegerius of the Ministery of Economic and Climate, it is impossible to prevent some renewable energy projects from receiving more subsidies than needed (Westerveld, 2021c).

2.2.2.2 Feed-in tariffs

In a feed-in tariff, the producer of goods will receive a predetermined fixed amount per unit produced. This fixed amount is permanently assigned regardless of the price of the good at that moment in the market. In the electricity market, this instrument is well known, as it guarantees a minimum price for the producer of its electricity (Haas et al., 2011).

2.2.2.3 Loan Guarantee

Without interfering in the banking system, the government could support actors by reducing the risk for lending organizations. When private actors want a loan e.g. a new electrolyzer, but the risks of loss are substantial because the hydrogen market is unknown for the future, the lender will probably only lend at a high interest rate (if it will lend at all). The government can guarantee repayment of the loan and thereby provide a loan guarantee to the lending source, which will result in a low-interest rate for the borrower (Vedung, 1998).

2.2.2.4 Tax credits

Taxes are a means that the government can deploy to make goods and services more expensive. Usually, the idea is that by pricing products, a disincentive is created, e.g. for petrol. However, because taxes are in place, the government can give goods and services tax credits (Veugelers, 2012).

2.2.2.5 Taxes

Like tax credits, the government can also increase tax rates on certain products to discourage potential buyers from buying a good or service. On goods like cigarettes and alcohol, an extra tax is in place. Regarding energy policy instruments, taxes are commonly used for fossil fuels, energy use, and pollution (Veugelers, 2012). For example, the government can charge polluters and ask for tariffs or fees (Vedung, 1998).

Besides price-based instruments, there are quantity-based instruments (presented in Table 4) (Vedung, 1998):

Table 4: Quantity-based instruments

Quantity-based instruments:	
• **Tradable certificates schemes**	**GBS**
• **Tendering or bidding schemes**	
○ **Investment grant**	**IFS**
○ **Long-term contracts**	**GBS**
○ **Permits**	
• **Cap and trade**	
• **Quota obligations**	

2.2.2.6 Tendering/bidding schemes

This instrument is repeatedly used in the offshore wind energy sector. The Dutch government organizes tenders for permits to build offshore wind farms. Private parties could make their offer, and this creates competition. The winner of the tender receives the permit and can start building the wind farm. Tender or bidding schemes can be deployed to "acquire specific amounts of capacity or generation from specified types of RES" (Haas et al., 2011, p. 1287). Other examples wherefore this instrument is used are allocating an investment grant to the economic best option or long-term contracts (e.g. public transport).

2.2.2.7 Tradable (green) certificates schemes

In this scheme, the government issues certificates that can be traded afterward. The market will determine the price of a certificate. An artificial market will be created where these certificated can be traded, which will incur costs. These costs will be passed on to the consumers (Haas et al., 2011).

2.2.2.8 Cap and trade

Cap and trade is straightforward, that is, a quantity cap combined with a trading mechanism. For pricing carbon emissions, a cap and trade scheme can be used. In this situation, a maximum (cap) is set for emitting carbon. To arrange a cap in the industry, the governments issued a maximum of carbon permits that cover carbon emission for a period of time. The permits have to be paid by the emitting firm. Otherwise, there will be a penalty. The market (demand and supply) will determine the price of the permits. The cap gets more strict over time, so there is an incentive for companies who can cut emissions relatively cheaply (Fankhauser et al., 2010).

Table 5: Hybrid instruments

Hybrid instruments:
○ **Trading scheme with price restrictions**

Next to price-based and quantity-based instruments are hybrid instruments. These instruments have both a price and quantity characteristic. A trading scheme in combination with a price ceiling (max) or price floor (minimum) is a crucial hybrid instrument (Hepburn, 2006). The EU ETS system is a hybrid instrument that is used in Europe. The EU-ETS system has been created to facilitate CO_2 reduction at the cheapest possible location. The philosophy is that it does not matter where the emission is reduced within Europa.

The industry gets free emission rights until the level of the best performing 10% companies. Companies that have a less efficient installation have to buy emission rights on the market. The CO_2 price is equal in the European Union, and the idea is that companies who can reduce their emissions by adaptions of their installation will do this first. When a company can relatively cheaply cut its emission, it probably does this because it can sell the carbon permits to other companies, for which decreasing emissions is a lot more expensive. The trading scheme creates an incentive to reduce emissions as cheaply as possible (Bleischwitz & Bader, 2010a).

2.2.3 Information (Soft instruments)

The government can deploy another class of voluntary instruments and are all about "the mutual exchange of information among actors" (Borrás & Edquist, 2013, p. 1516). The role of the government is changing in Europe, from a provider and regulator to a facilitator and coordinator. Within this new role, this class of instruments fits in. Instruments under this class are e.g., voluntary agreement, codes of conduct, public-private partnerships (PPP). There are different forms of agreements in terms of bindingness. Agreements could be legally binding but could also be just a press statement without any form of legal engagement (Oikonomou & Jepma, 2008). Campaigns and education also fall under this category of soft instruments, e.g. energy labeling informs consumers about a specific product's energy efficiency.

These are the three classes that are defined by Vedung (1998).

2.2.4 Economic criteria

The economic literature also writes about criteria for assessing policy instruments. Multiple papers derived criteria from the literature (Hepburn, 2006; Menanteau et al., 2003; Oikonomou & Jepma, 2008). All three papers have their foundation in economic theory. The economic theory focuses on maximizing social welfare and leaves other factors disregarded. To summarize, this theory evaluates policy on efficiency and effectiveness. This information is helpful but does not tell the policymaker if the desired transition is accomplished. Hepburn (2006) acknowledges that these theoretical prescriptions are more theoretical than practically met. Governments have to deal with political realities (the political forces of staying in power). However, the most efficient and effective policy instruments are not always the best solution to the problem. Other factors have to be considered when making a tradeoff of policy instruments. One has to keep in mind that the efficiency and effectiveness of policy instruments are dependent on the situation and circumstances (Perrels, 2001).

2.2.5 Policy mixes

In a compelling policy mix, different types of instruments are included. These instruments can complement each other as each instrument has weaknesses and strengthen (Rosenow et al., 2017). Policy mixes are helpful in sustainability transitions, requiring technical change (Rogge & Reichardt, 2016). Technological changes, interventions in markets, systems, and institutions are required because of system failures (Reichardt & Rogge, 2016; Rosenow et al., 2017). System failures can be defined as "factors that negatively influence the direction and speed of innovation processes and hinder the development and functioning of innovation systems" (Wieczorek & Hekkert, 2012, p. 79). A mix of policies can be deployed to deal with these failures. "The idea that one policy instrument is used to address one particular policy goal (known as the Tinbergen rule) has long been discredited" (Rosenow et al., 2017, p. 69). Studies on policy mixes focus on the interaction between these instruments. Studying these interactions is essential because choosing multiple instruments could lead to undesirable outcomes when instruments are inconsistent with each other (Hepburn, 2006).

2.3 Analytical framework

Now that all literature has been discussed, it is time to bring the pieces together in an analytical framework. Throughout the study, this analytical framework will be apprehended. The pressures from the transition literature and policy instruments from the economic literature will be merged in an analytical framework that can assess which policy instruments the Dutch government has to select to stimulate the hydrogen transition. This analytical framework will be based on the MCA methodology and is characterized by a Table.

2.3.1 Building the analytical framework

Step 1 and step 2 will form the bases for the analytical framework. The two strands of literature together composes the axes. The analytical framework is visualized in Figure 7)

Step 1 Policy instruments

In sections 2.1 and 2.2, the theory behind policy instruments is elaborated. The Dutch government can deploy these policy instruments to stimulate the transition process where needed. After the analysis of the system with help from the MLP, it will become clear what the pressures are of the socio-technical system. After that, suitable policy instruments have to be selected. Unfortunately, this is not that easy as it sounds. Policy instruments have their pros and cons and their strengths and weaknesses. In section 2.3, a selection of potentially suitable policy instruments is made based on the economic literature. The selected policy instruments will form the top row (x-axis) in the table.

Step 2 MLP for analysis of heavy industry sector

In section 2.1, the approach is explained that will be followed to do a case study of the socio-technical system of the heavy industry in the Netherlands. After the analysis with the MLP (chapter 3), the indicated pressures could be added to the analytical framework (y-axis).

It is expected that including the identified stabilizing and destabilizing pressures in the analysis instead of economic criteria as efficiency and effectiveness will arrange a more thorough and advanced assessment (Kern, 2012). Furthermore, the identified stabilizing and destabilizing pressures are unique to the heavy industry system and give a good representation of the context of the system. That enables the researcher to select the best policy instruments for this particular system. At last, economic criteria can reject a policy instrument, because it is (too) expensive, while it could have a positive impact on the transition. This analysis will show the best applicable policy instruments for to stimulate the transition instead of thinking about other aspects.

Policy instruments can influence these criteria to foster the transition. These criteria will form the left-most column.

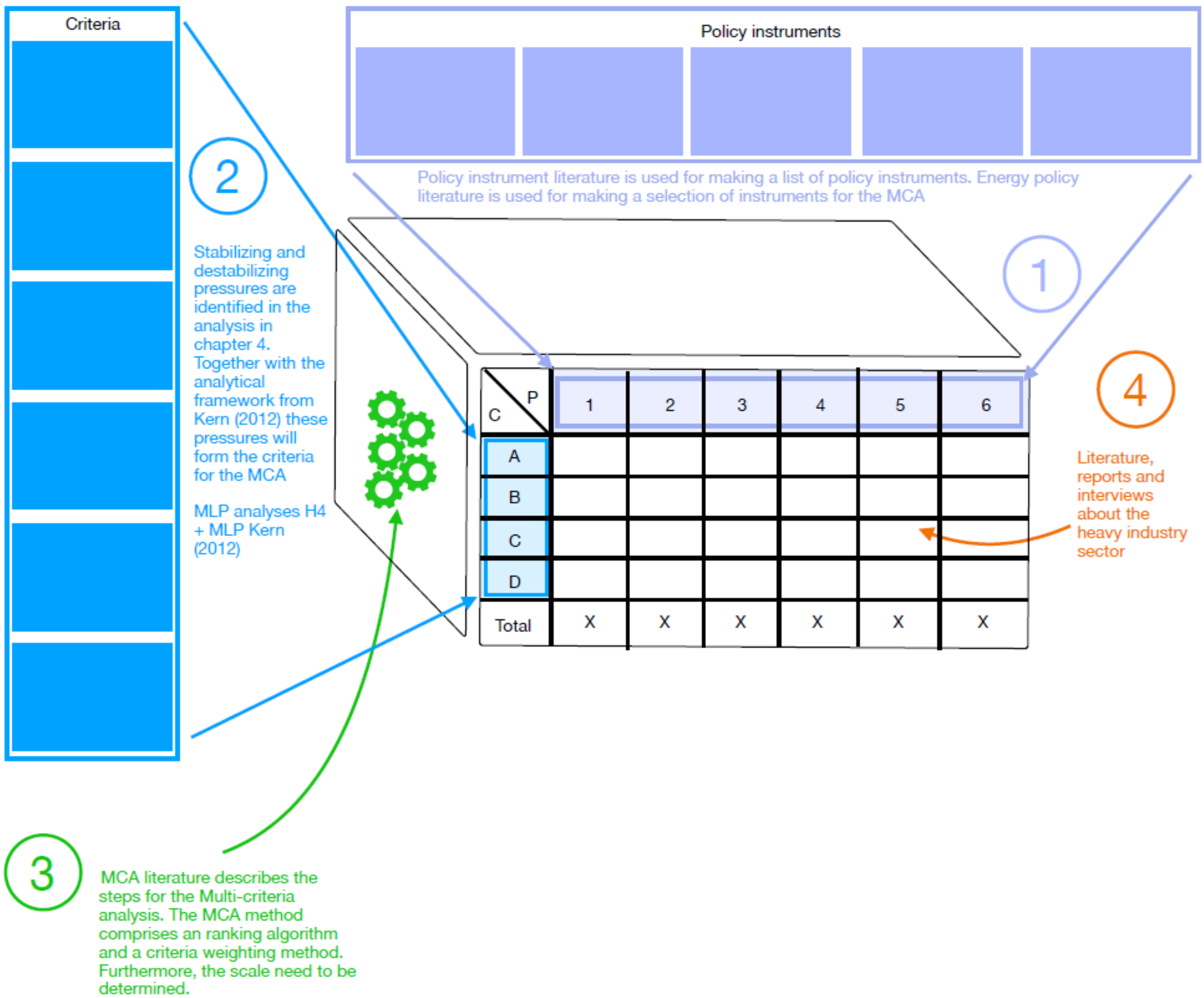

Figure 7: Analytical framework (Own work)

2.3.2 Filling in the analytical framework

Step 3 Decision making

Chapter 4 will explain the MCA method, including the ranking algorithm and criteria weighting method. A five-point scale will be used in this study to score the policy instruments on the criteria.

Step 4 Data

A desk study is performed to gather all relevant data for assessing the policy instruments on the criteria. All sorts of literature, academic literature, reports, and news articles are used to give a well-considered score. Next to that, semi-structured interviews are conducted. Interviews with experts from the socio-technical system are used to get practical knowledge and expertise that is not written down. The set of interviewees is has been kept as diverse as possible, to receive as much information as possible.

The experts that will be interviewed are presented in Table 6.

Table 6: Overview of the interviewees

Interviewee	Organization
Eddie Lycklama a Nijeholt	Gasunie
Jorg Gigler	TKI Nieuw Gas
Anne Melchers	Ministry of Economic Affairs and Climate Policy
Lydia Boktor	NorthH2
Zofia Lukzo	TU Delft
Anne Geurts	Port of Rotterdam

In this chapter, the transition and economic literature are used to conduct an analytical framework, presented in section 2.3. In chapter 4, the multi-criteria analysis will be performed. Now that the rows and columns are defined, the cells can be filled in.

Chapter 3 System analysis

In this chapter, an answer to the second sub-question is formulated by outlining the heavy industry system in the Netherlands. Knowing the ins and outs of this socio-technical system will help expose the stabilizing and destabilizing pressures present in this system. The government could take away these stabilizing pressures and support the identified destabilizing pressures using policy instruments, which will be assessed in chapter 4.

Firstly, in section 3.1, a literature study is conducted to deploy a hydrogen economy. Here, academic literature is reviewed on the deployment of hydrogen in general and possible destabilizing pressures and stabilizing pressures are determined. For this, the hydrogen chain will first be explained. Second, a systematic analysis of the hydrogen transition in the heavy industry sector in the Netherlands, based on the MLP framework (which is introduced in section 2.1), is carried out. In sections 3.2, the heavy industry system is discussed per level, from the socio-technical landscape, socio-technical regimes to niche innovations. The analysis is based on rapports, news articles, and the literature review of section 3.1.

3.1 Destabilizing pressures and stabilizing pressures in the transition to a hydrogen economy

In this section, a state of knowledge of the relevant literature will be given. In the introduction, a problem regarding the deployment of hydrogen in the Netherlands has been introduced. The cancellation of the plan to subsidize hydrogen projects via SDE++ gives reason to investigate whether there are other options for dealing with an unprofitable top and other obstructions that hold back the deployment of hydrogen.

The hydrogen supply chain (economy) is shown in Figure 8 (Kiwa, 2021a). Hydrogen, produced from electricity or natural gas, is possibly stored and otherwise transported via pipelines to the marketplace. Hydrogen can be used for several applications mentioned in the introduction, e.g. industry, build environment and transport. Via the industry (ports), hydrogen can also be imported or exported (this will also be possible via pipelines to neighboring countries).

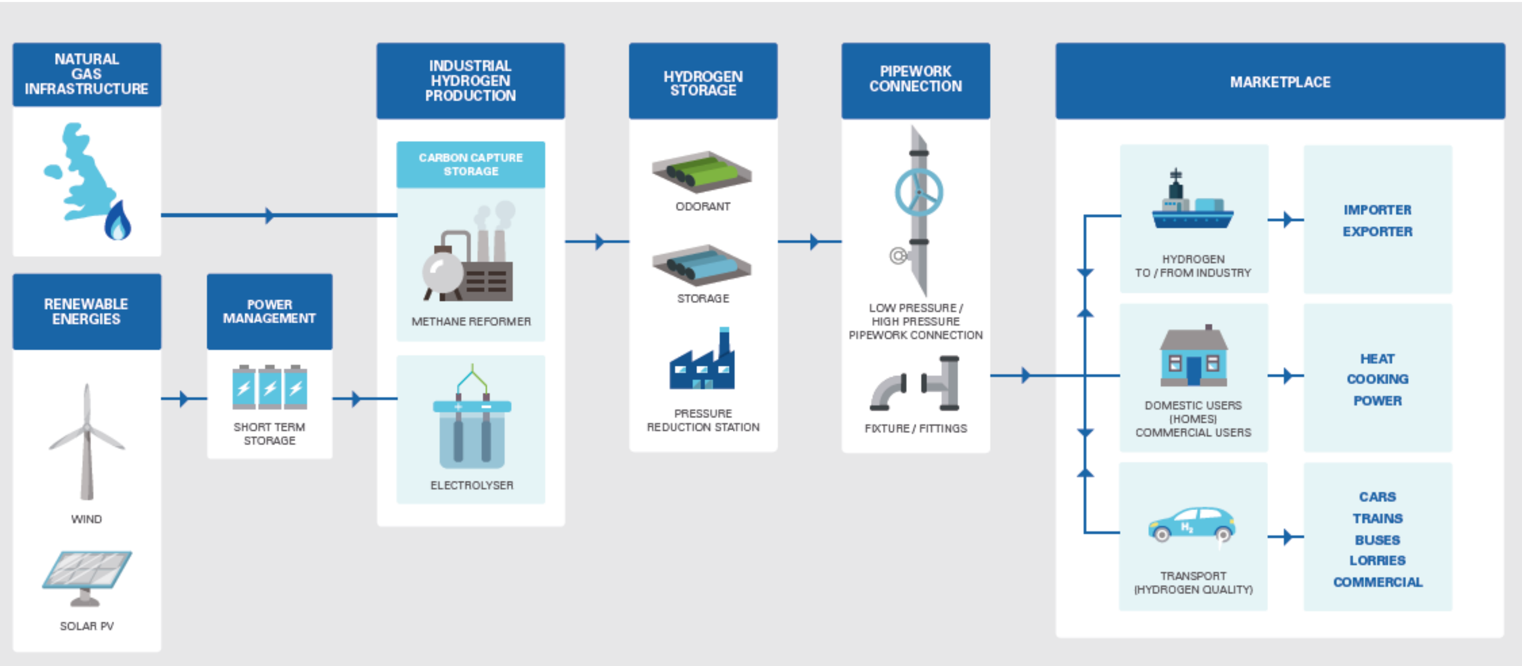

Figure 8: Hydrogen landscape (Kiwa, 2021a)

Before exploring destabilizing pressures and stabilizing pressures for the heavy industry sector can start, it will be of value to gain more insights into the deployment of a hydrogen economy in general. A literature review is conducted in this section (in Appendix A the reviewed literature is presented). At first, the hydrogen economy itself is discussed. Second, the stabilizing pressures and destabilizing pressures in this transition are identified and summarized. At last, other technologies which can influence the hydrogen transition are introduced.

3.1.1 Hydrogen economy

The (green) hydrogen economy, a notion widely known through the author Jeremy Rifkin, is the successor of the current hydrocarbon economy (Hisschemöller et al., 2006; Rifkin, 2003). Hydrogen can be used for different applications (storage, heat, transport), as discussed briefly in the introduction. Although these applications require other technologies, the deployment of these technologies is intertwined in the hydrogen economy. The deployment of these different applications depends on the production capacity of green hydrogen (van Renssen, 2020).

To operate production facilities, a hydrogen infrastructure (distribution) is necessary (Dunn, 2002). Gasunie is currently working on a hydrogen backbone in the Netherlands. However, the capacity of the infrastructure needs to be able to handle a proper transport volume, said Ulco Vermeulen, member of the Board of Directors of Gasunie (van Santen, 2020). Therefore, the demand for hydrogen is required to grow so the production and distribution can be on a large scale (Smit et al., 2007; van Renssen, 2020). The demand can grow if hydrogen technologies are introduced on a large scale in electricity production, transport, (heavy) industry, and chemistry (Ministerie van Economische Zaken en Klimaat, 2020a; Sherif et al., 2005; van der Burg, n.d. Zofia Lukszo, personal communication, June 25, 2021). Demand growth will also help lower the price of green hydrogen, which is essential, according to Vermeulen (van Santen, 2020). The deployment of a hydrogen economy depends on deploying the different parts in the supply chain (generation, distribution, and utilization) as they are all related. The deployment can be seen as a chicken and egg problem, as visualized in Figure 9.

In the following sections, a state of knowledge on stabilizing pressures (3.1.2) and destabilizing pressures (3.1.3) in the deployment of hydrogen will be given. The knowledge is gathered by carrying out a literature review. The scope is set on the hydrogen economy in the Netherlands. However, literature written about other countries could also be of value. In appendix A, the literature review table is presented. In section 3.1.5, other technologies will be mapped.

3.1.2 Stabilizing pressures

This section will give a state of knowledge about stabilizing pressures for a hydrogen economy in the Netherlands as a starting point. Furthermore, an analysis of these stabilizing pressures will be conducted, and gaps in the literature will be disclosed.

In general, three categories of stabilizing pressures are acknowledged in the literature: technical-, economic- and institutional- stabilizing pressures (presented in Figure 10). In Appendix A, an overview is presented of the stabilizing pressures found in the literature.

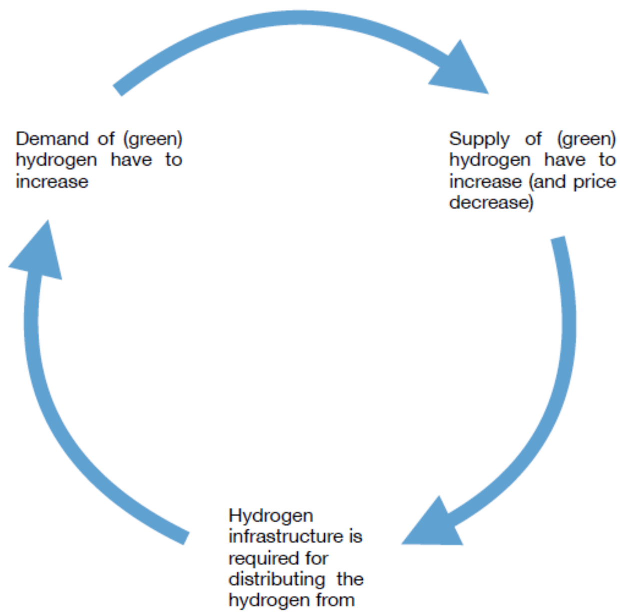

Figure 9: Conceptualization of the chicken egg problem (Own work)

Technical stabilizing pressure

Technical stabilizing pressures are related to drawbacks in hydrogen storage, the production of hydrogen, conversion of hydrogen in electricity, hydrogen storage in fuel cell vehicles, and hydrogen distribution (Astiaso Garcia, 2017; Balat & Kirtay, 2010; Bleischwitz & Bader, 2010; Demirbas, 2017; Hu et al., 2020; Moliner et al., 2016; Mueller-Langer, Tzimas, Kaltschmitt, & Peteves, 2007; Sherif et al., 2005; van Renssen, 2020). The technologies are in place, but there is much room for developments in efficiency and costs so they can compete with existing energy technologies (Balat & Kirtay, 2010; Hu et al., 2020; Sherif et al., 2005). Dunn (2002, p.255) even argues that there are no real technical stabilizing pressures; "if we really decided that we wanted a clean hydrogen economy, we could have it by 2010". With this, the politics should take care of the funding and support (Goltsov & Veziroglu, 2001; Lovins & Williams, 1999; Mcdowall & Malcolm, 2006; Rifkin, 2003)

Economic stabilizing pressure

As mentioned above, developments in costs are necessary before the technologies can compete with other energy technologies. This economic stabilizing pressure comes forward in multiple papers (Balat & Kirtay, 2010; & Weeda, 2015; Caumon et al., 2015; Demirbas, 2017; Dunn, 2002; Ehret & Bonhoff, 2015; Hu et al., 2020; Moliner et al., 2016; Sherif et al., 2005; van Renssen, 2020). A distinction can be made between different costs: hydrogen costs, operating costs, capital costs, and distribution costs (Demirbas, 2017). The price of hydrogen made from "green" electricity is far too high for customers in comparison with other energy sources as grey hydrogen or natural gas. That is because of the high green electricity price and expensive technology of electrolysis. An electricity price that is high enough to make renewable power viable and low enough to make hydrogen competitive with its competitors is needed (van Renssen, 2020). Important to mention that some of the literature focuses specifically on green hydrogen, which is currently very expensive. Others assume that grey hydrogen will be deployed first in the hydrogen economy to kickstart the development and make green hydrogen economically viable in the mid and long term (Mueller-Langer et al., 2007). The literature shows that the costs and development of technologies are heavily related. Both are also related to the last identified stabilizing pressure: institutions.

Institutional stabilizing pressure

Interference of governments is undoubted. Authorities need to be involved in: create awareness, stimulate and promote hydrogen, discourage other alternatives, subsidies, facilitating collaborations between stakeholders and between different countries (Mans, Alkemade, van der Valk, & Hekkert, 2008), (Astiaso Garcia, 2017; Ball & Weeda, 2015; Bleischwitz & Bader, 2010; Demirbas, 2017; Dunn, 2002; Ehret & Bonhoff, 2015; Hisschemöller, Bode, & van de Kerkhof, 2006; Mans et al., 2008; van Renssen, 2020). Figure 11 shows that in mid-2019, the total number of countries that directly support hydrogen in the industry sector via targets, mandates, and policy incentives was two.

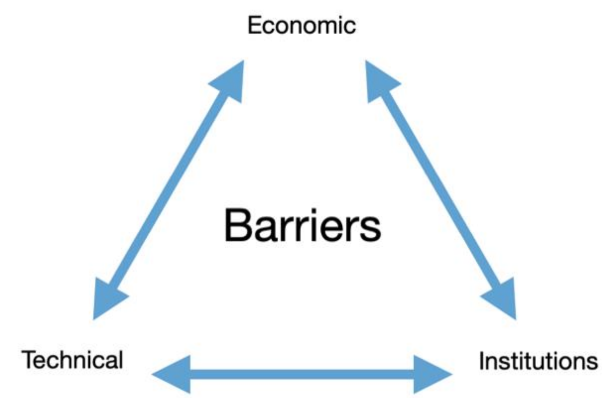

Figure 10: Conceptualization of the stabilizing pressures in the transition towards hydrogen (Own work)

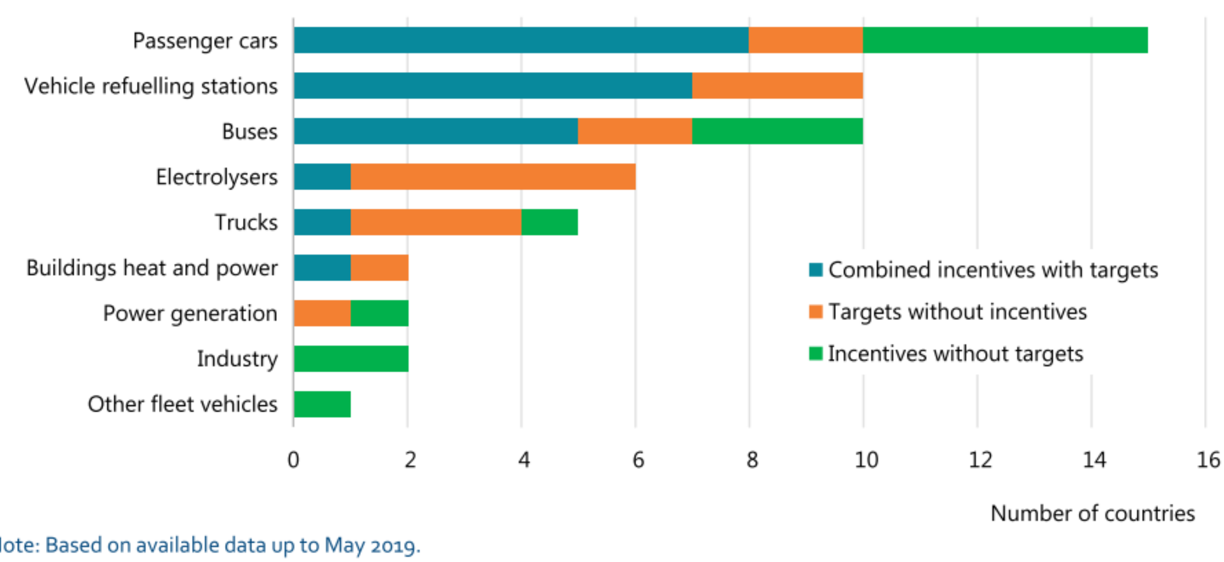

Figure 11: Policies directly supporting hydrogen deployment in various sectors, from (IEA, 2019)

Policies, e.g. subsidies, can close the gap between the price of hydrogen made by electricity and made by gas. Furthermore, institutions can stimulate the usage of hydrogen so that the demand increases and production and distribution can be on a large scale. It is stated in multiple papers that without the right policies, it will be impossible to create a hydrogen economy in the Netherlands (Demirbas, 2017; Dunn, 2002; Hisschemöller et al., 2006; van Renssen, 2020).

With the right policies, these could act as a destabilizing pressure and stimulate the transition. Destabilizing pressures are discussed in section 3.1.3.

3.1.3 Destabilizing pressures

Besides the stabilizing pressures discussed in section 3.1.2, there are also opportunities for hydrogen. The identified destabilizing pressures are an incentive to deploy a hydrogen economy in the Netherlands.

Before the destabilizing pressures for the deployment of hydrogen in the Netherlands will be discussed, one vital driving force for hydrogen worldwide will be mentioned. In the current hydrocarbon economy, the raw material resources of fossil fuels are not distributed equally around the world. For hydrogen, water is the most crucial resource that is almost everywhere available worldwide, and therefore this energy source is not dependent on geography (Demirbas, 2017). Although before using seawater in an electrolysis process, the salt must be removed first (there are innovations on this subject going on)(Middelweerd, 2018).

Hydrogen can be made of electricity via an electrolyzer. Converting electricity to hydrogen has two benefits relative to electricity. The first is that hydrogen can be transported via pipelines or boats (by cooling and compressing hydrogen)(Wereldprimeur: Transportschip Voor Vloeibare Waterstof, 2019). Therefore it can transport energy (e.g. from solar and wind farms) over large distances almost without losses. Especially the transport via pipelines is relatively cheap (Hydrogen Council, 2017; van Wijk, n.d.). The second is that hydrogen can easily be stored in salt caverns. This technique is primarily on a large scale the best solution there is at the moment. The hydrogen can be pumped up and used when there are moments of low electricity production (intermittency problem)(Hydrogen Council, 2017). The Netherlands already has a high-quality gas infrastructure that can be used for transport hydrogen after some modifications.

For making green hydrogen, a lot of wind or solar power is required. The potential for offshore wind energy is enormous in the Netherlands (Groningen, 2020). Another destabilizing pressure for hydrogen is that it can be used for multiple applications. Hydrogen can, for example, decarbonize heavy transport (fuel cell technology), aviation, and (heavy) industry. There are no good electricity alternatives for these applications (Hydrogen Council, 2017; van der Burg, n.d.). At last, the hydrogen economy can bring the Netherlands the opportunity to build a new sector and create new jobs. These are jobs for building the hydrogen economy (one-off 104.000 FTE's between 2030-2050) and jobs for keeping the hydrogen economy going (up to 41.000 FTE's in 2050)(Groningen, 2020).

3.1.4 Summary

To conclude, in the literature review, three main stabilizing pressures are identified:

- Technical stabilizing pressures
- Economic stabilizing pressures
- Institutional stabilizing pressures

In addition, the review determined several destabilizing pressures for the case of the Netherlands:

- Hydrogen is an energy carrier that can be easily transported and stored

- In the Netherlands, well-developed natural gas infrastructure is already available, which can be made suitable for hydrogen
- The Netherlands has a high offshore wind potential
- Hydrogen can be deployed in multiple sectors for multiple purposes
- Hydrogen offers an opportunity to create a new sector

In the previous section, the stabilizing and destabilizing pressures in the transition towards a hydrogen economy, in general, are exposed. In the following section, other technologies and types of hydrogen are examined to get an idea of the competitors of green hydrogen.

3.1.5 Other technologies

This section looks at other options for hydrogen in the decarbonization of the Netherlands.

Other technologies in the industry

For decarbonizing the industry, a distinction must be made between low- and high-grade heat. For low-grade heating, there are several options to produce this with the emission of CO_2. Heat pumps and electricity resistance could be a good solution. Hydrogen could be a fuel for fuel cells to make renewable electricity. High-grade heat is more problematic to decarbonize with electricity than low-grade heat. Hydrogen can be directly combusted to create heat, a good alternative for producing high-grade heat without emissions (Hydrogen Council, 2017). Using hydrogen is only sustainable as the hydrogen is produced without emitting greenhouse gasses, **"**Hydrogen is only as green as its energy source" (Bleischwitz & Bader, 2010, P.5390). Renewable energy is therefore essential for the deployment of green hydrogen.

Electrification

Simultaneously, the electricity sector has to reduce its carbon dioxide by 20.2 Mt in 2030 (Rijksoverheid, 2019). One of the measures to accomplish this goal is to shut down all coal-fired power plants by 2030. The electricity production from renewable energy sources, like wind and solar energy, has to increase to guarantee the security of supply and limit the emissions in the electricity sector (Rijksoverheid, 2019). Furthermore, the electricity demand will further rise because of the electrification of traffic, built environment, and industry due to abandoning fossil fuels. So the demand for renewable energy will increase even more (Otte & Hers, 2019). The downside of electrification is that the load on the electricity grid will expand (TenneT, n.d.-b). Therefore, the grid needs enforcement, and the intermittency problem with solar and wind needs to be solved (Heal, 2009). Many improvements are necessary before the electricity system is ready for the future (TenneT, n.d.-a).

Other applications of hydrogen

Hydrogen can be used to solve some of these problems, e.g. for energy storage to overcome intermittency and, as an energy carrier to transport energy (Ehret & Bonhoff, 2015; Murthy Konda et al., 2011; Sherif et al., 2005). Currently, our energy consumption is 20% electricity and 80% molecules. In a CO_2-free energy system, we need to find CO_2-free- molecules and hydrogen could fill in this gap. Also, the transport of molecules is 10-20 times cheaper than electrons (Lydia Boktor, personal communication, June 29, 2021). Hydrogen and electricity can complement each other in the transition towards sustainability. Besides electricity, hydrogen has to compete with the widely used fossil fuels: natural gas and oil (diesel and petrol). Hydrogen could be a good alternative for these hydrocarbon fuels, but as already mentioned, the price of hydrogen needs to drop (De wereld van waterstof, n.d.; van Zon, n.d.). However, there is also an option to mix natural gas and hydrogen, it is already possible to feed in hydrogen (up to 20%) into the natural gas grid (Gasunie, 2019; van Renssen, 2020). Eventually, this percentage can grow to 100%. Before 100% hydrogen can be transported in this grid, the pipes, shutters, couplings, valves, and compressors have to be adapted because the hydrogen molecule is the smallest there is, and without adjustments, it will leak (van Zon, n.d.).

For energy storage, there are multiple alternatives for hydrogen, like pumped hydro storage and compressed air or a battery. However, for long-term carbon-free (seasonal) storage, hydrogen is the most suitable. That is because other options have less power capacity or experience losses over time (Hydrogen Council, 2017).

Types of hydrogen

Green hydrogen is the preferred category of hydrogen for the future. Nevertheless, blue hydrogen can have a share in the transition towards a hydrogen economy. It could act as a catalyst, making the step to green hydrogen easier to take (van Renssen, 2020). Two major projects are announced for CCS; Porthos and Athos want to capture the carbon dioxide emitted by the industrial clusters in Rotterdam and Amsterdam. The CO_2 will be stored under the North Sea in empty gas fields, and there is room for 1600 Mton CO_2 (Rijksoverheid, 2021a). When Porthos is realized it is the first CCS-project of this size in the world (Ministerie van Economische Zaken en Klimaat, 2020).

Furthermore, there are other 'colors' of hydrogen. Hydrogen can be imported (yellow) or made from nuclear energy (orange). Orange hydrogen is not considered in this research because a lot is still unclear how this will unfolds and what the political opinion is (Westerveld, 2020). Hydrogen import is not taken into account in this research.

Besides the difference in blue and green hydrogen production, there is also a difference in hydrogen quality. The quality required depends on the application: fuel cell grade (in transport), feedstock, or combustion. Blue hydrogen is usually of lower quality, and additional cleaning measures are required. Green hydrogen is almost 100% pure and can also be used in fuel cells and synthetic fuels (van der Burg, 2021) For combustion, blue hydrogen (ca 70% purity) satisfies. At this point in time, green hydrogen is very scarce. Burning green hydrogen (with a purity of 99.99%) would be a waste and unnecessarily expensive (Eddie Lycklama a Nijeholt, personal communication, June 17, 2021 & Lydia Boktor, personal communication, June 29, 2021). Green hydrogen is more expensive than blue hydrogen and of higher quality. Therefore, it is not economically viable for combustion so long green hydrogen is scarce. However, for simplicity, this difference is ignored in this study.

Now is explained that hydrogen, whether blue or green, is a favorable solution for decarbonizing the heavy industry sector. The following section will look into this socio-technical system.

3.2 Case study: hydrogen in the heavy industry sector in the Netherlands

The Netherlands is a country that is situated on the continent of Europe (North-West). In the West and North, the Netherlands has a coastline of the North Sea. The Netherlands counts twelve provinces and has five populated islands in the Wadden Sea. There are living about 17.5 million people in the Netherlands (CBS, 2021). Furthermore, some big rivers flow into the North Sea, the Maas, the Rijn, the Schelde, and the Waal (Rijkswaterstaat, 2021). The unique location of the Netherlands is why the port in Rotterdam became internationally very important and is the largest seaport in Europe (Port of Rotterdam, 2021). Much industry is connected to the port of Rotterdam, especially the chemical industry is highly developed (CBS, 2018). This study will now have a good look at the various levels and analyze what is going on.

3.2.1 Landscape level

Currently, the Netherlands is in an energy transition. The expectations of the time horizon for the whole energy transition in the Netherlands are two generations (50 years). Meaning a long-term vision is required from all actors in the socio-technical system (Rotmans et al., 2000). Especially for the industry sector, which has assets that can run for 30-40 years (van Renssen, 2020). Therefore, companies must think about the future when they have to make new investments because of aging assets.

3.2.1.1 Energy

The port of Rotterdam plays an essential role in the energy provision in the European Union as it imports 13% of the total energy requirement (mainly crude oil). They expect to be also in the future an essential energy importer for Europe, but then commonly for hydrogen.

Another essential characteristic of the Netherlands cannot be seen on a standard world map. Under the surface (in the North of the Netherlands) is an enormous gas bubble. In the neighborhood of Slochteren, a small town in the province of Groningen, is in 1959 a gas field discovered of 2900 billion cubic meters of gas (NLOG, n.d.) The gasfields in the Netherlands are visualized in Figure 12. The gas extraction started in 1963 and caused a revolution in the energy sector in the Netherlands. The Netherlands became a natural gas economy, and a distribution network was created throughout the Netherlands, which is shown in Figure 13 (Netbeheer Nederland, 2019). In 2019, more than 136.000 kilometers of gas pipelines and 95% of the households were connected to the gas network (Netbeheer Nederland, 2019).

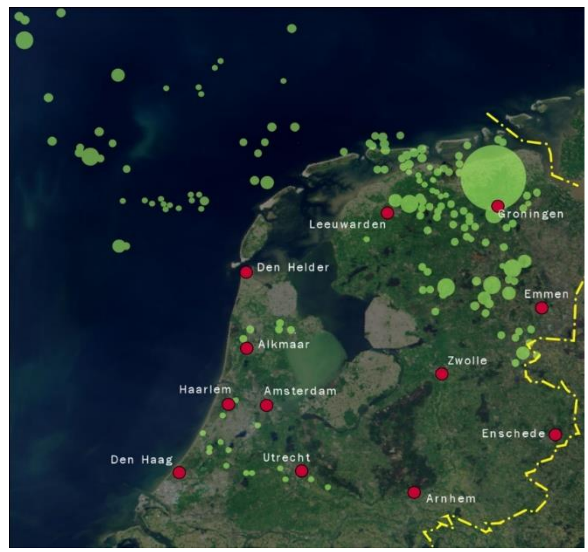

Figure 12: Gas fields in the Netherlands (van Loo, 2018)

As becomes apparent, some industry sectors depend on cheap energy (SER, 2019). Cheap energy is available in the form of coal (mainly the iron and steel industry (van der Burg, 2021)) and natural gas (the chemical industry). Because of the enormous natural gas stock in Groningen, natural gas was an energy source of whom the supply was more or less secured.

Figure 13: L-gas and H-gas network, from (GasTerra, 2019)

Extracting gas from the gas fields in the North Sea resulted in a well-developed offshore industry. These companies who earned big money in extracting fossil fuels are now playing an essential role in the offshore wind industry (Nederland, 2021). In the future, the Netherlands have enough space in their territorial waters to build more wind farms. In the North, there is an offshore wind potential of 20 GW (Provincie Groningen, 2020). Combined with the expertise and an experienced offshore wind energy sector, this offers an excellent opportunity to generate renewable energy.

Furthermore, the plans from the national government for scaling back natural gas lead to a destabilized pressure on the current regime. The province where the Netherlands has extracting natural gas from the Groninger gasfield, Groningen is plagued by earthquakes. This development fosters the decision-making process to stop gas extraction in Groningen (Groningen, 2020). Scaling back the production of natural gas makes the Netherlands dependent on other countries to import gas. Reliance on Russia's natural gas is geopolitically sensitive (Thiemann, 2018).

3.2.1.2 Industry

Due to the natural gas stock in Groningen, the Dutch industry is built on the availability of sufficient cheap energy. Multiple companies are dependent on cheap energy to be competitive in the world. When fossil fuels are relatively cheap compared to green hydrogen, the pressure on the regime to start the transition towards green hydrogen is not intense or even not present. The price of green hydrogen consists 70 - 80% of the renewable energy price (Collins, 2021). Currently, the renewable energy prices are high, and therefore green hydrogen cannot compete with natural gas, grey, and blue hydrogen. Green hydrogen is 2-4 times more expensive than grey hydrogen. More development and production of green hydrogen will also reduce the price of the technology and, therefore, the price of green hydrogen (Dutch Government, 2019; Ministry of Economic Affairs and Climate Policy, 2020; Rotman, 2020). Much more green hydrogen is required for the transition towards green hydrogen (Natuur en Milieu, 2018). The issue here is that there is not enough renewable energy available (Dutch Government, 2019). That was also why the EU denied the request for SDE++ (H2Platform, 2020b). The energy-intensive industry is suitable for 650.000 jobs and generates more than 80 billion GDP.

Furthermore, the port of Rotterdam fulfills an important role (because of the geographical location) in the fossil energy sector. The port imports oil, gas, and coals, processing and exports them (RVO & EZK, 2019). About 385.000 direct and indirect jobs are related to the port of Rotterdam (there is an overlap with the number of jobs in the energy-intensive industry as a part of the industry is located in the port of Rotterdam) (Port of Rotterdam, 2021).

3.2.1.3 Economy

The Netherlands is a so-called knowledge economy, which is "a system of consumption and production that is based on intellectual capital. In particular, it refers to the ablilty to capitalize on scientific discoveries and basic and applied research" (Hayes, 2021). A knowledge economy ranking is indicated by the knowledge economy index (KEI), which the World Bank Institute determines. Knowledge indexes make it possible to compare countries' positions. The Netherlands is ranked 6th (out of 145 countries), based on the median of absolute results and placements in individual years 2008-2017 (Širá et al., 2020). Therefore, the Netherlands belongs to the top, and we are dependent on our knowledge and using this effectively for economic developments. The Netherlands have to invest in their knowledge economy to keep up the pace and stay in the lead. The Growth Fund is one of the investments that have to make sure that the knowledge for the energy transition will stay state-of-the-art (MKB Nederland, 2021). The investments in hydrogen are crucial for strengthening the Dutch position compared to the energy region in Europe and is, therefore, a destabilizing pressure on the regime (Team Stadszaken, 2019).

3.2.*1.4* Politics

The Netherlands is since its establishment in 1993, member of the European Union. This membership means, among other things, that European laws are integrated into our national laws. More than half of our national laws are European policy or laws (Europa Nu, 2019). The Netherlands committed itself to the United Nations Climate agreement of Paris in 2015. All 28 member states signed this agreement, what is active since 2020. To achieve the goals of this agreement, the Dutch government conducted its own climate agreement (2019). The more than 200-page counting agreement is set up with the private sector, believing that everyone has to contribute (Dutch Government, 2019). The industry sector has to reduce their CO_2 emission by 59% relative to 1990. When the climate agreement was published, the industry has to reduce 19.4 Mton CO_2 in 2030 relative to 2015. The end goal is to have zero emissions in 2050 (Dutch Government, 2019). To accomplish these goals, the Dutch government is aware that a "future-oriented public-private approach in which the business community invests in a sustainable future, the Dutch government provides targeted facilitation and support and in which the focus is on the creation of new value" (Dutch Government, 2019, p. 87). The goals of the climate agreement puts an enormous pressure on the regime.

3.2.1.5 Summary

The events in the past created opportunities for the future. This theory is called path dependency. The theory is that previous choices, whatever that may be, impact future historical trajectories (Edelenbos & Monnikhof, 2001). The gas network and expertise of the gas sector can lead to a transition from a natural gas economy to a hydrogen economy. Compared to other countries, the Netherlands is a couple of steps ahead because of our past (Provincie Groningen, 2020). However, path dependency can cause lock-in situations. (Sunk) investments in the current socio-technical system, based mainly on natural gas, make this technology embedded to such a degree that it can hold back innovations. This phenomenon is known as carbon lock-in (Brown et al., 2011)

The landscape consists of a couple of characteristics that can be useful in a hydrogen economy. For example, Long-term (seasonal) storage in salt caverns and empty gas fields can be used (Rijksoverheid, 2020; RVO & EZK, 2019). The gas network can be used for the distribution of hydrogen. It is relatively easy and affordable to make the natural gas network suitable for hydrogen. Another aspect that positively influences the transition is that the Netherlands has a high potential for renewable energy, as there is much space for offshore wind farms (Provincie Groningen, 2020).

3.2.2 Regime level

The current heavy industry regime is characterized by a dominant configuration of certain technological artifacts, institutions, networks, user practices, market structures, regulatory and policy frameworks, cultural meanings, and scientific knowledge (Kern, 2012)**.** These are discussed in this section.

3.2.2.1 Users

The industry is clustered in the five regional clusters, as presented in Figure 19. Twelve heavy industry companies are responsible for 60% of the industrial CO_2 emissions in the Netherlands (Dutch Government, 2019). The twelve companies are presented in Table 7 (Wiskerke, 2020).

Table 7: Twelve heavy industry companies who emit together 60% of the industrial CO_2 emissions (Wiskerke, 2020)

Company	Emissions per year in tons
Tata Steel IJmuiden B.V. CO_2	emission: 10,4 million tons
Shell Nederland Raffinaderij B.V. CO_2	emission: 4,2 million tons
Shell Nederland Chemie B.V. CO_2	emission: 2,8 million tons
Bedrijventerrein Chemelot B.V. (DSM en SABIC) CO_2	emission: 4,6 million tons
Dow Benelux B.V. CO_2	emission: 4,2 million tons
Yara Sluiskil B.V CO_2	emission: 3,6 million tons
BP Raffinaderij Rotterdam B.V. CO_2	emission: 2,3 million tons
Air Liquide Industrie B.V. CO_2	emission: 2,0 million tons
Zeeland Refinery N.V. CO_2	emission: 1,6 million tons
Esso Nederland B.V. CO_2	emission: 1,6 million tons
Air Products Nederland B.V CO_2	emission: 0,9 million tons
Gunvor Petroleum Rotterdam B.V. CO_2	emission: 0,4 million tons
AKZO Nobel Chemicals B.V. CO_2	emission: 0,4 million ton

In the industry, hydrogen can have two applications. The first one is to use it as feedstock in the industry. The second is to use hydrogen for industrial heating processes (Gasunie, 2019).

Some of these heating processes could be made sustainable by electrification or deploying geothermal heat and sustainable residual heat (Dutch Government, 2019). However, electricity could not be used in all these processes (electrification is a solution for low-temperature heating processes). Hydrogen could be a solution for the (energy-intensive) heavy industry where 600 degrees or higher temperatures are necessary (Dutch Government, 2019; Ministry of Economic Affairs and Climate Policy, 2020; RVO & EZK, 2019; Savelkouls, 2021d).

Experience with hydrogen

Grey hydrogen is already used as feedstock (approximately 163 PJ per year) for the industry, for example, fertilizers production (Gigler et al., 2020). Furthermore, grey hydrogen is used for the production of Ammonia (65 PJ), Refining (59 PJ), Methanol (18 PJ) and, other chemical processes (21 PJ) (Gasunie, 2019). In 2019, the total hydrogen supply was 175 PJ, distributed over the five industrial clusters (Figure 14).

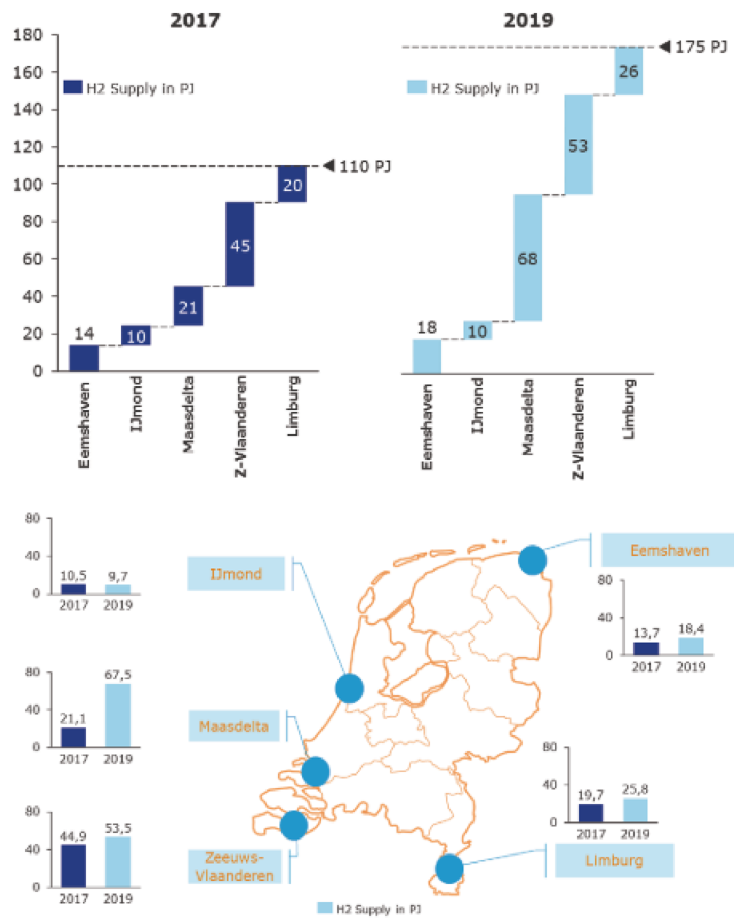

Figure 14: Hydrogen market in the Netherlands in 2017 and 2019, from (Gasunie, 2019)

Ammonia is produced with grey hydrogen and nitrogen and is widely used in the production process for fertilizer. In the refining process, hydrogen is used for desulfurizing and for cracking petroleum fractions. At last, hydrogen is used together with CO_2 to produce methanol (Gasunie, 2019). The could foster the transition towards green hydrogen in the heavy industry. Therefore this is a destabilizing pressure.

The heavy industry is a broad sector denotation. Within this sector, there are many subdivisions wherein hydrogen could be applied to make the industrial processes sustainable, as described above.

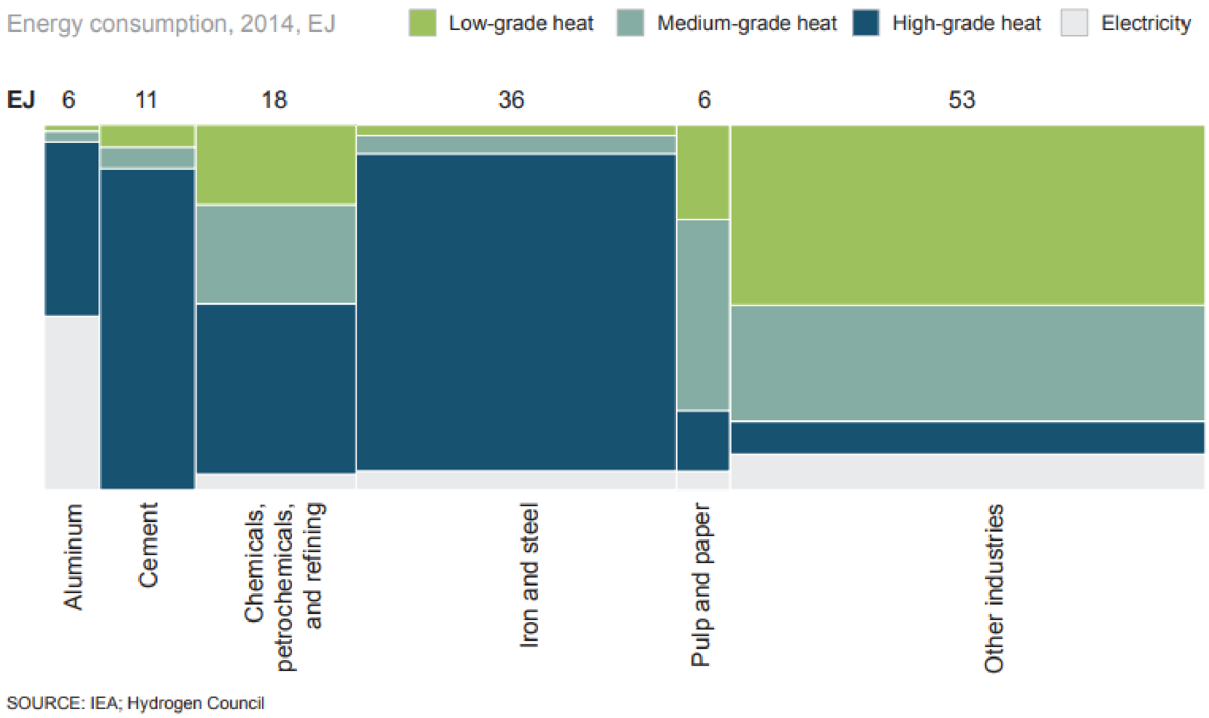

Figure 15: Energy consumption in 2014 (IEA, 2019)

Globally, five industries are responsible for almost two-thirds of all energy consumed by the industry sector (see Figure 15). The industries are:

- Iron & Steel
- Chemical, petrochemicals, and refining
- Cement
- Pulp and paper
- Aluminum

Green hydrogen could be a solution for energy-intensive industries that uses high-grade heat. In the chemical industry, green hydrogen can replace grey hydrogen as feedstock for chemical processes like making ammonia and fuel high-grade heat. In 2017, the total emissions of the iron & steel (7.3 Mton) and chemical industry (19.6 Mton), and refining industry (10.1 Mton) in the Netherlands emitted together 80% of the CO_2 (see Table 3) (Rooijers & Naber, 2019).

Table 8: CO_2-emission of subdivisions in the industry (Rooijers & Naber, 2019)

Subdivisions	**CO_2-emission in Mton 2017**
Chemical industry	19.4
Oil refining	10.1
Iron and Steel	7.8
Food, beverages and tobacco industry	4.3
Plastics and building material industry	2.2
Others	2.7
Total	**46.5**

The companies on the list of the twelve most polluting companies are all active in the chemical or metal sector. This study will therefore focus on the following two sectors:

- Iron & Steel
- Chemical, petrochemicals, and refining

As mentioned above, hydrogen is already widely used in the chemical and refining industry, which is a destabilizing pressure. Green hydrogen has a high potential for making these industries sustainable (IEA, 2019). In the iron & steel industry, green hydrogen will be used as a high-grade heat source. Green hydrogen will replace the current (grey) hydrogen feedstock in chemical, petrochemicals, and refining. Currently, the production of grey hydrogen emits about 13 Mton CO_2 per year, accounting for 8% of the total CO_2 emission in the Netherlands (Rijksoverheid, 2021b).

After Germany, the Netherlands is the second-biggest producer of grey hydrogen in Europa. 10% of the natural gas demand is used for hydrogen production (Ministry of Economic Affairs and Climate Policy, 2020). More than 90% of the hydrogen produced in the Netherlands is made with natural gas via a process that emits CO_2 (Natuur en Milieu, 2018). The hydrogen that is used as feedstock also needs to be sustainable (Dutch Government, 2019).

Heavy industry sector have much power

Due to the exploitation of the gas field in Groningen, a well-established gas sector has emerged. This sector consists of an enormous infrastructure, as mention above. The gas stock and the geographical position of the Netherlands resulted that the Netherlands became a gas roundabout. GasTerra (trade) and Gasunie (infrastructure) gained a lot of expertise and knowledge over the years, together with the industry, universities, consultancies, and other organizations (Ministry of Economic Affairs and Climate Policy, 2020). There are high sunk investments in the assets, especially the pipelines are very precious.

The natural gas economy, the oil and coal industry (in Rotterdam) resulted in many jobs, and years of research and business resulted in high expertise and knowledge of industrial gasses. Moreover, the assets have high sunk costs and are valuable, which lead to a very stable regime, as the whole society was configured to natural gas. In addition, the numerous jobs and expertise make the transition away from fossil fuels difficult. These elements keep stabilizing the regime and “protected” it against new technologies and innovations. These companies want to stay active, as they are commercial companies. They influence the regime by protecting it from external pressures, there is a lock-in (Dril, 2015).

On the other hand, these companies want to be relevant in the future as well. That is why they have to innovate and not miss the boat towards sustainability. Although the fear of decreasing employment is justified, the climate agreement plans can cause 6000 – 11.000 FTE job losses. However, the plans will also create 42.000 – 78.000 FTE in new jobs (Nederlandse Vereniging Duurzame Energie, 2019). Companies with a lot of expertise and essential assets can easily push new entrants away from the regime, which is a stabilizing pressure on the regime. The urge that these companies feel to have a future is a destabilizing pressure.

In this study, these pressures are not included in the assessment of policy instruments. It is assumed that companies have to innovate to stay competitive with their competitors in the sector. Although the transition can cause a backlog, this shall be temporary as the others have to run through the same transition in the end. Taking the lead in the transition can create a knowledge advantage and offer international business opportunities (Dutch Government, 2019).

Another aspect of the sector's power is that companies can decide to leave the Netherlands and move their production facilities somewhere else with less strict rules about the environment. In research by PwC (2019), they investigated the effect of a national CO_2 tax. They concluded that this would reduce the attractiveness of the Netherlands as a location for the industrial sector. The Dutch government needs the heavy industry sector to stay in the Netherlands (for jobs) and decrease their CO_2 emissions (Dutch Government, 2019). There is a fine line between potential leaking of economic activities (carbon leakage) and stimulating companies to reduce CO_2 emissions (PwC, 2019). The sector's power can be seen as a stabilizing pressure. However, they can also force the government to give e.g. subsidies, which could be a destabilizing pressure.

The Dutch government has spoken out that carbon leakage should be prevented because this will not reduce CO_2 on a global scale and create a decrease in employment in the Netherlands. This is a position of the Dutch government and creates a playing field with the sector. Eventually, the implementation of policy instruments will balance on the fine line but both parties do not want to cross that line. It will result in equilibrium. This study will not implement more strict CO_2 regulations than is already imposed by the Dutch government. Therefore, these pressures are not included in the study.

3.2.2.2 Lack of a hydrogen market

A dynamic market is required to successfully deploy hydrogen in the industry (Cefic, 2019).

Chicken and egg problem

This problem is already explained in section 3.1.1. For a hydrogen market, demand, supply, and distribution are all required. Looking at the supply, there are multiple project plans for the building of electrolyzers. These projects are useless as there is no demand for hydrogen and no infrastructure to transport the produced hydrogen to the customer.

The producers need customers for the hydrogen in order to have a business case. Some customers can easily fit in hydrogen because they already use hydrogen in their processes. These customers can agree to buy hydrogen from the producer for a specific price and pay a certain price to the distributor. It will be more difficult for customers who have to make adjustments to their assets. In other words, they have to make investments. These investments will only occur as the companies know that they can buy hydrogen on the market for a specific price. Therefore, they will wait until the moment that this is possible. The price of hydrogen will start decreasing if the technology is developing. The only option to start this development is building electrolyzers and experimenting, researching, and developing new technologies. When a company takes to starts developing, it could be a pioneer and taking the lead. However, pioneering brings some risks of making the wrong decisions (Hydrogen Council, 2017). If the new hydrogen technology is more expensive, they are afraid to lose market share. Again, the situation uncovers the chicken and egg problem. The chicken and egg problem is a stabilizing pressure.

International market

It is mentioned multiple times that there is a shortage of green hydrogen in the Netherlands and that import is unavoidable to comply with the demand in the future (Port of Rotterdam, 2020). An international market is therefore required to trade hydrogen. The Netherlands could profile itself as a hydrogen hub, given the current function in the energy trade and our assets and knowledge (Dutch Government, 2019).

Infrastructure for hydrogen

The business case for the distribution depends on subsidy and the conclusion of contracts, guaranteeing the distributor that it can earn back its investments (Eddie Lycklama a Nijeholt, personal communication, June 17, 2021).

Looking at the distribution, Gasunie is currently developing a hydrogen backbone. The backbone will be consist of 85% of existing gas pipes and 15% of new gas pipes (VEMW, 2021). The possibility of reusing the pipelines is a significant advantage as the realization will be much faster, and the costs will be a factor of ten lower when the backbone consists of only new pipelines (Eddie Lycklama a Nijeholt, personal communication, June 17, 2021).

In 2018, Gasunie established a hydrogen pipeline in Zeeland between Dow and Yara (project hydrogen symbiosis in the Delta region)(Green Deal, 2021). A significant difference between the future hydrogen backbone and the pipeline in Zeeland is that the supply and demand between Dow and Yara were pre-arranged. This gave Gasunie the guarantee that it will recoup its investments, and Gasunie could determine the transport tariff.

First, Gasunie shall establish regional clusters and connect these clusters in a later stadium (Savelkouls, 2021c). Within these clusters, it can be insightful where potential hydrogen customers are and where hydrogen could be produced (Eddie Lycklama a Nijeholt, personal communication, June 17, 2021). The next step is to make an expression of interest, and Gasunie can start with calculating the transport costs. However, this will not be static like in the project hydrogen symbiosis in the delta region. When clusters will be connected and there will be special production facilities (electrolysers) for production of hydrogen, it is tougher to predict the hydrogen flow and the tariffs, than when hydrogen is traded peer to peer. The market needs to be open and dynamic for a hydrogen economy, which means multiple suppliers and buyers (Eddie Lycklama a Nijeholt, personal communication, June 17, 2021).

Gasunie wil not invest in a project with an unhealthy business case. In onder to have a healthy business case, transport contracts and subsidies are needed. It makes no sense to invest in a hydrogen infrastructure without transport contracts, even with subsidies. Without subsidies there will be no positive business case, as there will not be enough hydrogen transport contracts in the initial phase with which the pipeline will get sufficient filling. So both subsidies and contracts are needed. If the transport contracts pick up swiftly, the transport tariffs will be reduced to keep the business case at a level which is in line with regulated tariffs, even if the hydrogen transport function is not yet regulated at this moment (Eddie Lycklama a Nijeholt, personal communication, June 17, 2021).

There are three options for Gasunie to obtain state aid, whereby designation of the hydrogen backbone program as a state interest is preferred (Eddie Lycklama a Nijeholt, personal communication, June 17, 2021). This option makes it a service of general economic interest, which is then seen as a basic service (European Commission, n.d.). The following sectors are marked as a basic service: telecom, post, energy, public transport, waste processing, broadband, and the natural gas network is also a service of general economic interest (Ministry of the Interior and Kingdom Relations, 2012).

Other state aid options are IPCEI (Import Project of Common European Interest) or via the tariff system. Using the IPCEI does not have the preference as the European Union grants it. It is more unpreditable and uncertain than receiving support from the national government. In addition, support from the national government will also be a quicker way of getting subsidies.

As is made clear, the infrastructure development is partly on support in the form of subsidies and partly depending on the other parts in the supply chain, the supply, and demand. When both will start with the so-called booking of capacity, Gasunie can start with the infrastructure deployment.

Gasunie made scenarios for the hydrogen demand in 2030. These scenarios match the expectations of the Dutch government, which expects a potential demand of 150 – 253 PJ / year in 2030 (Dutch Government, 2019; Gasunie, 2019).

In the end, the national backbone will be connected to the European backbone (Savelkouls, 2021e). Hydrogen infrastructure is of great importance for developing green hydrogen in the heavy industry. Without a hydrogen backbone, it is impossible to set up a hydrogen market (Nationaal Waterstof Programma, 2021). This makes the development of hydrogen very difficult compared to, for example, renewable energy. Because in contrast with natural gas and electricity, there is currently no market for hydrogen yet (Ministry of Economic Affairs and Climate Policy, 2020).

Together with a hydrogen infrastructure, a hydrogen exchange platform and certificates of origin are needed for an open market. Furthermore, regulation is essential for establishing a hydrogen market (Gigler et al., 2020). The lack of a hydrogen backbone is a stabilizing pressure.

Balance between supply and demand

When the hydrogen backbone is established, a new challenge presents itself. When the supply side is developing, the demand side must develop with new technologies. Equivalence of supply and demand is essential for a well-functioning market. It is a challenge to match the supply and demand and increase both equally over time. For both sides, enough demand/supply is required for a positive business case (Rotman, 2020). An open and liquid market is essential and cannot be realized without a hydrogen backbone (Duijnmayer, 2020). Until then, supply and demand try to find each other directly, for example, Zeeland with a hydrogen pipeline between Dow and Yara (Smart Delta Resources, 2020).

3.2.2.3 Lack of coordination

Now that the future of hydrogen is outlined, there must be looked at rules and policies.

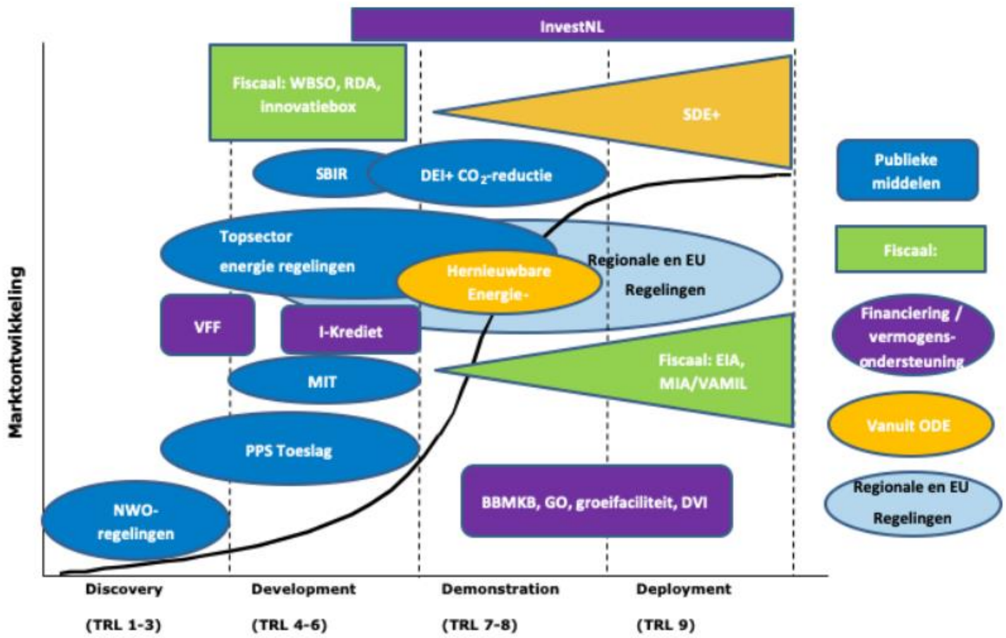

Figure 16: Flow chart of a low carbon energy system and different subsidy schemes arranged per TRL

Within the regime, multiple subsidies schemes are active. The most important ones are discussed. In Figure 16 is visualized the different subsidy schemes and ordered them to the technology readiness levels (TKI Nieuw Gas, 2021).

SDE++

In this study, the SDE++ scheme is mentioned. This scheme is a national subsidy for technologies that reduce emissions (allocated on a project basis). Characteristic for the SDE++ is the cost-effective approach. At first, the scheme only subsidizes the unprofitable top of a project. The projects are competing with each other, and the cheapest technologies will receive the subsidy. The subsidy is calculated in euros per avoided tonne CO_2 emission, and there is a maximum of 300 euro per tonne of CO_2. The total budget amounts to 5 billion euros. A disadvantage of this scheme is that the subsidy is granted to the most cost-effective technologies. More expensive technologies (like green hydrogen) have a hard time claiming a subsidy because other technologies are further developed so more cost-effective (Deloitte, 2021).

Producing hydrogen via electrolysis is one of the categories that can apply for subsidy (Rijksdienst voor Ondernemend Nederland, 2021b). By 2021, the Dutch government decided not to add a special category for building two hydrogen factories that produce hydrogen from residual gasses and natural gas (project H-vision) (Sluijters, 2021).

On the website of the RVO is listed the categories that can apply for the SDE++ (Rijksdienst voor Ondernemend Nederland, 2021b). Every year, the SDE++ is revised, and categories can be added or removed.

The SDE++ scheme could bridge (partly) the unprofitable top for the production of green hydrogen (SDE++ is not available for blue hydrogen) (Lensink & Schoots, 2021). Now that this scheme is canceled, many investment decisions are waiting on the green light (Redactie Duurzaambedrijfsleven.nl, 2020). The SDE++ was canceled because there was not enough renewable energy available in the Netherlands (H2Platform, 2020b).

DEI+

Another subsidy scheme is the DEI+ (Demonstration Energy and Climate innovation). This subsidy scheme is intended for demonstration projects which use innovative technology that reduces the emission of CO_2, for example, CCS. However, this subsidy scheme does not support projects to reduce the emissions of CO_2 hydrogen in the industry. The budget is amounted to 126,6 million euros (Rijksdienst voor Ondernemend Nederland, 2021a).

CO_2 tax industry

From 2021, a minimum CO_2 tax for the industry sector is applied. The price will function as an additional tax that companies must pay above the EU-ETS price (unless the EU-ETS price is higher) (Dutch Government, 2019). A disadvantage of a national CO_2 price is that only the companies in the Netherlands are affected. PwC (2019) concluded that a national CO_2 charge has the consequence that the attraction from the Netherlands as a country of residence for the industrial sector will decrease. There is a fine line between potential leaking of economic activities and stimulating companies to reduce CO_2 emissions (carbon leakage)(PwC, 2019).

EU-ETS

Another cornerstone of the EU's climate policy is the European Emissions Trading System. The EU ETS is a system that is incorporated which purpose is to reduce the emission of CO_2. The Dutch government has introduced an additional CO_2 tax from 2021.

A low EU-ETS price will enforce stabilizing pressures on the heavy industry regime. On the contrary, a high EU-ETS price pressure the heavy industry to make the transition towards green hydrogen, as that is cheaper than emitting CO_2. In 2018 the European Union agreed on a further acceleration of the phase-out of the emission rights (Dutch Government, 2019). The ETS ceiling will be reduced by 2.2% per year till 2030 (Dutch Government, 2019).

Low energy tax

In the current regime, the heavy industry gets discounts in energy taxes compared to small users. The difference between the price for the industry and small users can be a factor of 2.5 (Dril, 2015). The tax benefits lower the incentive to reduce CO_2 emissions (Westerveld, 2021b). Lower taxes originated from the concern that the competitive position of industrial companies in the Netherlands would deteriorate. The lower taxes results in for the base metal industry that 29% of the emissions are free of marginal CO_2 price and for the other 71% is a price that is lower than 30 euros per tonne CO_2 (ESB, 2021). The lower taxes are a stabilizing pressure, the price effects of CO_2 have less influence on the heavy industry. An solution for dealing with losing a competitive position is a European CO_2 boarder tax (Hylkema, 2020; Westerveld, 2021b).

Coordination

Although hydrogen is widely used in the Netherlands, the transition towards hydrogen requires rules and policies, but these are not there yet. The current laws and regulations are focused on fossil fuels, and not on hydrogen yet.

In the report: Meerjarig innovatieprogramma waterstof, a list with activities that need to be done is conducted. For example, measurements methods, rules about distribution, safety aspects, and division of tasks (who will be the network owner for transport and distribution) are in the nascent phase (Ministry of Economic Affairs and Climate Policy, 2020; Weeda et al., 2019). Even though these aspects are not the core of the hydrogen economy, they are relevant because they block the deployment of the hydrogen transition (Weeda et al., 2019). Clear regulations were one of the success factors in which offshore energy costs decreased rapidly (Verhelst, 2021).

A necessary standard that the actors will have to agree on before hydrogen can be transported via pipelines concerns the quality of hydrogen that will flow through the infrastructure (Weeda et al., 2019; Eddie Lycklama a Nijeholt, personal communication, June 17, 2021).

In the Cabinet's vision on hydrogen, the Minister of Economic Affairs and Climate formulated a policy agenda (five points) for law and regulations.

1. Use of the existing gas network
2. Market organization and temporary (for experiments) tasks for grid operators
3. Guarantees of origin of hydrogen and certification
4. Safety
5. Main Energy infrastructure

According to the Minister, these five points are essential for the hydrogen transition. In the interview with Lydia Boktor, it was pointed out that the ground rules are required before projects can take off. If these conditions have not been arranged, they form a stabilizing pressure of the current regime (Lydia Boktor, personal communication, June 29, 2021).

3.2.2.4 Lack of a business case

The potential blue or green hydrogen users in the industry are industrial companies who need hydrogen as a feedstock or a heating source. Hydrogen will replace the demand for grey hydrogen (feedstock) or fossil fuels, mainly natural gas (heat). The supply can be covered by companies who make hydrogen via (green) electricity or natural gas (with CCS).

When reading news articles about hydrogen projects, quite often is written about an unprofitable top. An unprofitable top means a gap between the cost price and the market value that the project will generate for the company. When this is negative, a single company (or multiple companies) investing in a project will make a loss. Usually, this is formulated as the difference in the product's market value that a project will produce, for example, green hydrogen, and the cost price. No commercial company will invest in a project with an unprofitable top. The unprofitable top differs for the application of hydrogen (burning or feedstock). If the hydrogen has to compete with natural gas, the unprofitable top will be higher than if the hydrogen has to compete with grey hydrogen (H2Platform, 2020a; Ministry of Economic Affairs and Climate Policy, 2021). "Grey hydrogen costs around €1.50 kg^{-1}, blue hydrogen €2–3 kg^{-1} and green hydrogen €3.50–6 kg^{-1}"(van Renssen, 2020, p. 801). If green hydrogen is 1.78 euro per kilo, it can be competitive (ABN AMRO, 2021).

- The price of grey hydrogen consists of the price of natural gas and CO_2 & production costs (H2Platform, 2020a)
- The price of blue hydrogen consists of the price of natural gas and CCS & production costs (Stedin, 2020)
- The price of green hydrogen consists of renewable energy & production costs (Stedin, 2020)

That means that there is a difference between the unprofitable top for blue and green hydrogen. One of the crucial factors of the unprofitable top is the low CO_2 price. When the CO_2 price increases, the unprofitable top for blue and green will be lower because grey hydrogen and natural gas become more expensive.

To conclude, there is a lack of a business case. Blue and green hydrogen are too expensive to produce, and therefore there is no demand for them.

Gasunie's (2019b) report states that the demand for sustainable hydrogen will start in 2030 due to the price of green hydrogen. It is in line with the expectation of the market that in 2030 green hydrogen become cheaper than blue hydrogen because of the decreasing price of green electricity and the increasing gas price (Dutch Government, 2019).

High renewable energy price

Another essential part is the price of green hydrogen, which is dependent on the development of green electricity (made from renewable energy (mainly wind and sun)). Eighty percent of the costs of green hydrogen are determined by the electricity price (van Renssen, 2020). Here is a struggle for the economy and politics. The renewable electricity price needs to be viable for the producer and compete with natural gas, which is impossible. Somehow, this price gap has to be bridged, for example, with a higher CO_2 price (van Renssen, 2020).

The high renewable electricity price also has to do with the fact that there is not enough green electricity available in the Netherlands to produce green hydrogen. A solution is to allocate more areas for offshore wind to increase the production of green electricity. Another solution is to import green hydrogen, but this is outside the scope of this research.

3.2.3 Niche level

Niche developments are waiting for a window of opportunity. In the introduction are already a couple of projects mentioned. TKI has a database with all projects that are currently announced. Some are presented in Figure 18 (de Laat, 2021). Experiments provide essential learning processes for all actors involved.

Learning process & involvement of powerful groups

The production process of green hydrogen has to become cheaper (Dutch Government, 2019). The TRL (technology readiness level) of electrolysis is too low, resulting in a non-competitive technology (Cefic, 2019; TKI Nieuw Gas, 2018). Developments of technologies and processes are essential to make the production process of hydrogen more efficient (Dutch Government, 2019; Weeda et al., 2019). "Innovation, pilots and demonstration projects are of great importance to make the necessary new technologies available, reliable and affordable" (Dutch Government, 2019, p. 89). Increasing the lifespan and robustness and decreasing the use of scarce materials are also important (TKI Nieuw Gas, 2018). Improving the TRL is essential to start with projects, but the unprofitable top is holding this back. Nevertheless, without technology improvements, the costs of green hydrogen production will remain (too) high.

For green hydrogen, electricity is converted towards hydrogen in an electrolyzer. This technology is more than 200 years old (Jongeneel, 2020). However, the technology is not efficient and therefore costly. The cabinet vision is about 65 percent cost reduction (65% reduction on the CapEx) (Dutch Government, 2019; Ministry of Economic Affairs and Climate Policy, 2020). That will mean that the price for 100MW installed electrolyze capacity will be reduced from 100 million euro to 35 million euro by an upscaling to 4 GW, which is the goal of the Dutch government for 2030 (Dutch Government, 2019). The project Djewels (20 MW) production facility will be the biggest in Europe and globally (Rotman, 2020). Currently, the Hystock facility of 1 MW is the biggest in the Netherlands (Lydia Boktor, personal communication, June 29, 2021). Nonetheless, the Dutch government wants 4 GW installed in 2030 (Dutch Government, 2019). The costs will decrease as more research and projects are set up. At the moment, the TRL is still too low for these techniques.

The hydrogen niche has to develop. The technology development can cause efficiency improvements and give insight into the necessary institutions for deploying hydrogen on a large scale. When the technology is developing, other actors necessary to break into the regime have to be in place. Actors as investors, local governance, and maintenance companies have to be in place to make the niche stable.

In chapter 1 is made clear that the industry is announcing various projects that are auspicious and, unfortunately, some far-off. There are many projects regarding green hydrogen. One project will be explained in more detail, called DJewels.

Project example: Djewels

Nouryon and Gasunie are working together to build a green hydrogen plant at Delfzijl. When this plant is realized, it will be the most significant water electrolyzer in Europe. The plant will have a power of 20MWe and can produce almost 3.5 Kton of green hydrogen per year. The motivation for building the plant is to learn about the processes on a large scale. The project had to choose one of the two available (on MW scale) water electrolyze technologies during the preparations. A choice has been made for the alkaline technology, instead of the PEM-technology. Advantages of alkaline technology over the PEM- technology are lower investment costs and lower energy consumption. Currently, the project is still in stage 1: hydrogen business analysis and development (Nouryon & Gasunie, 2019).

Niches try to create pressure on the regime from below and become the new regime. First, the niches perform worse than the incumbent technologies, but after innovations and research, the niches could surpass the established technologies and perform better, which is visualized in Figure 17.

Another function of the developments at the niche level

When a niche is created, there may also be a strategic idea behind it (Geels & Kemp, 2000). Besides the intention to learn from the experiments, the experiments could also create awareness and a support base for the new technology. An example is a project in Stad aan 't Haringvliet, where a city in the province of Zeeland with about 600 houses is switching from natural gas to hydrogen for heating their homes (Stedin, 2020). All actors involved could learn from this project, and others interested in this project like to watch over the shoulders. Furthermore, this project creates awareness for other people that hydrogen can be the future and safe to use (van Zon, 2020). When these projects become a success story, they could be used as publicity.

Sometimes the strategic intentions are known, but they also cannot be disclosed. Another strategic strategy is to take a competitive advantage by investing in R&D and take the lead (Geels, 2004). In an interview, Zofia Lukszo acknowledges the problem of public opinion, especially for blue hydrogen. Niche projects should create awareness for hydrogen and turning negativity into positivity. However, the heavy industry is no direct consumer market, and therefore, the public opinion of the consumer is less critical (Zofia Lukszo, personal communication, June 25, 2021).

To summarize, the analysis will expose the pressures that policy instruments should stimulate at niche and regime level and for which pressures are a lack of support by the policy instruments

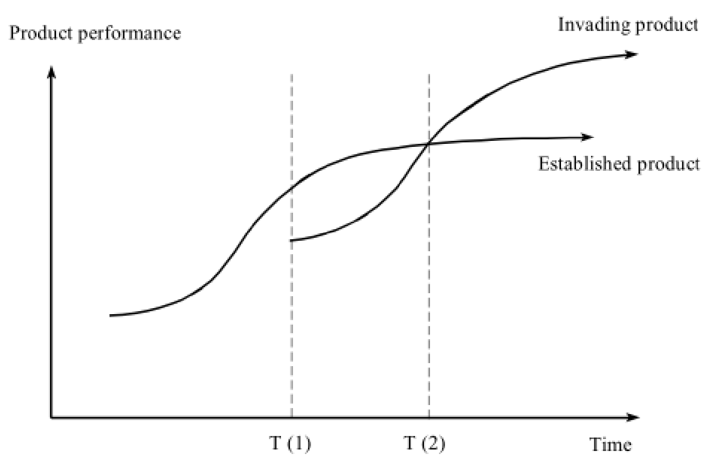

Figure 17: Competition between incumbent products and innovations, from (Geels & Kemp, 2000)

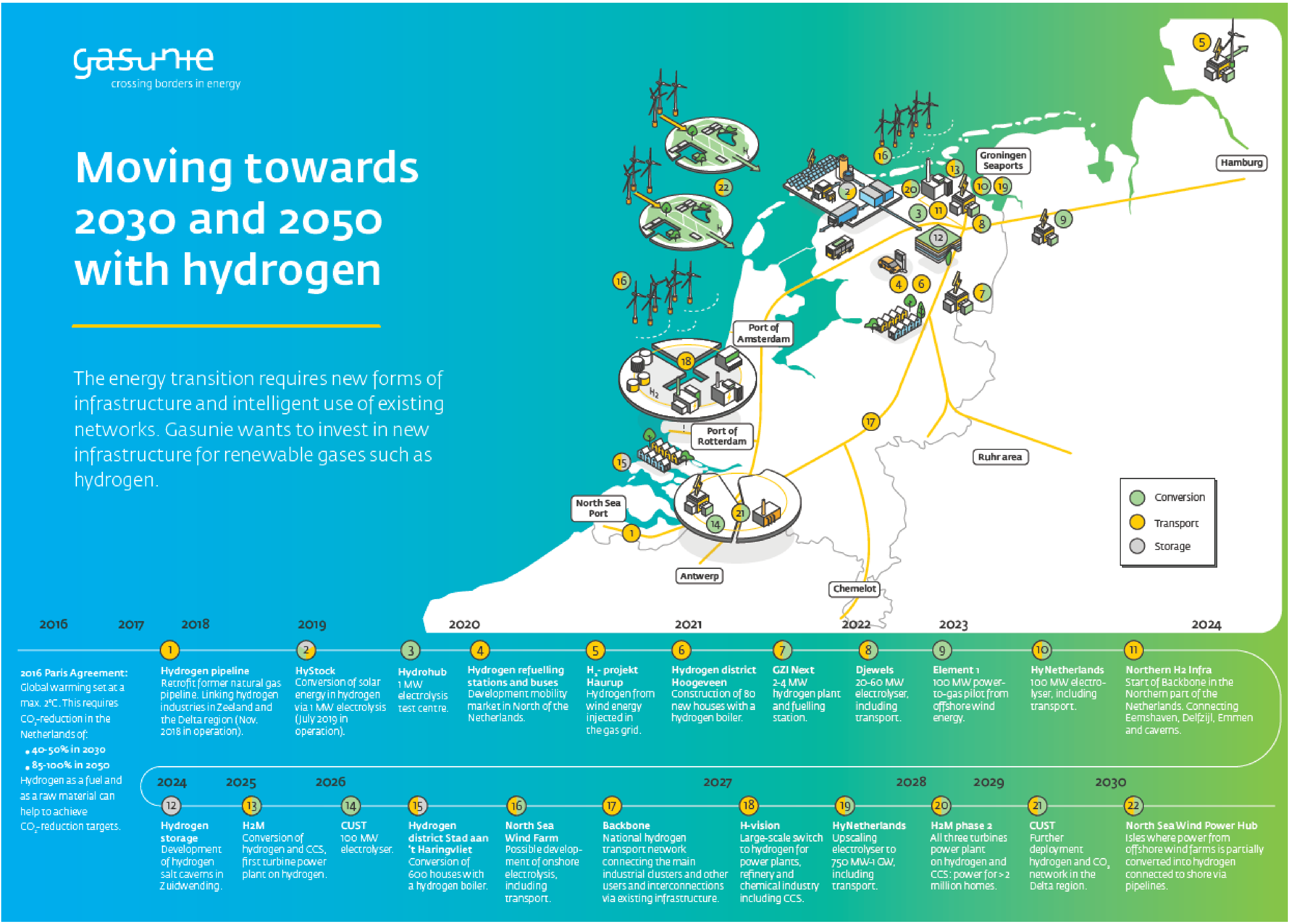

Figure 19: Hydrogen planning till 2030 (Gasunie)

3.3 Conclusion

In sections 3.1, the hydrogen transition in general is discussed. In section 3.2, hydrogen in the heavy industry sector in the Netherlands are discussed. In section 3.3.1, the policy instruments that are selected will be elaborated. In section 3.3.2, the pressures that are included in the assessment are explained.

3.3.1 Selected policy instruments

In section 2.2, the economic literature on policy instruments and the analytical framework are discussed. In section 3.2, the case study of the heavy industry sector in the Netherlands is done, and present policies are argued.

The SER (2019) presented the National Climate approach for regional industrial leaders. In the report, the SER presented a couple of policy measures that should foster the decarbonization of the industrial sector. The Netherlands focuses on two pillars in its climate policy, increasing CO_2 prices and stimulating new technologies (Westerveld, 2021b). These two pillars form the basis of the selected policy instruments. In this study, five policy instruments will be used in the assessment, all instruments which are not now used or are not used in this form (hypothetical instruments).

Higher CO_2 price

One of the measures is to improve the EU-ETS system. By increasing the price of CO_2, the stimulus to reduce the CO_2 emissions will increase. One of the benefits of the EU-ETS system is that it creates equality for industrial companies throughout Europe. This policy instrument is also mentioned by (Bleischwitz & Bader, 2010b). The EU-ETS system can be increased by taking rights from the market more quickly. The amount of ETS rights (ceiling) is reduced by 2,2% per year until 2030 (Dutch Government, 2019). However, it is hard to predict the CO_2 price, as it is very volatile (Duijnmayer, 2021).

BNP Paribas Asset Management calculates that a carbon price of 79 – 103 euro in 2030 can displace grey hydrogen with a reservation that the production price of green hydrogen will drop to €2 per kg. Zofia Lukszo acknowledges that green hydrogen will be interesting when the CO_2 is about 100 euros (Zofia Lukszo, personal communication, June 25, 2021). However, this calculation is based on assumptions of the gas price, renewable energy price, and others (Lewis, 2020). It is estimated that blue hydrogen will be profitable from €60 - €70 per tonne CO_2 (van Renssen, 2020). The EU-ETS price fluctuated a long time between 20 and 30 euros. Since November 2020, the price is rising. Currently, in June 2021, the price is about 50 euros for the first time in the history of the EU ETS (Beunderman, 2021; Opheikens, 2021). The CO_2 price is from July 2019 till April 2021 is presented in Figure 19. Last year, many production facilities were shut down due to Covid-19 (March 2020). This resulted in a drop in the ETS price. However, the price was recovered fairly quickly.

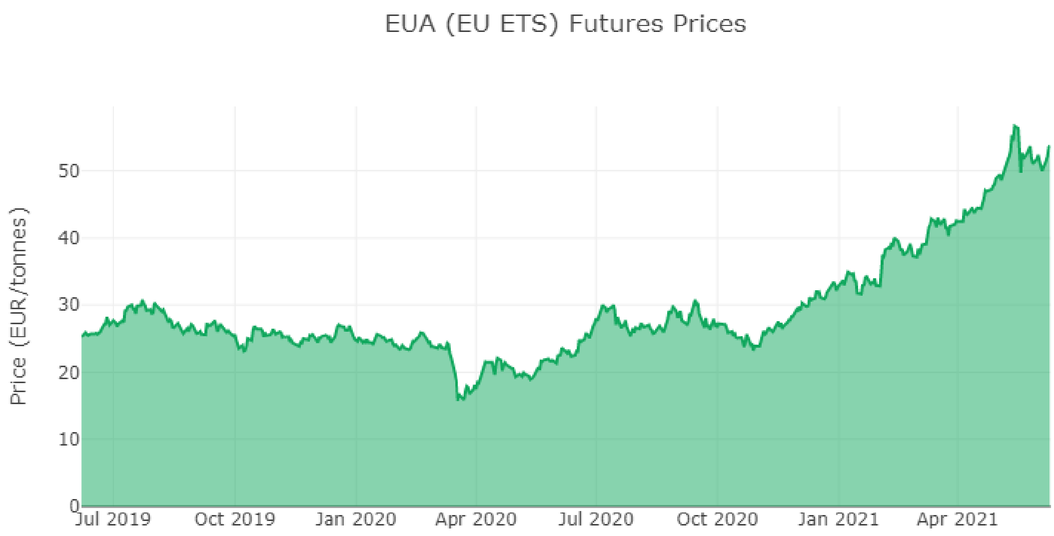

Figure 20: EU ETS price from July 2019 - May 2021 (Ember, 2021)

Another option to increase the price of emitting CO_2 is via a national CO_2 price. The price is set at €30 per tonne CO_2 and will increase by 10,56 euros per tonne CO_2 per year. This tax will overrule the EU-ETS in two years (at the current EU-ETS price). In this research, the national CO_2 tax for the heavy industry will be set at 75 euros per tonne CO_2 and increases by 5 euros per year. With a CO_2 price of 75 euros, blue hydrogen will become immediately viable and green hydrogen within 5 years. It has been decided not to set the price at 100 euros because then the step is huge and the risk of carbon leakage increases enormously (PwC, 2020). The CO_2 price for 2030 is just the same as the current national CO_2 tax scheme.

Carbon Contract for Difference

A policy instrument that is not mentioned by the SER is Carbon Contracts for Difference (CCfD). It is an alternative policy instrument to raise CO_2 prices. This policy instrument minimizes the price uncertainty for companies, just like the national CO_2 price. In this contract, the government will agree with a company upon a fixed carbon price (strike price) over a given period. When the carbon price is lower than the strike price, the government will pay the company the difference. If the market price is higher than the strike price, the company has to pay the additional revenue to the government (visualized in Figure 20)(Gerres & Linares, 2020). That is also the case when the companies sell the emission rights that they have been granted for free (Gerres & Linares, 2020).

By paying the difference to the company when the market price is lower than the strike price, the competitive position of the companies will remain the same compared with companies outside the Netherlands. CCfD takes away the risk for the company (risk shifts to the government)(Dieter & Cameron, 2014). Furthermore, the company will be stimulated to reduce its CO_2 emissions (because they can sell their free rights with an additional profit).

The Road project, a project for CCS for two coal power stations in Rotterdam, could have been saved with a CCfD (or national CO_2 price). The CO_2 price was too low for making a business case (2017) (about 8 euros per tonne CO_2 at that moment). Knowing that the current price is 50 euros per tonne, the project could have been profitable (van der Lugt, 2021). In this study, the strike price is set at 100 euros per tonne CO_2, a price where green hydrogen should be viable and is the mean of the starting price of the national CO_2 tax level in this study now and in 2026.

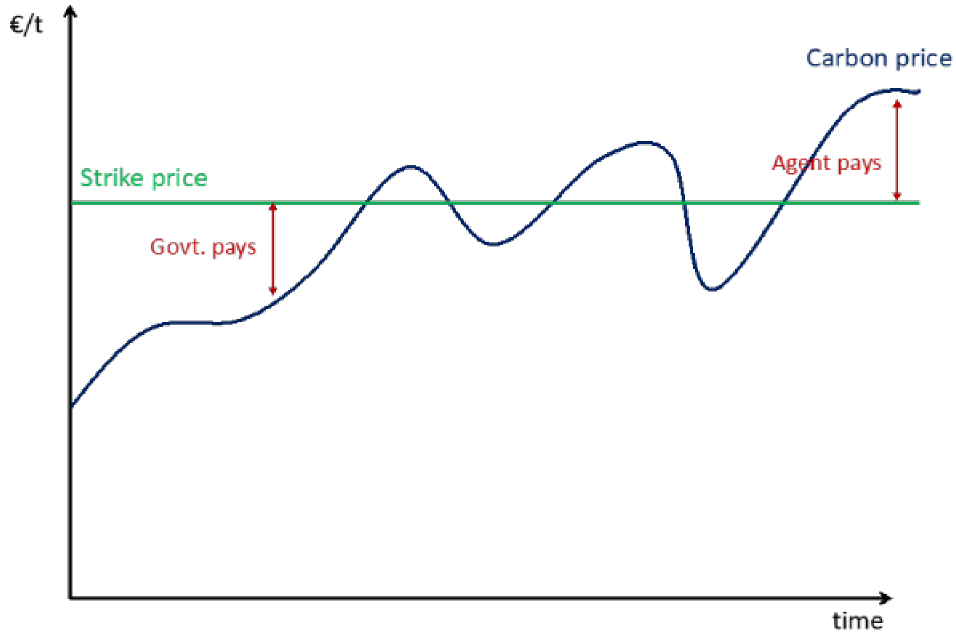

Figure 20: Visualization of the Carbon contract of difference with the strike and market price (Gerres & Linares, 2020 p.2)

Subsidy to increase the supply of hydrogen

The SER emphasizes the subsidies for R&D as technological innovations are essential to foster decarbonization. Three groups (generation, distribution, and utilization) can be subsidized, looking at the hydrogen supply chain. It is essential to watch out for over-subsidizing (SER, 2019; Westerveld, 2021c). The SER proposes to stimulate R&D via innovation subsidies and the SDE++. In this study is chosen for the SDE++ scheme. To make the SDE++ scheme suitable to stimulate hydrogen in the heavy industry, a couple of new categories have to be added to this scheme. To foster the hydrogen transition, projects that will increase blue or green hydrogen production will be included. Consideration could be to make a particular category for hydrogen to prevent it from competing with other CO_2 reduction technologies (e.g. offshore wind or geothermal for district heating) (Westerveld, 2021b). Furthermore, the maximum of SDE++ contribution is 300 euro per tonne prevented CO_2 emission. The Minister of Economic Affairs and Climate mentioned that 300 euro per tonne CO_2 is insufficient to cover the complete unprofitable top for green hydrogen projects (Ministry of Economic Affairs and Climate Policy, 2021). Therefore, it is chosen that the contribution for green hydrogen projects may be higher until it meets the unprofitable top.

Subsidy to increase the demand for hydrogen

Furthermore, projects for increasing the demand for hydrogen in the industry should also register for subsidy (DEI+). Currently, it is not possible to apply hydrogen projects for this subsidy scheme. This subsidy scheme is therefore adapted. A new category will be added for hydrogen projects in the industry. In addition, the maximum subsidy provided can be increased, which will be done in consultation with the government. Subsidies can be used, for example, for adaptions to the facilities and production process.

Financial support for infrastructure development

Section 3.2.2.2 discusses possible financial incentives for the infrastructure. The hydrogen infrastructure development should have access to financial support from the government, which is not possible via the SDE++ scheme as this project does not produce energy. Funding from the state to establish this infrastructure is considered appropriate and most realistic (approximately 1.5 billion euros) (VEMW, 2021; Eddie Lycklama a Nijeholt, personal communication, June 17, 2021).

3.3.2 Selected pressures

In section 2.1, the theory about stabilizing and destabilizing pressures is explained. With this knowledge, the heavy industry sector is analyzed in chapter 3, and stabilizing and destabilizing pressures are identified within the socio-technical system. Now, the selected pressures are discussed.

There are six main stabilizing pressures. Within these pressures, there are several more minor pressures active, as mentioned in section 3.2. The following regime pressures are identified and have to be removed by policy instruments:

Stabilizing pressures

- Lack of a business case
- Lack of a hydrogen market
- Lack of coordination

Destabilizing pressures

- Experience with hydrogen
- Learning process
- Involvement of powerful groups

Now, this is made insightful a deliberate choice can be made for specific policy instruments. In Figure 21, the stabilizing and destabilizing pressures are visualized

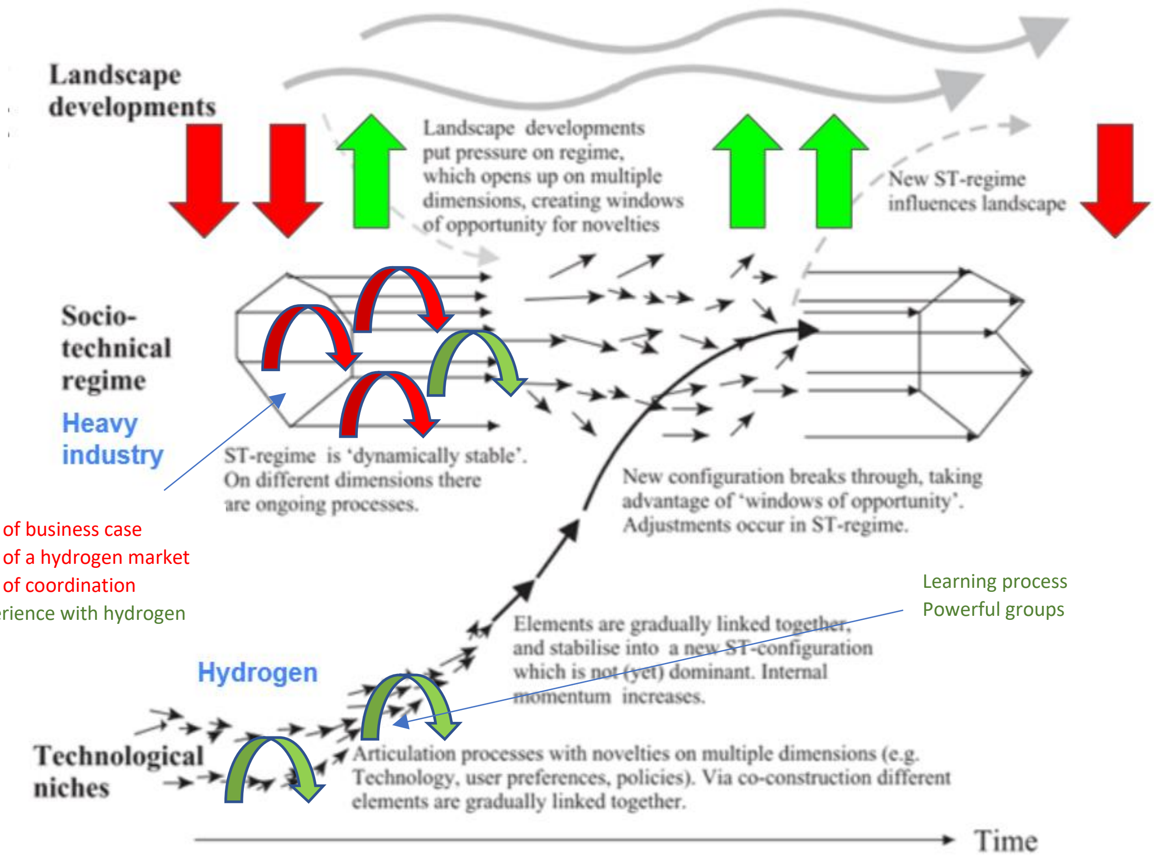

Figure 21: Landscape, regime and niche level and the destabilizing and stabilizing pressures (Own work based on Geels (2011))

3.4 Final analytical framework

The policy instruments and pressures for the analtytical framework are selected. The final analytical framework can be filled in:

Table 9: Final analytical framework with the selected pressures and selected policy instruments

Policy instruments / Pressures	Higher CO_2 price	Carbon Contracts for Difference (CCfd)	Subsidy for Supply	Subsidy for demand	Financial support for infrastructure development
Learning process					
Support from powerful groups					
Lack of coordination					
Lack of business case					
Lack of hydrogen market					
Experience with hydrogen					
Total					

3.5 Phases in the transition

Based on the interviews and other information in chapter 3, a prognosis is made for the four phases (Figure 1) defined in section 2.1.

1. Projects like Djewels and Hystock are both projects to learn, develop the technology, and eventually scale up the facilities (de Laat, 2021). When multiple projects are realized and are up and running, the transition will enter the second phase.

2. In phase 2, resources for further development of hydrogen are already provided. As discussed in section 3.2, the infrastructure design is explicitly discussed, together with a set of rules and policies for the future hydrogen economy. In phase 2, the preparation for the regime's intrusion will be made because, in phase 3, the competition with the incumbent regime will start.

3. Phase 3 will be from 2030, as the government's goal to have 3 – 4 GW installed electrolyze capacity is only a fraction of what the energy demand is currently in heavy industry. In 2019 the energy demand in the Netherlands was 3047 PJ, and 42.5% was from the industry sector (Compendium voor de Leefomgeving, 2021). 4 GW installed capacity is 126 * 10^{15} J per year of green hydrogen production. The demand from the industry is 1291,9 * 10^{15} J per year, that means that it can covers only 10% of the energy demand from the industry sector and only 4% of the total energy demand in the Netherlands. To conclude, 4 GW installed capacity is just the start of the hydrogen transition. As mentioned in section 3.1.5, not the whole energy demand will pass to hydrogen.

In the report of Gasunie (2019b) is stated that the expectation for the demand for sustainable hydrogen just will start in 2030. This has to do with the price of green hydrogen, it is in line with the expectation of the market that in 2030 green hydrogen become cheaper (it is expected that the technologies for green hydrogen are market-ready in 2030 (Sebastiaan Hers et al., 2018) than blue hydrogen because of the decreasing price of green electricity and the increasing gas price (Dutch Government, 2019). However, it is expected that blue hydrogen plays a crucial role in the transition towards green hydrogen.

First, blue hydrogen will dominate, and green hydrogen will slowly take over (Zofia Lukszo, personal communication, June 25, 2021). To prevent the lock-in of blue hydrogen, the government has to apply strict regulations e.g. that blue hydrogen is forbidden after 2035 (Zofia Lukszo, personal communication, June 25, 2021). Gasunie has planned to have a hydrogen backbone in 2027 up and running, as shown in Figure 22. In 2040, the North2 consortium wants to have 10 GW installed electrolyze capacity running on offshore wind farms.

4. After 2040, the transition will enter phase 4, especially when there is hydrogen imported. From phase 4 on, the transition will settle in the regime, and phase 4 is completed when the regime influences the landscape level. This phase is out of the scope of this study, as the focus is on the deployment of hydrogen in the heavy industry sector.

In Figure 24, the phases are visualized (Gasunie).

Figure 22: Prognosis development hydrogen (Gasunie)

Phase 1&2 (niche level):

The key processes of Kern (2012) are here essential to stimulate.

- Learning processes
- Support from powerful groups

Phase 3 (regime level):

The stabilizing pressures identified in the regime have to be removed and destabilizing pressures stimulated.

- Lack of coordination

- Lack of business case
- Lack of hydrogen market
- Experience with hydrogen

Phase 4 (out of the cope):

Chapter 4 Analysis of policy instruments

In chapter 3, relevant stabilizing and destabilizing pressures are identified. When these pressures and policy instruments are added to the analytical framework, the framework is complete and can be filled in. First, in section 4.1, the MCA is elaborated. Second, in section 4.2, the assessment of the selected policy instruments is performed.

4.1 Multi-criteria Decision making

For further assessment of the appropriate policy instruments, an MCA is found suitable. This is a technique for decision-making and is widely used for decision-making in environmental projects (Linkov et al., 2006). Environmental projects impact multiple factors, e.g. environment and economic. Decision-making is a trade-off between these impacts and can be made insightful by an MCA. In this application, policy instruments are the alternatives. The MCA method helps to identify the trade-offs that come when implementing different policy instruments based on the score of the selected criteria (i.e. pressures in this study) (Battles & Zoppoli, 2020; Konidari & Mavrakis, 2007). One of the decision-making conditions is that the results can be reproduced, which is possible with an MCA, according to Janssen (2001).

An MCA method consists of a ranking algorithm and a criteria weighting method (Hajkowicz, 2007).

4.1.1 Ranking algorithm

Within the MCA literature, there is a wide choice for different ranking methods. Every method is suited for another application. One of the considerations is the number of alternatives to be appraised (Department for Communities and Local Government UK, 2009; Hajkowicz, 2007; Linkov et al., 2006; Velasquez & Hester, 2016). Other characteristics are the type of decision, the time available, and the available data (Department for Communities and Local Government UK, 2009). Four examples of ranking algorithms are the weighted summation, lexicographic ordering, ELECTRE, and Evamix (Battles & Zoppoli, 2020; Hajkowicz, 2007; Janssen, 2001; Konidari & Mavrakis, 2007; Wang et al., 2009). For this study, it was decided to use the weighted summation algorithm. The weighted summation is the most commonly used algorithm and is simple in use (Battles & Zoppoli, 2020; Janssen, 2001). Also, in sustainable energy systems, this is the most frequently used method (Wang et al., 2009). In the weighted summation method, an alternative will be assigned a score on every criteria. A linear function can standardize the quantitative scores if the weight factor is not equal for criteria. Per criteria, the score will be multiplied by the weight factor, and then all the scores will be summed together, resulting in an overall score per alternative (Hajkowicz, 2007; Janssen, 2001; Wang et al., 2009). Because this algorithm is easy to understand, it refutes a possible complaint from stakeholders that the MCA is a ‘black box. Creating transparency will increase the acceptance of the results from the MCA by stakeholders (Janssen, 2001)

4.1.2 Weighting method

The performance is a value that consists of the score and the weight factor (Department for Communities and Local Government UK, 2009). “The expected consequences of each option are assigned a numerical score on the strength of preference scale for each option for each criterion” (Department for Communities and Local Government UK, 2009, p. 22). Scoring can also work with other scales like – and + (Battles & Zoppoli, 2020). Weighting is assigning numerical weight factors to criteria to present the relative impact of these criteria on the problem. Two different methods are distinguished within the literature: the equal weighting method and the rank-order weighting method (Wang et al., 2009). The rank-order weighting method assign a weight factor to criteria with the help of a weighting method like Best-Worst method, Analytical Hierarchy Process (AHP), Simple multi-attribute rating technique (SMART), or pair-wise comparison (Wang et al., 2009). The weighting factor is the relative importance or preferences of the criteria perceived by the decisionmaker (Wang et al., 2009). The equal weighting method speaks for itself, all criteria have in this method the same weights. The equal weighting method is the most popular and commonly used in sustainable energy decision-making (Battles & Zoppoli, 2020). One of the benefits is that it requires minimal knowledge about the priorities of the decision-makers (Wang et al., 2009). However, this method has some disadvantages in comparison with a rank-order weighted method. Possible preferences of decision-makers cannot be taken into account, just like the impact of the selected criteria (Battles & Zoppoli, 2020).

Considering the advantages and disadvantages of the different algorithms and methods, the equal-weighted method is selected for this study in combination with the weighted sum method. This means that there are no preferred criteria in the multi-criteria analysis.

4.1.3 Performance matrix

The final product of the MCA is a performance matrix, which is a table with the performance of an alternative per criteria (Department for Communities and Local Government UK, 2009). The performance can be measured in all kinds of units, depending on the criteria.

Criteria	−30 (%)	Permanent set-aside	Temporary set-aside	Progressive set-aside	CCB	Nationalpricefloor	EU pricefloor	Long-term target
Environmental performance								
Direct contribution to reduction of GHG emissions	1	1	0	1	1	0	1	1
Indirectenvironmentaleffects	1	1	0	1	1	0	1	1
Politicalacceptability								
Static efficiency	1	1	1	1	1	−1	1	0
Dynamic efficiency	0	0	−1	0	1	−1	1	1
Competitiveness	−1	−1	1	−1	0	1	−1	0
EU harmonization	0	1	1	1	1	−1	1	1
Flexibility	0	0	0	0	1	0	0	0
Stringency for non-compliance	1	1	1	1	1	1	1	1
Feasibility of implementation								
Implementation network capacity	1	1	1	1	−1	1	1	1
Timing of implementation	−1	−1	1	-1	−1	1	−1	−1
Impact on public finance	−1	1	−1	1	1	−1	1	0
TOTAL	**2**	**5**	**4**	**5**	**6**	**0**	**6**	**5**
Final ranking	**4°**	**2°**	**3°**	**2°**	**1°**	**5°**	**1°**	**2°**

Figure 23: Performance matrix with equal weight method (Battles & Zoppoli, 2020)

4.1.4 Scale

In Figure 23, an example of a performance matrix is given. Each column represents an alternative that is assessed during the multi-criteria analysis. Each row indicates the score per alternative for the particular criteria. In this example, the criteria are measured in a positive score (+1), neutral score (0), or a negative score (-1) (Battles & Zoppoli, 2020). In the assessment of criteria by Kern (2012), another three-point scale is used. The criteria are assessed by low +, medium + +, high + + +. Plus and minus scales are often used in the multi-criteria analysis (Janssen, 2001). “Qualitative scores are usually scores measured on a plus and minus [− − −/+ + +] scale. In many cases, this scale is used as a representation of an underlying classification of quantitative scores. The plusses and minuses are linked to different ranges in this classification. This is not a real ordinal scale, as the number of plusses or minuses reflects the size of the impact, and not just the order” (Janssen, 2001, p. 104). The range in this scale varies from + + +, very large positive to 0, no effect to − − −, very large negative. In this study, a 5 points scale [-, 0, +, + +, + + +,] will be used.

Table 10: explanation of the scores for the assessment of pressures

Score	Description
-	The policy instrument has, in an exceptional situation, detrimental effects
0	The policy instrument does not influence the criteria
+	The policy instrument has a positive effect on the pressure
+ +	The policy instrument has a very positive effect on the pressure
+ + +	The policy instrument has a very large positive effect on the pressure

One negative score is included in the scale when a policy instrument has detrimental effects for exceptional situations. Policy instruments are deployed to foster a transition (this study is about which policy instruments can best stimulate the transition). Therefore it is unexpected that a policy instrument will get a negative score.

When a policy instrument negatively affects the pressure, a stabilizing pressure is amplified, and a destabilizing pressure is attenuated. When a policy instrument has no or neutral effect on the criteria, the assigned score is 0. When a policy instrument has a positive effect on the pressure means that a stabilizing pressure is attenuated and destabilizing pressures are amplified. + is assigned when the policy instrument has indirect positive effect or when the effect is very small but not enough to influence the transition. When a policy instrument has a very positive effect, it means that the policy instrument has such an effect that the pressure influences the transitions positively but not enough to overcome a stabilizing pressure. The highest score, + + +, is assigned when a policy instrument has a very large positive effect and overcome a stabilizing pressure.

In this study, the policy instruments identified in section 3.2 are placed at the top of the columns of the performance matrix. Pressures are the measures of performance of the policy instruments on which the best option will be determined (Department for Communities and Local Government UK, 2009). The multi-criteria analysis manual (2009) prescribes the steps in a multi-criteria analysis. It is an incremental process. During the analysis, the steps will be constantly revised.

Steps from (Department for Communities and Local Government UK, 2009) are presented in Table 11.

Table 11: Steps in a multi-criteria analysis (Department for Communities and Local Government UK, 2009)

Steps in a multi-criteria analysis
1. Establish the decision context. What are the aims of the MCA, and who are the decision makers and other key players?
2. Identify the options.
3. Identify the objectives and criteria that reflect the value associated with the consequences of each option.
4. Describe the expected performance of each option against the criteria. (If the analysis is to include steps 5 and 6, also 'score' the options, i.e. assess the value associated with the consequences of each option.)
5. 'Weighting'. Assign weights for each of the criteria to reflect their relative importance to the decision.
6. Combine the weights and scores for each of the options to derive and overall value.
7. Examine the results.
8. Conduct a sensitivity analysis of the results to changes in scores or weights.

Steps 1, 2 & 3 are all conducted in chapter 3. Step 4 will be performed in section 4.2. Because of the equal weighting method, steps 5 and 6 are not relevant for this study. In chapter 5, the results will be examined (step 7). The idea behind a sensitivity analysis is to analyze if other weights (higher or lower) affect the outcome of the MCA. Step 8 is not relevant in this study as there are no weights that can be varied (Department for Communities and Local Government UK, 2009).

4.2 Results: Assessment of the policy instruments

The performance of the selected policy instruments will be assessed by the pressures, presented in chapter 3. Influencing these pressures with suitable policy instruments will build on the niche momentum enforce a breakthrough in the incumbent regime because this is destabilized by internal pressures. Building momentum occurs in phases 1 and 2 of the transition, where the elements can become aligned and stabilize in a design (see Figure 4)(Geels, 2018). When the regime is destabilized, there is an opportunity for the niche innovation to enter the regime and breakthrough and settle (phase 3&4), as stabilizing pressures are removed. Per section, a policy instrument is assessed, and the analytical framework from section 2.3 is filled in. In section 4.3, the final results are presented.

4.2.1 Higher CO_2 price

Learning process

A higher CO_2 price will not directly affect the learning processes of hydrogen technologies (niches) intended for the heavy industry sector. Demonstration and pilot projects are fundamental for the development of the niche (Geels & Kemp, 2000; Ministry of Economic Affairs and Climate Policy, 2020). The increasing CO_2 price will put the business cases from heavy industry companies using fossil fuels (natural gas and coal) under pressure, and companies may start investing in innovations to reduce their CO_2 emissions (Dutch Government, 2019). However, the CO_2 price is just a small part of the production costs for the steel and petrochemical industry. Therefore the effect is limited (the price of natural gas has a larger share in the production costs) (TKI Nieuw Gas, 2018). Furthermore, the heavy industry sector can pass the costs to their customers. However, it has an advantage when a company is sustainable and does not have to pay for CO_2 emissions.

Companies will likely invest in technologies that can reduce CO_2 emissions on short notice to meet the 2030 CO_2 reduction targets and not lose money to emission rights. This could be blue hydrogen as that is an available technology which TRL is more developed then green hydrogen (Lydia Boktor, personal communication, June 29, 2021). Therefore, blue hydrogen is currently cheaper than green hydrogen, however, do not underestimate the upfront investment in CCS technology (Ministry of Economic Affairs and Climate Policy, 2021). An additional incentive will be needed to shift toward green hydrogen, e.g. that 10% of the steel has to be produced sustainably, 20% of energy consumption should be renewable hydrogen (Lydia Boktor, personal communication, June 29, 2021). For that reason, the CO_2 price is scored a **+**.

Support from powerful groups

The heavy industry sector is covered by the EU-ETS scheme (EU) and the additional CO_2 tax (Dutch government) (Koelemeijer & Daniëls, 2020). Increasing the price of CO_2 means that the heavy industry, when emitting CO_2, is immediately affected and is “hit in the wallet” (to a limited extent). This policy instrument can trigger the market to transfer from fossil fuels to hydrogen (as mentioned in the learning process). However, this instrument has no direct influence on the other actors in the regime because only the heavy industry sector (emitting CO_2 and potential demand for hydrogen) is affected. Which is why the support from powerful groups is scored a **0**.

Lack of coordination

Lack of coordination is a stabilizing pressure that, in the end, has to be removed by the government (section 3.2.2.3). Improving the CO_2 price system will not affect the coordination problem, as it does not establish new rules or guidelines. Indirectly, this increases the pressure on the government to be involved in the transition as more and more companies will have to join the transition. Therefore, this is scored a **+**.

Lack of business case

A higher CO_2 price will indirectly influence the lack of a business case for the demand side (Rosenow et al., 2017). Instead of making the alternative technology (e.g. green hydrogen) cheaper, the incumbent technology (grey hydrogen, natural gas, coal, etcetera) becomes more expensive (Koelemeijer & Daniëls, 2020). This will make the price gap between those technologies smaller (Ministry of Economic Affairs and Climate Policy, 2020). Because the prices are getting closer to each other, it becomes more attractive to make the transition and switch to hydrogen (Dutch Government, 2019).

The moment when the business case for green hydrogen becomes more attractive than its fossil fuel counterpart differs per company and depends on the specific business case of the company. Due to the gradual increase of the CO_2 price, other technologies will be profitable first (blue hydrogen will become profitable sooner than green hydrogen because those are cheaper) (Lydia Boktor, personal communication, June 29, 2021). Companies have to choose what technology is suitable for their production process. Because of the closing of a business case, but not making the hydrogen technologies cheaper but making the alternatives more expensive, this solution is scored a **+**.

Lack of hydrogen market

When emitting CO_2 becomes more expensive, the absolute demand for blue or green hydrogen will increase (van Renssen, 2020). That is because processes that emit CO_2 (making grey hydrogen from natural gas and heating processes with natural gas) are becoming more expensive. However, due to different business cases (mentioned above), the transition to hydrogen will not start immediately and go step by step (Ministry of Economic Affairs and Climate Policy, 2020). A hydrogen market will not take off directly as the demand will not increase heavily at once (Ministry of Economic Affairs and Climate Policy, 2020). However, the chicken and egg problem has been broken, although a hydrogen infrastructure is required to connect the hydrogen supply chain. Therefore the higher CO_2 price is scored a **+**.

Experience with hydrogen

Higher CO_2 prices make the switch from grey hydrogen to blue or green smaller to take, looking at the business case. Since grey hydrogen is already widely used, the experience (knowledge) ensures that companies can switch more effortlessly, and demand can grow (gradually) for blue or green hydrogen (Gasunie, 2019). As mentioned above, companies will likely switch over to blue hydrogen as that production process stays the closest to the production process of grey hydrogen (Figure x) (H2Platform, 2020a). Other companies who have not yet experience with hydrogen can take advantage of the experience of other companies. Altogether, a higher CO_2 price scored a **+ +**.

4.2.2 Carbon Contracts for Difference

Learning process

As a result of this policy, the learning process is extra stimulated because the strike price gives the companies certainty to start investing in CO_2-reducing technologies (Dieter & Cameron, 2014; Gerres & Linares, 2020). The Dutch companies get a head start because other companies outside the Netherlands and fall out the CCfD will start investing later (when the CO_2 price is at the same level via

EU-ETS (or other regulations). The companies will likely invest in blue hydrogen as the strike price give no incentives to invest in green (although blue still emits some emissions) (Lydia Boktor, personal communication, June 29, 2021).

The government can immediately put the CO_2 price on a specific level as the government will compensate for the difference between the actual CO_2 price and strike price (Gerres & Linares, 2020). A higher CO_2 price, which is partly compensated, means that companies are more triggered to reduce the CO_2 emissions than a national CO_2 tax. Furthermore, the companies can invest the money in hydrogen technologies rather than paying for additional CO_2 rights (when a national CO_2 tax is deployed). For those reasons, CCfD scored a **+ +** at the learning process.

Support from powerful groups

This policy instrument gives the heavy industry certainty about the CO_2 price, resulting in more investments in hydrogen and more demand for hydrogen. At the same time, this could be interesting for investors to step in hydrogen because the risk of having no demand is decreased (Hydrogen Council, 2017), which is why it scored a **+**.

Lack of coordination

CCfD will enforce the government to stay actively involved with the market as they have first determined a strike price with the market and then pay or receive the difference between the strike price and EU-ETS price (Gerres & Linares, 2020). However, the government is not directly encouraged to work on the lack of coordination. Nonetheless, the government has to arrange everything around hydrogen so that the industry can switch to renewable alternatives. Think about new standards and rules about transportation and safety (Ministry of Economic Affairs and Climate Policy, 2020; Weeda et al., 2019). Indirectly, the government shall work on the coordination. Therefore, this is scored a **+**.

Lack of business case

The business case for blue or green hydrogen will be more interesting for the heavy industry, as predicted that this new strike price makes the gap between grey and blue/green or fossil fuels and blue/green smaller. The difference with a higher CO_2 price is that the Dutch government makes up the difference (Gerres & Linares, 2020). This policy instrument will not lead to a competition deterioration (in Europe), as the companies in the Netherlands pay the same price as other companies throughout Europe (PwC, 2020). When the CO_2 is above the strike price, the companies have to pay back the extra amount they earned with CO_2 rights (Gerres & Linares, 2020). It could be a risk that this amount of money will be more than the company initially received. However, that is not the core of this policy instrument. It is about risk mitigation (Dieter & Cameron, 2014; Gerres & Linares, 2020). Because of all this, it scored a **+ +**.

Lack of hydrogen market

A fixed (high) CO_2 price guarantee could lead to an increasing demand for green hydrogen, which gives the suppliers the guarantee that there is a buyer for their produced hydrogen (Stedin, 2020). When there is a supply and demand, Gasunie can set up contracts and determine tariffs, enabling them to invest in this new infrastructure (Eddie Lycklama a Nijeholt, personal communication, June 17, 2021). However, it must be mentioned that there is no hydrogen market until there is no infrastructure (infrastructures could be first established in the industrial clusters so that hydrogen can be traded within the clusters as soon as possible). Therefore, this is scored a **+ +**.

Experience with hydrogen

The line of reasoning here is the same as a higher CO_2 price. As the business case is becoming more viable because of the higher CO_2 price, together with the knowledge that the price will remain the same, stimulates the heavy industry to switch to promising technologies under these circumstances. Just as the previous policy instrument, this policy instrument is scored a **+ +** at this destabilizing pressure.

4.2.3 Subsidy for supply

Learning process

The SDE++ is a subsidy scheme that compensates for the unprofitable top (Lensink & Schoots, 2021). When the unprofitable top is compensated, hydrogen projects will not be loss-making. Companies will invest in R&D and build demonstration plants (Ministry of Economic Affairs and Climate Policy, 2020). The TRL of hydrogen technologies can only improve because of demonstration projects (Dutch Government, 2019; TKI Nieuw Gas, 2018; Weeda et al., 2019). One of the pillars is making hydrogen on a big scale (hundred of MW) cheaper. When the TRL increases (together with economies of scale), the price of the technology will simultaneously decrease (Weeda et al., 2019). For that reason, this is scored **+ + +**.

Support from powerful groups

The SDE++ scheme allocates subsidy for specific projects (Rijksdienst voor Ondernemend Nederland, 2021b). When blue or green hydrogen projects receive money, the projects need other influential actors in the regime to realize the projects (think about suppliers and banks for financing) (Gigler et al., 2020; Kern, 2012). There is a need for a lot of generation capacity. A subsidy makes it more attractive for parties to start producing green or blue hydrogen or invest in it. However, the powerful actors are not directly stimulated to be involved in a hydrogen project. Therefore, this is scored a **+**.

Lack of coordination

Allocating subsidies for hydrogen production also required coordination from the government (allocating the subsidy and measuring the KPI's). As seen in other projects stimulated with SDE++, the government must stay involved to make the project successful. (Lensink & Schoots, 2021). However, the SDE++ will not directly affect the coordination problems addressed in chapter 3, but will indirectly force the government to address this problem. The score for the subsidy for supply is scored a **+**.

Lack of business case

When the unprofitable top is compensated, there is a business case for suppliers, and they can start with realizing the projects and producing hydrogen. Closing the unprofitable top will eventually lead to cheaper hydrogen technology because the TRL will develop (TKI Nieuw Gas, 2018). That leads to a decrease in the price of hydrogen, which will also create a business case for hydrogen demand (van Santen, 2020). SDE++ is therefore scored a **+ + +**.

Lack of hydrogen market

The supply is one of the three parts required for a hydrogen market (Dutch Government, 2019; van Santen, 2020). When the supply increases, it is assumed that demand also will develop (the price of hydrogen will decrease) (chicken and egg). Infrastructure is, however, essential to link the supply with the demand. When there is a supply and demand, Gasunie has the guaranteed capacity that flows through the pipelines, and therefore Gasunie can start investing (Eddie Lycklama a Nijeholt, personal communication, June 17, 2021). For this reason, the SDE++ is scored a **+ +**.

Experience with hydrogen

Companies that already use grey hydrogen shall be interested in green hydrogen, especially when green hydrogen will become cheaper (van Renssen, 2020), which means the demand for green hydrogen is already in place (if there is an infrastructure to distribute the hydrogen). Because the industry is clustered, the distribution can start within these clusters and not wait until the entire hydrogen backbone is completed. However, another push is required to let the industry switch from grey hydrogen and fossil fuels to blue or green hydrogen, e.g. CO_2 emission restrictions (Lydia Boktor, personal communication, June 29, 2021). This is why subsidy for supply is scored **+ +**.

4.2.4 Subsidy for demand

Learning process

Stimulating the demand in the heavy industry will positively influence the learning process for both the supply and demand. The demand side is discouraged from implementing other technologies (Napp et al., 2014) It would be more interesting for suppliers to start delivering (van Renssen, 2020; Eddie Lycklama a Nijeholt, personal communication, June 17, 2021). However, there is still a lot to learn on the supply side (low TRL) (TKI Nieuw Gas, 2018; Weeda et al., 2019), and these remain expensive without subsidies. Until the demand is sufficient or the price of green hydrogen can rise enough that it is profitable for the supply to invest in the production of green hydrogen, the supply will stay behind. The demand should make adaptions, although because of the experience in hydrogen and with burning natural gas, these are on a small scale compared to the learning curve of the supply (adjustments to burners) (Hydrogen Council, 2017). The subsidy for demand scores a **+**.

Support from powerful groups

Increasing the demand by granting subsidies in the heavy industry will not directly lead to the involvement of new actors except for suppliers, as those trying to meet the demand and the constructor of infrastructure, who can set up contracts when there is demand and supply (Eddie Lycklama a Nijeholt, personal communication, June 17, 2021). However, when demand increases, there is a business case for the suppliers, which will attract investors to step into the hydrogen market (Hydrogen Council, 2017). Therefore, this is scored a **+**.

Lack of coordination

When the subsidy is granted to companies willing to step over to green (or temporarily to blue before they shift to green) hydrogen, they will start making the adaptions (Hydrogen Council, 2017). The government will have to monitor how the subsidy is spent and will be more involved in the development of hydrogen so that the subsidy can achieve the intended goals (Weeda et al., 2019). Lack of coordination scores a **+**.

Lack of business case

Stimulating the demand could be interesting when the government wants to stimulate a particular sector, for example, the steel sector. Furthermore, small production companies can start producing when stimulating supply instead of the big companies with enough budget to make investments. Finally, because in the Netherlands hydrogen can be easily stored and transported, the hydrogen will have a destination. Therefore, stimulating the supply is more logical than stimulating demand. However, when the supply grows, the demand have to follow, and a subsidy for demand is beneficial (Lydia Boktor, personal communication, June 29, 2021). However, it is expected that when the demand increases, the supply will also increase, and the learning process will bring the price down (van Renssen, 2020). Altogether, the subsidy for demand is scored a **+ +**.

Lack of hydrogen market

Demand is one of the three essential parts of a hydrogen market. When the demand increases, the supply will increase, as mentioned above by the learning process. All three parts must be developed simultaneously, and enough demand is required for a viable hydrogen market. Therefore, the heavy industry is perfect as it uses enormous amounts of energy and already has a vast demand for grey hydrogen (Gasunie, 2019; Rotman, 2020).

Anyhow, without an infrastructure, these companies cannot trade hydrogen. This argumentation is the same for subsidy for supply. Creating more demand will eventually lead to a hydrogen market (Rotman, 2020; van Santen, 2020). Therefore, this is scored a **+ +**.

Experience with hydrogen

Hydrogen is already widely used in the heavy industry sector (Gasunie, 2019). Because of the vast amounts of hydrogen already used, there will immediately be a great demand for green hydrogen (van Renssen, 2020). Stimulating the demand for green hydrogen lets the demand for grey hydrogen switch to green hydrogen and create additional demand for green hydrogen (van Renssen, 2020). Therefore, this is scored **+ + +**. The experience with hydrogen will ensure that the switch will run faster than building from scratch, although there is supply needed for this demand. As mentioned, the supply will follow, but there is a delay. Importing hydrogen could be a solution. However, this is outside the scope of this research.

4.2.5 Financial support for infrastructure development

Learning process

Building the hydrogen infrastructure will create practical knowledge for building the hydrogen infrastructure (Smart Delta Resources, 2020). The project in the Delta hydrogen symbioses showed that Gasunie is already far advanced with the knowledge to transform the current natural gas network into a hydrogen network (Smart Delta Resources, 2020). A significant advantage is that projects do not have to arrange everything by themselves when infrastructure is up and running (supply, demand, and infrastructure), unlike the NorthH2 project, which arranges all three because of the lack of hydrogen market. When the distribution is arranged, this indirectly stimulates small demonstration projects which can produce and sell their hydrogen (Lydia Boktor, personal communication, June 29, 2021). For this reason, this is scored a **+**.

Support from powerful groups

Having green light for the infrastructure will give other actors the certainty to join the hydrogen industry. The government implicitly says it sees a future in hydrogen with the investment and gives the private sector confidence to invest. Creating a good investment climate will ensure care from powerful actors' support (Zofia Lukszo, personal communication, June 25, 2021). Furthermore, when infrastructure is in place, the risk for companies to invest in hydrogen is lower because it guarantees that the produced hydrogen can be transported or the demanded hydrogen can be supplied. The lower risk would attract more actors to the hydrogen market. Therefore, this is scored a **+ +**.

Lack of coordination

Gasunie or the Dutch government has to define standards before they can run a hydrogen infrastructure (Eddie Lycklama a Nijeholt, personal communication, June 17, 2021). When Gasunie receives funding, they will put pressure on the coordination. When the infrastructure is a service of general economic interest, this will prioritize having all regulations and coordination in place, which is why this scored a **+**.

Lack of business case

This policy instrument will not close the business case for producing hydrogen. Of course, the financing ensures that the hydrogen infrastructure can be realized and operated when the infrastructure is not profitable for Gasunie. Although, when the infrastructure is supported with governmental funding, the tariffs can be lower, saving money for the demand side (Eddie Lycklama a Nijeholt, personal communication, June 17, 2021). Therefore, this is scored a **+**.

Lack of hydrogen market

One of the benefits of using hydrogen in the heavy industry sector is that these are all clustered, enabling a sub-hydrogen market within these clusters. Trading hydrogen within the clusters can occur earlier than 2027 (completion of the hydrogen backbone) (Eddie Lycklama a Nijeholt, personal communication, June 17, 2021), accelerating the transition. A complete hydrogen infrastructure enables the actors to trade hydrogen in an open market (when the other conditions are also satisfied) (Eddie Lycklama a Nijeholt, personal communication, June 17, 2021). If the supply and demand, the hydrogen market can be built. However, without government support for the business case for hydrogen, the market will not grow (van Santen, 2020)(Anne Geurts, personal communication, June 23, 2021 & Zofia Lukszo, personal communication, June 25, 2021). Because of this, the financial support is scored a **+ + +**.

Experience with hydrogen

The hydrogen symbiosis in the Delta region is an example of actors who can quickly set up a new project. All actors (Dow, Yara, and Gasunie) were familiar with hydrogen, resulting in fruitful cooperation (Green Deal, 2021). It is a massive advantage that the current gas infrastructure can be transformed into a hydrogen infrastructure. That saves money and time (Weeda et al., 2019). When a hydrogen backbone is realized, the experience and knowledge that companies have gathered in the past can be fully applied in the future. Companies that already use hydrogen can easily switch to blue or green hydrogen, and others who use natural gas in their heating processes can also start adapting their assets. For that reason, this is scored a **+ + +**.

4.3 Results of the assessment

The analytical framework proposed in section 2.3 is now filled in with the scores assigned in the previous section.

Table 12: Results of the assessment

Policy instruments / Pressures	Higher CO_2 price	Carbon Contracts for Difference (CCfd)	Subsidy for Supply	Subsidy for demand	Financial support for infrastructure development
Learning process	+	+ +	+ + +	+	+
Support from powerful groups	0	0	+	0	++
Lack of coordination	0	+	+	+	+
Lack of business case	+ +	+ +	+ + +	+	+
Lack of hydrogen market	+	+ +	+ +	+ +	+ + +
Experience with hydrogen	+ +	+ +	+ +	+ + +	+ + +
Total	**6+**	**9+**	**12+**	**8+**	**10+**

The final ranking of the policy instruments is as follows:

1. Subsidy for Supply
2. Financial support for infrastructure development
3. Carbon Contracts for Difference
4. Subsidy for demand
5. Higher CO_2 price

Chapter 5 Discussion and reflection

The analysis from chapter 4 resulted in a ranking of the five selected policy instruments. This chapter will interpret these results and discuss them. Next, a reflection will be given on the used research design and this research's limitations. At last, the scientific and social relevance of this study will be discussed.

5.1 Interpretation of the results

Subsidy for supply

It is not unexpected that the SDE++ is a good policy instrument as it provides funding for new technologies to make hydrogen (supply). Making a particular category for green hydrogen, causing that hydrogen technologies do not have to compete against more developed technologies and therefore more cost-efficient, is effective in improving the innovation of electrolyzers. The SDE++ has, therefore, the most positive impact on the learning process. Furthermore, the SDE++ scores the best on the lack of a business case. The learning process is closely related to this pressure. The SDE++ was conceived to close the unprofitable top for specific projects. As the unprofitable top is closed, the innovation projects can take off (although they are not cost-efficient compared to other technologies).

In this research, the SDE++ is adapted by the researcher in order to be convenient for stimulating green hydrogen projects. When the actual SDE++ scheme would be applied, this policy instrument would be ranked lower. One of the reasons is that green hydrogen projects are underdeveloped and are therefore not cost-efficient. Competing with other technologies is, therefore, a lost race. Furthermore, 300 euro per tonne CO_2 compensation is not enough to cover the unprofitable top of green hydrogen projects. Therefore, the business case is not entirely closed.

Financial support for infrastructure development

The argumentation in the assessment underlines once again the importance of the hydrogen infrastructure. In multiple interviews (Lydia Boktor, personal communication, June 29, 2021, Anne Geurts, personal communication, June 23, 2021) was mentioned that the construction of the hydrogen infrastructure is the biggest project after the Delta Works and the construction of the national natural gas grid (Gasunie could do investments upfront). The government has to make this significant investment in order to remain a frontrunner in the future. The analysis shows that without infrastructure, it is impossible to have a successful transition to hydrogen.

The policy instrument to financially support the realization of the infrastructure scores good on the lack of a hydrogen market (logical) and the destabilizing pressure of experience with hydrogen. This policy instrument scored well because the economic instruments are not included in this research. Otherwise, this instrument would have had a lower ranking. The example of the hydrogen symbiosis in the Delta region showed that a (sub) hydrogen market could be established real quickly when all three parts are there (generation, distribution, utilization). Knowing that many companies already use hydrogen at this moment could foster the hydrogen transition.

Furthermore, it is the only policy instrument that scores a **+** on lack of coordination. However, this policy instrument will not directly enforce the government to solve the problems around coordination. However, indirectly the government has to come up with regulations so that the infrastructure can be realized.

Carbon Contracts for Difference

The third is the CCfD, which is better than the higher CO_2 price for one reason only: the government's financial contribution. This higher CO_2 price will not affect the competitive position of companies in the Netherlands. However, the strike price allows the heavy industry sector to implement more expensive CO_2-reducing technologies that are not profitable in a situation with a low CO_2 price.

Compared with a higher CO_2 price, companies can start investing in hydrogen (instead of investing in cheaper CO_2 reducing technologies) and getting 100% sustainable when is the strike price is high enough to pass other reducing technologies. A higher CO_2 price lets companies wait with investing until the national CO_2 price or EU-ETS price rises and the business case is no longer viable. Meanwhile, the industry is paying for the CO_2 emission rights while they also could have invested that money in getting sustainable on beforehand.

When the strike price is not high enough, the companies still experience an incentive to reduce their CO_2 emission. When the strike price is, for example, 70 euros per tonne CO_2, it is interesting for companies to deploy blue hydrogen, but green hydrogen is still not viable.

As already explained, when the demand rises, the other components in the hydrogen chain will be more interesting also to start investing.

Subsidy for demand

Next is the subsidy for demand, which scores good points on the lack of a hydrogen market and hydrogen experience. The current demand for hydrogen (grey) can transfer to green hydrogen, but enough supply and sufficient infrastructure are necessary. Unfortunately, the big innovation problem is on the supply side, and also the infrastructure costs a substantial amount of money. The only thing that is increasing is the demand for green hydrogen will do is giving the companies who want to invest in the supply and distribution the certainty that there is a demand for green hydrogen. Compared with the CCfD and higher CO_2 price, this policy instrument only stimulates hydrogen for the demand side. The other two policy instruments affect the demand side but leave room for other hydrogen reduction technologies.

Higher CO_2 price

At last, the national CO_2 price for the industry. What stands out is that this is the only policy instrument that costs nothing for the Dutch government. This is, therefore, the preferred policy instrument from an economic point of view. However, the economic criteria are not relevant in this study. Although a higher CO_2 price is needed to enforce the companies to innovate on emissions, this policy instrument will not substantially contribute to the hydrogen transition. One of the reasons is that rising CO_2 prices will ensure that the lowest cost abatement technologies become ‘in the money’ first. For hydrogen technologies, that starts with blue hydrogen (will become in the money first), which is today not economically viable yet (Lydia Boktor, personal communication, June 29, 2021). The CO_2 price is set at 75 euros and steadily increases by 5 euros per year. This is enough to stimulate blue hydrogen from the beginning. When the price is higher, for example, 100 euros, it will directly make green hydrogen profitable. Lower CO_2 prices will not force the heavy industry to make the transition to blue or green hydrogen.

5.1.1 Reflection on the results

5.1.1.1 Expectations

The results that emerge from the analytical framework align with the researcher's expectations and what the experts have said. So there are no odd results. Several times, it has been concluded that a hydrogen infrastructure is crucial and that the learning process (price improvements) is essential. Therefore, it aligns with expectations that funding will score best for the hydrogen supply chain's parts (supply and distribution).

The lack of coordination is a stabilizing pressure that is often mentioned in the literature and interviews. From the analysis, it became clear that the policy instruments do not influence the lack of coordination pressure except the subsidy for infrastructure, but that is an indirect relation. It is logical that the selected policy instruments have no real contribution to the lack of coordination because none of the policy instruments was about regulations and standards.

5.1.1.2 Possible bias

During the scoring process, information is used from the literature and interviews, which could be biased. Scoring in an MCA is very sensitive to the interpretation of information and perception of the included pressures by the researcher. Each researcher can interpret the identified pressures differently and look at them from a different angle. Both the possibility of bias of the information and the researcher's bias ensures that if the analytical framework is filled in by someone else, different results may be obtained. Other researchers have to consider that there is a chance that if the research is reproduced, different results will be obtained because of bias of information from literature and interviews.

5.1.1.3 Combination of instruments

From the analysis in chapter 4, it can be concluded that multiple policy instruments are also needed to foster the transition. Although the multi-criteria analysis focuses on ranking from top to bottom, the policy mix literature discusses the advantages of deploying multiple policy instruments. Several combinations are possible, but what has become clear is that a subsidy also needs a CO_2 reducing policy instrument. Furthermore, without a hydrogen infrastructure, it is not feasible to initiate a hydrogen transition.

In this study, the subsidy for supply is the number one in the ranking, but it is also essential to ensure that the CO_2 price increases. This can be done with either an increase in the national CO_2 tax or through CCfD. The CO_2 tax is charged to the CO_2 emitters on the demand side. A significant advantage of CCfD is that companies have certainty of a specific fixed CO_2 price and can therefore start investing. The CCfD shall therefore obtain better results.

Another way to give companies clarity about the future of hydrogen is the financing for the hydrogen infrastructure, which came second in the ranking. Developing this infrastructure is extremely important for the transition, and government funding is the only option. If the government indicates that they will invest in this, it is also a strong signal to the market (the government indirectly says hydrogen is a long-term policy). The financial contribution from the government could decrease to a certain extent because if there is more supply and demand, the contracts can provide enough certainty for Gasunie to build a business case. The problem here is that Gasunie can only lay the pipes once and cannot increase the capacity of the pipes each time, so this must be done right the first time, and financing is therefore required.

When both the infrastructure and the supply are stimulated and growing, the subsidy for supply and infrastructure could slightly shift to stimulate demand. Subsidy for supply can kick-start the transition, but when the developments are moving, subsidies are not (entirely) necessary anymore, and the focus should go to stimulating the demand. A CO_2 restriction push companies towards sustainable technologies, but this is not necessarily hydrogen.

5.1.1.4 Results of this thesis related to other studies

It would be of added value to compare the results of this analytical framework with the results conducted from other frameworks. Although a multi-criteria analysis is a well-known method to compare policy instruments and rank them (Battles & Zoppoli, 2020 ; Konidari & Mavrakis, 2007), no papers are found that rank policy instruments for the hydrogen transition. Furthermore, the used research design, based on the theory of Kern (2012), has not yet been used in other studies. In the paper of Kern (2012) there is no trade-off between multiple instruments as just one policy instrument is assessed. Therefore this paper cannot be used for comparison.

5.2 Reflection of the used research design

Now that the results are discussed, it is time to critically look at the research design used to get these results. Step by step, the research design is reflected. By using this research design, the research has been steered in a particular direction.

5.2.1 MLP

First, the transition literature is discussed in which general transitions as transitions towards sustainability can be analyzed. The transition literature has two methods to conceptualize socio-technical transitions and look to obstacles for the transition.

In this study, the MLP was used instead of the TIS. The MLP is a framework that enables the researcher to analyze the socio-technical transition process (Geels & Kemp, 2000). Because this framework has been used, the focus of this study is on breaking the incumbent regime and the present stabilizing and destabilizing pressures. If the TIS had been used in this study, the emphasis would have been on developments at the niche level. Although developments at the niche level are of great importance in the hydrogen transition, the TIS does not address the pressures at the regime and landscape level. If the TIS approach had been chosen, this study would have found information about further stimulating the niches (done via critical processes of the niche level) but not about breaking into the regime. The pressures found at the landscape and regime level had received less attention. This meant that the research had provided a less complete overview of the entire transition.

With the application of Florian Kern (2012) to assess ex-ante policy instruments whether they stimulate the transition, the MLP has been deployed differently than usual. This research adds that the MLP is used to identify the stabilizing and destabilizing pressures (Geels, 2012).

This study focuses on the regime and niche level, not on the landscape level because actors cannot directly influence the landscape level. The landscape pressures identified in the analysis of section 3.2.1 could have played a more prominent role in the analysis because these pressures can influence the effectiveness of the policy instruments (but not the other way around). At the niche level, general key processes, identified by Kern (2012), have been selected for the analysis. Case-specific information may have been lost by taking all niche pressures together and assessing them via these key processes. A deeper analysis of the niche level would be of added value for this research.

5.2.2 MCA

The stabilizing and destabilizing pressures from the case study and policy instruments of the economic literature are merged into a analytical framework. In order to assess the policy instruments from the economic literature on the stabilizing pressures, a multi-criteria analysis is conducted. The MCA is a suitable method for assessing policy instruments against specific criteria. However, an MCA is also restrictive because a score per criteria defines the MCA. Information that falls just outside will not be mentioned. For example, a policy instrument that only scores well on the pressure during certain circumstances. This cannot be read directly from the performance matrix. Also, a score from – to +++ is not quantitative. It says nothing about e.g. how much a higher CO_2 tax contributes to the learning process (the price/improvement). The actual effect cannot be deduced from this. Another more in-depth analysis is needed. However, that was not necessary for this study as it had to compare policy instruments which can be done via the proposed five points scale.

Furthermore, it is inconvenient that an MCA is conducted at a specific moment in time while the transition is dynamic. It must continuously be monitored whether the instrument still works and whether the scores are still correct. For example, the policy instrument, a higher CO_2 price, is only effective if the higher CO_2 price is higher than the EU ETS price. If the "higher" CO_2 price is the same as the EU ETS price, the effect is no longer present. That means that the results of this research hold for this moment, but the analysis has to be adapted when the socio-technical system has changed.

The focus of this study could have been less on specifically assessing the policy instruments, which would result in a broader analysis of specific policy instruments as it may look beyond the selected pressures. This makes it possible to see how the instrument behaves within the context instead of how a policy instrument scores on specific criteria. The disadvantage of this approach is that the scoping would automatically become more narrow and policy instrument-specific, making it more challenging to compare policy instruments. Such an approach would be better if just one policy instrument has to be analyzed. For example, if the government already had a policy instrument in mind and wanted to know whether it would be suitable to stimulate the transition. With fewer policy instruments in the analysis, it is automatically possible to go more in-depth.

It should be mentioned that the research with multiple policy instruments could also be more in-depth when there was more time. In this research, the time was limited, and therefore this was not possible.

The outcome of the multi-criteria analysis itself gives no policy advice. The MCA is more about the information hidden behind this analysis which can be of value. Moreover, the result is suggestive and can be a disguised representation of reality. This is partly because the policy instruments have only been assessed on a limited number of aspects, and also that the personal opinion of the researcher can influence the score.

5.2.2.1 Scale

The scale chosen in this study is a five-point scale from – to +++. This scale enables the researcher to indicate how well a policy instrument contributes to the identified pressures. For example, a seven-point scale is often used in multi-criteria analyses and gives the researcher more room to rank the policy instruments in detail. A disadvantage of using a 7 point or even bigger scale is that a more explicit argument must be made about why a specific score has been assigned. Using a five-point scale is sufficient. This scale provides sufficient space to differentiate the policy instruments from each other.

5.2.2.2 Equal Weighting method

In this research, the equal weighting method was selected. A disadvantage of this method is that any crucial pressures are not given priority. For example, essential pressures could be given a higher score using a weighting method like the best-worst method. The weights could cause a different result. To be able to work with weights, the scores must be standardized. For this analysis, assigning scores to the criteria is not necessary, as the policy instruments focus on a specific pressure. Because there is a policy mix needed, assigning weights would be redundant.

5.2.2.3 Selecting pressures

As mentioned above, the researcher made a selection of pressures for the analysis. It should be mentioned that in this research, government requirements have not been taken into account. This research focused on the transition needs (the current stabilizing and destabilizing pressures present in the heavy industry sector). The possible requirements from the government have not been taken into account. However, rules and requirements are permanently attached to what the government can do, and the yearly budget is not infinite.

Because criteria that are important to the government (efficiency and effectiveness) are not included, the outcome gives a distorted picture for the government. Including these criteria in the analysis would make an investigation more complete. Currently, this research shows in its purest form what it takes to help the transition. This information can be valuable because now, no policy instruments are excluded because they do not come through the selection of the government.

5.2.2.4 Selecting policy instruments

In section 2.2.5, it was discussed that policy instruments are often used together to achieve a goal. It would be interesting to look at the score of linked policy instruments, also known as a policy mix. For example, the subsidy for demand and a higher CO_2 price. Due to time constraints, this was not included in this study, but it can certainly be valuable for further research.

The selection that has been made in this study means that many policy instruments are not included. Regulation policy instruments are not included in this thesis. However, these could be of value to enforce the transition, for example, with a law about a percentage of the produced products, have to be CO_2 neutral. Furthermore, in the assessment comes forward that the Dutch government has to constitute standards, rules, and laws to facilitate the transition.

During the interview with Anne Geurts, the importance of initiating hydrogen in the refineries is emphasized. The refinery can cause an increasing demand for green hydrogen because large amounts of hydrogen are already used in this sector. In this interview, Anne mentioned that via RED 2, an economic instrument that stimulates the use of sustainable fuels in the transport sector, the use of green hydrogen in refineries could be subsidized. This policy instrument is not included in this thesis. However, it is recommended to include this in future research (Anne Geurts, personal communication, June 23, 2021).

This ensures that the research cannot say emphatically that these are the best policy instruments. However, it can be concluded that this is the best policy instrument of this set.

Finally, it should be mentioned that many policy instruments are discussed and determined at the European level (the majority of energy legislation comes from the EU (Lydia Boktor, personal communication, June 29, 2021).

5.2.2.5 Scoping

In this study, several demarcations have been made in order to keep the study feasible within time. For example, it has been decided not to discuss when blue or when green hydrogen is used, import of hydrogen has not been taken into account, and only the heavy industry sector in the Netherlands has been considered. During discussions with experts, it was stated that it could be of added value to look at other sectors to get the hydrogen transition started, for example, the mobility sector. Collaboration could lead to an acceleration of the transition.

The Netherlands is not the only country working on hydrogen. Germany and France are also working on it and are even further in the transition. Connecting with these countries can also help to kick-start the transition. For example, it is expected that an enormous demand for hydrogen will come from Germany because they know that their products will not be sufficient (Lydia Boktor, personal communication, June 29, 2021& Anne Geurts, personal communication, June 23, 2021). This can offer opportunities for the development of supply in the Netherlands. Other recommendations for future research are discussed in conclusion.

5.2.2.6 Subjectivity in the analysis

Input for the multi-criteria analysis, the policy instruments (x-axis) and pressures (y-axis), is based on literature research and discussions with experts, as can be read in chapter 3. The scoring is also based on literature research and discussions with experts. Ultimately, the researcher chooses which policy instruments and pressures will be included and decides which score will be assigned. Although the choices are substantiated, the choices are sensitive to subjectivity.

In the study, all information was processed as objectively as possible in the analysis. However, the researchers' interpretation may play a role in the considerations made. This applies to both the literature that has been used and the interviews, which can be interpreted differently.

As mentioned in the research design, the information used should also be tested for potential bias. Literature and reports can have a particular bias, for example, if an author is sponsored or adheres to a particular political ideology. The information from experts can also be subjective. The experts provide information from their point of view and often act from their interests. While these points of view are extremely important to map out the overall context, any potential bias must be kept in mind while interpreting the results of this study. It is essential to talk to diverse a group of experts as possible. Suppose the group of experts all represent a different interest. In that case, the researcher also has to be careful that the experts do not know each other and do not have influenced each other, for example, at a conference.

5.3 Scientific contribution

The scientific contribution of this research is in exploring the possibility of combining the transition literature with the economic literature and whether it is possible to create an analytical framework from both strands. This is discussed in the knowledge gap in section 1.3 and is further elaborated in the literature research in chapter 2.

Multi-level perspective

The MLP, described in the transition literature, is often used to analyze historical or future transitions. Although the analysis is also used to provide policy advice, it is not the strength of this framework. Kern (2012) has used the framework to assess ex-ante one policy instrument to see how a particular policy instrument contributes to a transition. Kern (2012) used commonly identified key processes from the MLP literature to assess a policy instrument and only analyzes one policy instrument per analysis. These key processes have been found essential in a transition. However, general key processes do not ensure that the assessed policy instruments contribute to the particular transition (the hydrogen transition in the heavy industry).

To be more specific about the hydrogen transition, this study attempted to use the most essential stabilizing and destabilizing pressures present in the hydrogen transition (Geels & Kemp, 2000) in an assessment process of policy instruments. These pressures are unique to the situation and give a good representation of the context of the system using these pressures.

Policy instruments

In order to be able to assess which policy instrument is suitable for accelerating the transition, not one but five policy instruments have been examined in this study. In doing so, this study responds to the recommendation of Florian Kern's paper (2012) that stresses that future research should analyze multiple policy instruments instead of one. The literature about policy instruments stresses that using multiple policy instruments can be helpful when technical change is required (Reichardt et al., 2016).

This is especially important in sustainable transitions because it is a process that can take many years. Different policy instruments will therefore be needed for each phase to complete the transition.

The economic literature has been added to this study to discuss policy instruments in more detail and their associated effects, enabling the researcher to compare multiple policy instruments. Usually, the economic literature mainly focuses on the effectiveness and efficiency of a policy instrument, which means that the costs and benefits are examined (Haas et al., 2011; Menanteau et al., 2003; Perrels, 2001). This economic way of looking at situations means that the essence of the problem, speeding up the transition, can be lost sight of.

Analytical framework

This study contributes to the science to merge both strands of literature into a analytical framework for assessing policy instruments that have not been done before. The approach from Kern (2012) forms the basis of this analytical framework. This is expanded with the MCA methodology (rank policy instruments (x-axis) by pressures (y-axis). That is something new and shows the scientific community that it is possible to do so.

Added-value of the multi-level perspective

Following, the question comes up whether looking through the MLP lens is worth it because an extra analysis also takes extra time. What would the outcome be if the MLP were not involved in the investigation?

Not using the MLP for identifying stabilizing and destabilizing pressures

First of all, the stabilizing and destabilizing pressures will have to be identified differently. This can be done, for example, by interviews within the sector. However, this creates a possible bias, and actors will argue for their interests, which is for commercial parties, often money. Of course, other problems will also be discussed, such as the coordination problem or the lack of infrastructure.

Although the results are not surprising, the effort is not for nothing. Applying the MLP in a case study takes extra time, but it pays to invest this time because the stabilizing and destabilizing pressures still have to be identified. These pressures show the problems and possible solutions in the transition.

This study used expert interviews to gather additional practical knowledge about the stabilizing and destabilizing effects identified by the MLP analysis using literature. The case study outcome could be an excellent topic to talk about, so that more targeted discussion can be started with the sector. Instead of going into what they need, the discussion can be about the cause of the problems.

Using key processes of Kern (2012) or economic criteria in the assessment instead of pressures

When the key processes of Kern (2012) were included in the assessment instead of the identified pressures, the best-ranked policy instruments would not necessarily be helpful for the transition towards hydrogen. The key processes are namely defined for general transitions. That lowers the credibility of the policy advice.

When efficiency and effectiveness (economic criteria) were included in the assessment, the policy instruments that cost much money would be ranked lower. Then, the importance of the transition is no longer paramount, and the assessment says nothing about the effectiveness of the transition. This has changed with this analytical framework. When it is unclear which policy instrument is needed to stimulate the transition, an answer can be gathered using this analytical framework. At the moment, it is insightful which policy instruments could foster the transition, the government can determine ex-post which policy instrument to deploy or not.

These economic criteria can easily be added to the analytical framework. It is expected that the government will do this before deciding which policy instruments to deploy. However, when the government needs advice on which policy instruments can stimulate the transition, the economic criteria are not of added value.

Once the problems have been identified, it is difficult to assess the overall effect of a policy instrument. The economic literature can reasonably predict the effect on a specific aspect, such as subsidy on demand. However, the economic criteria do not include the context of the problem in the assessment. It is therefore difficult to determine whether the policy instrument contributes to the transition or not.

Using the MLP has the advantage that it can (1) identify stabilizing and destabilizing pressures and (2) see the effect of policy instruments in a broader context. This context is essential for stimulating transitions because, as described in Chapter 4, multiple policy instruments are often needed. It is, therefore, of added value to apply the MLP.

Added-value of the economic literature

Now that the contribution of the MLP is explained, the added value of the economic literature will be discussed. Florian Kern (2012) has shown that the MLP can assess ex-ante a policy instrument on how it influences a transition. Although Kern (2012) assessed only one policy instrument, it is possible to assess and rank multiple policy instruments.

The economic literature has detailed information about policy instruments' effects, missing in the transition literature. Including the economic literature in this study complement the transition literature and enables the research to gives detailed information about which policy instruments should be deployed after the stabilizing and destabilizing pressures are exposed. Including only the transition literature in the analysis will not lead to detailed advice about policy instruments. It is, therefore, of added value to include the economic literature in the research.

Conclusion

Using this analytical framework would also be interesting for other transitions towards sustainability or hydrogen transitions in other contexts (e.g. another sector of another country). Germany, for instance, knows that their hydrogen production will not be sufficient and has therefore also a focus on import (potentially via the Port of Rotterdam)(Anne Geurts, personal communication, June 23, 2021). Because of this, Germany has other priorities (goal and scope) and other stabilizing and destabilizing pressures. This analytical framework enables the researcher to identify these pressures and indicate suitable policy instruments via a specific socio-technical system case study. Via the analytical framework, these policy instruments can be scored and ranked.

In conclusion, this research shows that combining both strands of literature and adding value is possible. The extra time and effort invested in the case study provides so much information about the particular transition, which can be used in the assessment for further monitoring the transition, and is useful when entering the discussion with actors in the socio-technical system about the problems in the transition.

At the same time, this research contributes to knowledge about the hydrogen transition to green hydrogen because the analytical framework is applied to a case study of the heavy industry sector in the Netherlands. The analytical framework described in this research can also be helpful for other transitions to apply and find suitable policy instruments.

5.4 Social contribution

At the moment, the transition to hydrogen needs a push in the right direction. Although it was overall known what the problems for the general hydrogen transition are (literature review in section 3.1), it is difficult to determine the actual destabilizing pressures and stabilizing pressures in the transition to green hydrogen in heavy industry. Besides the fact that these destabilizing pressures and stabilizing pressures are not transparent, the government also does not know what policy instruments should be used to accelerate the transition. These two problems are mentioned in the problem statement. Both are resolved in this study.

First of all, this study maps the stabilizing and destabilizing pressures in an extensive case study based on the MLP, using literature and interviews with experts. As already mentioned, research has been done on the pressures present in the transition to hydrogen in general. Furthermore, multiple reports write about making the heavy industry sustainable. However, there is no report describing the pressures for the hydrogen transition in heavy industry. These pressures have been mapped out with an extensive case study.

These pressures were used to determine which policy instruments would work best to stimulate the transition. It was decided not to assess with criteria from the economic literature because these do not consider the context in which the instrument functions. By making proper use of the pressures, the government can deploy a policy instrument with more precision. It can also monitor when the transition enters a different phase and whether a policy instrument is still needed or is still working. Using the policy instruments recommended in this study, the hydrogen transition in the heavy industry can take off. Once the hydrogen transition has been deployed in heavy industry, the transition can also play an essential role in other sectors.

Another contribution is that other governments can apply this analytical framework to investigate which policy instruments they must deploy. By first identifying the present pressures, the analysis of policy instruments can be adapted to the socio-technical system and transition.

To conclude, this research contributes in four ways:

1. The proposed analytical framework could be used by any government to assess a set of policy instruments to determine whether they stimulate a particular transition in a particular socio-technical system.

2. Identifying what the destabilizing pressures and stabilizing pressures are in the transition towards green hydrogen in the heavy industry.

3. It advises the Dutch government on which policy instruments should be deployed to stimulate the hydrogen transition in heavy industry.

4. An approach to talk about the destabilizing pressures and stabilizing pressures in interviews with experts, so talking about the problems instead of only discussing solutions.

Chapter 6 Conclusion and recommendations

This final chapter provides an overview of the results of this research. For each research question, the conclusions will be presented. Finally, recommendations for future research will be made based on the conclusions of this study.

This research formulates an answer to the following main research question:

Main research question: Which policy instruments should the Dutch government implement to accelerate the deployment of green hydrogen in the heavy industry by 2050?

In order to be able to answer this main research question, the sub-questions are first discussed and answered.

6.1 Formulating an answer to the research questions

First, a conclusion to the sub-questions is presented in this section.

Sub-question 1: How can an analytical framework be made of the transition literature and economic literature to assess policy instruments' performance?

Sub-question is answered in chapter 2. The literature study conducted in chapter 2 outlines the value of the two strands of literature combined in the research design. First, the transition literature is discussed, and it emerges that the MLP is a practical approach to analyze a future transition. The MLP focuses on stabilizing and destabilizing pressures that can stimulate or hinder a transition. The literature study showed that the MLP framework is also used for another purpose: to assess whether a policy instrument can stimulate a transition process or not by ranking them on key processes crucial in transition processes. In this research, both applications of the MLP framework are combined.

The analysis of the heavy industry system identifies stabilizing and destabilizing pressures that hold back or stimulate the hydrogen transition. These are used to assess policy instruments. The economic literature is included in this study to know more about how the policy instruments behave and their effects.

Eventually, both are merged into a performance matrix based on the multi-criteria analysis methodology. The stabilizing and destabilizing pressures stand on the y-axis, and the policy instruments stand on the x-axis. This analytical framework consists of the essential pressures identified with the MLP analysis of the transition. Furthermore, the policy instruments that are found suitable in the analysis are also enclosed. The analytical framework is visualized in Figure 28.

Table 13: Analytical framework with policy instruments and stabilizing and destabilizing pressures

Pressures \ Policy instruments	Higher CO_2 price	Carbon Contracts for Difference (CCfd)	Subsidy for Supply	Subsidy for demand	Financial support for infrastructure development
Learning process					
Support from powerful groups					
Lack of coordination					
Lack of business case					
Lack of hydrogen market					
Experience with hydrogen					
Total					

Sub-question 2: Which policy instruments are there to stimulate the hydrogen transition in the heavy industry in the Netherlands?

Now an analtyical framework is proposed in sub-question 1. The policy instruments on the x-axis need to be filled in. The economic literature is consulted to answer this sub-question. The literature reveals that the policy instruments can be classified into three classes: regulations, economic means, and information, also called the stick, carrot, and the sermon. In terms of regulations, standards, laws, and rules in the form of prices and quantities. Economic means can be distinguished into price-based instruments and quantity-based instruments. Price-based instruments include subsidies, feed-in tariffs, setting up a fixed price, tax credits, and taxes. With quantity-based instruments, one can think of bidding schemes, cap and trade, and tradable certificates. Furthermore, there are hybrid instruments (both price-based and quantity-based), like the EU-ETS system.
From the case study, with the help of the MLP analysis of the regime, the essential policies are briefly discussed. The SDE++ subsidy scheme, DEI+ scheme, CO_2 tax for the heavy industry, and the EU-ETS system are active within the heavy industry sector.

Based on the present policy instruments, the rapport of the SER, and conversations with experts, a selection of policy instruments for this research is made. The selection consists of (1) higher national CO_2 price for the industry sector (2) Carbon contracts for Difference (3) a subsidy of the supply (adaption of the SDE++) (4) subsidy for demand, and (5) a financial contribution for the construction of the infrastructure.

Sub-question 3: What are the characteristics of the socio-technical system, the heavy industry sector in the Netherlands (niche, regime, and landscape level), and what kind of destabilizing pressures and stabilizing pressures are there?

The answer to sub-question 2 resulted in the x-axis of the analytical framework. Sub-question 3 will take care of the y-axis of the analytical framework.

The landscape of the heavy industry sector is characterized by the use of natural gas, which arises from the natural gas source in Groningen, and smaller fields throughout the Netherlands. The consequence of this was that a distribution network for natural gas was created. An entire industry has been built around natural gas. The port of Rotterdam has a crucial role in the energy distribution of the Netherlands but also for Northwestern Europe. The current empty gas fields can be used for the capture and storage of CO_2. Furthermore, the Netherlands has a substantial offshore wind energy potential. The landscape level has been analyzed, but the pressures are not included in the assessment because actors cannot directly influence the landscape level.

The iron & steel, (petro)chemical, cement, pulp and paper, and aluminum industries are all categorized as heavy industries. Of them, the iron & steel and chemical industries emit together 80% of the CO_2. The chemical industry mainly uses a lot of grey hydrogen in its processes (heating and feedstock). These industries are important for employment opportunities in the Netherlands.

The stabilizing and destabilizing pressures from the niche level have not been identified. Instead, the key processes identified by Kern (2012) are used. This is because the niche level consists of hundreds of innovation projects (e.g. Djewels), to combine the pressures, it was decided to do this with key processes.

The most important pressures are:

Stabilizing pressures

- Lack of a business case
- Lack of a hydrogen market
- Lack of coordination

Destabilizing pressures

- Experience with hydrogen
- Learning process
- Involvement of powerful groups

Sub-question 4: What is the ranking of these instruments in stimulating the hydrogen transition in the Netherlands by overcoming the identified stabilizing pressures and supporting the destabilizing pressures?

Both answers, on sub-question 3 and 4, filled in the analytical framework that is proposed when answering sub-question 1. In chapter 4, an answer is formulated to sub-question 4.

The final ranking is as follows:

1. Subsidy for supply
2. Financial support for infrastructure development
3. Carbon Contracts for Difference
4. Subsidy for demand
5. Higher CO_2 price

The subsidy for supply scored the best. It scored well in the learning process and the lack of a business case. On all other pressures, it scored at minimum an + or ++. Second is the financial support for infrastructure development. This policy instrument gets a high score at lack of a hydrogen market and experience with hydrogen. The third is the CCfD, which scores a ++ on the learning process, business case, lack of hydrogen market, and experience with hydrogen. Fourth comes the subsidy for demand, scoring high on the experience with hydrogen and lack of a hydrogen market. However, in the beginning, phases this subsidy scheme is less effective. The higher CO_2 price is scored last, which scored minimal on the learning process, lack of business case and lack of hydrogen market and ++ on experience with hydrogen.

Main research question: Which policy instruments should the Dutch government implement to accelerate the deployment of green hydrogen in the heavy industry by 2050?

This study was conceived to formulate policy advice for the Dutch government about which policy instruments should be deployed to accelerate de deployment of green hydrogen by 2050 in the heavy industry sector. This research will advise the Dutch government to deploy multiple policies to stimulate the transition. The literature emphasizes multiple times that a combination of policy instruments gives the best results.

First, it is advisable to deploy the adapted SDE++ scheme. This adapted scheme is convenient for green and blue hydrogen projects and stimulates the transition as it empowers the learning process and encloses the business case. At the same time, it is recommended to fund the hydrogen infrastructure to develop it as soon as possible. The infrastructure is, literally and figuratively, the core of the hydrogen economy. Without it is impossible even to start the transition. Applying this subsidy scheme ensures that the hydrogen market and experience with hydrogen are stimulated. These two policy instruments complement each other.

The last policy instrument is setting applying a CCfD. This will create an immediate incentive for the industry to think about CO_2 reduction technologies. It puts extra tension on the need to get sustainable. Setting a strike price in the form of a Carbon Contract of Difference is also possible. However, a CCfD will not necessarily push the industry towards hydrogen. An extra regulation, for example, 10% of all steel has to be produced sustainably or that 20% of energy consumption should be renewable hydrogen, could push the industry towards hydrogen.

Another option is to stimulate the demand of hydrogen. It is advised first to kick-start the transition with the above three policy instruments. When the supply is growing and profitable, a subsidy for demand should be deployed and the subsidy for supply should be phased out.

In addition, it should be noted that none of the proposed policy instruments (sub-question 2) solves the coordination problem. However, this problem is also essential and will have to be addressed by the government.

To summarize, an ideal policy mix would be:

- Subsidy for supply
- Financial support for infrastructure development
- CCfD

6.2 Recommendations for Sia Partners

Recommendations for Sia Partners are based upon the answers to research questions 3 and 5. The case study conducted in chapter 3 gives rise to approach companies in this system (heavy industry system) and see together with these companies whether solutions can be formulated to their problems. Sia Partners can put the effort in lobbying at the government, but what is more effective and fits better to the expertise of this consultancy firm is to approach the Dutch government with this study and explains that they have an analytical framework that can help the Dutch government in stimulating this transition. The case study gives know-how about what obstacles need to be removed. This alone is already valuable information for the Dutch government. The knowledge is helpful for the government as a topic of conversation or reason for follow-up research. The research on policy instruments gives them insights into what kind of policy instruments can remove these obstacles.

As mentioned, this analytical framework can be applied to all kinds of sustainable transitions in all kinds of contexts (for example, other countries, as Sia Partners, is active worldwide). The MLP enables the researcher to adapt the pressures to the context.

As has become clear, many strings have to be tied together. The government is in the best position to do this best but will need advice on which strings should be connected.

6.3 Recommendations for future research

During this study, several points came up that may serve in future research:

1. Including economic criteria could make this analytical framework more valuable for the government.

2. Including more policy instruments would give a complete overview of the policy instruments that could stimulate the hydrogen transition. As mentioned in the discussion, many policy instruments, for example, regulations and the RED 2 policy scheme, are not included in this research but could positively impact the transition.

3. Including import as a feasible alternative to stimulate the hydrogen in the transition. The import of hydrogen is not included in this research. It is recommended to study the effects of import in future research.

3. Conducting more research on policy mixes, what are the effects of combining policy instruments. The effects of combining multiple policy instruments are not identified in this study.

4. Deeping out the case study so that more specific information about pressures at the regime and especially the niche level can be included in the assessment.

5. Applying this analytical framework to another case (another transition or context) would be of value. This analytical framework is now carried out, which does not guarantee that it is valuable in other cases. It would be interesting to apply this analytical framework to the hydrogen transition in e.g., Germany or France.

Bibliography

ABN AMRO. (2021). *Alternatief Voor Fossiele Brandstoffen in 2030 Komt Dichterbij*.

Alkemade, F., Hekkert, M. P., & Negro, S. O. (2011). Transition policy and innovation policy: Friends or foes? *Environmental Innovation and Societal Transitions*, *1*(1), 125–129. https://doi.org/10.1016/j.eist.2011.04.009

Battles, S., & Zoppoli, P. (2020). *Policy options to improve the effectiveness of the EU emissions trading system : A multi-criteria analysis*. *57*(2013), 477–490. https://doi.org/10.1016/j.enpol.2013.02.015

Beckman, K. (2020). *Waterstof in Nederland: overheid stelt te weinig geld beschikbaar, waardoor er kansen verloren gaan*. https://www.change.inc/energie/waterstof-nederland-34447

Beunderman, M. (2021, May 4). *Emissieprijs voor een ton CO_2 bereikt record van 50 euro*. https://www.nrc.nl/nieuws/2021/05/04/emissieprijs-voor-een-ton-CO_2-bereikt-record-van-50-euro-a4042344

Bleischwitz, R., & Bader, N. (2010a). *Policies for the transition towards a hydrogen economy : The EU case*. *38*, 5388–5398. https://doi.org/10.1016/j.enpol.2009.03.041

Bleischwitz, R., & Bader, N. (2010b). Policies for the transition towards a hydrogen economy: The EU case. *Energy Policy*, *38*(10), 5388–5398. https://doi.org/10.1016/j.enpol.2009.03.041

Borrás, S., & Edquist, C. (2013). The choice of innovation policy instruments. *Technological Forecasting and Social Change*, *80*(8), 1513–1522. https://doi.org/10.1016/j.techfore.2013.03.002

Brown, M. A., Chandler, J., Lapsa, M. V., & Sovacool, B. K. (2011). Carbon lock-in: Barriers to deploying climate change mitigation technologies. In *Barriers to Climate Change Mitigation Technologies and Energy Efficiency* (Issue March 2019).

CBS. (2018). *Het industriële landschap van Nederland*. 1–15.

CBS. (2021, July 16). *Bevolkingsteller*. https://www.cbs.nl/nl-nl/visualisaties/dashboard-bevolking/bevolkingsteller

Cefic. (2019). *Cefic Vision on Hydrogen*.

Collins, L. (2021, January 21). *Nel to slash cost of electrolysers by 75%, with green hydrogen at same price as fossil H2 by 2025*. https://www.rechargenews.com/transition/nel-to-slash-cost-of-electrolysers-by-75-with-green-hydrogen-at-same-price-as-fossil-h2-by-2025/2-1-949219

Compendium voor de Leefomgeving. (2021, March 31). *Energieverbruik per sector, 1990-2019 | Compendium voor de Leefomgeving*. https://www.clo.nl/indicatoren/nl0052-energieverbruik-per-sector

de Laat, P. (2020). *Overview of Hydrogen Projects in the Netherlands*.

de Laat, P. (2021). *Overview of Hydrogen Projects in the Netherlands - TKI Nieuw Gas*. *May*, 89. https://www.topsectorenergie.nl/sites/default/files/uploads/TKI Gas/publicaties/Overview Hydrogen projects in the Netherlands versie 1mei2020.pdf

Deloitte. (2021). *SDE++, new sustainable possibilities in 2020*. https://www2.deloitte.com/nl/nl/pages/energy-resources-industrials/articles/sde-new-possibilities-in-2020.html

Demirbas, A. (2017). Future hydrogen economy and policy. In *Energy Sources, Part B: Economics, Planning and Policy* (Vol. 12, Issue 2, pp. 172–181). https://doi.org/10.1080/15567249.2014.950394

Department for Communities and Local Government UK. (2009). *Multi-criteria analysis : a manual*.

Dieter, H., & Cameron, H. (2014). *Carbon contracts and energy policy : An outline proposal*. *May*.

Dril, T. Van. (2015). *Doorbreek de lock-in van het energiebeleid voor de zware industrie*.

Duijnmayer, D. (2020, December 7). *Eerste gecombineerde tender wind en waterstof mogelijk binnen tien jaar*. https://energeia.nl/energeia-artikel/40090653/eerste-gecombineerde-tender-wind-en-waterstof-kan-binnen-tien-jaar-plaatsvinden

Duijnmayer, D. (2021, June 17). *Hoge ETS-prijs doet Kamer twijfelen aan nut van CO_2-bodemprijs voor stroomopwek*. https://energeia.nl/energeia-artikel/40093811/hoge-ets-prijs-doet-kamer-twijfelen-aan-nut-van-co-bodemprijs-voor-stroomopwek

Dunn, S. (2002). Hydrogen futures: Toward a sustainable energy system. *International Journal of Hydrogen Energy*, *27*(3), 235–264. https://doi.org/10.1016/S0360-3199(01)00131-8

Dutch Government. (2019). *Klimaatakkoord*.

Edelenbos, J., & Monnikhof, R. (2001). Hoofdstuk 7 : Interactieve beleidsvorming en de instituties van het lokale bestuur [Chapter 7: Interactive policy-making and the institutions of local administration]. *Lokale Interactieve Beleidsvorming*, 117–142.

Ember. (2021). *Carbon Price Viewer*. https://ember-climate.org/data/carbon-price-viewer/

ESB. (2021). Het beleid voor een CO_2-arme industrie in Nederland kan efficiënter. *Milieu*, *tot 2030*, 2–4. https://esb.nu/esb/20062603/het-beleid-voor-een-CO_2-arme-industrie-in-nederland-kan-efficienter

Europa Nu. (2019). *Nederland en Europa* . https://www.europa-nu.nl/id/vh72ma0flbwg/nederland_en_europa

Fankhauser, S., Hepburn, C. J., Park, J., & Angeles, L. (2010). *Combining Multiple Climate Policy Instruments : How Not To Do It*. *May 2014*. https://doi.org/10.1142/S2010007810000169

FME, & TNO. (2021). *Elektrolysers: Kansen voor de Nederlandse Maakindustrie*. 1–69. https://www.fme.nl/system/files/publicaties/2020-11/FME-TNO Rapport elektrolyser productie in NL-DEF_0.pdf

Gasunie. (2019). *Waterstof Vraag en Aanbod nu - 2030*. *november*.

Geels. (2002). Technological transitions as evolutionary reconfiguration processes: A multi-level perspective and a case-study. *Research Policy*, *31*(8–9), 1257–1274. https://doi.org/10.1016/S0048-7333(02)00062-8

Geels. (2004). From sectoral systems of innovation to socio-technical systems: Insights about dynamics and change from sociology and institutional theory. *Research Policy*, *33*(6–7), 897–920. https://doi.org/10.1016/j.respol.2004.01.015

Geels. (2005). Processes and patterns in transitions and system innovations: Refining the co-evolutionary multi-level perspective. *Technological Forecasting and Social Change*, *72*(6 SPEC. ISS.), 681–696. https://doi.org/10.1016/j.techfore.2004.08.014

Geels. (2006). Understanding Industrial Transformation. *Understanding Industrial Transformation*, *February 2006*. https://doi.org/10.1007/1-4020-4418-6

Geels. (2011a). The multi-level perspective on sustainability transitions: Responses to seven criticisms. *Environmental Innovation and Societal Transitions*, *1*(1), 24–40. https://doi.org/10.1016/j.eist.2011.02.002

Geels. (2012). A socio-technical analysis of low-carbon transitions: introducing the multi-level perspective into transport studies. *Journal of Transport Geography*, *24*, 471–482. https://doi.org/10.1016/j.jtrangeo.2012.01.021

Geels. (2018). Disruption and low-carbon system transformation: Progress and new challenges in socio-technical transitions research and the Multi-Level Perspective. *Energy Research and Social Science*, *37*(September 2017), 224–231. https://doi.org/10.1016/j.erss.2017.10.010

Geels, F. W. (2011b). The multi-level perspective on sustainability transitions: Responses to seven criticisms. In *Environmental Innovation and Societal Transitions*. https://doi.org/10.1016/j.eist.2011.02.002

Geels, & Kemp, R. (2000). “Transities vanuit sociotechnisch perspectief.” Report for the Dutch Ministry of Environment. *Universiteit Twente, and Maastricht: MERIT*, 63.

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

Gerres, T., & Linares, P. (2020). *Carbon Contracts for Differences : September*.

Gigler, J., Weeda, M., Hoogma, R., & Boer de, J. (2020). *Waterstof voor de energietransitie*. 145. https://www.topsectorenergie.nl/nieuws/werk-aan-de-winkel-voor-waterstof-voor-de-energietransitie

Goltsov, V. A., & Veziroglu, T. N. (2001). From hydrogen economy to hydrogen civilization. *International Journal of Hydrogen Energy*, *26*(9), 909–915. https://doi.org/10.1016/S0360-3199(01)00045-3

Green Deal. (2021). *Waterstof Symbiose in de Delta Regio*. https://www.greendeals.nl/green-deals/waterstof-symbiose-de-delta-regio

H-vision. (2021). *H-vision Rotterdam*. https://www.h-vision.nl/

H2Platform. (2020a, March). *Kostenaspecten van waterstof - H2Platform*. https://opwegmetwaterstof.nl/kostenaspecten-van-waterstof/

H2Platform. (2020b, September 17). *Aanpassingen in SDE++ regeling slecht nieuws voor groene waterstof*. https://opwegmetwaterstof.nl/aanpassingen-in-sde-regeling-slecht-nieuws-voor-groene-waterstof/

Haas, R., Resch, G., Panzer, C., Busch, S., Ragwitz, M., & Held, A. (2011). Efficiency and effectiveness of promotion systems for electricity generation from renewable energy sources: Lessons from EU countries. *Energy*, *36*(4), 2186–2193. https://doi.org/10.1016/j.energy.2010.06.028

Hajkowicz, S. (2007). A comparison of multiple criteria analysis and unaided approaches to environmental decision making. *Environmental Science and Policy*, *10*(3), 177–184. https://doi.org/10.1016/j.envsci.2006.09.003

Hayes, A. (2021, January 22). *Knowledge Economy*. https://www.investopedia.com/terms/k/knowledge-economy.asp

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

Hepburn, C. (2006). *Regulation by prices, quantities or both: A review of instrument choice*. *22*(2), 226–247. https://doi.org/10.1093/oxrep/grj014

Hisschemöller, M., Bode, R., & van de Kerkhof, M. (2006). What governs the transition to a sustainable hydrogen economy? Articulating the relationship between technologies and political institutions. *Energy Policy*, *34*(11), 1227–1235. https://doi.org/10.1016/j.enpol.2005.12.005

Hydrogen Council. (2017). How hydrogen empowers the energy transition. *Https://Hydrogencouncil.Com/Wp-Content/Uploads/2017/06/Hydrogen-Council-Vision-Document.Pdf.*, *Accessed September 17*, *2020*, 1–28.

Hylkema, W. (2020, July 7). *Regeringsleiders tekenen voor Europese CO_2-grenstaks per 2023*. https://energeia.nl/energeia-artikel/40089127/regeringsleiders-tekenen-voor-europese-co-grenstaks-per-2023

IEA. (2019). The Future of Hydrogen. *The Future of Hydrogen*, *June*. https://doi.org/10.1787/1e0514c4-en

Jacobsson, S., & Karltorp, K. (2013). Mechanisms blocking the dynamics of the European offshore wind energy innovation system - Challenges for policy intervention. *Energy Policy*, *63*(June 2010), 1182–1195. https://doi.org/10.1016/j.enpol.2013.08.077

Janssen, R. (2001). On the use of multi-criteria analysis in environmental impact assessment in the Netherlands. *Journal of Multi-Criteria Decision Analysis*, *10*(2), 101–109. https://doi.org/10.1002/mcda.293

Jongeneel, C. (2020, December). *Elektrolyse wacht op opschaling*. https://www.tudelft.nl/delft-integraal/articles/dec-2020-waterstof/elektrolyse-wacht-op-opschaling

Kamp, L. M., & Vanheule, L. F. I. (2015). Review of the small wind turbine sector in Kenya: Status and bottlenecks for growth. *Renewable and Sustainable Energy Reviews*, *49*, 470–480. https://doi.org/10.1016/j.rser.2015.04.082

Kern, F. (2012). Using the multi-level perspective on socio-technical transitions to assess innovation policy. *Technological Forecasting and Social Change*, *79*(2), 298–310. https://doi.org/10.1016/j.techfore.2011.07.004

Kiwa. (2021a). *De Waterstof Keten*. https://www.kiwa.com/nl/nl/themas/energietransitie-in-nederland/de-waterstof-keten/

Kiwa. (2021b). *Waterstof als Grondstof met tal van Industriële Toepassingen*. https://www.kiwa.com/nl/nl/themas/energietransitie-in-nederland/waterstof/industrie/

Koelemeijer, R., & Daniëls, B. (2020). *Actualisatie inzichten CO_2 heffing industrie*. *september*.

Konidari, P., & Mavrakis, D. (2007). A multi-criteria evaluation method for climate change mitigation policy instruments. *Energy Policy*, *35*(12), 6235–6257. https://doi.org/10.1016/j.enpol.2007.07.007

Koster, R., & Opheikens, T. (2021, May 9). *Miljardensubsidie voor CO_2-opslag onder Noordzee is rond | NOS*. https://nos.nl/artikel/2380052-miljardensubsidie-voor-CO_2-opslag-onder-noordzee-is-rond

Lensink, S., & Schoots, K. (2021). *Eindadvies basisbedragen SDE++ 2021*.

Lewis, M. (2020, October 2). *Why the need for green hydrogen points to higher carbon prices | Financial Times*. https://www.ft.com/content/ecdeabd5-e013-44e1-b885-0b7264923e29

Linkov, I., Varghese, A., Jamil, S., Seager, T. P., Kiker, G., & Bridges, T. (2006). Multi-Criteria Decision Analysis: A Framework for Structuring Remedial Decisions at Contaminated Sites. *Comparative Risk Assessment and Environmental Decision Making*, 15–54. https://doi.org/10.1007/1-4020-2243-3_2

Lovins, A. B., & Williams, B. D. (1999). *A Strategy for the Hydrogen Transition*. *April*, 7–9.

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

McDonald, O. (2021, March 4). *Milieuclubs en industrie vragen €2,5 mrd aan nieuw kabinet voor waterstof*. https://energeia.nl/fd-artikel/40091732/milieuclubs-en-industrie-vragen-2-5-mrd-aan-nieuw-kabinet-voor-waterstof

Mcdowall, W., & Malcolm, E. (2006). *Forecasts , scenarios , visions , backcasts and roadmaps to the hydrogen economy : A review of the hydrogen futures literature*. *34*, 1236–1250. https://doi.org/10.1016/j.enpol.2005.12.006

Menanteau, P., Finon, D., & Lamy, M. L. (2003). Prices versus quantities: Choosing policies for promoting the development of renewable energy. *Energy Policy*, *31*(8), 799–812. https://doi.org/10.1016/S0301-4215(02)00133-7

Middelweerd, H. (2018, August 18). *Waterstof uit zeewater? Onderzoekers zetten belangrijke stap*. https://www.change.inc/energie/waterstof-uit-zeewater-29737

Milieu Centraal. (2021). *Waterstof: welke kansen zijn er?* https://www.milieucentraal.nl/klimaat-en-aarde/energiebronnen/waterstof/

Millet, P., & Grigoriev, S. (2013). Water Electrolysis Technologies. In *Renewable Hydrogen Technologies* (pp. 19–41). Elsevier. https://doi.org/10.1016/B978-0-444-56352-1.00002-7

Ministerie van Economische Zaken en Klimaat. (2020). *Klimaatnota 2020*.

Ministry of Economic Affairs and Climate Policy. (2020). Aanbiedingsbrief Kabinetsvisie Waterstof. *Dgke / 20087869*, *387*, 1–20. https://www.rijksoverheid.nl/documenten/kamerstukken/2020/03/30/kamerbrief-over-kabinetsvisie-waterstof

Ministry of Economic Affairs and Climate Policy. (2021). *Antwoorden op Kamervragen over het bericht 'Gasunie vraagt om jaarlijkse bijdrage van €100 miljoen om draai te maken naar 'groen.'*

MKB Nederland. (2021, April 12). *Investeringen uit Groeifonds goed voor kenniseconomie*. https://mkb.nl/nieuws/investeringen-uit-groeifonds-goed-voor-kenniseconomie

Napp, T. A., Gambhir, A., Hills, T. P., Florin, N., & Fennell, P. S. (2014). A review of the technologies , economics and policy instruments for decarbonising energy-intensive manufacturing industries. *Renewable and Sustainable Energy Reviews*, *30*, 616–640. https://doi.org/10.1016/j.rser.2013.10.036

Nationaal Waterstof Programma. (2021). *Beleid Industrie & havens*. https://nationaalwaterstofprogramma.nl/cms/view/ce0b5fd2-f8b1-48d2-8b7f-f5c02d65e19b/beleid-industrie-havens

Natuur en Milieu. (2018). *Duurzaamheidskaders waterstofgebruik in de industrie*.

Nederland, M. (2021). *De Nederlandse Offshore-industrie*.

https://www.maritiemnederland.com/vakgebieden/offshore-2

Nederlandse Vereniging Duurzame Energie. (2019, March 18). *Klimaatakkoord kan ruim 70.000 banen creëren, blijkt uit ECN-onderzoek*. https://www.nvde.nl/nvdeblogs/klimaatakkoord-ruim-70-000-banen-creeren-blijkt-ecn-onderzoek/

Netbeheer Nederland. (2019). *Basisinformatie over*.

NLOG. (n.d.). *Groningen gasveld*. https://www.nlog.nl/groningen-gasveld

Nouryon, & Gasunie. (2019). *Eindrapportage MegaWatt Design Delfzijl*. *July*.

Oikonomou, V., & Jepma, C. J. (2008). A framework on interactions of climate and energy policy instruments. *Mitigation and Adaptation Strategies for Global Change*, *13*(2), 131–156. https://doi.org/10.1007/s11027-007-9082-9

Opheikens, T. (2021, June 13). *Industrie ziet de CO_2-prijs snel oplopen: "Het is een soort bitcoin."* https://nos.nl/artikel/2384855-industrie-ziet-de-CO_2-prijs-snel-oplopen-het-is-een-soort-bitcoin

Perrels, A. (2001). *Efficiency and effectiveness of policy instruments: Concepts and Practice*. *October*, 8–10.

Port of Rotterdam. (2020). *Waterstof economie in Rotterdam start met Backbone*.

Port of Rotterdam. (2021). *Port of Rotterdam*. https://www.portofrotterdam.com/en

Provincie Groningen. (2020). *Investeringsplan waterstof Noord-Nederland 2020*.

PwC. (2019). *nationale heffing op broeikasgas in de industrie*.

PwC. (2020). *Speelveldtoets 2020*.

Redactie Duurzaambedrijfsleven.nl. (2020, August 19). *Nederland dreigt achterop te raken met groene waterstof*. https://www.change.inc/energie/waterstof-nederland-34447

Reichardt, K., Negro, S. O., Rogge, K. S., & Hekkert, M. P. (2016). Analyzing interdependencies between policy mixes and technological innovation systems: The case of offshore wind in Germany. *Technological Forecasting and Social Change*, *106*, 11–21. https://doi.org/10.1016/j.techfore.2016.01.029

Reichardt, K., Rogge, K. S., & Negro, S. O. (2017). Unpacking policy processes for addressing systemic problems in technological innovation systems: The case of offshore wind in Germany. *Renewable and Sustainable Energy Reviews*, *80*(May), 1217–1226. https://doi.org/10.1016/j.rser.2017.05.280

Rifkin, J. (2003). *The Hydrogen Economy: The Creation of the Worldwide Energy Web and the Redistribution of Power on Earth*.

Rijksdienst voor Ondernemend Nederland. (2021a, June 17). *Demonstratie Energie- en Klimaatinnovatie (DEI+)*. https://www.rvo.nl/subsidie-en-financieringswijzer/demonstratie-energie-en-klimaatinnovatie-dei

Rijksdienst voor Ondernemend Nederland. (2021b, June 23). *Stimulering duurzame energieproductie en klimaattransitie (SDE++)*. https://www.rvo.nl/subsidie-en-financieringswijzer/sde

Rijksoverheid. (2020). *Government Strategy on Hydrogen*. *387*, 1–14.

Rijksoverheid. (2021a). *Overheid stimuleert CO_2-opslag*. https://www.rijksoverheid.nl/onderwerpen/duurzame-economie/overheid-stimuleert-CO_2-

opslag

Rijksoverheid. (2021b). *Overheid stimuleert de inzet van meer waterstof*. https://www.rijksoverheid.nl/onderwerpen/duurzame-energie/overheid-stimuleert-de-inzet-van-meer-waterstof

Rijkswaterstaat. (2021). *Rivieren*. https://www.rijkswaterstaat.nl/water/waterbeheer/beheer-en-ontwikkeling-rijkswateren/rivieren

Roberts, C., & Geels. (2019). Conditions and intervention strategies for the deliberate acceleration of socio-technical transitions : lessons from a comparative multi-level analysis of two historical case studies in Dutch and Danish heating. *Technology Analysis & Strategic Management*, *0*(0), 1–23. https://doi.org/10.1080/09537325.2019.1584286

Rooijers, F., & Naber, N. (2019). Uitstoot broeikasgassen in Nederland Een analyse van de sectoren en Uitstoot broeikasgassen in Nederland Een analyse van de sectoren en bedrijven met de meeste. *19.190227.152*, 1–50.

Rosenow, J., Kern, F., & Rogge, K. (2017). The need for comprehensive and well targeted instrument mixes to stimulate energy transitions: The case of energy efficiency policy. *Energy Research and Social Science*, *33*(March), 95–104. https://doi.org/10.1016/j.erss.2017.09.013

Rotman, E. (2020, May 20). *NorthH2: 's Werelds grootste project voor groene waterstof verduurzaamt de Nederlandse industrie*. https://www.change.inc/energie/groene-waterstof-north2-industrie-33839

Rotmans, J., Kemp, R., van Asselt, M., Geels, F., Verbong, G., & Molendijk, K. (2000). *De casus van een emissiearme energievoorziening*.

RVO, & EZK. (2019). *Waterstof: kansen voor de Nederlandse industrie*.

Savelkouls, J. (2021a). *Geen steun voor waterstoffabrieken H-Vision in nieuwe SDE++*. 22-02-21. https://energeia.nl/energeia-artikel/40091713/geen-steun-voor-waterstoffabrieken-h-vision-in-nieuwe-sde

Savelkouls, J. (2021b, March 10). *Geen "showstoppers" voor NortH2, maar zoektocht naar geld en steun begint pas*. https://energeia.nl/energeia-artikel/40091733/geen-showstoppers-voor-north2-maar-zoektocht-naar-geld-en-steun-begint-pas

Savelkouls, J. (2021c, March 18). *Waterstofleiding in Rotterdams havengebied mogelijk in 2024 gereed*. https://energeia.nl/energeia-artikel/40091763/waterstofleiding-in-rotterdams-havengebied-mogelijk-in-2024-gereed

Savelkouls, J. (2021d, March 31). *Nog meer waterstofplannen: Ørsted zint op 1 GW elektrolyse in Zeeland*. https://energeia.nl/energeia-artikel/40091891/nog-meer-waterstofplannen-rsted-zint-op-1-gw-elektrolyse-in-zeeland

Savelkouls, J. (2021e, April 13). *Toekomstig pan-Europees waterstofnetwerk groeit tot 40.000 kilometer*. https://energeia.nl/energeia-artikel/40092122/toekomstig-pan-europees-waterstofnetwerk-groeit-tot-40-000-kilometer

Sebastiaan Hers, Scholten, T., Veen, R. van der, Water, S. van de, Leguijt, C., Rooijers, F., & Delft. (2018). *Waterstofroutes Nederland Waterstofroutes Nederland*. 56.

SER. (2019). *Nationale klimaataanpak voor regionale industriële koplopers*.

Shackley, S., & Green, K. (2007). A conceptual framework for exploring transitions to decarbonised energy systems in the United Kingdom. *Energy*, *32*(3), 221–236.

https://doi.org/10.1016/j.energy.2006.04.010

Sherif, S. A., Barbir, F., & Veziroglu, T. N. (2005). Wind energy and the hydrogen economy-review of the technology. *Solar Energy*, *78*(5), 647–660. https://doi.org/10.1016/j.solener.2005.01.002

Širá, E., Vavrek, R., Vozárová, I. K., & Kotulič, R. (2020). Knowledge economy indicators and their impact on the sustainable competitiveness of the EU countries. *Sustainability (Switzerland)*, *12*(10). https://doi.org/10.3390/su12104172

Sluijters, S. (2021, February 23). *Geen steun voor H-Vision*. https://www.change.inc/energie/waterstof-rotterdam-35697

Smart Delta Resources. (2020). *Regioplan 2030-2050*. *0*. https://doi.org/10.31866/2410-1176.33.2015.158281

Stedin. (2020). *Waterstof in de gebouwde omgeving - working paper*. https://www.stedin.net/-/media/project/online/files/duurzaamheid-en-innovatie/waterstof-workingpaper.pdf

Team Stadszaken. (2019, July 26). *€ 2,8 miljard voor waterstof in Noord-Nederland*. https://stadszaken.nl/artikel/2067/euro-2-8-miljard-voor-waterstof-in-noord-nederland

Thiemann, F. (2018, December 10). *Aardgas: geopolitiek per pijpleiding*. https://oikosonline.nl/2018/12/10/aardgas-geopolitiek-per-pijpleiding/

TKI Nieuw Gas. (2018). *Contouren van een Routekaart Waterstof*.

TKI Nieuw Gas. (2021). *Regelingen*. https://www.topsectorenergie.nl/regelingen

TNO. (n.d.). *Duurzame waterstof optimaliseren met elektrolyse*. Retrieved July 15, 2021, from https://www.tno.nl/nl/aandachtsgebieden/energietransitie/roadmaps/CO_2-neutrale-industrie/waterstof-voor-een-duurzame-energievoorziening/optimalisatie-productieproces-waterstof/

van der Burg, L. (2021). *15 dingen die je moet weten over waterstof*. https://www.tno.nl/nl/aandachtsgebieden/energietransitie/roadmaps/CO_2-neutrale-industrie/waterstof-voor-een-duurzame-energievoorziening/15-dingen-die-je-moet-weten-over-waterstof/

van der Laak, W. W. M., Raven, R. P. J. M., & Verbong, G. P. J. (2007). Strategic niche management for biofuels: Analysing past experiments for developing new biofuel policies. *Energy Policy*, *35*(6), 3213–3225. https://doi.org/10.1016/j.enpol.2006.11.009

van der Lugt, H. (2021, June 23). *"Wie geeft ons de garantie dat waterstof een goed idee is?"* https://energeia.nl/energeia-artikel/40093829/wie-geeft-ons-de-garantie-dat-waterstof-een-goed-idee-is

van Renssen, S. (2020). The hydrogen solution? *Nature Climate Change*, *10*(9), 799–801. https://doi.org/10.1038/s41558-020-0891-0

van Santen, H. (2020). *Groene waterstof is nog te duur voor de fabriek*.

van Zon, H. (2020). *Waterstof maakt inhaalslag, maar ultieme energiebron heeft één nadeel*. https://www.ad.nl/auto/waterstof-maakt-inhaalslag-maar-ultieme-energiebron-heeft-een-nadeel~a999f85d/

Vedung, E. (1998). *Policy Instruments: Typologies and Theories*.

Velasquez, M., & Hester, P. T. (2016). An Analysis of Multi-Criteria Decision Making Methods. *Progress in Artificial Intelligence*, *5*(4), 315–322. https://doi.org/10.1007/s13748-016-0093-1

VEMW. (2021, July 2). *Kabinetsplan voor ontwikkeling waterstofvoorziening*. https://www.vemw.nl/Nieuwsoverzicht/2021-07-02-Waterstof-infrastructuur-marktordening.aspx

Verbong, G., & Geels. (2007). The ongoing energy transition: Lessons from a socio-technical, multi-level analysis of the Dutch electricity system (1960-2004). *Energy Policy*, *35*(2), 1025–1037. https://doi.org/10.1016/j.enpol.2006.02.010

Verhelst, K. (2021, March 31). *"Ik zie wel een analogie tussen wind toen en waterstof nu."* https://energeia.nl/fd-artikel/40091800/ik-zie-wel-een-analogie-tussen-wind-toen-en-waterstof-nu

Veugelers, R. (2012). Which policy instruments to induce clean innovating? *Research Policy*, *41*(10), 1770–1778. https://doi.org/10.1016/j.respol.2012.06.012

Wang, J. J., Jing, Y. Y., Zhang, C. F., & Zhao, J. H. (2009). Review on multi-criteria decision analysis aid in sustainable energy decision-making. *Renewable and Sustainable Energy Reviews*, *13*(9), 2263–2278. https://doi.org/10.1016/j.rser.2009.06.021

Weeda, M., Hoogma, R., & Boer, J. De. (2019). *Meerjarig waterstof programma*. *september*.

Wereldprimeur: transportschip voor vloeibare waterstof. (2019, December 24). https://opwegmetwaterstof.nl/wereldprimeur-transportschip-voor-vloeibare-waterstof/

Westerveld, J. (2020, November 6). *VVD wil subsidie voor kernenergie uit SDE++ en Groeifonds*. https://energeia.nl/energeia-artikel/40090446/vvd-wil-subsidie-voor-kernenergie-uit-sde-en-groeifonds

Westerveld, J. (2021a). *Grootverbruikers willen duidelijkheid van politiek over CO_2-opslag*. https://energeia.nl/energeia-artikel/40093915/grootverbruikers-willen-duidelijkheid-van-politiek-over-co-opslag

Westerveld, J. (2021b, April 16). *"Efficiënte transitie industrie vraagt om schrappen belastingvrijstellingen."* https://energeia.nl/energeia-artikel/40092034/efficiente-transitie-industrie-vraagt-om-schrappen-belastingvrijstellingen

Westerveld, J. (2021c, June 21). *Staatssecretaris: overstimulering groene energieprojecten niet uit te sluiten*. https://energeia.nl/energeia-artikel/40093821/staatssecretaris-overstimulering-groene-energieprojecten-niet-uit-te-sluiten

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

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

Wiskerke, W. (2020). *Wob : Minister Wiebes lost belofte niet in , vooral mkb betaalt voor vergroening van de grootste vervuilers in de industrie*. 1–9.

Appendix A Literature review

In Table 3, an overview is presented of the stabilizing pressures found in the literature.

Title	Authors	Technical	Economic	Policy and regulations
Analysis of non-economic barriers for the deployment of hydrogen technologies and infrastructures in European	Davide Astiaso Garcia	X		X
Future hydrogen economy and policy	A. Demirbas	X	X	X
Hydrogen futures: toward a sustainable energy system	S. Dunn	X	X	X
Wind energy and the hydrogen economy—review of the technology	S.A. Sherif	X	X	
The hydrogen solution?	S. van Renssen	X	X	X
Major technical barriers to a "hydrogen economy"	M. Balat & E. Kirtay	X	X	
What governs the transition to a sustainable hydrogen economy? Articulating the relationship between	M. Hisschemöller, R. Bode, M. van de Kerkhof			X
Policies for the transition towards a hydrogen economy: the EU case	R. Bleischwitz, N. Bader	X		X
Flexible hydrogen production implementation in the French power system: Expected impacts at the French	P. Caumon, M. Lopez-Botet Zulueta, J. Louyrette et al.		X	
Techno-economic assessment of hydrogen production processes for the hydrogen economy for the short and	F. Mueller-Langer, E. Tzimas, Kaltschmitt et al.	X		
The hydrogen economy – Vision or reality?	M. Ball, M. Weede		X	X
A Review of Technical Advances, Barriers, and Solutions in the Power to Hydrogen (P2H) Roadmap	G. Hu, C. Chen, H. Thuan Lu et al.	X	X	
Analysis of the strategies for bridging the gap towards the Hydrogen Economy	R. Moliner, M.J. Lázaro, I. Suelves	X	X	
Hydrogen as a fuel and energy storage: Success factors for the German Energiewende	O. Ehret, K. Bonhoff		X	X
Is cluster policy useful for the energy sector? Assessing self-declared hydrogen clusters in the Netherlands	P. Mans, F. Alkemande, T. van der Valk et al.			X

Table 14: Stabilizing pressures found during a literature review

Appendix B Interviews

Subjects for the interviews

Stabilizing en destabilizing pressures

1. Herkennen de interviewees de geïdentificeerde stabilizing en destabilizing pressures. Zijn de interviewees het ermee eens, wat is volgens hen de oorzaak? Zijn er nog andere pressures die niet zijn meegenomen in dit onderzoek maar die wel relevant zijn?

Policy instruments

2. Zijn alle interviewees op de hoogte van de geselecteerde beleidsinstrumenten. Heb ik belangrijke beleidsinstrumenten niet meegenomen? Hoe kijken ze in het algemeen aan tegen deze beleidsinstrumenten?

Assessment

3. Hoe kijken de experts aan tegen deze beleidsinstrumenten aan, welke zijn volgens hen effectief op de stabilizing en destabilizing pressures? Welke zou de overheid moeten inzetten en waarom? Op wat voor manier zou de overheid ze moeten inzetten? Zijn ze effectief als ze alleen worden ingezet, of is er een policy mix nodig?

Scenarios

4. Wat als de Nederlandse overheid geen effectieve (of helemaal geen) beleidsinstrumenten inzet? Is Nederland al te laat met het inzetten van beleidsinstrumenten? Hoe ziet volgens u de tijdshorizon eruit op de waterstof ontwikkeling in Nederland?